Effects of biodegradable mulch on soil water and heat conditions, yield and quality of processing tomatoes by drip irrigation (postprint)

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Abstract

To combat the problem of residual film pollution and ensure the sustainable development of agriculture in oasis areas, a field experiment was carried out in 2019 at the Wuyi Farm Corps Irrigation Center Test Station in Urumqi, Northwest China. Four types of biodegradable mulches, traditional plastic mulchs and a control group (bare land; referred to as CK) were compared, including a total of six different treatments. Effects of mulching on soil water and heat conditions as well as the yield and quality of processing tomatoes under drip irrigation were examined. In addition, a comparative analysis of economic benefits of biodegradable mulches was performed. Principal component analysis and gray correlation analysis were used to evaluate suitable mulching varieties for planting processing tomatoes under drip irrigation. Our results show that, compared with CK, biodegradable mulches and traditional plastic mulch have a similar effect on retaining soil moisture at the seedling stage but significantly increase soil moisture by 0.5%-1.5% and 1.5%-3.0% in the middle and late growth periods ($P<0.050$), respectively. The difference in the thermal insulation effect between biodegradable mulch and plastic mulch gradually reduces as the crop grows. Compared with plastic mulch, the average soil temperature at 5–20 cm depth under biodegradable mulches is significantly lowered by 2.04°C–3.52°C and 0.52°C–0.88°C ($P<0.050$) at the seedling stage and the full growth period, respectively, and the water use efficiency, average fruit yield, and production-investment ratio under biodegradable mulches were reduced by 0.89%-6.63%, 3.39%-8.69%, and 0.51%-6.33% ($P<0.050$), respectively. The comprehensive evaluation analysis suggests that the black oxidized biological double-degradation ecological mulch made from eco-benign plastic is the optimal film type under the study condition. Therefore, from the perspective of sustainable development, biodegradable mulch is a competitive alternative to

plastic mulch for large-scale tomato production under drip irrigation in the oasis.

Full Text

Preamble

Effects of Biodegradable Mulch on Soil Water and Heat Conditions, Yield and Quality of Processing Tomatoes by Drip Irrigation

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Abstract: To combat the problem of residual film pollution and ensure sustainable agricultural development in oasis areas, a field experiment was conducted in 2019 at the Wuyi Farm Corps Irrigation Center Test Station in Urumqi, Northwest China. Four types of biodegradable mulches, traditional plastic mulch, and a control group (bare land; referred to as CK) were compared, comprising six different treatments total. The effects of mulching on soil water and heat conditions, as well as the yield and quality of processing tomatoes under drip irrigation, were examined. Additionally, a comparative analysis of the economic benefits of biodegradable mulches was performed. Principal component analysis and grey correlation analysis were used to evaluate suitable mulching varieties for planting processing tomatoes under drip irrigation. Our results show that, compared with CK, biodegradable mulches and traditional plastic mulch have a similar effect on retaining soil moisture at the seedling stage but significantly increase soil moisture by 0.5%-1.5% and 1.5%-3.0% in the middle and late growth periods ($P<0.050$), respectively. The difference in thermal insulation effect between biodegradable mulch and plastic mulch gradually reduces as the crop grows. Compared with plastic mulch, the average soil temperature at 5–20 cm depth under biodegradable mulches is significantly lowered by 2.04°C–3.52°C and 0.52°C–0.88°C ($P<0.050$) at the seedling stage and throughout the full growth period, respectively. Water use efficiency, average fruit yield, and production-investment ratio under biodegradable mulches were reduced by 0.89%–6.63%, 3.39%–8.69%, and 0.51%–6.33% ($P<0.050$), respectively. Comprehensive evaluation analysis suggests that the black oxidized biological double-degradation ecological mulch made from eco-benign plastic is the optimal film type under the study conditions. Therefore, from the perspective of sustainable development, biodegradable mulch is a competitive alternative to plastic mulch for large-scale tomato production under drip irrigation in oasis areas.

