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Plastic Pollution in Soil and Crops: Effects of Film Residuals on Soil Water Content and Tomato Physiology

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Abstract: Agricultural producers in China are presently confronting the challenge of "white pollution" caused by the continuous expansion of plastic film area coverage. The main objective of this research is to address the increasing interest in the effects of film residual on tomato growth, yield, and quality under drip irrigation. To reveal the effects of film residual on tomato physiology, field trials were conducted with five levels of film residual treatment applied in two consecutive cropping seasons from 2019 to 2020. Soil water content, plant height, stem diameter, photosynthetic characteristics, yield, soluble sugar content (SSC), organic acid (OA), vitamin C (VC), and nitrate content (NC) were measured; furthermore, four analysis methods were used to assess the comprehensive tomato quality. The results showed that film residuals significantly affected soil water content in 2019 and 2020 and inhibited tomato plant height and stem diameter. The variations in photosynthetic rate and stomatal conductance showed practically the same trend, increasing with an increase in the film residual at the seedling stage. The maximum yields were observed at 94.02 ton/hm^2 and 84.44 ton/hm^2 in 2019 and 2020, respectively, and tomato yield exhibited a shape reduction with increasing amounts of film residual in all years. SSC, VC, and NC showed an increasing trend with increasing amounts of film residual. The best tomato comprehensive quality was observed when the amount of film residual was lower than 200 kg/hm^2 and declined with an increasing amount of film residual. Overall, the soil water content, tomato growth, and fruit quality changed significantly under the influence of film residual. These results not only deepen our understanding of the harm caused by film residual to tomato growth and fruit quality but also provide reasonable advice to establish a management system for residual pollution on cultivated land.

Keywords: plastic film residual; water distribution; fruit quality; comprehensive quality

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1. Introduction

Film mulching technology was introduced to China in 1978 and has become a key tool to ensure agricultural production and development in arid or high-altitude areas, which are subject to water shortages and alpine chill [1,2]. According to statistical results, the use of plastic mulch reached a cumulative total of 1.404 million tons and covered 17.764 million hectares at the end of 2018 [3]. Currently, China is the country with the greatest productivity and consumption of plastic mulch film in the world. Plastic mulch film has become an indispensable material in agricultural production [4] and plays an indispensable role in water-saving and increasing yield. Gao et al. [5] reported that the contribution of plastic film mulching technology to crop yield and water efficiency in China is 24.32% and 27.63%, respectively. The widespread use of plastic film is needed in arid and semi-arid areas of northern China due to water and rainfall shortages. In the 50 years since plastic mulch was first applied, advantages have included improved soil hydrothermal condition [6], weed control [7,8], and increased yield and quality [9]. The use of plastic film in China is expected to increase at a rate of 7% over the next few years [10]. Nonetheless, polyethylene film mulch used in agricultural production has some disadvantages, including that it tends to be less than 0.008 mm and is susceptible to breakage and weathering [11]. Moreover, the lack of efficient post-harvest recycling pathways makes it easy to leave film residual in the soil [12], which causes concern of pollution risk. The accumulation of plastic film residual has been rapidly growing with the increasing consumption amount and covered area. He et al. [13] reported that plastic film residual has reached 121.85–325.38 kg/hm^2 in Xinjiang. This affects soil structure and properties, crop growth, and yield.

There is a concern that the film residual retained in soils induces "white pollution" and damages the agricultural environment. In general, film residual pollution has a range of negative impacts on soil and crops. The presence of film residual in the soil can destroy the soil structure and interfere with water and nutrient transport. Li et al. [14] concluded that more water and nitrate remained in the upper part of the wetted volume with film residual less than 360 kg/hm^2. The minimum wetting front and the maximum accumulative infiltration were observed when the film residual amount was 50–100 kg/hm^2 [15]. It has been reported that film residual increased soil bulk density and reduced soil porosity, changed microbial communities' dynamics, and resulted in lower microbial biomass C and N levels, with unfavorable effects on soil properties in maize fields [16]. The increase in the residual membrane was accompanied by lower fertility and was harmful to seed germination and seedling growth [17]. Soil's physical properties can impede root growth, causing plant growth to slow down and reducing yield [18]. Furthermore, it expanded greenhouse gas emissions and increased the accumulation of carcinogens and food safety risks [19,20]. So far, the impacts of film residual in the soil on the growth processes have not been assessed. Due to its potential harm to the soil–crop cycle, it was necessary to conduct research on soil factors and crop physiological factors affected by film residuals.

Tomatoes are one of China's most important agricultural products and play an important role in the human daily diet. Natural antioxidants, such as vitamin C and lycopene, which decrease the risk of cancer, are found in tomatoes. Social development and improved living standards in China have led to higher requirements for tomato yield and have also placed higher demands on tomato comprehensive quality, which interacts with different indexes, such as nutrition and taste. There has been much research on the impact of other mixtures in soil on crop quality or mixed film residual on crop yield [16,21]. Nevertheless, there have been inadequate studies on tomato comprehensive quality subjected to film residual stress.

At present, there are more than 100 evaluation analysis methods [22–24] used in various research fields, which Principal Component Analysis (PCA) [25], Membership Function Analysis (MFA) [26], Gray Relational Grade Analysis (GRDA) [27], and the Technique for Order Preference by Similarity to an Ideal Solution analysis (TOPSIS) [28] are commonly used in agriculture. However, it is easy to conduct an incomplete evaluation of the objective facts by choosing just one evaluation analysis method because of the different evaluation results caused by the different principles. In order to optimize the evaluation analysis methods and solve the problem of inconsistent evaluation results, many scholars have proposed the combination evaluation analysis based on results, weights, and methods, including the Borda Analysis [29], Fuzzy Borda Analysis [30], or Copeland Evaluation Analysis [31]. As a series of new evaluation analyses, combined evaluation analysis has been widely used in urban management [32] and industrial technology [33]. So far, film residual in the top of the soil for possible implications on the tomato comprehensive quality has not been reported. Due to the potential impact on the tomato comprehensive quality, research on the film residual in soil on crop growth and fruit quality needs to be conducted for the use and application of plastic film mulch in the future.

There is an urgent need to explore how film residual disrupts water distribution, hinders crop growth, and disturbs fruit quality. Currently, the effect of film residual amount in the soil on tomato comprehensive quality is predominantly unknown. Therefore, the film residual amount that can significantly affect soil moisture, crop growth, and fruit quality needs to be designed for developing mitigation measures to alleviate the harm. This research investigated the film residual on the top 30 cm of soil on soil water content, tomato growth, and fruit quality. A two-year field experiment was conducted to explain how the increasing film residual amount influences tomatoes. This research is innovative because it utilizes a combination evaluation analysis to assess the comprehensive quality of tomatoes under various film residual amounts. The major objectives are as follows:

(i). To evaluate the impact on the soil water content with increasing film residual;
(ii). To monitor crop physiological characteristics (plant height, stem diameter, photosynthetic rate) and fruit quality (yield, SSC, OA, VC, NC) under different film residual treatments;
(iii). To assess the comprehensive quality of tomatoes and use combination analysis methods to rank the tomato comprehensive quality.

2. Materials and Methods

2.1. Experimental Site Description

A two-year experiment (May 2019–September 2020) was conducted at the Dryland Research Center of Shanxi Academy of Agricultural Sciences located at Yangqu, Shanxi Province, China (38°24′ N, 112°53′ E, 1240 m altitude). The mean annual air temperature was 5–7 °C at the experiment site, and the mean annual precipitation was 441 mm, which was recorded at the Yangqu weather station. The experiment was carried out in the greenhouse, which is widely used in the experimental area. The total soil nitrogen was 0.782 g/kg; the organic matter content was 13.5 g/kg; the available phosphorus was 43.7 mg/kg; the available potassium was 170.0 mg/kg; and soil bulk density was 1.49 g/cm^3 at effective root depth (0–50 cm, the main soil layer at which tomato roots absorb water and nutrients). The groundwater was more than 10 m high.

