Can Drip Irrigation without Film Mulching Be Favorable for Potato Growth in Eastern China?

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Abstract: The main measures to improve potato cultivation in eastern China are film mulching and drip irrigation. However, the film can cause soil pollution and inhibit plant growth because of non-degradable polyethylene, which is the main component of the film. Whether drip irrigation without mulching can improve potato yield needs to be fully explored. Field experiments were conducted at the Special Potato Experimental Station, China Agricultural University, Rizhao City, Shandong Province, China, in 2019 and 2020 to investigate the effects of mulching and soil wetted percentage on soil water and temperature distribution, as well as potato growth. In 2019, three treatments with soil wetted percentage of 50% were set up: black plastic film mulching (BMP2), transparent plastic film mulching (TMP2), and no mulching (NMP2). In 2020, soil wetted percentage treatments were added to the existing mulching treatments: no mulching without irrigation (NMP0) and no mulching with soil wetted percentage of 25% (NMP1), 50% (NMP2), and 75% (NMP3); black plastic film mulching without irrigation (BMP0) and black plastic mulching with 50% soil wetted percentage (BMP2); and transparent plastic film mulching with no irrigation (TMP0) and transparent plastic film mulching with 50% soil wetted percentage (TMP2). The results indicated that mulching did not have a significant effect (\( p < 0.05 \)) on soil temperature, potato growth, and yield. Irrigation reduced soil temperature by a range of 0.4 to 3.0 °C during the high air temperature season. Irrigation significantly increased potato plant height, stem thickness, and yield. The potato yield under the irrigation treatment could be 16.0–24.9% greater than that under the non-irrigation treatment. The highest irrigation water use efficiency (IWUE) was achieved at soil wetted percentage P1 and P2, which were beneficial for water saving. The NMP1 and NMP2 treatments had 83.4% and 81.0% significantly higher IWUE than NMP3 treatment. Considering environmental protection, resource conservation, and economic efficiency, drip irrigation without mulching under soil wetted percentage P2 was suitable for potato cultivation in eastern China.

Keywords: potato; mulch; soil wetted percentage; soil temperature; yield

1. Introduction

The potato is the fourth largest food crop in the world [1] and is widely cultivated because of its environmental adaptability. It requires less water to produce the same amount of dietary energy than other food crops and is rich in a wide variety of dietary nutrients such as protein and carotenoids [2,3]. The harvested potato area in China was 5.33 million ha in 2020 [4]; Shandong, a large agricultural province, is an important potato production base with a planting area of 140,000 ha [5].

Mulch can affect the soil thermal environment and its effects depend on mulch optical properties. Generally, transparent mulch has a greater soil heat flux and soil temperature than other mulches because of its high solar radiation transmissivity [6]. Soil thermal environment change can in turn affect crop growth [7]. The hydrothermal conditions and
crop growth affected by plastic film in different areas are different [8–12]. The average soil temperature of film mulching treatments is 1.4 °C higher in northwest China than that in eastern China and film mulching has significant effects on potato yields in northwest China, but it has no significant effects on potato yield in eastern China [8]. The average daily soil temperature of mulching treatments is higher (6.5 °C to 7.5 °C) than no mulch treatment with the black mulch treatment being 1 °C higher than the white mulch treatment in southern China [9]. Mulching can reduce the soil temperature by up to 3.3 °C when the soil temperature is high and it increased the tomato yield in Singapore [10]. Light-colored mulch increases soil temperature by 2.5 to 2.9 °C, which causes soil temperature stress and affects sweet pepper growth and yield, while dark-colored mulch can lower the soil temperature by 1.1 to 1.5 °C compared to light-colored mulch, with no significant difference in yield in Hungary [11]. The soil temperature in the transparent film treatment is higher than that in the black film treatment during the early sweet potato growth stage and the effect of mulching on soil temperature is smaller because of the sweet potato canopy development [12]. Therefore, the effect of plastic film is uncertain in agricultural production.