Keywords: biodegradable plastic mulch; processing tomato; water use efficiency; soil water and heat; comprehensive evaluation; regional agricultural sustainability; Xinjiang

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1 Introduction

Film mulching has proven effective for regulating soil temperature, inhibiting weed growth, improving water use efficiency (WUE), and increasing economic benefits \cite{Hou_{et}{al}{2010}, Yin_{et}{al}{2012}, Li_{et}{al}{2015}}. The film-covering moisture protection technology has been widely adopted in agricultural production. To date, the film-covering planting area in China exceeds 20 million hm^2 \cite{Zhao_{et}{al}{2017}}, with more than 50 crops under film-covering cultivation and annual mulch usage of approximately 1.2 million tons. This practice is especially prominent in Xinjiang, where ultra-thin (0.006–0.008 mm), long-degradation-cycle ($ $200 years), and difficult-to-recycle polyethylene mulch has been widely used nationwide. With extended service life and low recovery rates, residual film continues to accumulate in the soil cultivation layer \cite{Jiang_{et}{al}{2017}}.

Continuous film mulching for 20 years has caused residual film to reach 307.9 ($±35.84)$kg/hm^{2,withthehighestresidualamountsfoundintomato-plantingsoils[?].Residualfilmdensityincreasesatarateof16}$ per year, concentrated primarily in the 0–15 cm soil cultivation layer, with film residue in Xinjiang' s oasis areas considerably exceeding national standard limits \cite{He_{et}{al}{2018}}. Film residue in the cultivation layer reduces soil porosity, hinders water infiltration, weakens soil water retention capacity, and consequently limits crop growth \cite{Du_{et}{al}{2018}}. Residual film in the tillage layer significantly impedes root system growth in tomato seedlings during flowering and fruiting, with root volume and root length density negatively correlated with residual film amount \cite{Zou_{et}{al}{2016}}. The negative effects of residual film on crop yields can completely offset the positive effects of plastic film cultivation after 16 years. Hence, from a long-term perspective—and given that residual film recycling technology remains immature—plastic film cultivation is not economically efficient \cite{Bi_{et}{al}{2008}}. Based on previous studies, the research goal of completely replacing polyethylene (PE) film in the future focuses on developing new mulch films and degradable mulches \cite{Hu_{et}{al}{2019}}.

Using degradable mulch represents the most effective solution to the "white pollution" caused by PE film. Numerous studies demonstrate that degradable mulch cover provides similar benefits to traditional PE film in reducing soil evaporation, maintaining moisture storage, balancing ground temperature \cite{Yin_{et}{al}{2012}, Wu_{et}{al}{2017}, Wang_{et}{al}{2019a}, Wang_{et}{al}{2019b}}, and improving soil structure, fertility, and salinity control \cite{Shen_{et}{al}{2012}, Danierhan_{et}{al}{2013}, Zong_{et}{al}{2020}}. Previous research has examined four mulch types: liquid mulch, photolysis mulch, bio/photodegradable mulch, and biodegradable mulch. Photodegradable film was the earliest research focus \cite{Nan_{et}*{al}*{1994}, Zhao_{et}*{al}*{2005}}, and degradable mulch is believed to eventually replace non-degradable mulch \cite{Zhao_{et}*{al}*{2017}}. Currently, however, degradable and traditional plastic mulches coexist in agricultural management. Previous research on degradable mulch primarily addressed composition, degradation characteristics, product development, and material development \cite{Ammala_{et}*{al}*{2011}}, though some scholars have conducted field experiments analyzing effects on farmland moisture and crops \cite{Kapanen_{et}*{al}*{2008}, Wang_{et}*{al}*{2016}, Fan_{et}*{al}*{2017}}. However, crop yield, quality, and economic benefits resulting from degraded mulches have not been thoroughly analyzed. Additionally, current field research on degradable mulch often focuses on cotton \cite{Wang_{et}*{al}*{2019b}}, corn \cite{Yin_{et}*{al}*{2017}}, and potatoes \cite{Gao_{et}*{al}*{2015}}, with limited research on processing tomatoes under degradable film.

Processing tomatoes (*Lycopersicon esculentum* Mill.) are primarily used for tomato sauce production. In 2014, China' s processing tomato area reached 2.1$×10^{7}$ hm^2, making China one of the world' s largest producers and exporters \cite{Ren_{et}*{al}*{2018}}. Due to Xinjiang' s natural climate, the processing tomato area exceeded 7.3$×10^{4}$ hm^2 in 2017, establishing Xinjiang as one of China' s largest production and export regions, with processing tomatoes becoming an important local economic pillar. However, the film coating rate for processing tomatoes approaches 100%. To combat "white pollution" and increase output value, promoting processing tomato cultivation under degradable films is urgent. It is essential to select suitable drip irrigation applications in Xinjiang and reveal how degradable film mulching affects soil water and heat conditions, crop yield, quality, and economic benefits.

