EFFECTS OF CARBOXYMETHYL CELLULOSE AND BIOSTIMULANTS ON SOIL HYDRATION, APPLE GROWTH, AND YIELD

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(Received 2nd Jan 2025; accepted 19th Mar 2025)

Abstract. The low water and fertilizer retention capacity of sandy soils poses a challenge for apple cultivation in Xinjiang, China. Severe drought stress adversely affects apple growth and yield. We investigated the effects of sodium carboxymethyl cellulose (CMC) and a biostimulant (BS) on soil water and nutrient retention, apple growth, and yield. Field experiments were performed in Alar City, Xinjiang, using three application levels of CMC and BS, nine treatments, and one control (without CMC and BS, CK treatment). CMC had the greatest effect on soil moisture content, increasing soil water content to over 11.33%, while total nitrogen (TN) content increased 5.83% compared to CK treatment. CMC and BS had a highly significant effect on soil TN content in flowering and fruiting stages. The combined application of CMC and BS enhanced new shoot growth, stem thickness, and leaf area index (LAI) compared to CK treatments. BS had the greatest effect on these parameters. Among the treatments, B3C2 exhibited the highest water consumption, while CK had the lowest. CMC most affected yield, and BS most affected water production efficiency; B2C2 had the highest yield (43,890 kg ha^{-1}) and water productivity (8.20 kg m^{-3}) among treatments. The highest water production efficiency was achieved with a BS application of 26.25 kg ha^{-1} and a CMC application of 26.25 kg ha^{-1}, as determined by modeling the relationship between CMC application rate and water production efficiency.
Keywords: *sandy soil, CMC, water consumption, yield, WUE*

Introduction

Growing water scarcity and its uneven distribution have raised concerns about efficient use of water resources and sustainable development of global agriculture (Chen and Zhu, 2024). In China, where approximately 25% of the total land area is arid or semi-arid, water shortage limits agricultural development. Because most arable lands also lack irrigation, considerable annual drought stress seriously affects crop yield and quality (Zhang et al., 2020). Drought stress was identified as the primary constraint on agricultural production in China nearly two decades ago (Cai, 1996) and continues to be a major challenge (Yu et al., 2024).

South Xinjiang, at the edge of Taklamakan Desert, is a typical arid region with limited rainfall. This region is affected by water shortage and inefficient water resource use because of poor water and fertilizer retention capacity of sandy arable land (Zhang et al., 2019). Drought stress caused by the soil's poor water-holding capacity limits crop growth in this region (Zhang et al., 2018a). Sandy soil affects the structure and activity of soil microbial communities, and the effectiveness of soil nutrients, which affects crop yield by reducing crop uptake of N and other nutrients, inhibiting crop growth (He et al., 2015; Han et al., 2021). Therefore, improving the water and fertilizer retention capacity of sandy soils in southern Xinjiang is central to solving the production dilemma of this region's sandy cropland.

Water retaining agents (new polymer types) have been recently, successfully used to improve soil-water retention and fertilizer capacity. These polymers can absorb water equivalent to hundreds of times their own weight, and then release the water slowly. With repeated absorption and release of water, surface runoff can be reduced, the effective soil water content increased, precipitation infiltration enhanced, and water evaporation reduced (Li et al., 2017). Because these polymers also help to retain soil and fertilizer, regulate soil temperature, and promote plant growth and development, they play an important role in improving the ability of soil water and fertilizer retention (Chen et al., 2008; Yang et al., 2010). However, the cost, short-lived effect, and possible negative environmental impacts of these water retention agents have limited their application in agricultural production. Therefore, research on alternative, more environmentally friendly and sustainable soil-water retention agents is required.

While CMC has been widely used in food, medicine, cosmetics, and other fields, it can also improve the physical and chemical properties of soil, reduce soil bulk weight, increase its porosity, and improve its structure, as well as enhance particulate adhesion to promote formation of soil macro-agglomerates (Qiu et al., 2013). However, while CMC can improve water-retention capacity and soil structure, promote plant-root development, and enhance soil nutrient sequestration capacity (Jiang et al., 2023), how it does so is imperfectly known (Li et al., 2024).

Biostimulants are a class of substances that regulate plant growth. They contain certain active ingredients or microorganisms that can act on plant leaves or root systems to promote plant nutrient uptake, alleviate abiotic stress, accelerate growth and development, and improve yield and quality (Jardin, 2012; Bai, 2017; Xie et al., 2019). Biostimulants have increased yields and quality of tomato (Zhang et al., 2020), sweet corn (Chen et al., 2020), rice (Shu et al., 2019), and cereals (Mi, 2021). Accordingly, we developed a novel biostimulant—a water-soluble, organic–inorganic composite regulator—coupled with components such as glycine, proline, *Bacillus subtilis*, xanthohumic acid, and sodium alginate oligosaccharides, formulated using magnetically charged water treated with a combination of magnetization and de-electronization techniques. This biostimulant achieved good yield and quality improvement in cotton (Sun et al., 2024), Sudangrass (Liu, 2023), and silage maize (Yuan, 2023). We here appraise the effect of its application on "Royal Gala" apple.

We couple carboxymethyl cellulose (CMC) and our biostimulant and analyze their effects on soil water content, soil nutrients, new growth, leaf area index, and yield of sandy apples in the southern Xinjiang region. Additionally, we appraise water production efficiency, and identify optimal water use conditions to inform sustainable development of apple production in southern Xinjiang.

Materials and methods

Experimental site

The experiment was performed in a field in the 10th Regiment of Alar City, the First Division of Xinjiang Production and Construction Corps (40°39'N, 81°16'E), the specific location of the experimental site is shown in *Figure 1*. The area experiences an extremely arid climate, with a multi-year average temperature of 11 ± 1°C, and annual

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

rainfall (~50 mm), evapotranspiration (~2100 mm), total solar radiation (552.73 kJ cm^{-2}), and sunshine hours (~2900 h); and a frost-free period exceeding 200 d. Averages of soil water-holding capacity to 120 cm are 18.5% (volumetric water content) and soil bulk density are 1.51 g cm^{-3}, the water table is at ~3.0 m depth, and the sand content in the upper 100 cm of soil exceeds 90%.