Mulching can reduce water evaporation in soil [13,14]. Plastic film mulch can decrease the amount of irrigation and increase the irrigation water use efficiency, especially in arid areas [8]. Sufficient water in the soil with a mulching treatment improves the evapotranspiration and yield of the crop [15]. And, the main water consumption of crops comes from natural conditions rather than artificial irrigation, which reduces the consumption of irrigation water and improves the utilization efficiency of irrigation water. Drip irrigation can achieve small amounts and high-frequency irrigation [16,17]. Drip irrigation with film mulching can provide suitable soil moisture for the potato, which is a water-prefering crop. Compared with drip irrigation, the combination of drip irrigation and film mulching significantly reduces root development, enhances potato plant growth, and increases the potato tuber yield in Northwest China [18,19]. However, drip irrigation with film mulching did not significantly increase the potato tuber yield or even lead to potato tuber yield loss in the North China Plain [8,20]. Previous researchers have studied potato water requirements and the effect of water on potato growth [21–23]. Soil water stress causes potato stem and leaf reduction during the early growth stage and affects potato tubers and yield if soil water stress is sustained [21]. The compensatory effect of rehydration after mild drought stress in the potato seedling stage promotes the nutrient partitioning of potato tubers and increases the tuber yield [22]. The irrigation effects on potato yield and irrigation water use efficiency depend on the potato variety [23]. Drip irrigation has a positive influence on crop yield [24]. The drip-irrigated potato can reach a high yield and irrigation water use efficiency when the plant is irrigated at a soil matric potential of −25 kPa at 20 cm soil depth directly below the drip tape in northern China [25,26]. Potato yield and tuber weight can be increased and water can be saved by 20% under mild drought stress conditions for drip irrigation treatment [27].

The disadvantages of film mulching have been revealed with the film’s widespread use. The film cannot be fully recycled after shredding, and a large amount of residual film can exist in soil [28]. The main component of the film is polyethylene, which is difficult to degrade, and pieces of film entering the soil can cause pollution and inhibit plant growth [29,30]. Therefore, film mulching should not be applied in some regions if it is not beneficial for crop growth. To our knowledge, the existing study about potato cultivation was mainly carried out under the condition of drip irrigation with plastic film mulching in eastern China. Whether drip irrigation without film mulching can be used to increase potato yields in this area needs further research. The purpose of this research was to determine the following: (1) how the film mulching and soil wetted percentage of drip irrigation affect the soil hydrothermal environment; (2) whether mulching or irrigation is the main factor that improves potato growth in eastern China; and (3) what the suitable soil wetted percentage for potato growth is.
2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted from March 2019 to July 2019 and from March 2020 to July 2020 at the Special Potato Experimental Station (35°25′ N, 118°59′ E, altitude 131 m), China Agricultural University, Rizhao City, Shandong Province, China (Figure 1). The station is located in the low hilly region of southeast Shandong. The region has a warm, temperate, humid monsoon climate with annual average sunshine of 2533 h, annual average temperature of 13.2 °C, annual average rainfall of 897 m, and a frost-free period of 213 d. The soil is sandy loam with an average dry capacity of 1.50 g/cm³ and an average field capacity of 26.02%.

Figure 1. Experimental location of the Special Potato Experimental Station.

2.2. Experimental Design

In 2019, three treatments were set up: black plastic film mulching (BMP2), transparent plastic film mulching (TMP2), and no mulching (NMP2). The drip irrigation soil wetted percentages were set at 50% for each treatment. Five replications were designed for each treatment and the replications were laid out in a completely randomized arrangement.

In 2020, the drip irrigation soil wetted percentage treatments were added to the existing mulching treatments. The treatments were as follows: no mulching without irrigation (NMP0) and no mulching with soil wetted percentage of 25% (NMP1), 50% (NMP2), and 75% (NMP3); black plastic film mulching without irrigation (BMP0) and black plastic mulching with 50% soil wetted percentage (BMP2); and transparent plastic film mulching with no irrigation (TMP0) and transparent plastic film mulching with 50% soil wetted percentage (TMP2). Three replications were designed for each treatment and the replications were laid out in a completely randomized arrangement.

The crop was irrigated using a drip irrigation system. Each plot had a valve, a pressure meter, and a water meter to control and regulate the irrigation. After drip irrigation system installation, each mulching treatment was mulched with film in close contact with soil. A tensiometer (clay head buried 20 cm deep) was installed at 20 cm soil depth directly below the drip tape in each plot. The irrigation was applied when the average soil matric potential of each treatment reached −25 kPa. The irrigation amount \( m \) was determined using the following equation [18]:

\[
m = \frac{h(\theta_a - \theta_b)P}{\eta}
\]
where \( h \) is the planned wetted depth (mm), \( \theta_a \) is the volumetric soil water content after irrigation (cm\(^3\)/cm\(^3\)), \( \theta_b \) is the volumetric soil water content immediately before irrigation (cm\(^3\)/cm\(^3\)), \( P \) is the soil wetted percentage which is the ratio of actual wetted soil volume to the planned wetted total soil volume, and \( \eta \) is the water utilization coefficient of the drip irrigation system which is the ratio between the water delivered to the crop and the water pumped from the well.