This study investigated thermal insulation and water retention effects under different degradable plastic mulch types in Xinjiang. Our objectives were to: (1) evaluate the potential of degradable plastic film to replace plastic film in drip-irrigated processing tomatoes in Xinjiang; (2) recommend biodegradable films suitable for Xinjiang; and (3) provide scientific guidance for further promotion and application of degradable mulch. This work aims to alleviate damage from residual film to farmland ecological environments and ensure sustainable agricultural ecology and economy in oasis areas.

2.1 Study Site

The experiment was conducted at the Wuyi Farm Corps Irrigation Center in Toutunhe District, Urumqi, from May to September 2019. Wuyi Farm (43°55 52 -44°03 10 N, 87°19 52 -87°27 23 E; 364 m a.s.l.) is located on the southern edge of the Junggar Basin, on the northern slope of the Tianshan Mountains. The local climate belongs to the mid-temperate continental semi-arid zone. The average air temperature from May to September is 26.8°C, with an annual mean temperature of 6.5°C [Figure 1: see original paper]. Mean annual precipitation is 194 mm, mean annual potential evaporation is 2647 mm, sunshine duration is 2800 h, and the frost-free period is 165 days.

The study site soil was loam. Soil samples were collected with a ring knife to measure soil bulk density and field water holding capacity before tomato sowing .

2.2 Experimental Design

In 2019, five mulch film treatments (four degradable mulches and traditional PE film) plus a control group were established. All selected mulch films were 1.20 m wide , resulting in a complete combination design with six treatments, each replicated three times. The study plot layout is shown in [Figure 2: see original paper]. Irrigation volume was set to 450 mm during the full growth period based on values suggested by Hanson (2004) and local production practices in the Toutunhe Irrigation District. Drip irrigation was combined with fertilizer application at 1.35 g/L N:P_2O_5:K_2O at a ratio of 290:188:188 kg/hm^2.

2.3 Field Management

The tested tomato variety was "heniz1015," transplanted in May 2019 and completely harvested on 5 September 2019, with a growing period of 121 days. The irrigation schedule for processing tomatoes is shown in . Field agronomic management measures for weeding and pesticide application were consistent with local practices. Processing tomatoes were planted at 35 cm spacing with 30 cm row spacing. Single-wing labyrinth drip irrigation tape produced by Xinjiang Tianye (Group) Co., Ltd. was used, with 16 mm outer diameter, 0.30 mm wall thickness, 60 cm capillary spacing, 35 cm dripper spacing, and 1.8 L/h flow rate. To reduce water and fertilizer interpenetration between adjacent treatments, a 50 cm wide bare land buffer was maintained between treatments.

The crop planting mode was "1 film with 2 tubes and 4 rows" under film drip irrigation, with water temperature sensors embedded [Figure 2: see original paper]. The drip irrigation and fertilization system equipment consisted mainly of water storage tanks, water pumps, return pipes, fertilization tanks, rotary-wing water meters, and a water pipeline system.

2.4 Sampling and Determination

2.4.1 Determination of Soil Moisture

A tube-type soil temperature and water intelligent monitor was buried at a fixed location to monitor moisture and temperature changes in the 20–120 cm soil layer throughout the growth period, as well as 24 h before and 48 h after irrigation. A soil drill was used to sample soil at 0–60 cm depth under the drip irrigation belt, between wide rows, and between membranes, with samples taken every 10 cm. Soil moisture was determined by drying. Additionally, water consumption (ET) and WUE were calculated at different crop growth periods.

$$ET = Pr + I + Wp - Wh \quad (1)$$

$$WUE = Y/ET \quad (2)$$

where ET is crop water consumption (mm); Pr is rainfall during crop growth (mm); I is irrigation water during growth (mm); Wp and Wh are soil water storage before sowing and harvest (mm), respectively.

2.4.2 Soil Temperature

A curved tube mercury geothermometer measured soil temperature at depths of 5, 10, 15, 20, and 25 cm during the seedling, flowering, first fruit expansion, second fruit expansion, and mature stages. Soil temperature was measured every 4 h from 08:00 to 20:00 (LST) for five consecutive days, with the average value considered representative of the growth period.