2.2. Experimental Design

The effects of film residual on soil water content, tomato physiological characteristics, and fruit quality were studied by applying 5 levels of various film residual amounts: (1) control treatment (CK), no film residual, (2) R1 200 kg/hm^2 of polyethylene residual film, (3) R2 400 kg/hm^2 of polyethylene residual film, (4) R3 800 kg/hm^2 of polyethylene residual film, (5) R4 1600 kg/hm^2 of polyethylene residual film. The film residuals in the field experiment were Low-Density Polyethylene (LDPE) plastic films with a thickness of 0.008 mm. The irrigation water in the experiment came from a rainwater collection system each year. Due to the large difference in rainfall collection in the two years, the irrigation amounts in 2019 and 2020 were designed to be 3100 m^3/hm^2 and 1300 m^3/hm^2, respectively. The experimental design was set up randomly with 3 replications for a total of 15 test plots. Each plot measured 7.2 m^2 (1.2 m × 6 m). An artificial drip irrigation control system was used in 2019 and 2020, and a water meter was applied to control irrigation amounts. The rate of nitrogen fertilizer (urea), phosphorus fertilizer (P pentoxide), and potassium (K oxide) fertilizer were the same in each plot with 350 kg/hm^2,200 kg/hm^2, and 400 kg/hm^2, respectively.

The crushed film residual preparation was performed before the 2019 growing season, and the effects of film residual were studied for two years. Film residual for the experiment was obtained by cutting plastic films into small pieces. The film residual in the soil was picked up before the experiment. Before tomato planting, different film residual amounts were applied to each individual plot according to film residual treatment. In each treatment, the film residual fragments with dimensions of <25 cm^2 and 25–100 cm^2 were mixed into the soil at a ratio of 6 to 1 (the weight ratio of the 2 types of dimensions was 6 to 1) based on the statistical results before the experiment. Then, the base fertilizer and film residual were mixed into 0–30 cm depth soil by a tractor-drawn rotary cultivator and repeated rotary tillage for uniform distribution of fertilizer and film residual in the soil. After applying the treatments, ridges and furrows of 80 and 40 cm were applied in each plot. Then, the ridges and furrows were mulched with LDPE plastic film, which was applied manually over the plot, perpendicular to the ridges, and fastened securely by placing soil on the top of the film mulch. The diagram of tomato planting is shown in Figure 1.

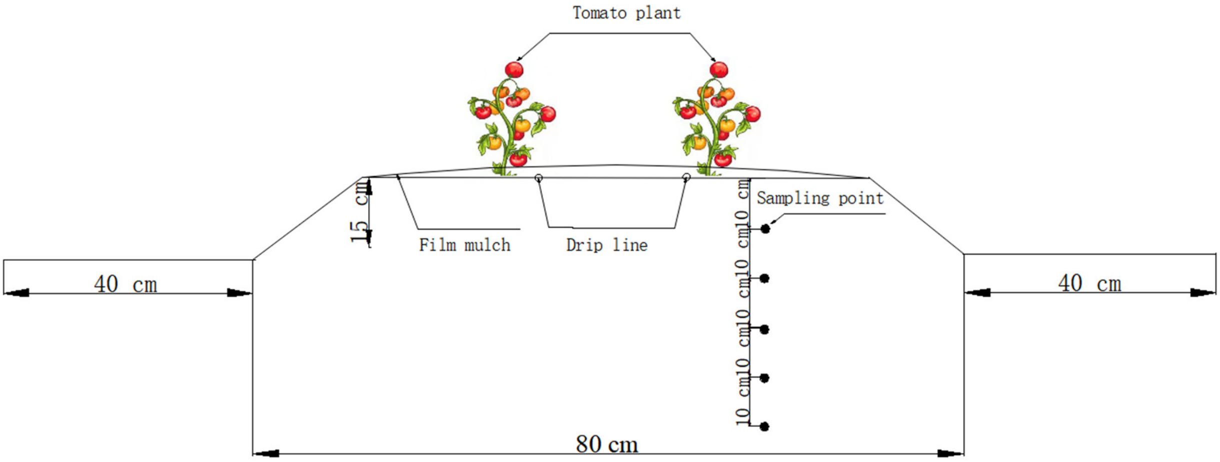

Figure 1. Diagram of tomato planting in the experiment with surface drip irrigation. The planting arrangement of one ridge, one film, two drip lines, and two rows of tomato.

Tomatoes (Hongfenshijia) were planted for artificial cultivation on 13 May 2019 and 25 May 2020 for the experiment and ended on 30 August 2019 and 15 September 2020, respectively. Each plot included two rows of tomatoes with the plant spacing of 50 cm maintained for all treatments. The experimental arrangement and growth period division in 2019 and 2020 are shown in Tables 1 and 2.

Table 1. Experiment arrangement for tomato planting.

Years	Treatment	Film Residual (kg/hm^2)	Irrigation Amount (m^3/hm^2)	Urea (kg/hm^2)	P Pentoxide (kg/hm^2)	K Oxide (kg/hm^2)
2019	CK	0	3100	350	200	400
	R1	200				
	R2	400				
	R3	800				
	R4	1600				
2020	CK	0	1300			
	R1	200				
	R2	400				
	R3	800				
	R4	1600				

CK—control treatment.

Table 2. Division of tomato growth period in 2019 and 2020.

Stage	2019		2020	
	Date	Irrigation Amount (m^3/hm^2)	Date	Irrigation Amount (m^3/hm^2)
Seeding stage	5.13–5.29	300	5.25–6.15	200
Flowering and fruit-bearing stage	5.30–7.1	800	6.16–7.5	300
Fruit swelling stage	7.2–7.23	1250	7.6–8.7	500
Mature stage	7.24–8.30	750	8.8–9.15	300

In order to understand the quality of irrigation water, the rainwater collected in the test area was sampled regularly. A total of 18 water samples were collected in 2019 to 2020. The average of irrigation water quality during the experiment is shown in Table 3.

Table 3. Irrigation water quality test result in experiment.

Detect Item	Detect Method	Standard Limit Value	Detection Value
PH	glass electrode method	5.5–8.5	7.9
Total salt (mg/L)	gravimetric method	≤1000	128
Suspended matter (mg/L)	gravimetric method	≤100	41
Chloride (mg/L)	titration method	≤350	7.3
Ammoniacal nitrogen (mg/L)	flowing analyzer		1.67
Nitrate nitrogen (mg/L)	colorimetric method		0.05

"Blank" indicates "no policy limitation".

2.3. Measurements

2.3.1. Soil Water Content

Soil water content was monitored in each plot at seeding, flowering and fruit-bearing, fruit swelling, and mature stage in the 2019 and 2020 growing seasons. Soil samples were measured after tomato planting by the drying method, sampling the soil to the depth of 0–50 cm with an interval of 10 cm, and they were sampled at a 20 cm distance from the tomato plant. A soil auger was used to obtain three replicate soil samples in each treatment. The soil samples were dried at 105 °C to constant weight to determine the water content of each soil layer. The sampling point for soil water content is shown in Figure 1.

2.3.2. Tomato Physiological Characteristics (Plant Height, Stem Diameter, Photosynthetic Rate, and Stomatal Conductance)

At tomato growth stages, the plant height, stem diameter, photosynthetic rate, and stomatal conductance were measured. Plant height and stem diameter was determined by using three random plants in each treatment. To observe the growth of the tomato, every week, plant height was measured from the soil surface to the top of the tomato plant by using a flexible ruler, and stem diameter was determined 2 cm above ground of the plant using digital vernier calipers.