In 2019, the average total irrigation for BMP2, TMP2, and NMP2 was 167, 162, and 155 mm, respectively. In 2020, the average total irrigation for BMP2, TMP2, NMP1, NMP2, and NMP3 was 274, 184, 172, 188, and 314 mm, respectively.

2.3. Agronomic Practice

The potato variety was ‘Holland XV’. Potatoes were planted in raised beds (6.4 m long, 90 cm wide, and 20 cm high) in the north–south direction. Each bed had two rows with wide row spacing of 60 cm and narrow row spacing of 30 cm. Each plot had 8 beds with an area of 46.08 m\(^2\).

In 2019, potatoes were planted on 9 March and harvested on 26 June. Base fertilizer was applied on 7 March and additional fertilizer was applied on 27 April and 24 May. In 2020, potatoes were planted on 22 March and harvested on 2 July. Base fertilizer was applied on 19 March and additional fertilizer was applied on 14 May and 2 June.

Fertilizer application was based on the local farmers’ experience with a total of 82 kg/ha of P\(_2\)O\(_5\), 385 kg/ha of K\(_2\)O, and 147 kg/ha of N fertilizer. The base fertilizer was applied with all P fertilizer (P\(_2\)O\(_5\)), 80% K fertilizer (K\(_2\)O), 47% N fertilizer, 10% K fertilizer (K\(_2\)O), and 24% N fertilizer during tuber initiation and 10% K fertilizer (K\(_2\)O) and 29% N fertilizer during tuber bulking. Other agronomic measures such as fertilizer and pest control were the same for all treatments.

2.4. Measurement

Meteorological data (precipitation, temperature, relative humidity, and so on) were monitored by the meteorological station in the vicinity of the experimental field. One plot was randomly selected for each treatment and the instrument was laid out in the middle of the bed directly below the drip tape at 10, 20, 30, 50, and 70 cm soil depth. The typical daily soil temperature was measured at 10, 15, 20, and 25 cm soil depth using a metal curved tube geothermometer (Hebei Huayu Instrument Co., Ltd., Hengshui, China). Soil temperature observations were made at 8:00, 10:00, 12:00, 14:00, 16:00, and 18:00 every 7 days or so after planting.

Ten potato plants were selected and marked in each plot for plant height and stem thickness measurement using a steel ruler and electronic vernier caliper at each growth stage. Potatoes in the middle three beds of each plot were harvested for yield. Potatoes of ten plants were randomly selected from each plot to measure the number and weight of the individual potatoes at each grading. The grading standard was defined as commercial potatoes over 50 g and large potatoes over 200 g.

Irrigation water use efficiency was calculated as follows:

\[ IWUE = \frac{Y}{I} \]

where \( IWUE \) is irrigation water use efficiency (kg/ha/mm), \( Y \) is potato yield (kg/ha), and \( I \) is irrigation water amount (mm).

Ten tubers of each plot were selected for potato quality measurement. The starch content was determined using the water weight method. The vitamin C content was determined using the 2.6-dichloroindophenol (DCIP) titration method. The protein content was determined using the Kjeldahl method.

2.5. Statistical Analyses

Data on soil temperature, plant height, plant thickness, tuber grade, tuber yield, and quality were subjected to variance analysis using SPSS Version 24.0 software. Differences
among treatments were analyzed using the F-test and differences between treatments were analyzed using Duncan’s multiple range test.

3. Results

3.1. Weather Conditions

The variations in maximum temperature (T_{\text{max}}), minimum temperature (T_{\text{min}}), average temperature (T_{a}), average relative suitability (RH), and rainfall (RF) during the whole potato growth period in 2019 and 2020 are shown in Figure 2 and Table 1. The average temperatures were 17.7 and 18.4 °C and the average sunshine hours were 6.7 and 10.4 h for the 2019 and 2020 growing seasons, respectively. The higher air temperature and long sunshine hours resulted in a greater potato yield in 2020 than in 2019. The rainfall was 75.8 and 252.6 mm in the 2019 and 2020 growing seasons, respectively.