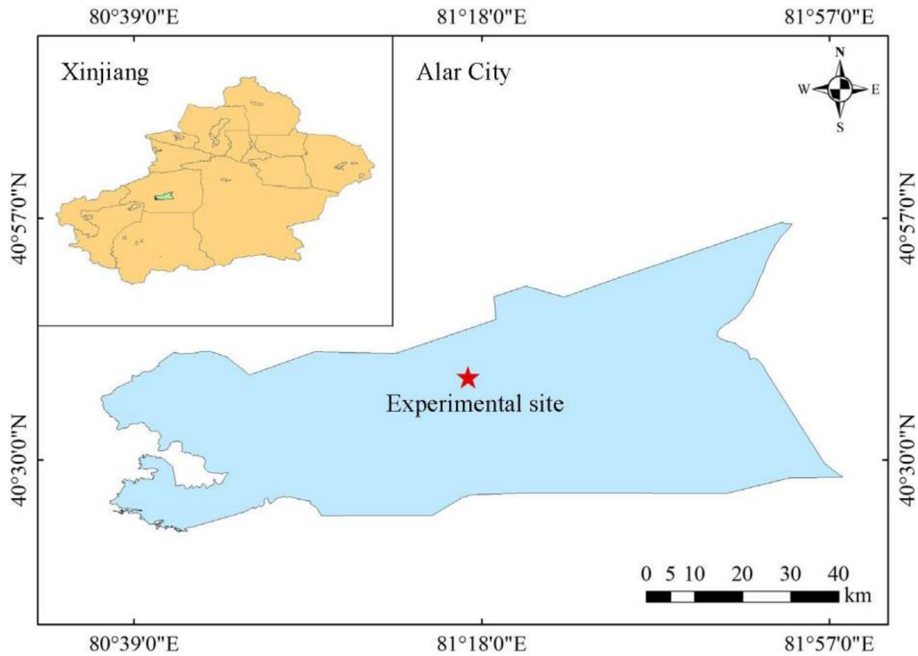

Figure 1. *The map of this test study area*

Planting and experimental design

The experiment was performed from April to August 2023 on “Royal Gala” apple trees of 9-years age, 3 m height, with 1 m spacing between trees in a row and 4 m spacing between rows; trees were planted in a dwarf dense planting mode, with trees fixed at either row ends by cement stakes (*Figure 2*). A single drip irrigation pipe with drip head flow rate 4 L h^{-1} and drip head spacing 50 cm was fixed to the ground with a wire at a height of 50 cm (to facilitate weeding). Tree fertility stage was divided into flowering and fruiting, fruit expansion, and maturation stages.

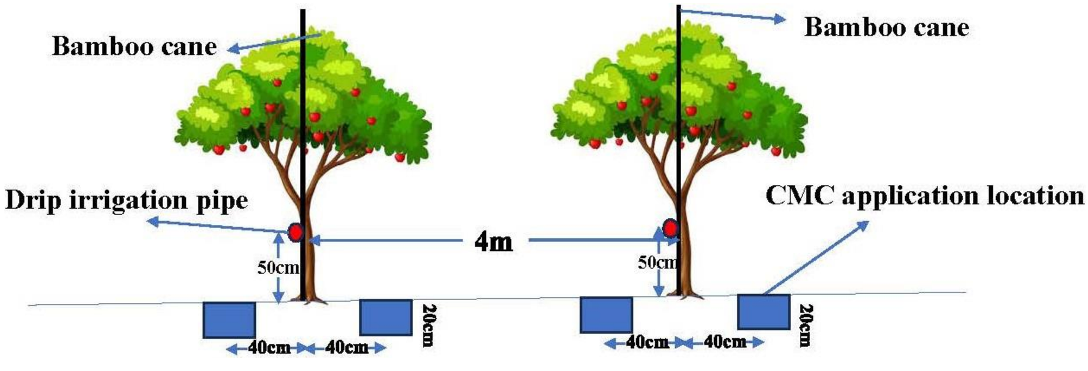

Figure 2. *Apple planting pattern in the experimental field*

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DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

The experiment was performed under the same irrigation and fertilization conditions, with 32 irrigations and 32 fertilizer applications throughout the reproductive period, with an irrigation quota of 554 mm. Sodium CMC was used as the soil conditioner, at three concentrations (C1, 12 kg ha^{-1}; C2, 24 kg ha^{-1}; C3, 36 kg ha^{-1}), and the biogenic stimulant (glycine, proline, fulvic acid, *B. subtilis*, and sodium alginate oligosaccharides) was developed independently at three concentrations (B1, 15 kg ha^{-1}; B2, 22.5 kg ha^{-1}; B3, 30 kg ha^{-1}). Nine experimental treatments were established using all permutations of CMC and BS, in addition to a control treatment (CK) with no CMC and BS. Each treatment covered an area of 0.08 ha and included 4 rows of trees, each 50 m long (200 trees per treatment); the total experimental area of the 10 treatments was 0.8 ha. At the beginning of the reproductive stage, CMC was applied using trenches of 40 cm length and width, 20 cm depth, and excavated 40 cm from the tree roots on a single side; CMC was applied by mixing it evenly with the soil. BS was applied with water by drip three times during the flowering and fruiting, young fruit development, and fruit expansion stages using a differential pressure fertilization tank. Nitrogen was supplied via urea of content of 46%, with phosphate and potash selected as potassium dihydrogen phosphate (containing $P_2O_5 \geq 52\%$ and $K_2O \geq 34\%$), combined with an ammonium compound fertilizer containing $N \geq 19\%$, $P_2O_5 \geq 19\%$, and $K_2O \geq 19\%$. Cultivation management was the same for all treatments. The specific experimental design is detailed in *Table 1*.

Table 1. *Experimental treatment design*

Treatments	BS (kg ha^{-1})	CMC (kg ha^{-1})
B1C1	12	15
B1C2	12	22.5
B1C3	12	30
B2C1	24	15
B2C2	24	22.5
B2C3	24	30
B3C1	36	15
B3C2	24	22.5
B3C3	36	30
CK	0	0

Measurement items and methods

Soil moisture content

During the reproductive stage the soil was sampled by auger at distances of 0, 30, and 60 cm from the fruit trees (horizontal direction), to 1 m (vertically), with samples collected every 20 cm through the soil column, and soil from 3 sampling points was taken for each treatment (3 samples per treatment). All samples were dried to determine the mass water content; the volumetric water content of the soil was determined using some samples (the product of soil bulk weight and mass water content); and some samples were sieved to determine nutrients.

Treatment water consumption was calculated using the water balance method (Yu and Han, 2020). Because irrigation was achieved by drip, which did not achieve deep seepage, and because the sandy soils were not conducive to surface runoff, both deep seepage and runoff could be disregarded. Because the water table was ~3 m, and the

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apple root system occurred mainly in the upper 60 cm, the contribution of groundwater to apple growth could also be disregarded. Therefore, the simplified water balance equation is:

$$ET_a = I + P + \Delta W \quad \text{(Eq.1)}$$

where ET_a is effective water consumption (mm), P is effective rainfall during the reproductive period (mm), I is irrigation water quantity (mm), and ΔW is the calculated change in soil water storage in soil layers (mm).

Soil total N content

During the reproductive period, three fixed soil sampling points were established for each treatment, with samples taken at the same distance from the tree trunk. For each soil sample, they were collected at the same depth (40 cm) to ensure consistency and comparability. soil samples were air dried, ground into powder, and passed through a 0.15 mm sieve (to ensure particle size consistency); a 200 mg subsample was then taken, accurately weighed, and packed in specific tinfoil to ensure sample accuracy and reproducibility. Soil total nitrogen (TN) content from the root zone of each treatment crop was determined by the Flow injection analyzer (AA3 continuous flow analyzer, SEAL, Germany).

New shoot growth and stem thickness

According to tree growth conditions, at the early stage of new shoot growth, new shoot samples (consistent growth and representative of the current year's new shoots) were selected in the east, south, west, and north directions, and marked (Red label paper was used as a marker). From April 15, stem length was measured by tape measure and thicknesses by Vernier calipers, every 15 d.