Photosynthetic characteristics in different growth periods of the tomatoes were determined using an LI-6400 portable photosynthesis system (LI-COR Inc., Lincoln, NE, USA) for each treatment. Visible healthy and consistent growth plants were used to determine the photosynthetic rate (Pn, $\mu mol/m^2 \cdot s$) and the stomatal conductance (Gs, $mol/m^2 \cdot s$), and repeated measurements were carried out 3 times for each treatment. The photosynthetic characteristics data were measured between 9:00 and 11:00 h.

2.3.3. Tomato Yield and Fruit Quality

At the mature stage in 2019 and 2020, the fruit was picked manually from a plant when the tomato ripened. The process was repeated by three replicates at each picking. Tomato yield was the sum of the fruit mass from the first cluster to the fourth cluster [34].

The fresh tomato pulp with skin removed was juiced, and the juice was poured into a test tube. The following operations were carried out to calculate the fruit quality parameters, which were averaged from three tomato fruit samples of every treatment. The content of vitamin C (VC) in the fruit was calculated by molybdenum blue colorimetry. The soluble sugar content (SSC) was calculated using the anthrone colorimetry method. The organic acid (OA) content was determined by the acid–base titration method. The nitrate content (NC) was calculated by salicylic acid colorimetry.

2.4. Construction of Comprehensive Analysis Model

2.4.1. The Analysis Methods for Tomato Comprehensive Quality

The comprehensive quality of tomato was assessed by four evaluation analysis methods: PCA, GRDA, MFA, and TOPSIS.

2.4.2. Ex Ante Assessment of Combination Evaluation Analysis

It was necessary to construct a combination evaluation analysis if inconsistent evaluation results were observed in different analysis methods. Whether PCA, GRDA, MFA, or TOPSIS was used to construct a combination, evaluation analysis was required to be assessed by ex ante assessment. In this paper, the Kendall coefficient was used to assess the consistency of the evaluation results as an ex ante assessment. The Kendall consistency coefficient is expressed as:

$$s = \sum_{i=1}^{n} M_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} M_i\right) \tag{1}$$

where s is the Kendall consistency coefficient, n is the number of treatments, and the M_i calculation formula is as follows:

$$M_i = \sum_{j=1}^{m} r_{ij} \tag{2}$$

where r_{ij} is the rank of film residual treatment i under analysis method j, I = 1, 2 ... n, j = 1, 2 ... m, and m is the number of analysis methods.

2.4.3. The Analysis Methods of Combination Evaluation

On the basis of the Kendell consistency coefficient, a combination evaluation analysis of Mean Value Analysis [35], Borda Analysis [29], Copeland Analysis [31], and Fuzzy Borda Analysis [30] were used to assess tomato comprehensive quality. If the Kendall consistency checking could not be carried out, it was necessary to deny the evaluation analysis methods with the lowest correlation and to re-conduct the above-mentioned test process until all the methods passed the Kendall consistency checking.

2.5. Statistical Analysis

Data significance analysis, pre-and post-test, and principal component analysis were completed utilizing SPSS 18.0. GRDA and TOPSIS were completed by SPSSAU. PCA, MFA, mean average method, Borda method, Copeland method, and fuzzy Borda method were implemented by Excel 2010 (Microsoft Corporation, Redmond, WA, USA). Origin 2021b (OriginLab Corporation, Northampton, MA, USA) was used to generate figures.

3. Results

3.1. Climate Factors for the Experiment

The dynamics of air temperature and relative humidity in two growing seasons are displayed in Figure 2. Due to experiments being conducted in the greenhouse, the effect of rainfall on the experiment was ignored in the 2019 and 2020 growing seasons. In 2019 and 2020, the highest average air temperatures were recorded in July, at 24.4 °C and 24.8 °C, while the lowest average air temperatures were 22.3 °C and 21.0 °C, respectively. The average air temperatures during the growing season in 2019 and 2020 were 23.5 °C and 23.4 °C, respectively. The results showed a similar average air temperature between 2019 and 2020. The average value of relative humidity (RH) recorded in the main growth months (June, July, and August) was 82.7% in 2019 compared with 83.6% in the same months in 2020, which were essential for biomass accumulation. Thus, the climate conditions provided by the greenhouse were similar in the 2019 and 2020 growing seasons, eliminating the effect of meteorological factors on tomato growth.

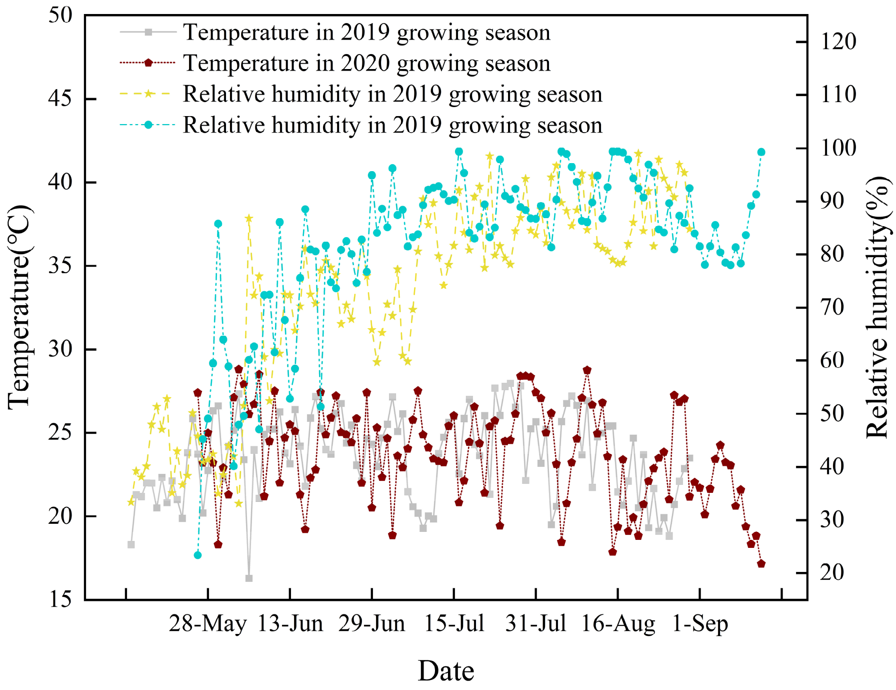

Figure 2. Daily dynamics of air temperature and relative humidity in 2019 and 2020.

3.2. Dynamics of Soil Water Content under Film Residual

The water content dynamics changed in 50 cm soil depth with an interval of 10 cm for all treatments at seedling, flowering and fruit-bearing, fruit swelling, and mature stages in the 2019 and 2020 growing seasons are shown in Figure 3. In this research, the dynamics of soil water content varied with tomato growing stage, growing season, soil depth in 0–50 cm, and particularly, film residual amount. The film residual mixed in the soil played a critical role in the change in soil water content dynamics in the two growing seasons. Lower soil water content was observed at the 50 cm soil depth, but it showed a different trend in soil water content, which decreased with increasing soil depth in 2019 and increased and then decreased with increasing soil depth in 2020 (Figure 3). In the general trend within 0–30 cm depth, the CK treatment demonstrated a lower water content compared with the other residual treatments at seedling and flowering and fruit-bearing stage in the two growing seasons. Furthermore, within 40 cm and 50 cm depth, CK showed higher water content compared with other treatments in the two growing seasons.