2.4.3 Output, Quality and Economic Benefits

After reaching maturity, processing tomatoes were harvested by hand at three stages (early, middle, and late; every seven days) to determine total yield per plant and per hectare. These values were converted to economic output (Y, t/hm^2) according to the Codex Alimentarius Commission's quality classification for processed tomatoes (special grade, first grade, and second grade). Quality indicators including fruit shape and color were evaluated simultaneously, with grade used to weight price for final income calculation.

The production-investment ratio was calculated as the ratio of production (CNY/hm^2) to investment (CNY/hm^2). For each treatment, 500 g fresh fruit samples were selected for quality index determination. Processing tomato quality was quantified by five indicators: total soluble solids (TSS), vitamin C content, total soluble sugar content (SSC), titratable acid (TA), and sugar-acid ratio (SAR) calculated from soluble sugar and titratable acid content. TSS was measured using a handheld refractometer (RHBO-90; LINK Co., Ltd., Taiwan, China), vitamin C content by spectrophotometry (Thermo Fisher Scientific Inc., Waltham, MA, USA), and SSC by direct titration (Lane-Eynon method).

2.5 Data Analysis

Test data were processed and analyzed using Microsoft Excel 2016 (Microsoft Corporation, USA) and DPS statistical software (Zhejiang University, China). ANOVA was performed on measurement results, with multiple comparisons conducted using the LSD method. Origin 2018 (OriginLab, USA) was used to produce figures.

2.5.1 Principal Component Analysis

Principal component analysis is a statistical method that converts multiple indicators into fewer comprehensive indicators through dimensionality reduction, finding several comprehensive factors to replace original variables while reflecting the original information as much as possible and ensuring they are uncorrelated, thus achieving simplification. The calculation steps in the DPS data statistics system are as follows:

(1) Standardize the original data by centering columns and standardizing with standard deviation.

$$x^*_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j} \quad (3)$$

$$\bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \quad (4)$$

$$s_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2} \quad (5)$$

(2) Calculate the correlation coefficient matrix of the sample matrix.

$$R = \frac{1}{n-1} X^{*T} X^* \quad (6)$$

(3) For correlation coefficient matrix R, use the Jacobi method to find the p non-negative eigenvalues (λ_1>λ_2>···>λ $ 0)*ofthecharacteristicequation*|*R*− $I|=0. The eigenvector corresponding to eigenvalue λ satisfies:

$$l_i^T l_i = 1, \quad i = 1, 2, \ldots, p \quad (7)$$

and satisfies Equation 8:

$$Z_i = X^* l_i \quad (8)$$

(4) Choose m (m<p) principal components. When the ratio (${}_1$ λ)/(${}_1$ λ) of the sum of variances of m principal components Z_1, Z_2, ···, Z to total variance is close to 1, select these m factors as the principal components.

2.5.2 Grey Correlation Analysis

Grey system theory proposes correlation analysis to clarify relationships between system factors, identify the most influential factors, and grasp primary contradictions. Grey correlation analysis quantitatively describes and compares system development and change. In the DPS data statistics system, correlation analysis includes:

(1) Original data transformation using standardized transformation in DPS.

(2) Calculate correlation coefficient. With mother sequence {X_0(t)} and child sequence {X (t)} after transformation, the correlation coefficient L_0 (k) between parent sequence {X_0(k)} and subsequence {X (k)} at time t=k is:

$$L_{0i}(k) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{0i}(k) + \rho\Delta_{\max}} \quad (9)$$

where Δ_0 (k) is the absolute difference between sequences at time k; Δ and Δ are maximum and minimum absolute differences across all sequences; and is 0.1-0.5.

(3) Find the degree of relevance:

$$r_{0i} = \frac{1}{N}\sum_{k=1}^{N} L_{0i}(k) \quad (10)$$

where r_0 is the association degree between subsequence i and parent sequence 0, and N is comparison sequence length.

(4) Sort association order by arranging association degrees of m subsequences to the same parent sequence, forming association sequence {X} that reflects the "pros and cons" relationship.

(5) List incidence matrix R = [r] (i=1,2,⋯,n; j=1,2,⋯,m). If column i satisfies r > r for all k≠i, then parent sequence {Y } is optimal relative to other parent sequences.