![Figure 2. Variations in maximum temperature (T_{\text{max}}), minimum temperature (T_{\text{min}}), average temperature (T_{a}), average relative suitability (RH), and rainfall (RF) in the 2019 and 2020 growing seasons.](image)

3.2. Effect of Mulching and Soil Wetted Percentage on Soil Temperature

3.2.1. Effect of Different Mulching on Soil Temperature

Daily soil temperature variations across four typical days with different potato growth stages in 2019 and 2020 are shown in Figure 3. Soil temperatures at 10 and 15 cm soil depth, affected by air temperature, increased the most between 10:00 and 12:00 and then continued to rise with the peak soil temperature occurring during 14:00 to 18:00. The daily soil temperature changes at 20 and 25 cm soil depth became smaller.
Table 1. Summaries of maximum temperature (T\text{max}), minimum temperature (T\text{min}), average temperature (T\text{a}), average relative suitability (RH), rainfall (RF), and sunshine hours during different potato growth stages in 2019 and 2020.

<table>
<thead>
<tr>
<th>Year</th>
<th>Growth Stage</th>
<th>Average RH (%)</th>
<th>Total RF (mm)</th>
<th>Average T\text{a} (°C)</th>
<th>Average T\text{max} (°C)</th>
<th>Average T\text{min} (°C)</th>
<th>Average Sunshine Hours (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Sprout development (9 March–18 April)</td>
<td>55.7</td>
<td>32.4</td>
<td>11.3</td>
<td>18</td>
<td>5.4</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Tuber initiation (19 April–5 May)</td>
<td>64.8</td>
<td>16</td>
<td>15.5</td>
<td>21.8</td>
<td>10.2</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Tuber bulking (6 May–16 June)</td>
<td>56.4</td>
<td>22.4</td>
<td>22.3</td>
<td>28.8</td>
<td>16.3</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Maturation (17 June–30 June)</td>
<td>68.8</td>
<td>5</td>
<td>25.3</td>
<td>31.3</td>
<td>21.1</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Whole growth (9 March–30 June)</td>
<td>58.9</td>
<td>75.8</td>
<td>17.7</td>
<td>24.2</td>
<td>12</td>
<td>6.7</td>
</tr>
<tr>
<td>2020</td>
<td>Sprout development (20 May–22 April)</td>
<td>52.8</td>
<td>34.5</td>
<td>11.9</td>
<td>18.3</td>
<td>6</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>Tuber initiation (23 April–10 May)</td>
<td>59.4</td>
<td>47.8</td>
<td>17.2</td>
<td>24</td>
<td>11</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>Tuber bulking (11 May–20 June)</td>
<td>68.4</td>
<td>115</td>
<td>22.7</td>
<td>29</td>
<td>17.5</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td>Maturation (21 June–3 July)</td>
<td>78.8</td>
<td>55.3</td>
<td>23.5</td>
<td>27.7</td>
<td>20.1</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>Whole growth (20 March–3 July)</td>
<td>63</td>
<td>252.6</td>
<td>18.4</td>
<td>24.6</td>
<td>13</td>
<td>10.4</td>
</tr>
</tbody>
</table>

The soil temperatures in the TM treatment were the highest in the early potato growth stage with no significant differences between the BM and NM treatments. For example, the average daily soil temperature was 18.1 °C for the TM treatment and 16.6 °C and 16.4 °C for the BM and NM treatments on 17 April 2019, and was 22.7 °C for the TM treatment and 21.3 °C and 21.2 °C for the BM and NM treatments on 3 June 2020 at 10–25 cm soil depth. This may be due to the high solar radiation transmissivity of TM which made more sunlight able to pass through and increased the soil temperature.

The effect of the mulching on soil temperature became smaller as the plant canopy grew. For example, the maximum average daily temperature difference between the mulching and no mulching treatments was 1.9, 0.6, and 0.5 °C on 20 March, 16 May, and 28 June 2019, respectively. The daily soil temperature differences between the mulching and no mulching treatments were very small during the tuber bulking and maturity stages.