The dynamics of water content were observed; the higher the film residual amount, the lower the water content in 2019 (Figure 3a–d). In 2020, there was an opposite trend in water content: the higher the film residual amount, the higher the water content (Figure 3e–h). The average soil water content of R1, R2, R3, and R4 treatments were 16.0%, 16.0%, 15.8%, and 15.6%, respectively, which was lower than CK with 16.1% in the 2019 growing season. While in 2020, the average water content increased with increasing film residual amount in the order of CK < R3 < R1 < R2 < R4 within the 0–50 cm soil layer (the depth that tomato roots mainly uptake water). The minimum and maximum values of average water content were observed at R4 treatment in the 2019 and 2020 growing seasons, which had significantly changed compared with CK, indicating that higher film residual amount affected water content. Soil water content showed a similar trend at the seeding and mature stage in the same growing season due to insufficient evapotranspiration (Figure 3a,d,e,h).

In both growing seasons, the water content of CK was higher at 30–50 cm depth than in the other treatments. Dynamics of water content at 30 cm and even deeper soil layers in both growing seasons were significantly altered compared with 10 cm due to the blocking effect of film residual on water movement. In general, the dynamics of water content indicated that film residual affected water movement significantly and, in turn, soil water storage and crop water uptake.

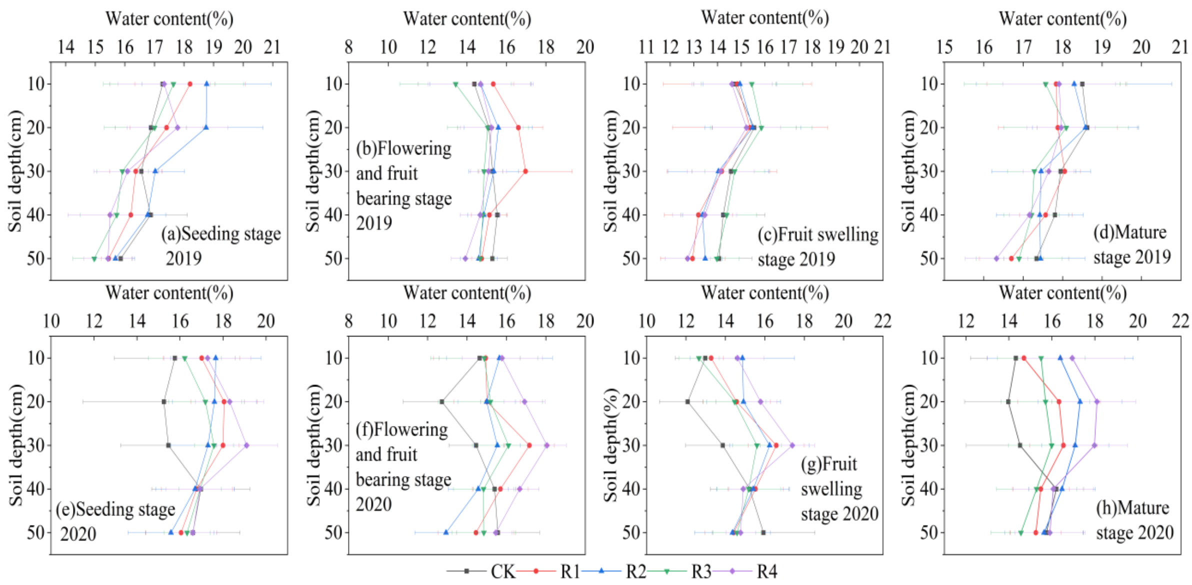

Figure 3. Dynamics of soil water content in the 0–50 cm soil depth with increasing film residual amount in 2019 (**a**–**d**) and 2020 (**e**–**h**) growing seasons. The data in each figure are the average water content of three replicates, with standard deviation by error bars.

3.3. Tomato Growth and Photosynthetic Characteristics

3.3.1. Plant Height and Diameter

The plant height and stem diameter showed different increments of growth with each film residual treatment after tomato planting (Tables 4 and 5).

Film residual addition inhibited tomato growth with respect to plant height and stem diameter in two growing seasons. Especially in the late growth stage, significant variance was observed between CK and residual treatments (Tables 4 and 5). During the stem extension stage (flower and fruit-bearing to fruit swelling stage), the tomato plant height in all treatments entered a rapid elongating period (Tables 4 and 5). At this stage, plant height showed no significant difference among treatments. After that (fruit swelling to mature stage), a slow elongating period appeared in all treatments. At the late growth stage, CK had the highest plant height in both growing seasons, with 113.00 cm and 124.40 cm, respectively.

Table 4. The effects of film residual on plant height and stem diameter in 2019. Values given as averages for three replicates and followed by different letters in each column are significantly different ($p < 0.05$).

Growth Indicators	Treatment	Seedling	Flowering and Fruit Bearing		Fruit Swelling		Mature
Plant height	CK	12.67 ± 0.94^{b}	28.37 ± 1.21^{a}	39.37 ± 2.42^{a}	73.17 ± 1.55^{a}	100.07 ± 1.37^{b}	113.00 ± 2.94^{a}
	R1	13.01 ± 0.83^{ab}	28.80 ± 0.86^{a}	37.50 ± 2.04^{a}	72.00 ± 2.16^{a}	101.13 ± 1.47^{ab}	108.00 ± 1.63^{ab}
	R2	13.70 ± 1.00^{ab}	29.00 ± 1.47^{a}	41.33 ± 1.42^{a}	73.10 ± 1.56^{a}	100.87 ± 2.29^{ab}	111.33 ± 2.25^{ab}
	R3	14.59 ± 0.47^{a}	27.17 ± 1.30^{a}	38.00 ± 1.08^{a}	70.33 ± 1.91^{a}	100.33 ± 2.10^{b}	106.00 ± 2.69^{b}
	R4	14.00 ± 0.82^{ab}	29.33 ± 1.25^{a}	40.50 ± 1.08^{a}	72.33 ± 2.34^{a}	104.67 ± 1.48^{a}	105.90 ± 2.84^{b}
Stem diameter	CK	6.24 ± 0.57^{a}	9.85 ± 0.31^{a}	10.72 ± 0.50^{ab}	12.62 ± 0.16^{a}	13.99 ± 0.47^{a}	14.39 ± 0.37^{ab}
	R1	5.26 ± 0.33^{b}	8.31 ± 0.18^{b}	8.92 ± 0.47^{c}	13.57 ± 0.61^{a}	13.98 ± 0.59^{a}	14.93 ± 1.06^{a}
	R2	4.96 ± 0.43^{b}	8.17 ± 0.39^{b}	9.97 ± 0.66^{abc}	13.50 ± 1.00^{a}	13.97 ± 0.56^{a}	14.46 ± 0.68^{ab}
	R3	5.35 ± 0.38^{ab}	8.97 ± 0.41^{b}	9.46 ± 0.41^{bc}	12.17 ± 1.09^{a}	13.42 ± 0.43^{a}	13.70 ± 0.75^{ab}
	R4	4.96 ± 0.24^{b}	8.90 ± 0.24^{b}	10.99 ± 0.53^{a}	12.11 ± 0.54^{a}	13.99 ± 0.14^{a}	13.05 ± 0.73^{b}

Table 5. The effects of film residual on plant height and stem diameter in 2020. Values given as averages for three replicates and followed by different letters in each column are significantly different ($p < 0.05$).