Leaf area index

Leaf area index (LAI) was measured using a LAI-2200C canopy analyzer (Li-Cor, USA), read directly from radiation transmittance measurements, measured every 10 d. Each time, the same three sample trees were consistently measured, with measurements taken from the east, south, west, and north directions at a fixed distance of 50 cm from each sample tree and at a height of 50 cm above the ground. Because apple leaf area tends to increase and then decrease through the fertility cycle, consistent with a modified logistic model (Zhao et al., 2023), we used a modified logistic model to regress apple LAI on the change in effective cumulative temperature, to construct a logistic LAI growth model. The expression of the logistic model for new stem thickness is:

$$LAI = \frac{LAI_m}{1+e^{a_4 - a_5 GDD + a_6 GDD^2}} \quad \text{(Eq.2)}$$

where LAI is the apple leaf area index, LAI_m is the theoretical maximum of the LAI, GDD is effective accumulated temperature (°C) (Lin et al., 2023), and a_4, a_5 and a_6 are empirical coefficients.

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DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

Meteorological data and effective accumulated temperature

A small automatic monitoring weather station (RX3000, HOBO, USA) was established in an open space within the experimental field at 2 m height. Radiation (kJ cm^{-2}), photosynthetically active radiation, rainfall (mm), wind speed, relative humidity, air temperature (°C), and barometric pressure were monitored, with a recording time set to 30 min.

Effective cumulative temperature refers to the cumulative temperature within a certain temperature range, and is usually obtained by subtracting the ambient temperature from the reference temperature, and then considering the limitation of temperature on growth. The specific calculation formula is (Wang et al., 2020):

$$GDD = \sum(T_{avg} - T_{base}) \quad \text{(Eq.3)}$$

where *GDD* is effective accumulated temperature, and T_{avg} is average daily temperature. In the calculation, when T_{avg} is ≤ the lowest suitable crop temperature (T_{base}), take $T_{avg} = T_{base}$; when T_{avg} is ≥ the highest suitable crop temperature (T_{upper}), take $T_{avg} = T_{\text{upper}}$; in all other cases, take the average value of the daily maximum and minimum temperatures. Where T_{base} is the lower temperature limit required for crop activity, Tx is the daily maximum temperature; Tn is the minimum temperature; and T_{upper} is the upper temperature required for crop activity.

Apple yield

During fruit ripening (August 20), five trees in each treatment were randomly selected for fruit picking. The apple weights from the five sample trees were used to obtain the average yield per apple tree, which was then multiplied by the number of fruit trees per hectare to obtain yield per hectare.

Water production efficiency

Apple water productivity refers to the ability of an apple tree to effectively use water during growth, and usually refers to the economic yield per unit of water consumption, calculated as follows:

$$WUE = \frac{Y}{10ET_a} \quad \text{(Eq.4)}$$

where *WUE* is water production efficiency (kg m^{-3}), and *Y* is apple yield (kg ha^{-1}).

Statistical analysis

Microsoft Excel 2019 was used to organize data, and Origin 2021 and 1stOpt1.5 were used to plot and fit data, respectively; the least significant difference (LSD) test was performed on ANOVA results and for main effect analysis ($P < 0.05$).

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Results

Main effects analysis of indicators

CMC had a highly significant ($P < 0.01$) effect on soil water content at all stages (flowering and fruiting, fruit expansion, and maturation); BS had a significant effect on soil water content at the maturation stage, but any interaction between the two was not significant ($P > 0.05$) on soil water content at different reproductive stages; and the main effect of soil water content was that CMC > BS (*Table 2*). CMC and BS had highly significant effects on soil TN content during the flowering and fruiting stage, no significant effect on soil TN content during fruit expansion and maturation stages, and there was no significant interaction between the two on soil TN content throughout the reproductive period. BS had a highly significant effect on the maximum length of new shoots (TL_{max}), a significant effect on the maximum thickness of new shoots (TR_{max}); CMC did not significantly affect TL_{max}. CMC and BS had highly significant and significant effects on LAI_{max}, respectively, with the main effect on LAI_{max} being that CMC > BS. The effect of CMC and BS on LAI_{max} was highly significant, with the main effect on LAI_{max} being that BS > CMC. CMC and BS significantly affected yield (Y) and water production efficiency (WUE), there was no interaction effect on Y and WUE, the main effect of CMC on Y was that it was more than BS, and the main effect of BS on WUE was that it was more than CMC.

Table 2. *Main effect analysis of CMC and BS application rates on indicators*

Indicator	CMC×BS (F value)	CMC (F value)	BS (F value)
T1	1.74ns	53.17**	3.25ns
T2	1.65ns	54.61**	3.32ns
T3	3.74ns	57.24**	4.46*
N1	0.68ns	6.03**	6.09**
N2	2.00ns	0.42ns	1.19ns
N3	1.50ns	0.12ns	0.65ns
TL_{max}	0.12ns	1.17ns	16.91**
TR_{max}	1.17ns	2.48ns	4.98*
LAI_{max}	1.10ns	6.10**	19.82**
Y	0.56ns	5.53*	5.02*
WUE	2.83ns	10.12**	13.82**

Note: * indicates significant effect ($P < 0.05$), ** indicates highly significant effect ($P < 0.01$), and ns indicates non-significant effect ($P > 0.05$). T1, T2, T3, N1, N2, N3, TL, TR, LAImax, Y, and WUE represent the soil moisture content of 30 cm at the flowering and fruiting stage, 30 cm at the fruit expansion stage, 30 cm at the maturation stage, soil total nitrogen content at the flowering and fruiting stage, soil total nitrogen content at the fruit expansion and maturation stages, maximum new shoot length, maximum new shoot stem thickness, maximum leaf area index, yield, and water production efficiency, respectively

Soil moisture content

Soil moisture differed by treatment (*Figure 3*). CMC and BS treatments in the flowering and fruiting, fruit expansion, and maturation stages all had the greatest soil moisture content at 30 cm from the tree, then 60 cm away, and least at 0 (mainly related to the location of the CMC application (which was buried 40 cm from the tree, 20 cm wide, and 30 cm from the tree body). The soil moisture content (At a distance of 30 cm)

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of all CMC and BS combination treatments exceeded that of the CK treatment, compared to CK treatment, the soil water content was enhanced to more than 15.80%, 12.40% and 11.33% at the flowering and fruiting, fruit expansion and maturation stages, respectively.