3.2.2. Effect of Soil Wetted Percentage on Soil Temperature

The daily soil temperature variation for different soil wetted percentages in 2020 is shown in Figure 4. Generally, soil temperatures were higher in the non-irrigated treatment than in the irrigated treatment. On 16 May (during the tuber bulking stage), the soil temperature at 10–25 cm soil depth in the non-irrigated treatment was 1.6 and 1 °C higher than in the irrigation treatment for the BM and TM treatments, respectively. The soil temperature in the NMP0 treatment was 2.3, 2.1, and 3 °C higher than in the NMP1, NMP2, and NMP3 treatments, respectively. On 21 June (during maturation), the soil temperature at 10–25 cm soil depth in the non-irrigated treatment was 0.5 and 0.4 °C higher than in the irrigation treatment for the BM and TM treatments, respectively. The soil temperature in the NMP0 treatment was 1.2 °C, 1.4 °C, and 1.1 °C higher than in the NMP1, NMP2, and NMP3 treatments, respectively.

The irrigation treatment could cool the soil either with mulching or no mulching because the greater soil water content increased the soil specific heat capacity. The effects of irrigation on soil temperature became smaller because of the high air temperature during the maturation stage.
3.3. Effect of Mulching and Soil Wetted Percentage on Soil Water Content

The average soil water content in different soil layers in 2019 and 2020 under different treatments is shown in Table 2. Generally, the soil water content in the TM treatment was lower than in the other treatments. In 2019, the TMP2 treatment had 15% and 4% smaller soil water content than the BMP2 and NMP2 treatments. In 2020, the TMP0 treatment had 26% and 18% smaller soil water content than the BMP0 and NMP0 treatments and the TMP2 treatment had 14% and 40% smaller soil water content than the BMP2 and NMP2 treatments, respectively. This might be due to the more vigorous underground potato growth in the TM treatment which caused higher soil water consumption.

![Figure 3. Cont.](image)
Figure 3. Daily variation in soil temperature at different soil depths for the different mulch treatments: black mulch with soil wetted percentage of 50% (BMP2), transparent mulch with soil wetted percentage of 50% (TMP2), and non-mulched check with soil wetted percentage of 50% (NMP2) on different typical days in 2019 (a) and 2020 (b).

In 2020, the ranking of the soil water content in the non-mulched treatments was NMP3 ≈ NMP2 > NMP1 > NMP0, which showed that the soil water content was related to irrigation. The NMP1, NMP2, and NMP3 treatments had 5.6%, 29.6%, and 32.8% more soil water content than the NMP0 treatment at 0–70 cm soil depth.
3.2.2. Effect of Soil Wetted Percentage on Soil Temperature

The average soil water content in different soil layers in 2019 and 2020 under different treatments is shown in Table 2. Generally, the soil water content in the TM treatment was statistically similar according to Duncan’s multiple range test (p > 0.05). NS: difference between different treatments was not significant according to F-test (p > 0.05). * Difference between different treatments was significant according to F-test (p < 0.05). Values in a column with the same letter were statistically similar according to Duncan’s multiple range test (p < 0.05).

Table 2. Soil water content (g·g⁻¹) at different soil depths for the different mulch treatments with different soil wetted percentage treatments: black mulch with soil wetted percentage of 50% (BMP2), transparent mulch with soil wetted percentage of 50% (TMP2), no mulch without irrigation (NMP0), no mulch with soil wetted percentage of 25% (NMP1), no mulch with soil wetted percentage of 50% (NMP2), and no mulch with soil wetted percentage of 75% (NMP3) on different typical days in 2020.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Soil Layer/m</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0–0.1</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td>2019</td>
<td>NMP0</td>
<td>0.115 NS</td>
<td>0.131 NS</td>
</tr>
<tr>
<td></td>
<td>NMP1</td>
<td>0.129</td>
<td>0.141</td>
</tr>
<tr>
<td></td>
<td>NMP2</td>
<td>0.139</td>
<td>0.148</td>
</tr>
<tr>
<td></td>
<td>NMP3</td>
<td>0.151</td>
<td>0.153</td>
</tr>
<tr>
<td></td>
<td>BMP0</td>
<td>0.108</td>
<td>0.137</td>
</tr>
<tr>
<td></td>
<td>BMP1</td>
<td>0.134</td>
<td>0.151</td>
</tr>
<tr>
<td></td>
<td>BMP2</td>
<td>0.110</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>TMP0</td>
<td>0.130</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td>TMP2</td>
<td>0.124</td>
<td>0.140</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.110</td>
<td>0.134</td>
</tr>
</tbody>
</table>