3.1 Dynamic Changes of Soil Moisture Under Different Mulching Treatments

3.1.1 Effects of Different Mulch Treatments on Moisture Content in Different Soil Layers During the Seedling Stage

Figure 3 shows dynamic changes in moisture content across the film-covered cross-section before and after irrigation for tomatoes under different mulching treatments. Soil moisture content varies with depth. Figures 3a and 3b show water content distribution in the 0-60 cm soil layer of the film-covered section 24 h before and 48 h after irrigation under traditional plastic mulch treatment, with average moisture content changes of 4.11%, 3.81%, and 5.62% ($P<0.010$). Figures 3c and 3d show significant changes in average moisture content of each soil layer before and after irrigation, increasing by 2.37%, 1.73%, and 1.69% ($P<0.050$). Figures 3e and 3f show post-irrigation increases of 3.11%, 4.48%, and 3.67% ($P<0.050$). Figures 3g and 3h show increases of 1.7%, 1.48%, and

2.02% (P<0.050). Figures 3i and 3j show increases of 1.59%, 1.28%, and 2.34% (P<0.050).

Pre-irrigation water content distribution shows that average water content in the 0-20 cm layer is lower than in the >20-40 cm layer, which is lower than the >40-60 cm layer, though the magnitude of decrease varies by treatment. Pre-irrigation soil water content ranking was: BM2>WM2>WM1>BM1>PE for 0-20 cm; BM2>WM1>WM2>PE>BM1 for >20-40 cm; and BM2>WM1>BM1>WM2>PE for >40-60 cm. Post-irrigation moisture redistribution increased differently across layers, with average moisture increase in the 0-60 cm layer ranking as: PE>BM1>BM2>WM1>WM2. In summary, traditional plastic film treatment performs better than all biodegradable plastic mulch treatments in terms of water content changes before and after irrigation; black degradable mulch treatment outperforms white degradable mulch treatment; and BM1 treatment is slightly better than BM2 treatment.

3.1.2 Effects of Different Mulch Treatments on Water Content Throughout the Growth Period

Figure 4 displays the changing trend of average soil water content in the 0-60 cm layer during processing tomato growth under different mulching treatments. All mulching treatments contrast starkly with CK, as the mulch acts as a water-repellent layer that effectively prevents inefficient soil moisture evaporation. Soil water content fluctuates with crop growth, primarily due to irrigation frequency and rainfall. During the seedling and early flowering stages (20-45 days after sowing, DAS), the four degradable mulches remain intact, but crops are small and sunlight reaches the ground directly, creating differences in soil water content. Water content under degradable mulch and CK treatments did not differ significantly (P>0.050). Between 45 and 75 DAS, PE treatment soil water content was significantly greater than BM1, BM2, WM1, WM2, and CK treatments (P<0.050), with increases of 1.39%, 0.83%, 0.63%, 0.34%, and 0.27% over CK (P<0.050). As processing tomatoes grew, the degradable film gradually cracked and degraded. However, increased irrigation frequency and higher inter-plant shading rates caused water content under all mulching treatments to increase gradually. Among degradable mulch treatments, BM1 and BM2 showed better water retention effects. Between 75 and 105 DAS, soil water contents under PE, BM1, BM2, WM1, and WM2 treatments were significantly higher than CK (P<0.050), with increases of 1.81%, 1.03%, 1.18%, 0.61%, and 0.66% (P<0.050), respectively. As processing tomatoes matured, the water retention effects of BM1 and BM2 treatments improved further, indicating that black degradable mulch outperforms white degradable mulch, with BM2 better than BM1. Analysis of dynamic water content changes throughout the growth period shows that both degradable and traditional plastic films improve soil moisture in the 0-60 cm layer, but traditional film increases soil moisture by 1.5%-3.0% while degradable film increases it by 0.5%-1.5% (P<0.050) in the later growth stages.