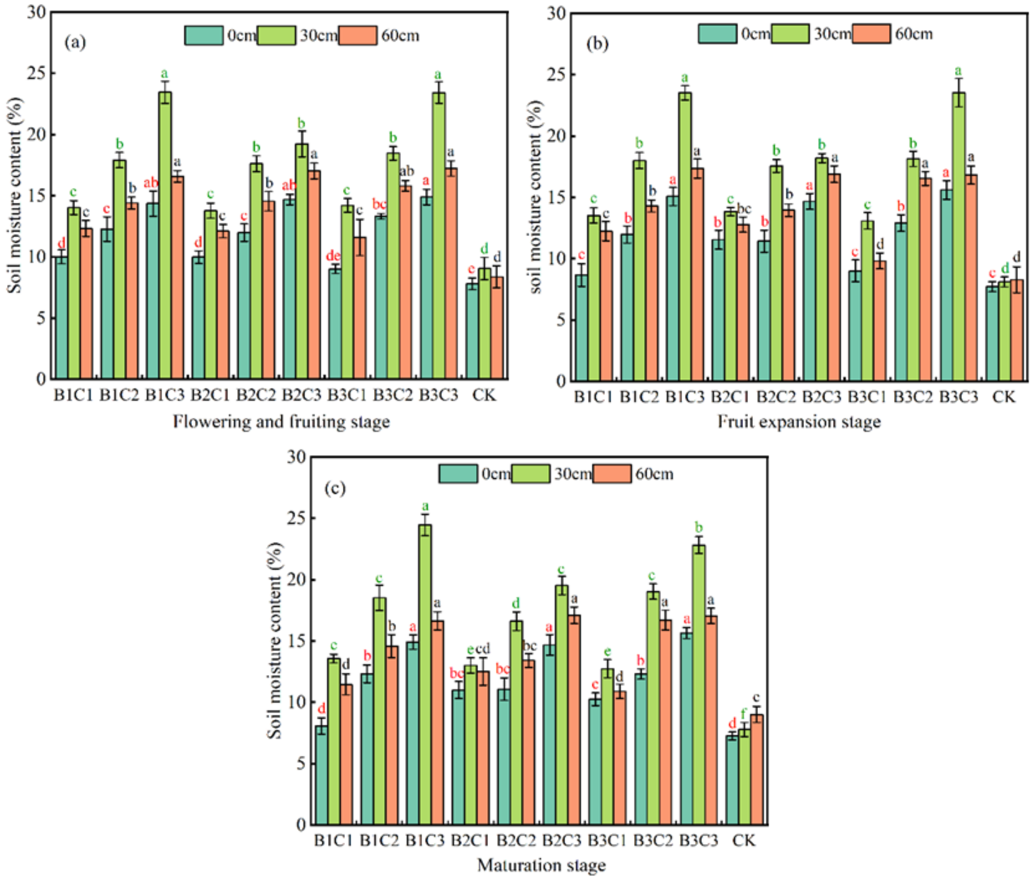

Figure 3. *Mean soil moisture content of treatments by fertility period. Note: Different letters in the same color font in the same graph are significantly different (P < 0.05)*

At a constant BS application rate, soil moisture contents at 30 cm for each fertility stage trended upwards with increased CMC application rate, indicating that CMC had good water retention properties. However, under the B2 application rate, the increase in soil moisture content was not significant ($P > 0.05$) between the C2 and C3 treatments. At a constant CMC application rate, soil moisture contents at 30 cm for each tree for all fertility stages did not differ significantly among treatments with increased BS application rate. Soil moisture contents at 30 cm for different fertility stages in treatment B3 were greatest and in B2 lowest, possibly because tree water consumption was greatest in treatment B2.

Soil total nitrogen contents

Treatment soil TN contents are shown in *Figure 4*. During the same reproductive period, TN contents in each treatment exceeded that of the CK treatment. Compared with CK, TN contents in treatments at the flowering and fruiting stage increased by

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6.03%–33.46%, at the fruit expansion stage by 5.83%–28.89%, and at the maturation stage, by 12.51%–26.38%. When CMC was applied at a constant rate, soil TN contents at the flowering and fruiting stage first trended upwards and then downwards with increased BS application, but this pattern changed in the fruit expansion and maturation stages.

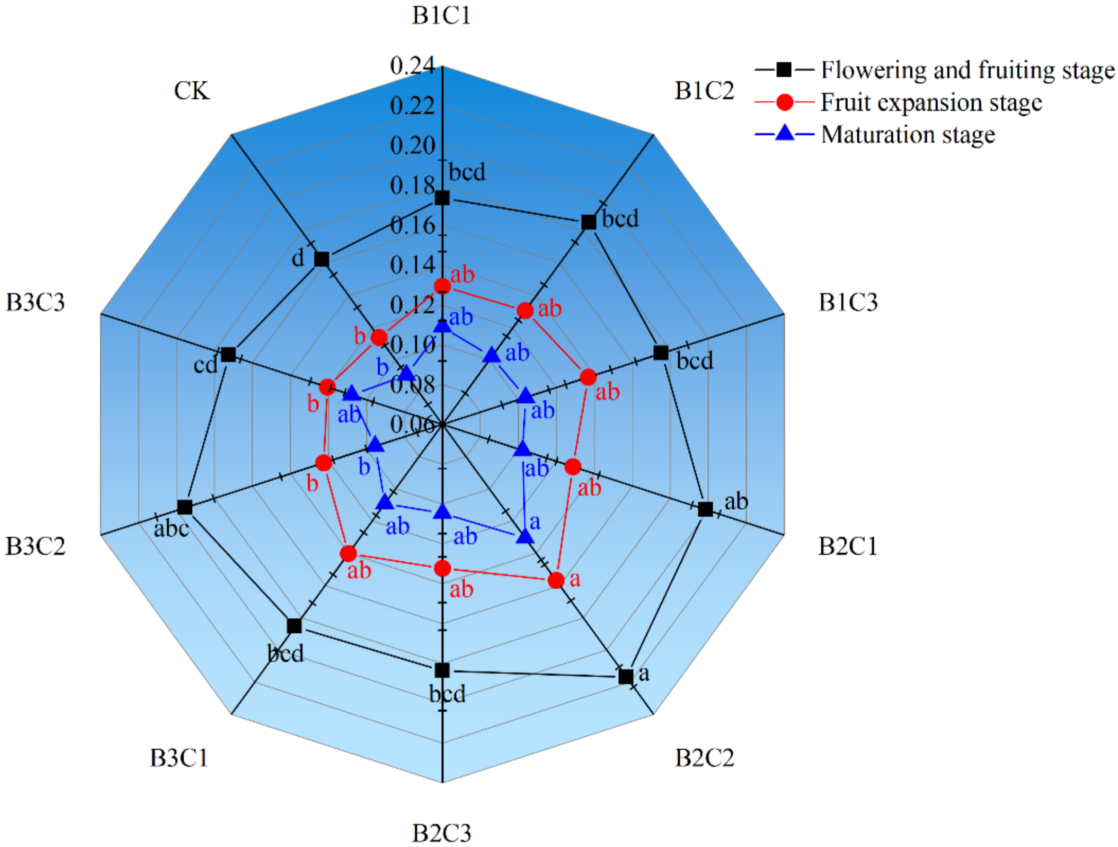

Figure 4. *Change in average total nitrogen content in treatments by fertility stage. Note: different lowercase letters indicate significant differences (P < 0.05)*

New shoots and stem thickness

Change in new shoots by treatment is shown in *Figure 5*. New shoot length in each treatment gradually increased and stabilized over time, (an “S-type” trend). From April 15–30, new shoot length growth was slow, and the difference between treatments was not significant. From April 30 to June 29, new shoot growth was rapid, averaging 0.22 cm d^{-1} (shoot length 31.3–40.8 cm), the difference between treatments became gradually more obvious, and new shoot length exceeded that of the CK treatment. At a constant CMC application rate, new shoot length first increased, then decreased with increased BS application rate. Among treatments, new shoot length was greatest in treatment B3C2 (40.9 cm) and least in the CK treatment (34.7 cm), indicating that CMC promoted new shoot growth.