Growth Indicators	Treatment	Seedling		Flowering and Fruit Bearing		Fruit Swelling		Mature
Plant height	CK	15.00 ± 0.71^{d}	22.17 ± 1.47^{b}	35.00 ± 2.55^{b}	64.33 ± 1.55^{ab}	91.00 ± 2.52^{b}	111.00 ± 2.17^{a}	124.40 ± 2.62^{a}
	R1	18.20 ± 0.50^{a}	23.80 ± 1.40^{ab}	35.17 ± 2.01^{b}	62.27 ± 2.37 b	85.30 ± 1.91^{c}	104.33 ± 2.57^{b}	117.43 ± 2.13^{b}
	R2	16.67 ± 0.62^{bc}	24.87 ± 1.41^{ab}	36.23 ± 2.10^{b}	64.83 ± 2.49^{ab}	83.20 ± 2.82^{c}	106.77 ± 2.11^{ab}	117.70 ± 2.62^{b}
	R3	18.00 ± 0.16^{ab}	25.90 ± 1.19^{a}	41.17 ± 2.30^{a}	66.17 ± 2.94^{ab}	85.30 ± 2.94^{c}	109.70 ± 3.18^{ab}	124.00 ± 2.02^{a}
	R4	16.50 ± 0.82^{c}	24.83 ± 0.82^{ab}	40.93 ± 2.14^{a}	70.57 ± 3.43^{a}	98.40 ± 3.43^{a}	108.97 ± 2.41^{ab}	122.50 ± 2.97^{ab}
Stem diameter	CK	5.15 ± 0.41^{a}	6.25 ± 0.24^{a}	8.75 ± 0.38^{a}	11.40 ± 0.44^{a}	12.72 ± 0.61^{a}	13.64 ± 0.11^{a}	14.37 ± 0.49^{a}
	R1	5.25 ± 0.57^{a}	6.36 ± 0.16^{a}	7.97 ± 0.29^{a}	11.45 ± 0.70^{a}	12.08 ± 0.76^{a}	12.99 ± 0.97^{ab}	13.91 ± 0.74^{b}
	R2	4.99 ± 0.27^{a}	6.42 ± 0.29^{a}	8.40 ± 0.34^{a}	11.37 ± 0.25^{a}	12.29 ± 0.55^{a}	12.47 ± 0.11^{ab}	12.97 ± 0.51^{b}
	R3	4.36 ± 0.38^{a}	5.99 ± 0.50^{a}	8.16 ± 0.16^{a}	11.22 ± 0.08^{a}	11.72 ± 0.10^{a}	12.11 ± 0.43^{b}	12.99 ± 0.42^{b}
	R4	4.61 ± 0.37^{a}	6.28 ± 0.68^{a}	8.31 ± 0.59^{a}	10.85 ± 0.33^{a}	12.09 ± 0.37^{a}	12.40 ± 0.59^{ab}	13.12 ± 0.38^{b}

At the seedling and flower and fruit-bearing stage, plant height increased with an increase in film residual, and it decreased with increasing film residual in the fruit swelling and mature stage. Compared with CK, the reduction in plant height for R1 to R4 were 4.4%, 1.5%, 6.2%, 6.3% in 2019 and 5.6%, 5.4%, 0.3%, 1.5% in 2020 at mature stage, respectively. For stem diameter, the highest values were observed when the film residual amount was less than 200 kg/hm^2 and showed a decreased trend with increasing film residual in two years (Tables 4 and 5). In general, the effects of residual mulch film on plant height and stem diameter had evident regular change, and the growth trend of plant height and stem diameter basically accorded with the logistic growth model.

3.3.2. Photosynthetic Characteristics

In this study, there was an obvious influence on photosynthetic rate and stomatal conductance by film residual in both growing seasons (Figure 4). The photosynthetic rate in the 2019 growing season for each treatment was 20.60 μmol/m^2·s, 19.68 μmol/m^2·s, 22.19 μmol/m^2·s, 21.68 μmol/m^2·s, and 18.21 μmol/m^2·s on average, respectively. In 2020, it was 19.73 μmol/m^2·s, 19.57 μmol/m^2·s, 20.06 μmol/m^2·s, 20.67 μmol/m^2·s, and 20.98 μmol/m^2·s on average, respectively. Film residual in soil enhanced the photosynthetic rate at the seedling stage. The photosynthetic rate changes exhibited a significant variance among the treatments at the early growth stage in the two growing seasons. On the other hand, the increased film residual dropped the photosynthetic rate level at the flower and fruit-bearing stage and swelling stage in the two growing seasons (Figure 4a,b).

Similar change trends were obtained between stomatal conductance and photosynthetic rate in two growing seasons (Figure 4c,d). The results also indicated a significant variance in stomatal conductance with increasing film residual amount at the seedling stage in 2019 and 2020. The CK treatment without film residual incorporated in soil significantly reduced stomatal conductance of 0.26 mol/m^2·s and 0.54 mol/m^2·s compared with the R4 treatment (0.29 mol/m^2·s in 2019 and 0.61 mol/m^2·s in 2020) in the seedling stage. Ck treatment showed almost no significant difference from R1 treatment. It revealed that the effects of a slight film residual amount were limited on crop stomatal conductance.

In conclusion, an increasing film residual amount was found to enhance the photosynthetic rate and stomatal conductance level in seedlings but reduced the photosynthetic rate at the flower and fruit-bearing stage and swelling stage. The implications of film residual on crop photosynthetic characteristics and its subsequent impact on crop growth and biomass accumulation have not been extensively studied before. Thus, our research can improve the knowledge to understand the harm of film residuals in agriculture.

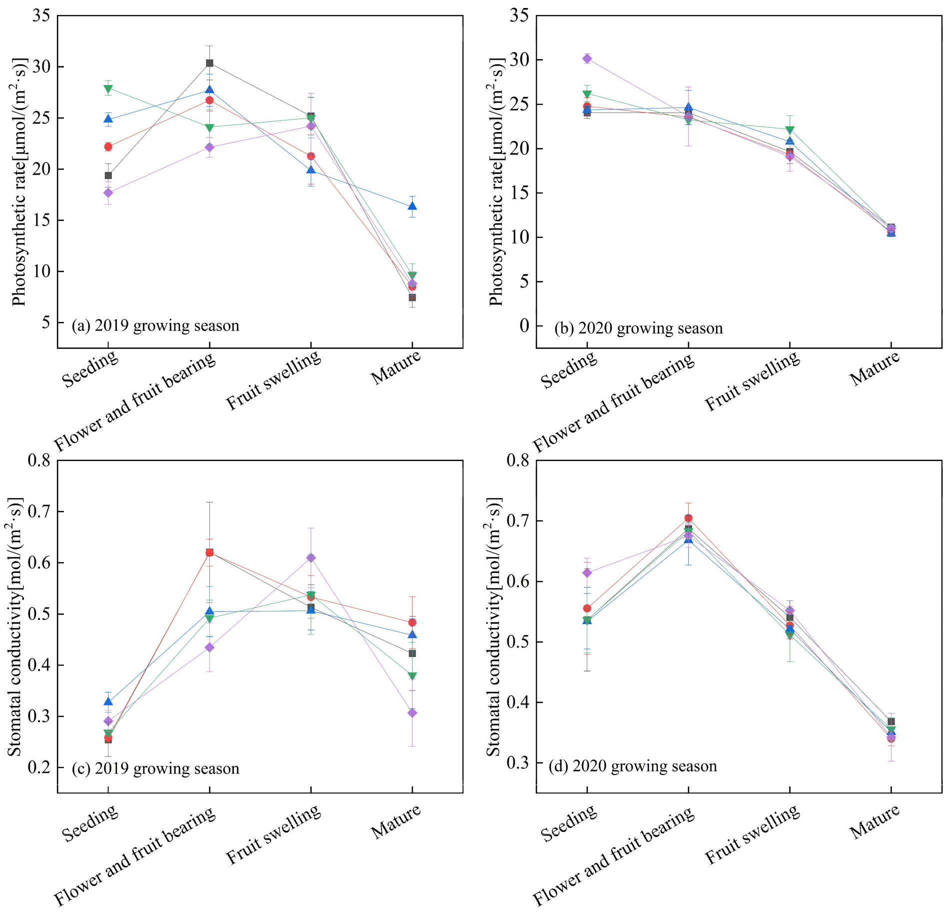

Figure 4. Effects of film residual treatment on photosynthetic (**a**,**b**) rate and stomatal conductance (**c**,**d**) in 2019 and 2020. The data in each figure are the average photosynthetic rate and stomatal conductance of three replicates, with standard deviation by error bars.