3.2 Soil Temperature Changes in the Cultivated Layer Under Different Mulching Treatments

3.2.1 Effects of Different Mulching Treatments on Soil Temperature at 5-20 cm Depth During the Seedling Stage

Table 4 demonstrates time-dependent temperature changes in the 5-20 cm soil layer of tomato seedlings under different mulching treatments. Overall, ground temperature changes across soil layers follow a consistent pattern, with minimum temperatures at 08:00 (LST) and maximum at 16:00 (LST). Amplitude decreases with depth, with average maximum-minimum differences of 18.09°C, 13.49°C, 10.9°C, and 5.75°C at 5, 10, 15, and 20 cm, respectively. Ground temperature shows regular changes with soil depth under different film treatments. Surface (0-5 cm) soil temperature under black degradable mulch is lower than under white degradable mulch, but the 5-20 cm layer shows better thermal insulation with black degradable film. Analysis reveals that average 5-20 cm soil temperatures during the seedling stage under BM1, WM1, BM2, and WM2 were lower than PE treatment by 2.08°C, 2.44°C, 2.04°C, and 3.52°C ($P<0.050$), but higher than CK by 3.48°C, 3.12°C, 3.52°C, and 2.03°C ($P<0.050$). In the 20-25 cm layer, soil temperature changes little, and mulching effects on the 0-20 cm layer gradually weaken with increasing depth. Therefore, film covering during the seedling stage can alter 0-20 cm soil temperature. The degradation process of plastic film is similar to traditional plastic film, but PE film outperforms all degradable mulches, and black degradable mulch outperforms white degradable mulch.

3.2.2 Effects of Different Mulching Treatments on Soil Temperature Throughout the Growth Period

As processing tomatoes grew, dynamic changes in average soil temperature under different mulching treatments (5-20 cm) are shown in Figure 5. The temperature trend throughout the growing period increases initially, reaching a maximum between 60-70 DAS, then decreasing until harvest.

During the seedling stage (5-25 DAS), plant leaf area index is small, and different mulching types affect soil temperature differently, with thermal insulation ability ranking PE>BM2>BM1>WM2>WM1. During flowering (25-45 DAS), average ground temperatures under BM1, WM1, BM2, and WM2 were lower than PE by 0.67°C, 0.91°C, 0.52°C, and 0.88°C ($P<0.050$). During fruit expansion stages I and II (45-70 DAS), as temperature rose, degradable mulch cracked and began degrading, but fruits, branches, and leaves blocked solar radiation. Increased soil moisture content prevented degradation from altering thermal insulation effects. Average ground temperatures under BM1, WM1, BM2, and WM2 were lower than PE by 0.30°C, 0.47°C, 0.51°C, and 0.83°C ($P<0.050$). During maturity, fruit discoloration and leaf fall occurred while soil moisture decreased and degradable mulch developed long cracks, significantly reducing average ground temperature under each degradable mulch treatment more than under traditional film. Average ground temperatures under BM1, WM1, BM2, and WM2 were lower than PE by 0.50°C, 0.57°C, 0.26°C, and 0.60°C ($P<0.050$). As the growth period extended, degradable plastic film' s effect on ground temperature weakened. Traditional mulching film continued affecting soil temperature until tomato maturity ended, while degradable plastic mulches did not significantly reduce soil temperature during the maturity period due to their own degradation ($P<0.050$).

3.3 Yield, Quality, WUE, and Economic Benefits of Processing Tomatoes Under Different Covering Treatments

Yield, quality, WUE, and investment for processing tomato fruits under different film treatments are displayed in Figure 6. Based on maturity timing, fruit yield was divided into early, middle, and late harvests. PE treatment fruit yield reached 173.25 t/hm^2, while BM2 treatment reached 167.36 t/hm^2. Fruit yields under all film treatments were 26.91% (PE), 21.73% (BM1), 18.72% (WM1), 22.60% (BM2), and 15.60% (WM2) higher than CK ($P<0.050$). Total yield was 2.56%-5.48% higher than white degradable mulch treatments ($P<0.050$), while black degradable mulch treatments BM1 and BM2 showed no significant difference ($P>0.050$). Early, middle, and late harvests accounted for approximately 45%, 35%, and 20% of total yield, respectively ($P<0.050$). Significant differences existed in fruit quality between degradable mulch and PE treatments ($P<0.050$). SAR, a comprehensive fruit flavor index reflecting SSC and TA, reached up to 15.779 mg/100g FW under BM2 treatment. WUE differed significantly among mulching treatments ($P<0.050$). WUE under BM1, WM1, BM2, and WM2 degradable mulches decreased by 2.50%, 3.51%, 0.89%, and 6.63% ($P<0.050$), respectively, compared with PE. Economic benefits varied among film treatments, with different choices leading to different production-investment ratios. Degradable mulch costs exceeded traditional film costs, with production-investment ratios decreasing by 5.53%, 6.33%, 0.51%, and 4.49% compared with PE treatment. In summary, traditional plastic film treatment slightly outperformed BM2 degradable mulch in yield, WUE, and production-investment ratio, while degradable mulch treatment produced slightly better fruit quality. Considering the production-investment ratio, fully biodegradable mulch degrades after covering, causes no secondary environmental pollution, and reduces labor costs. Although current degradable mulch production-investment ratios are lower than traditional mulch, resulting in lower net income, the negative environmental effects of traditional mulch will exceed its positive effects over time. As large-scale production of various degradable mulches increases domestically and internationally, costs will decrease. Using degradable mulch in processing tomato planting will increase economic benefits and has broad application prospects. Among the four degradable mulch types, BM2 black degradable mulch treatment demonstrates better economic effects.