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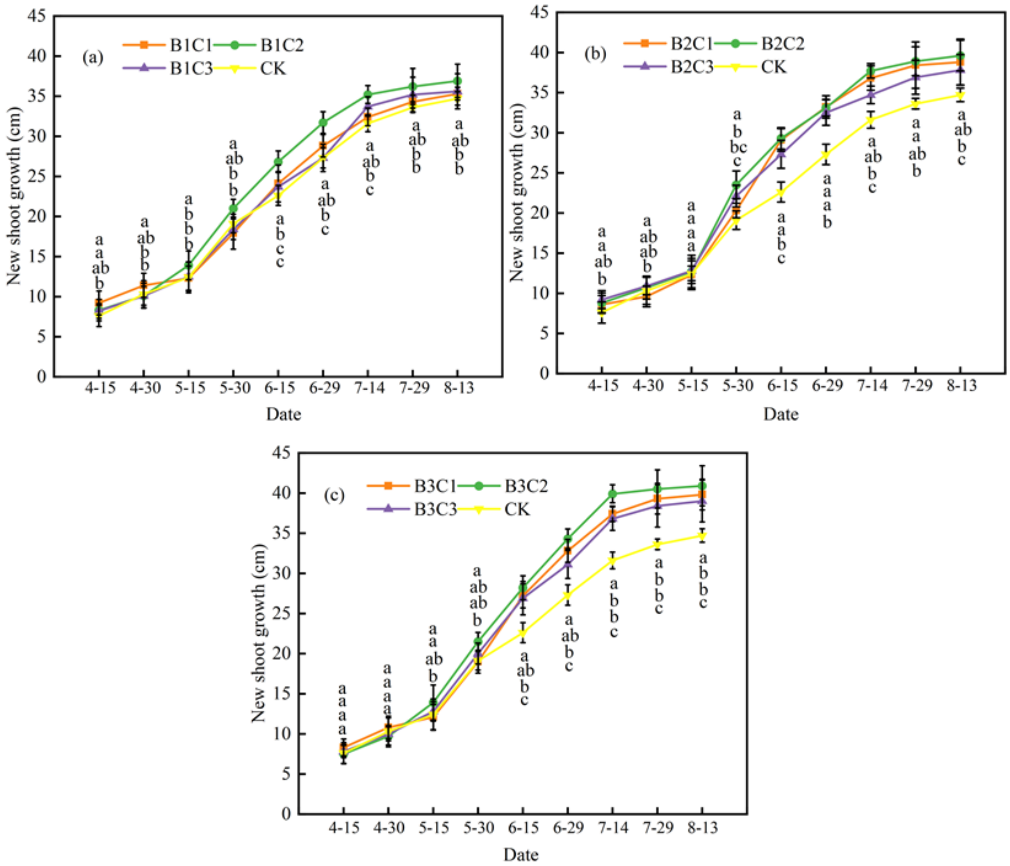

***Figure 5.** New shoot growth by treatment. Note: different lowercase letters indicate significant differences (P < 0.05)*

Change in thickness of new stems by treatment is shown in *Figure 6*. New stem thickness in each treatment grew continuously over time, but was fastest during the fruit-expansion stage, slowed during the maturation stage, and gradually trended upwards and then stabilized over time. Specifically, in the new growth period (April 15–30), growth in new stem thickness was slow, and the difference between treatments was not obvious. In the middle stage of new growth (April 30 to June 29), the increase in new stem thickness was rapid (0.049 mm d^{-1}), stems were 5.16–6.41 mm thick, and the difference between treatments became more obvious; the average daily growth in stem thickness in treatment B3C1 (0.055 mm d^{-1}) was greatest. Compared with the CK treatment, the average daily growth rate in new stem thickness of other treatments increased by 7.14%–26.42%. During the late growth stage (June 30 to August 13), new stems increased by an average of 0.022 mm d^{-1}, and growth rate decreased. At a constant CMC application rate, new stem thickness first increased, then decreased with increased BS application rate. At a constant BS application rate, new stem thickness increased with increased CMC application rate. Among treatments, the B3C2 treatment had the largest new stem thickness (7.2 mm), and the CK treatment had the least (6.4 mm), indicating that coupling CMC and BS promoted new stem growth.

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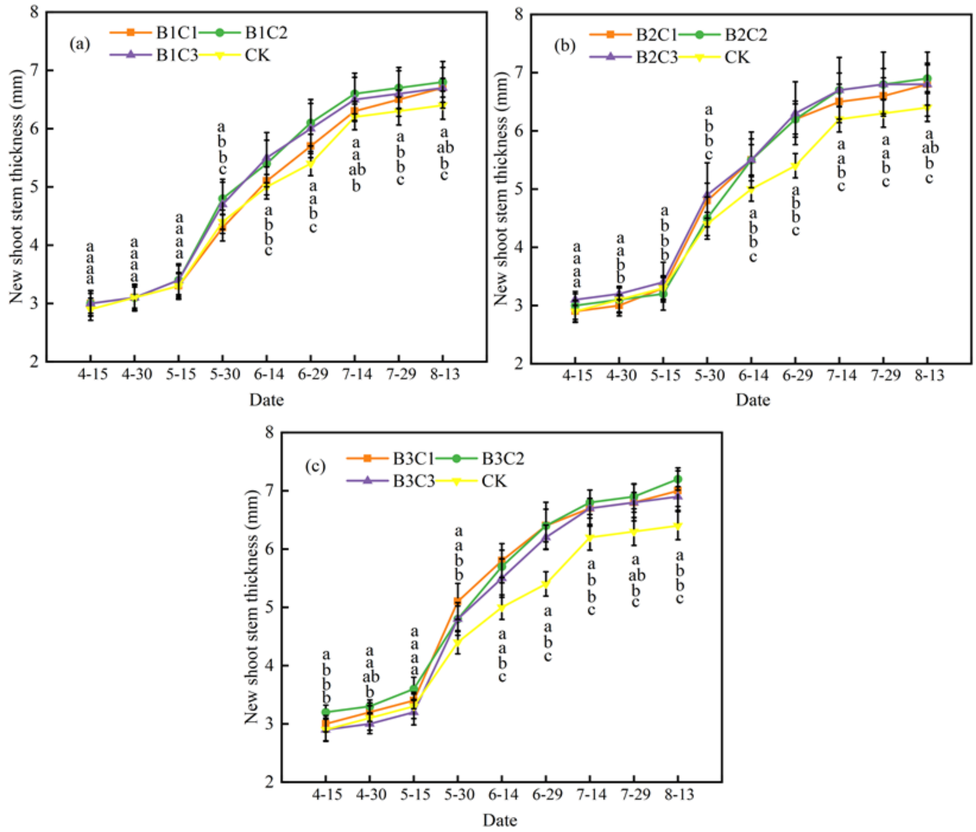