3.4. Yield and Fruit Quality Responses to Increasing Film Residual Amount

Changes in the amount of film residual had a significant impact on tomato fruit quality and yield (Table 6). In 2019, almost the same yield was observed for CK and R1 treatment with 94.00 ton/hm^2 and 94.02 ton/hm^2, which significantly decreased by 12.5% in R3. Although R2 and R4 treatment revealed a decreased trend in yield, there was no significant difference compared with CK, as shown in Table 6. In 2020, the yield decreased with the increase in film residual, and the higher the film residual amount, the lower the yield. The reduction in yield in R2, R3, and R4 treatment was lower in 2020 (decreased by 19.1%, 19.7%, 8.6%) than in 2019 (decreased by 4.6%, 12.5%, 3.9%, respectively). In general, the film residual produced negative effects on tomato yield. The yield of film residual treatments did not significantly vary but reduced compared with CK in 2019, and insufficient irrigation and film residual stress in 2020 significantly deteriorated yield as compared with the 2019 season.

Table 6. SSC, OA, VC, NC, and yield data across film residual levels. Values given as averages for three replicates and followed by different letters in each column are significantly different ($p < 0.05$). * represents a significance level of 0.05.

Growing Seasons	Treatment	VC (mg/100 g)	SSC (%)	OA (%)	NC (mg/100 g)	Yield (ton/hm^2)
2019	CK	17.59 ± 0.17 ^{d}	1.53 ± 0.03 ^{b}	0.34 ± 0.01 ^{a}	2.26 ± 0.12 ^{c}	94.00 ± 1.98 ^{a}
	R1	19.98 ± 0.69 ^{c}	1.33 ± 0.07 ^{c}	0.31 ± 0.01 ^{b}	3.13 ± 0.46 ^{c}	94.02 ± 3.63 ^{a}
	R2	19.97 ± 0.21 ^{c}	1.33 ± 0.04 ^{c}	0.32 ± 0.02 ^{ab}	1.98 ± 0.14 ^{c}	89.70 ± 2.82 ^{a}
	R3	28.86 ± 1.13 ^{a}	1.26 ± 0.01 ^{c}	0.25 ± 0.01 ^{c}	7.61 ± 0.34 ^{a}	82.29 ± 3.12 ^{b}
	R4	25.31 ± 0.48 ^{b}	1.68 ± 0.02 ^{a}	0.30 ± 0.01 ^{b}	4.91 ± 0.37 ^{b}	90.35 ± 3.90 ^{a}
	Film residual	*	*	*	*	*
2020	CK	28.06 ± 0.44 ^{c}	1.72 ± 0.14 ^{b}	0.84 ± 0.01 ^{a}	3.10 ± 0.72 ^{c}	84.44 ± 4.37 ^{a}
	R1	44.98 ± 1.42 ^{a}	3.44 ± 0.11 ^{a}	0.61 ± 0.01 ^{a}	3.76 ± 0.47 ^{c}	60.00 ± 5.99 ^{a}
	R2	34.50 ± 1.50 ^{b}	4.20 ± 0.48 ^{a}	0.67 ± 0.01 ^{a}	11.71 ± 0.34 ^{a}	68.33 ± 6.08 ^{a}
	R3	45.04 ± 2.58 ^{a}	4.13 ± 0.41 ^{a}	0.74 ± 0.02 ^{a}	11.47 ± 0.15 ^{a}	67.78 ± 7.86 ^{a}
	R4	32.29 ± 1.69 ^{b}	3.50 ± 0.36 ^{a}	0.78 ± 0.01 ^{a}	8.23 ± 0.90 ^{b}	77.22 ± 4.88 ^{a}
	Film residual	*	*	ns	*	*

Fruit quality was considered the most valuable indicator of tomato, including SSC, OA, VC, and NC. Fruit quality and quality variations during the two growing seasons are shown in Table 6. Film residual produced positive effects on tomato quality, such as VC, SSC, and NC. On the contrary, it produced negative effects on OA. Film residual had a significant impact on VC. The maximum VC values were observed in R3 treatment in two growing seasons with 28.86 mg/100 g and 45.04 mg/100 g, 64.1% and 60.5%, which were significantly higher than CK. On average, VC was higher in the 2020 season than in the 2019 season, with CK showing significantly lower VC in both seasons. In our study, SSC and NC showed a similar trend with VC with the more film residual and the higher SSC and NC values in two growing seasons. A high level of film residual amount significantly increased SSC and NC in the two consecutive seasons. The maximum SSC and NC were observed in R4 and R3 with 1.68% and 4.91 mg/100 g in 2019, respectively. The maximum SSC and NC were 4.20% and 11.71 mg/100 g in 2020, which appeared in the R2 treatment. In comparison, CK and R1 did not show significant variance in NC in either 2019 or 2020. The reduction in NC in residual treatments was higher in 2020, with 16.6% on average, than in 2019, with 13.3% on average. Mainly, NC decreased with increasing film residual, and the water deficit in 2020 played a role in improving fruit NC compared with 2019. In comparison with CK, R1, R2, R3, and R4 significantly reduced OA by 8.8%, 5.9%, 26.5%, and 11.8% in 2019 and 27.3%, 20.2%, 11.9%, and 7.1% in 2020, respectively, but there was no significant difference between treatments in 2020, as shown in Table 6.

3.5. Comprehensive Evaluation Analysis of Tomato, Based on Fruit Quality and Yield

3.5.1. Comprehensive Evaluation of Tomato Fruit Quality and Yield Based on PCA, GRDA, MFA, Topsis Analysis

A single index of tomato fruit cannot effectively evaluate the comprehensive quality of tomato, so it is necessary to use comprehensive evaluation analysis to assess the yield and fruit quality of the tomato. Therefore, the fruit quality and tomato yield were used as evaluation factors for comprehensive evaluation analysis in 2019 and 2020. PCA, GRDA, MFA, and TOPSIS were used to evaluate the comprehensive quality of tomato. The result and ranking of tomato quality are presented in Table 7.

Table 7. Evaluation results and ranking of tomato yield quality. The F, ρ_i, X_μ, C were the sum of the main factor and the weighting factor under PCA, Gray relation coefficient, membership function value, and the relative approach degree of TOPSIS, respectively.

Growing Seasons	Treatment	PCA		GRDA		MFA		TOPSIS	
		F	Ranking	ρ_i	Ranking	X_μ	Ranking	C	Ranking
2019	CK	0.976	1	0.631	2	2.591	1	0.510	2
	R1	0.412	2	0.580	4	2.508	2	0.501	3
	R2	0.390	3	0.546	5	2.232	4	0.462	4
	R3	−1.646	5	0.600	3	2.000	5	0.449	5
	R4	−0.132	4	0.638	1	2.296	3	0.636	1
2020	CK	−0.197	5	0.600	3	2.000	5	0.449	5
	R1	0.636	1	0.763	1	3.613	1	0.635	1
	R2	0.290	3	0.574	4	2.459	3	0.494	3
	R3	0.366	2	0.636	2	2.753	2	0.532	2
	R4	0.037	4	0.505	5	2.336	4	0.472	4

As shown in Table 7, the greater the value of F, ρ_i, X_μ, C, the better the tomato's comprehensive quality. In general, the value of F, ρ_i, X_μ, C decreased with the increasing film residual amount, which had negative effects on tomato comprehensive quality. It was intriguing that the four analysis methods disclosed various rankings for R4 treatment in 2019. For GRAD and TOPSIS, the best tomato comprehensive quality appeared at R4, but PCA and MFA showed the opposite trend, with poor comprehensive quality in this treatment. In 2020, we observed that the higher tomato comprehensive quality ranking appeared at R1 treatment, and it meant a few film residual amounts could improve the comprehensive quality of tomato, but excess film residual amounts still had a negative effect on tomato quality.