3.4 Comprehensive Evaluation of Suitable Mulching Species for Drip-Irrigated Processing Tomatoes in Arid Oasis

3.4.1 Evaluation Based on Principal Component Analysis

Evaluating suitable mulching types for drip-irrigated processing tomatoes in arid oasis areas based solely on single response indicators such as heat preservation, moisture retention, or yield quality at the seedling stage is not credible. To obtain the most suitable mulch treatment scheme, principal component analysis was used for quantitative analysis of comprehensive indices including ground temperature, soil moisture content, yield, WUE, production-investment ratio, TSS, TA, vitamin C, SSC, and SAR . Ground temperature and soil water content were selected from average temperature (5–20 cm) and average water content (0–60 cm) during the seedling stage.

Principal component analysis using DPS statistical software calculated comprehensive evaluation values. Results for different mulching treatments based on drip-irrigated processing tomato response indices are shown in . PE treatment had the highest integrated evaluation value, followed by BM2 and BM1, indicating PE treatment provides the best comprehensive response index. Among all treatments, PE, BM2, and BM1 showed higher comprehensive response indicators, with black degradable mulches significantly outperforming white degradable mulches. The control treatment had the lowest comprehensive evaluation value and poorest effect. Results demonstrate that appropriate film-covering types can optimize comprehensive response indicators for drip-irrigated tomatoes, promoting crop growth and development to improve yield and quality. Therefore, BM2 treatment is selected as the optimal mulching treatment.

3.4.2 Evaluation Based on Grey Correlation Analysis

Grey correlation analysis was used to comprehensively evaluate suitable film-covering varieties for drip-irrigated processing tomatoes, with meaning and purpose consistent with principal component analysis. To evaluate the most suitable film treatment, comprehensive indices including ground temperature, soil moisture content, yield, WUE, production-investment ratio, TSS, TA, vitamin C, SSC, and SAR were used for quantitative analysis. Response index data under different film treatments served as the comparison sequence, with maximum response indices as the reference frame. Ground temperature and soil water content were selected from average temperature (5–20 cm) and average water content (0–60 cm) during the seedling stage .

Grey correlation analysis using DPS statistical software calculated correlation values. Comprehensive evaluation of different film treatments based on drip-irrigated tomato response indices is shown in . PE treatment showed the highest correlation, followed by BM2 and BM1. Among different film treatments, PE, BM2, and BM1 had higher comprehensive response indices, with black degradable mulch significantly better than white degradable mulch. The control treatment had the lowest comprehensive evaluation value and poorest effect. These results are basically consistent with principal component analysis conclusions, further demonstrating that suitable mulching film types can improve crop comprehensive response indices for quality and efficiency enhancement. In short, considering environmental pollution hazards of PE mulch, BM2 treatment is recommended as the optimal film treatment.

4 Discussion

Film mulching has been used for many years in the Xinjiang Oasis Irrigation Area where evaporation is strong. Film mulching acts as an isolation layer between soil and atmosphere that prevents inefficient soil moisture evaporation and improves water use efficiency \cite{Li_{et}*{al}*{2001}}. This study found that degradable mulch covering significantly affected redistribution of moisture content across the film-covered section before and after irrigation at the seedling stage, impacting soil water content in the 0–40 cm layer ($P<0.050$). Black degradable mulch treatment outperformed white degradable mulch treatment. Analysis of dynamic water content changes throughout the processing tomato growth period showed that both degradable and traditional plastic films improved soil moisture in the 0–60 cm layer, with traditional film increasing soil moisture by 1.5%-3.0% and degradable film by 0.5%-1.5% ($P<0.050$) compared with CK. Plastic film planting can improve water use efficiency \cite{Li_{et}*{al}*{2001}}. This study found significant differences in WUE among film treatments ($P<0.050$), with degradable mulch treatments reducing WUE by 0.89%-6.63% ($P<0.050$) compared with PE treatment.