Figure 6. *Growth in new shoot stem thickness by treatment. Note: different lowercase letters indicate significant differences (P < 0.05)*

Leaf area index

Variation in LAI by treatment is shown in *Figure 7*. Over time, LAI in each treatment first trended upwards, and then decreased. Growth in LAI falls roughly into three periods. Initially (April 15 to May 15) LAI increased on average by 0.006 d^{-1}, and peaked at 0.482 during a period of slower growth, when the LAI in each treatment was lower. May 15 to July 14 was a period of rapid leaf growth, with an average increase in LAI of 0.012 d^{-1}, and with LAI ranging 1.532–0.699. B3C2 had the greatest average rate (0.032 d^{-1}); compared with the CK treatment, the increase in LAI for other treatments ranged 0.73%–12.58%, and differences among treatments became increasingly obvious. The average daily growth in LAI increased by 50% and the mean LAI increased by 306.9% compared with the early growth period. At the end of the growth period (July 14 to August 28), the LAI trended downward, but remained high, and was greatest in B3C2 (1.912) and lowest in CK (1.551).

Results of the logistic model fitting for the LAI of each treatment are shown in *Figure 8*, and results of model parameters are presented in *Table 3*. The maximum LAI value deduced using this model was close to the measured value. The coefficient of determination of the model fitting (R^2) was close to 1, and root-mean-square errors were smaller, all less than 0.084, indicating that the modified logistic model could fit the process of change in LAI. The theoretical maximum LAI value in the coupled CMC and BS treatment increased by 1.8%–24.4 % compared with CK, indicating that CMC and BS can effectively promote LAI growth.

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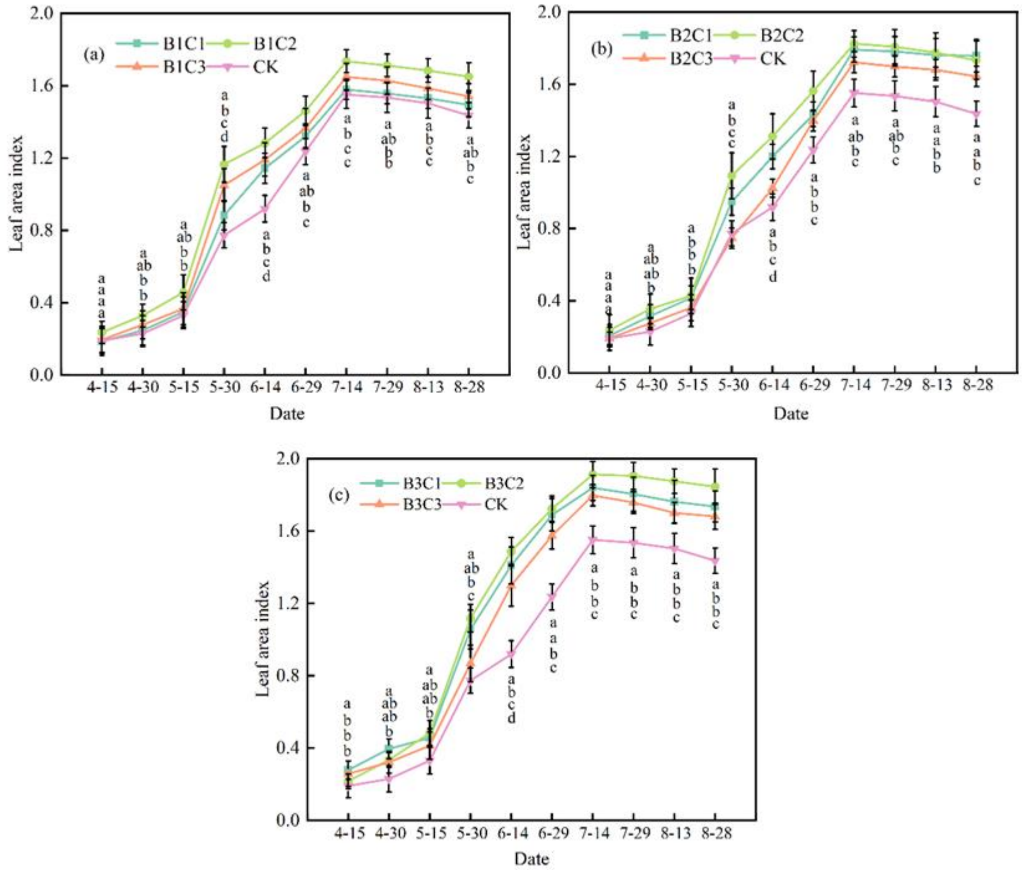

Figure 7. *Change over time in leaf area index by treatment. Note: different lowercase letters indicate significant differences (P < 0.05)*

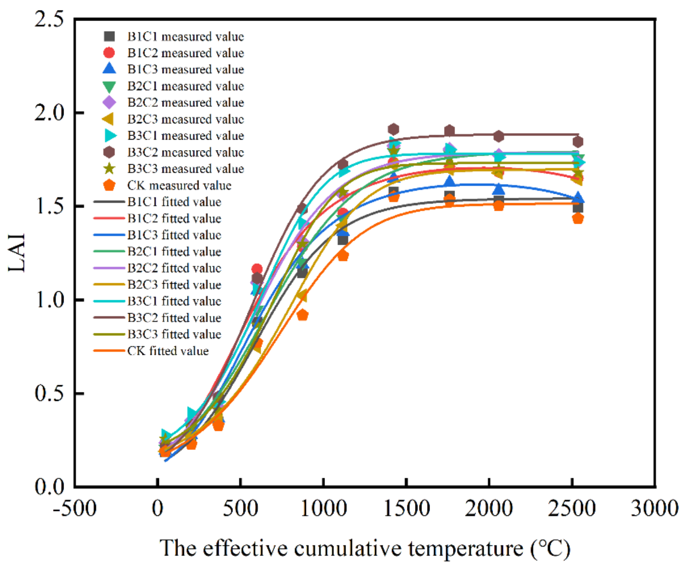

Figure 8. *Logistic growth model fit of leaf area index (LAI) by treatment*

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DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

Table 3. *Leaf area index (LAI) logistic model fitting parameters for different treatments*

Treatments	LAI_m	a_4	a_5	a_6	R^2	RMSE
B1C1	1.542	2.483	0.0043	−8.84E-08	0.983	0.057
B1C2	1.824	2.483	0.0052	−1.33E-06	0.968	0.084
B1C3	1.751	2.698	0.0054	−1.39E-06	0.968	0.082
B2C1	1.794	2.263	0.0035	−1.62E-06	0.984	0.064
B2C2	1.788	2.255	0.004	−3.14E-08	0.977	0.074
B2C3	1.697	2.092	0.002	−1.15E-06	0.990	0.047
B3C1	1.783	1.906	0.0024	−1.70E-06	0.988	0.053
B3C2	1.885	2.443	0.0043	−1.85E-07	0.992	0.047
B3C3	1.731	1.946	0.002	−1.84E-06	0.992	0.041
CK	1.515	2.129	0.0026	−6.99E-07	0.974	0.066