3.5.2. Ex Ante Assessment of Combination Evaluation Analysis Based on PCA, GRDA, MFA, TOPSIS

Due to there being variance in the results across PCA, GRDA, MFA, and TOPSIS for the same treatment, a combination evaluation analysis was required to conform the ranking results in order to determine the influence degree of fruit quality parameters. In this research, the average correlation coefficients of PCA, GRDA, MFA, and TOPSIS ranged from 0.225 to 0.475 in 2019 and 0.525 to 0.675 in 2020, indicating that there was a certain correlation between each method. According to Formula (1), in 2019 and 2020, the Kendall consistency coefficient values were 98 and 142, respectively, higher than 80.5 (according to the critical value table of Kendall consistency coefficient), which indicated that the results of PCA, GRDA, MFA, and TOPSIS in 2019 and 2020 were compatible and met the requirements of the ex ante assessment of combination evaluation analysis.

3.5.3. Combination Evaluation Analysis of Tomato Growth Quality

There were some differences in the evaluation results of tomato comprehensive quality by PCA, GRDA, MFA, and TOPIS analysis (Table 7). Thus, the combination analysis methods (Mean Value Analysis, Borda Analysis, Copeland Analysis, Fuzzy Borda Analysis) were used to evaluate the results in PCA, GRDA, MFA, and TOPIS to reduce the variance between evaluation ranking and ensure accurate analysis of the advantages and disadvantages of each treatment (Table 8).

Table 8. Evaluation results of tomato comprehensive quality based on combination evaluation. M_v, B_i, C_i, and B_f were the value of Mean Value Analysis, the value of Borda count, the value of Copeland Analysis, and the value of fuzzy Borda count, respectively.

Growing Seasons	Treatment	Mean Value Analysis		Borda Analysis		Copeland Analysis		Fuzzy Borda Analysis	
		M_v	Ranking	B_i	Ranking	C_i	Ranking	B_f	Ranking
2019	CK	3.4	1	3	1	3	1	8.406	1
	R1	2.4	3	2	3	0	3	4.695	3
	R2	1.6	4	1	4	−2	4	1.989	5
	R3	1.2	5	0	5	−4	5	2.030	4
	R4	3.0	2	3	2	3	2	7.025	2
2020	CK	1.5	5	0	5	−4	5	1.769	4
	R1	5	1	4	1	4	1	10.000	1
	R2	2.75	3	2	3	0	3	2.585	3
	R3	4	2	3	2	2	2	6.000	2
	R4	1.75	4	1	4	−2	4	0.895	5

The rankings of Mean Value Analysis, Borda Analysis, Copeland Analysis, And Fuzzy Borda Analysis are given in Table 8, which clearly indicates the consistency of the combination evaluation results. It was concluded that Mi, Bi, Ci, and Bf evaluated the positive and negative levels of tomato comprehensive quality, which represented a downward trend with a growing film residual amount in general. In 2019, the ranking of four analysis methods showed an initial decrease followed by an increase in the order of CK > R4 > R1 > R3 > R2. In 2020, it was demonstrated that a few film residual amounts (R1 treatment with 200 kg/hm^2 film residual amount) improved the tomato comprehensive quality, which promptly declined when the film residual amounts were more than 200 kg/hm^2. Based on the above analysis results, it can be summarized that the best tomato comprehensive quality appeared when the film residual amount was lower than 200 kg/hm^2.

4. Discussion

This research provides proof of the water content response to film residual amounts in different tomato growth stages. Film residual directly deteriorated dynamics of soil water content and water storage and modified crop growth, ultimately leading to transforming the fruit quality and yield.

4.1. The Water Content in Soil

The higher the film residual mixed in the soil, the more evident the water content changes compared with CK. In general, it showed a different trend in soil water content under a depth of 30 cm compared to the surface soil layer in the two growing seasons. Dong et al. [36] reported a similar result in water content under film residual events. This can be ascribed to the soil properties being altered by film residual, which restricted soil porosity and blocked the continuity of pores [37], enhanced the difficulty of infiltration, and reduced the infiltration rate [38], which led to water accumulation in the soil surface layer and limited infiltration in the residual treatments.

The higher water content of CK treatment indicated that the soil provided a growth environment for tomato roots. Water uptake did not suffer from water stress in 2019, and less water content in CK showed that tomato roots grew untrammeled with enhanced water uptake from the surface soil layer in 2020. Mainly, the more film residual amount, the more the water movement was hindered, influencing capillary water absorption and migration. In addition, although the water content in CK was higher at a depth under 30 cm, we found that the effects of film residual on soil water content under 30 cm soil layer weakened in the mature period. This can be interpreted that the water progressively infiltrated under the action of gravity, which alleviated the hindering effect of film residual. Soil can be regarded as a discontinuous medium when blending with film residual modified the undisturbed soil properties, and the probability of preferential flow generation increased [39,40]. In addition to the impact of film residual, irrigation events usually influenced water content during the two growing seasons. Although there were varied irrigation amounts in 2019 and 2020, the trend of water content showed similar performance. The changes in irrigation led to variations in water content, but the effects of film residual were consistent in the two growing seasons.

The mechanism of water movement under film residual stress is similar to straw mulching. Water-retaining capacity can be improved when the substance is mingled in the soil, which results in higher water content in the surface soil layer at residual treatments than CK. The reason the soil water content in the surface was higher than that in the deep layer can be attributed to the fact that film residual increases soil water storage by hindering water infiltration. However, the difference between film residual and straw mulch in the soil is that film residual completely clogs water infiltration pores due to the molecular properties of plastic, which leads to water shortage in the deep soil layer.

4.2. Tomato Growth and Photosynthetic

The photosynthetic rate was increased with increasing film residual at the seedling stage in the two growing seasons. The ground temperature change was impacted by film residual, which caused significant changes in the leaf photosynthetic rate [41] because the increasing soil temperature repaired the photosynthetic system damage of the leaves [42]. Avramova et al. [43] reported that the response of crop photosynthesis rate to ground temperature was related to the crop growth period. The sensitivity of leaf photosynthetic characteristics to ground temperature increased with increasing crop growth rate [44]. In our study, the stomatal conductance showed a similar trend to the photosynthetic rate, which can be ascribed to the response to water shortage. Film residual could increase water storage in surface soil, which made water content in R1 to R4 treatments higher than CK. The response of the plant to the water shortage was to close stomata, which reduced the stomatal conductance over time. Stomatal conductance is affected not only by water shortage but also by photosynthetic rate.

In addition, it could be speculated that the reason for the increase in photosynthetic rate and stomatal conductance was that water stress caused by film residual could induce crop prematurity, which meant an advance in the growth period. It was recognized that mild water deficits were observed in the soil layer under the influence of film residual. In a water deficit situation, Gregory et al. [45] reported that limiting soil water had little effect on the growth stages of jointing and an increasingly greater effect on the growth stages of heading, anthesis, and physiological maturity. Morales et al. [46] reported that raspberry development was accelerated under water stress, advancing flowering and a shorter fruit production period. Therefore, it can be reasonably speculated that the phenomenon in our study, the advancement of the growth period from water deficit, led to the advancing growth of flag leaves and enhanced photosynthetic rate in residual treatments.