Xinjiang' s Oasis Irrigation District has unique geographical advantages for tomato cultivation by drip irrigation, with a special irrigation planting mode. This study found that degradable mulch treatments decreased average fruit yield by 3.39%-8.69% compared with PE treatment ($P<0.050$). Significant differences existed in processed tomato quality indicators among mulching treatments ($P<0.050$), consistent with \cite{Moreno_{and}*{Moreno}*{2008}}. Although yield decreased under degradable film, fruit quality improved. BM2 degradable mulch coverage significantly improved vitamin C and SSC content and increased tomato flavor index SAR. Nutritional value, color, and flavor drive consumer purchases of processed tomato products.

Film mulch changes soil surface temperature, with different colors and thicknesses significantly affecting soil temperature \cite{Li_{et}*{al}*{2018}}. During corn vegetative growth, degradable mulches and PE treatments increased average 5-25 cm ground temperature by 1.4°C–2.6°C compared with CK \cite{Wang_{et}*{al}*{2011}}. Average soil temperatures at 5, 15, and 25 cm under processing tomato degradable mulch were 0.73°C, 0.60°C, and 0.54°C lower than CK \cite{Wang_{et}*{al}*{2019}}. These results are similar to our findings: average 5-20 cm soil temperature during the seedling stage was 2.04°C–3.52°C lower than PE treatment ($P<0.050$), and average ground temperature throughout the growth period was 0.52°C–0.88°C lower under degradable mulch (P<0.050). Effects on deeper soil temperature were not significant because heat transfers naturally from high- to low-temperature objects and cannot conduct reversibly. As daily temperature rises, external heat enters and ground temperature of each treatment increases with soil temperature but remains lower than bare ground temperature, demonstrating that plastic film hinders heat transfer. The same occurs at night, showing that plastic film covering has bidirectional obstruction effects on soil heat, effectively suppressing soil temperature fluctuation ranges.

Using ground temperature, soil moisture content, yield, WUE, production-investment ratio, and quality indicators during the drip-irrigated processing tomato growth period as comprehensive evaluation indicators, principal component analysis and grey correlation analysis quantitatively evaluated different mulching treatments. Results show BM2 treatment is optimal. This study found that degradable mulch film input costs are higher (about 5.8%) than PE mulch films, with production-investment ratio reduced by 0.51%–6.33%. BM2 treatment had the smallest evaluation index values. Considering that biodegradable mulching film cost is a restrictive factor for large-scale promotion, along with Xinjiang' s natural conditions and crop types, the mulching scheme was optimized to ensure crops maintain good physiological growth states. To achieve efficient production and coordinated development of economic and environmental benefits through sustainable agricultural production strategies, black degradable mulch based on EBP (eco-benign plastic) material is recommended as the optimal coating treatment.

5 Conclusions

The moisture retention effect of biodegradable film at the seedling stage is similar to traditional plastic film, significantly impacting soil moisture content in the 0–40 cm layer (P<0.050). Compared with CK during flowering to maturity, traditional plastic film significantly increased soil moisture by 1.5%–3.0%, while degradable plastic film increased it by 0.5%–1.5% (P<0.050). Significant differences in WUE existed among mulching treatments (P<0.050), with degradable film treatments reducing WUE by 0.89%–6.63% compared with traditional plastic mulching (P<0.050).

Average 5-20 cm soil temperature during the seedling stage under biodegradable film was 2.04°C–3.52°C lower than traditional plastic film treatment (P<0.050). Average ground temperature throughout the growth period under degradable film was 0.52°C–0.88°C lower than traditional plastic film (P<0.050). Black degradable mulch based on EBP material outperformed other mulch films in heat preservation and moisture retention.

Compared with traditional plastic film, average fruit yield under biodegradable mulch treatments decreased by 3.39%–8.69% (P<0.050). Significant differences existed in various quality indicators of processed tomatoes between plastic film and CK treatments (P<0.010). Compared with traditional plastic mulch, degradable mulch film input costs increased by about 5.8%, while production-investment ratio decreased by 0.51%-6.33% (P<0.050). Principal component analysis and grey correlation analysis indicate that using degradable mulch instead of traditional mulch film in tomato production is feasible. Therefore, black degradable mulch treatment based on EBP material is recommended as the optimal coating treatment.

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Note: Figure translations are in progress. See original paper for figures.