Note: LAIm is the theoretical maximum LAI; a_4, a_5, and a_6 are model fitting parameters; R^2 is the model coefficient of determination; and RMSE (root mean square error) is the departure from the mean

Water consumption, yield, and water production efficiency

Water consumption, yield, and water production efficiency of treatments are presented in *Table 4*. Throughout the reproductive period the B3C2 treatment consumed most water (558.00 mm), and the CK treatment consumed the least (528.03 mm). At a constant BS application rate, there was a tendency for water consumption to decrease and then increase with increased CMC application, with increases of 2.81% (C1), 2.71% (C2), and 3.46% (C3) compared with the CK treatment. For a constant CMC concentration, but increased BS application, water consumption tended to first increase, then decrease, with B1, B2, and B3 treatments increasing by 2.11%, 5.21%, and 2.08%, respectively, compared with the CK treatment. Water productivity in different treatments significantly increased by 7.20%–25.92% compared with the CK treatment. For a constant BS application rate, the water production efficiency first trended upwards and then downwards with increased CMC. At each CMC application rate, water production efficiency first trended upwards, then downwards with increased BS. Water production efficiency peaked in B2C2 (8.20 kg m^{-3}) and was lowest (6.51 kg m^{-3}) in the CK treatment.

Table 4. *Water consumption, yield, and water productivity in treatments*

Treatment	Water consumption (mm)	Yield (kg ha^{-1})	Water production efficiency (kg m^{-3})
B1C1	529.77	38070 ± 2792.42ab	7.19
B1C2	553.12	40050 ± 1402.00ab	7.24
B1C3	545.66	38100 ± 2042.20b	6.98
B2C1	546.64	40620 ± 750.60ab	7.43
B2C2	535.15	43890 ± 1571.50a	8.20
B2C3	545.18	40350 ± 2460.73ab	7.40
B3C1	548.60	41460 ± 2448.63a	7.56
B3C2	558.00	42480 ± 2682.95a	7.61
B3C3	532.34	38730 ± 1837.61ab	7.28
CK	528.03	34392 ± 837.38c	6.51

Note: data are means ± standard deviations; different letters within the yield column indicate significant differences at $P < 0.05$

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DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

Optimizing water production efficiency

Water productivity was affected by a combination of CMC and BS, so the functional relationship between them was established (*Figure 9*) in accordance with the following equation:

$$WUE = 0.00175x^2+0.07484x-0.00158y^2+0.03194y+0.000959xy+6.44092 \quad R2 = 0.7491 \qquad \text{(Eq.5)}$$

where *WUE* is water production efficiency (kg m^{-3}), *x* is the amount of BS applied (kg ha^{-1}), and *y* is the application rate of CMC (kg ha^{-1}).

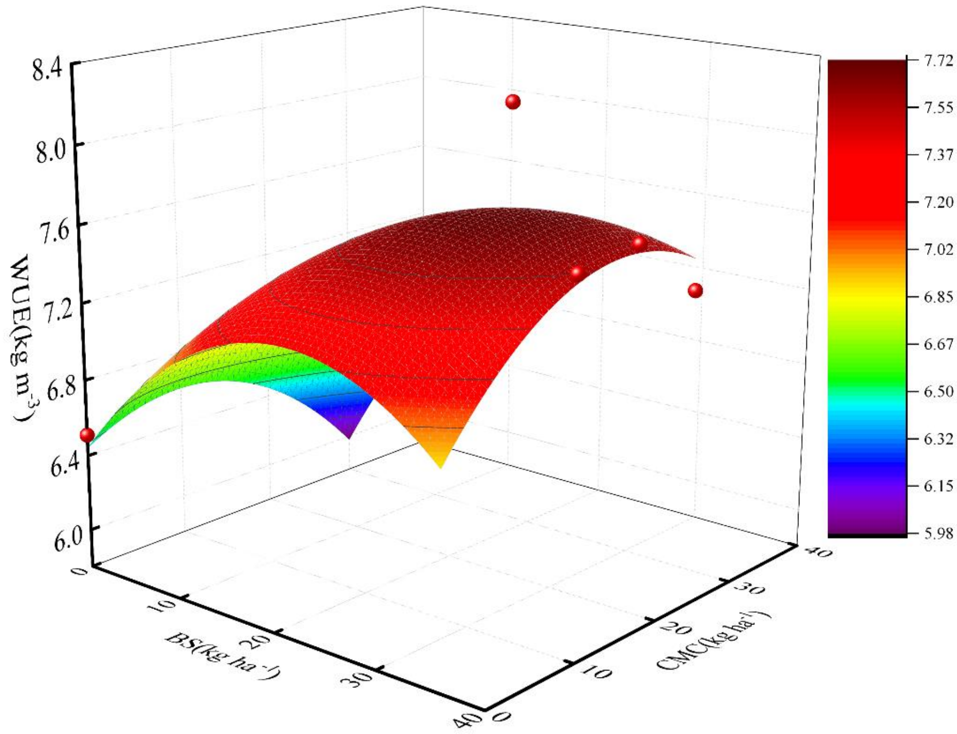

Figure 9. *BS, CMC application as a function of water production efficiency*

The R^2 (0.7491) and *RMSE* (0.21) of model-fitted values to measured values (*Figure 10*) indicates the model fit is highly accurate. Fitted regression equations were used to calculate first-order partial derivatives, then the system of equations with partial derivatives equal to zero was solved to find extreme points, and finally, the second-order partial derivatives were calculated and used to determine extreme values of functions at these points to obtain the CMC and BS application rates for maximum moisture production efficiency. The theoretical moisture production efficiencies of the BS application rate (26.25 kg ha^{-1}) and CMC application rate (26.25 kg ha^{-1}) were as high.

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DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