Indicators of crop growth include plant height and stem diameter. The changes in plant height and stem diameter reflected the utilization of water and nutrients by crops [47]. This study found that plant height and stem diameter were decreased with increasing film residual amounts. Soil plastic residual pollution aggravated the soil structure as well as hydraulic characteristics, which were relevant to the reduction in plant height and stem diameter. The higher the film residual level, the more water distribution and storage were restricted, hence, reducing capillary water migration and uptake [16]. Moreover, the change of soil physical properties by film residual could inhibit root elongation, resistance in the absorptive ability for water, and nutrients. Zou et al. [34] interpreted these results as film residual impeding tomato root growth, which leads to less water and nutrient uptake. Gao et al. [5] also reported that film residual inhibited root growth and further reduced plant height and stem diameter, which led to tomato growth reduction. In summary, film residual directly affects the water and nutrient environment in soil, and changes in the root morphology cause a difficulty of uptake, which plays a main role affecting tomato growth.

4.3. Yield and Fruit Quality

This research showed that the film residual had an impact on soil water content and the different physiological indicators of the tomato growth stage, which was finally reflected in the yield and fruit quality. The implications of film residual on soil water content and physiological characteristics were consistent with previous research. Lin et al. [48] reported that compared with no film residual, a large amount of film residual in the soil led to reduced crop yields. The yield of CK treatment was significantly higher than the other residual treatments because the photosynthetic rate of CK was higher during the flowering and fruit-bearing and fruit swelling stages, which were mainly growing stages, so the amount of dry matter accumulation was significantly better than the other treatments, and higher yields were obtained. Wang et al. [49] reported that crop yield increased with the increasing photosynthetic rate. On the other hand, film residuals affect the physical and chemical properties of the soil and lead to deterioration of the microbial environment, further affecting crop yield. Thus, the reduction in tomato yield can be explained by the effects of film residual on soil water movement and distribution as well as photosynthetic rate.

In our study, the yield reduction compared with CK ranged from 3.9 to 12.5% in 2019 and from 8.6 to 28.9% in 2020 across all residual treatments. The yield had the same trend during the two growing seasons in the study. Nevertheless, due to the different irrigation amounts in the two years, the yield reduction in 2020 was higher than in 2019. The results demonstrated that film residual had negative effects on tomato yield, but the amount of irrigation could be appropriately increased to moderate the downside of yield. Research on other crops confirmed these results: that increasing film residual amount significantly reduced the yield. Yield reductions in cotton, wheat, and maize had been presented to be 0.8%–22.1%, 13.5%–18.1%, and 1.1%–9.1%, respectively, in film residual treatment compared with control experiments [16,36].

The main factor affecting fruit quality was soil water [50,51]. In the two growing seasons of this study, the change trend of Vc, SSC, OA, and NC obtained was analogous to previous studies under water stress [52]. Chen et al. [53] reported that tomato quality was highly sensitive to water stress from flowering and fruit swelling and mature stage. Zou et al. [34] reported that changes in water content had a significant impact on the Vc, SSC, and OA of tomatoes. When the film residual amount was higher than 800 kg/hm^2, the fruit Vc, SSC, and NC significantly increased, and the organic acid content was reduced. It can be shown that excessive film residual amounts not only disturbed soil water dynamic distribution but also deteriorated tomato fruit parameters.

Furthermore, uneven water distribution caused by residual film has been shown to induce changes in nutrient availability [36], leading to differences in root absorption, and ultimately to changes in tomato quality. Kim et al. [54] reported that the soluble sugar content in tomatoes increased significantly under the condition of low nitrogen. The Vc content of tomatoes increased by 7.3–26.6% when the irrigation amount and the potassium fertilizer application amount were 80% of the normal level [55]. Therefore, the water deficit caused by variance film residual amount was considered one of the most important factors for tomato fruit quality.

4.4. Tomato Comprehensive Quality

This paper utilized PCA, GRDA, MFA, TOPSIS to assess tomato comprehensive quality. Since there was variance between assess results, the combination evaluation analysis was used to eliminate differences and obtain accurate comprehensive quality rankings under residual stress. The Mean Value Method, Borda Method, Copeland Method, and Fuzzy Borda Method had the characteristics of simple principles, convenient calculation, and strong accuracy. Considering the evaluation score or combining the ranking result overcomes the difference caused by a single evaluation method. Especially, the Fuzzy Borda Method wholesale considered the evaluation score and ranking [56]. Each independent index of tomatoes can be converted into a comprehensive index that can fully reflect the overall information on tomato quality and physiology by using the Fuzzy Borda Analysis. In our study, it was found that the increase in tomato nutrient factors such as VC and SSC in two growing seasons can be attributed to the increasing film residual, but it still had a negative impact on tomato growth and other aspects in general. An analysis of the final rankings of the treatments in 2019 and 2020 showed that the best comprehensive quality performance was observed when the film residual amount was lower than 200 kg/hm^2. The higher the film residual level, the lower the comprehensive quality. It showed that although film residual improved fruit flavor, it reduced the tomato comprehensive quality. Therefore, it is necessary to find a balance point compromising plastic pollution, fruit flavor, and crop quality.

Considering the results in this study and previous related research, the policy of plastic film mulch control and substitution needs to be implemented to govern "white pollution", which threatens the sustainable use of cultivated land in China. This study provides knowledge to understand the effects of film residual on tomato growth and suggests the following subjects for future studies. Film residual hampered tomato comprehensive quality by hindering the soil water movement and influencing crop photosynthetic characteristics, but in this study, we did not involve nutrient distribution and absorption. Thus, we suggest that nutrient dynamics in different growth stages be studied under film residual stress. The results of this paper were restricted by varieties, planting patterns, and other conditions, and further research needs to be carried out on the soil types and crops.

5. Conclusions

This research analyzed the influence of film residual on soil water content, growth characteristics, and fruit quality and considered tomato comprehensive quality with the aim of providing suggestions for planting crops on film residual-tainted soil. In this study, the results indicated that the higher the film residual amount was, the more significant the effect on soil water content, tomato photosynthetic characteristics, and comprehensive quality would be. The effects tended to be aggravated by an increasing amount of film residual. The soil water content decreased in 2019 and increased in 2020, with increasing residual levels. The residual treatments increased average photosynthetic rate by 19.5% and 9.6% with CK in the seedling stage in two growing seasons. In this case, the highest soluble sugar content, vitamin C, and nitrate content were observed in R3 and R4 treatment. Compared with CK, the average tomato plant height, stem diameter, and yield in film residual treatment reduced by 4.6, 2.5, and 5.2% in 2019 and 3.2, 7.8, and 19.1% in 2020. Based on the comprehensive analysis results, excessive film residual threatens growth and gravely affects the comprehensive quality of tomatoes. Controlling film residual amount within 200 kg/hm^2 is helpful to achieve the sustainable use of plastic debris contaminated land.

Overall, our study revealed that plastic film residual blocked water movement, interfered with plant growth, diminished tomato yield, affected fruit quality, and had adverse effects on the comprehensive quality of tomatoes. In summary, this paper provides direct proof that film residual postponed the growth of tomato above-ground parts, and it expounds on the mechanism of the effects of film residual on tomato plants and fruit quality. In addition, it reinforces our view that film residual negatively impacts crop growth and water distribution. Undoubtedly, more research is urgently needed in order to better understand the effects of film residual on the microbiological cycle and agro-ecosystem.

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