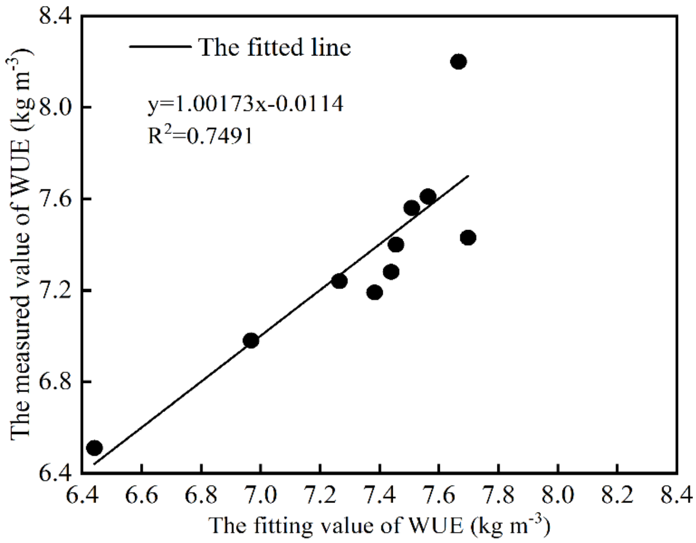

Figure 10. *Relationship between model fitted and measured values*

Discussion

As a natural polymer coating material, CMC also has excellent water retention and soil-conditioning ability in stressful environments (Akalin and Pulat, 2020; Wang et al., 2023). The negative charge on its carboxymethyl group interacts with cations in the soil solution to form a gel-like substance, which forms a water-retention film between soil particles, slows down the vertical infiltration and horizontal diffusion of water in soil, enhances adhesion of soil particles, and promotes formation of soil macroaggregates (Qiu et al., 2013). This enhances the soil's water-holding capacity (Chen et al., 2022) and adsorbs soil nutrient ions and reduces nutrient loss. Addition of CMC to soil can significantly increase the contents of nitrate N, quick-acting phosphorus, and quick-acting potassium (Yang et al., 2022), and help to improve the soil structure, prevent soil compaction, and promote water infiltration, thereby providing a more-favorable environment for plant growth (Mazloom et al., 2020).

We report that for a constant BS application rate, soil TN contents at the flowering and fruiting stage gradually increased with increased CMC application rate, but this pattern differed at fruit expansion and ripening stages, because we applied considerable N fertilizer to promote nutrient growth to enhance leaf photosynthesis at the flowering and fruiting stage (Li et al., 2013). At the fruit expansion and ripening stage, we mainly regulated change in nutrient growth to reproductive growth, that's why we no longer apply large amounts of nitrogen fertilizer. However, during fruit expansion and ripening stages, we mainly regulated the transition from nutritive to reproductive growth, so large amounts of N fertilizer were not applied. Considerable nitrate N and ammonium N applied during the flowering and fruiting period may have been consumed and lost, and the soil's TN content may comprise mostly organic N that cannot be directly absorbed and used by plants (Cui et al., 2008). Organic N needs to be decomposed by microorganisms and converted into inorganic nitrogen (N) (ammonium N or nitrate N) before it can be absorbed and used by the root system of the plants. Accordingly, the main effect of CMC and BS on soil TN content was not influenced by fruit expansion and ripening periods (Coimbra et al., 2011), so large amounts of N fertilizer were not applied, thus showing no effect of CMC and BS on soil total nitrogen content during

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DOI: http://dx.doi.org/10.15666/aeer/2303_53855403

fruit expansion and maturation stage (*Table 2*). However, BS increased plant water and nutrient use efficiency, as evidenced by greater new shoot length, stem thickness, and LAI than in the CK treatment (*Table 2, Figs. 5-7*), a characteristic that is particularly important in arid regions because it enhances crop resilience to water scarcity, and supports implementation of sustainable agricultural practices.

Because it can be naturally degraded by microorganisms (Coimbra et al., 2011), CMC causes no secondary pollution, and gradually decomposes into substances that are beneficial to plants. This aids maintenance of a natural ecological balance in the soil. Because sandy soil has poor water and fertilizer retention and low organic matter content, and low soil microbial populations and numbers, this delays decomposition of CMC. We applied BS with *B. subtilis* to regulate and influence soil microbial communities over time (Zhao et al., 2024), which facilitated degradation of CMC. Survival of *B. subtilis* in soil requires a suitable temperature and humidity, and the water- and fertilizer retention of CMC provides a more-suitable environment for its survival and reproduction. Water retention may affect CMC degradation in soil. The water retention of CMC may be related to its degree of degradation in the soil, and the different treatments of CMC in this experiment may show different degrees of degradation during fruit expansion and maturation stage, in the flowering and fruiting period, different CMC treatments at a constant BS application are increasingly affected by soil water content. Therefore, the variability of soil water content of different treatments with the same BS application rate was more significant at the flowering and fruiting stage, but showed different patterns of change at the fruit expansion and maturation stage (*Figs. 2-4*).

BS effectively improves plant resistance (Yakhin et al., 2016), which improves the soil, promotes crop growth, improves soil nutrient use efficiency, and significantly affects crop quality and yield (Zhang et al., 2018b). The main components of our bio-hormone are proline, chelator, glycine, xanthohumic acid, and *B. subtilis*. Proline has antioxidant activity and protects plant tissues from stresses brought on by reactive oxygen bursts from scavenging free radicals. Chelators of amino acid components help in the translocation and uptake of micronutrients required by crops (Posmyk and Katarzyna, 2016; Patkowska et al., 2020). Glycine, an amino acid species required by plants that can regulate the activity of enzymes related to the N assimilation process, acts as a signaling molecule in the process of N uptake in plant roots. This activates the activity of C-element metabolizing enzymes and N-element reducing and assimilating metabolizing enzymes, stimulates the secondary metabolism of plants, and enhances the plant defense response and resistance (Ertani et al., 2016). Xanthohumic acid activates plant plasma membrane H^+-ATPase. ATP hydrolysis-released free radicals can be converted into transmembrane potential energy to enhance the plant's uptake of nitrate and other soil nutrients, which contributes to cell wall relaxation, cell enlargement, and growth of nutrient organs (Aguirre et al., 2009). *Bacillus subtilis* promotes the conversion and plant uptake and use of organic phosphorus (Burns et al., 2013). Therefore, BS was the main controlling factor for maximum new shoot length and stem thickness, and LAI (*Table 2*), which promoted apple growth and enhanced yield and water productivity (*Figs. 5-7, Table 3*). We report maximum new stem growth and thickness, and LAI in treatment B3C2, but the highest yield and water production efficiency in treatment B2C2. This may be because of excess nutrient growth and suppression of reproductive growth in the B3C2 treatment, reducing yield and water production efficiency compared with treatment B2C2.

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Conclusions

The positive effect of CMC and BS on soil water retention varied by tree fertility stage, and the degree of enhancement varied over time. The greatest increase in soil moisture content occurred during the flowering and fruiting stage (15.80%), then fruit expansion stage (12.40%), and was lowest during maturation (11.33%). CMC most affected soil moisture content. CMC and BS affected soil TN content at the flowering and fruiting stages, respectively, with soil TN content in coupled treatments increasing by 6.03%–33.46% compared with the CK treatment. Coupled CMC and BS treatments affected new shoot growth and stem thickness, and LAI in different ways compared with the CK treatment. CMC most affected yield and BS most affected water productivity. Water consumption was greatest in the B3C2 treatment and least in the CK treatment. Yield and water production efficiency were greatest in the B2C2 treatment and least in CK treatment. Modeling revealed theoretical water production efficiency to be greatest when BS was applied at 26.25 kg ha^{-1} and CMC was applied at 26.25 kg ha^{-1}. Application of these results would contribute to more sustainable development of apple production in southern Xinjiang.

Acknowledgments. The authors would like to acknowledge the financial support from Xinjiang Uygur Autonomous Region Major Science and Technology Projects (2022A02003-2), Xinjiang Uygur Autonomous Region "Tianshan Talents" Program for Leading Talents in Science and Technology Innovation (2022TSYCLJ0069).

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