*1661<ref>Figure 4. Daily variation in average 2 h soil temperature at different soil depths for the different mulch treatments with different soil wetted percentage treatments: black mulch without irrigation (BMP0), black mulch with soil wetted percentage of 50% (BMP2), transparent mulch without irrigation (TMP0), transparent mulch with soil wetted percentage of 50% (TMP2), no mulch without irrigation (NMP0), no mulch with soil wetted percentage of 25% (NMP1), no mulch with soil wetted percentage of 50% (NMP2), and no mulch with soil wetted percentage of 75% (NMP3) on different typical days in 2020.</ref>
3.4. Effect of Mulching and Soil Wetted Percentage on Potato Growth

Potato plant height and stem thickness for different mulching treatments are shown in Figure 5. Mulching had no significant effect on potato plant height and stem thickness, while a significant effect was shown in the soil wetted percentage treatment. In both years, the TM treatment showed a lower potato plant height than the other treatments, but there were no significant differences. The BM treatment had a slightly greater stem thickness than the other treatments, with no significant differences.

![Figure 5. Potato plant height on different dates (a) in 2019 and (b) in 2020 and potato stem thickness on different dates (c) in 2019 and (d) in 2020 for different treatments: black mulch with soil wetted percentage of 50% (BMP2), transparent mulch with soil wetted percentage of 50% (TMP2), non-mulched check with soil wetted percentage of 50% (NMP2) in 2019 and black mulch without irrigation (BMP0), black mulch with soil wetted percentage of 50% (BMP2), transparent mulch without irrigation (TMP0), transparent mulch with soil wetted percentage of 50% (TMP2), no mulch without irrigation (NMP0), no mulch with soil wetted percentage of 25% (NMP1), no mulch with soil wetted percentage of 50% (NMP2), and no mulch with soil wetted percentage of 75% (NMP3) in 2020.](figure5.png)

The soil wetted percentage had a significant effect on potato plant height. In 2020, the plant height in the BMP2, TMP2, and NMP2 treatments was 17.8, 13.6, and 36 cm significantly higher than that in the BMP0, TMP0, and NMP0 treatments, respectively. The potato plant height was high with the high irrigation amount. Compared with the NMP0 treatment, the NMP1, NMP2, and NMP3 treatments increased in height by 28.9, 36, and 40 cm, respectively, with no significant differences. During 60 and 80 d after planting, the potato plants in the irrigation treatment grew by 39% to 77.2% in height, while those in the non-irrigation treatment only grew by 34.5% to 42%.

There was a significant effect of soil wetted percentage on potato stem thickness. Generally, irrigation significantly increased the potato stem thickness, but the potato stem thickness differences between the different soil wetted percentage treatments with no mulching were not significant. In 2020, the BMP2, TMP2, and NMP2 treatments had
a 0.94, 0.93, and 1.49 mm significantly greater potato stem thickness than the BMP0, TMP0, and NMP0 treatments, respectively. The potato stems in the NMP1, NMP2, and NMP3 treatments became 1.23 mm, 1.49 mm, and 1.49 mm thicker than those of the NMP0 treatment, respectively.

3.5. Effect of Mulching and Soil Wetted Percentage on Potato Yield and Quality

3.5.1. Effect of Mulching and Soil Wetted Percentage on Potato Tuber Grading

Mulching had a significant effect on the commercial potato rate (>50 g), while soil wetted percentage and the interaction between mulching and soil wetted percentage had no significant effects on the commercial potato rate (Table 3). The commercial potato rate in the mulching treatment (95.52% to 98.04%) was significantly higher than in the no mulching treatment (91.32% to 94.60%). The difference between the commercial potato rate between the TM and BM treatments was not significant. Mulching had a significant effect on the weights of jumbo and super jumbo potato tubers (>200 g). The TM treatment had significantly larger potato tubers than those of the BM and NM treatments.

Table 3. Potato tubers’ (10 plants) weight from different mulch treatments: black mulch with soil wetted percentage of 50% (BMP2), transparent mulch with soil wetted percentage of 50% (TMP2), no mulched check with soil wetted percentage of 50% (NMP2) in 2019 and black mulch without irrigation (BMP0), black mulch with soil wetted percentage of 50% (BMP2), transparent mulch without irrigation (TMP0), transparent mulch with soil wetted percentage of 50% (TMP2), no mulch without irrigation (NMP0), no mulch with soil wetted percentage of 25% (NMP1), no mulch with soil wetted percentage of 50% (NMP2), and no mulch with soil wetted percentage of 75% (NMP3) in 2020.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Total Tubers (g)</th>
<th>Rate of W &gt; 50 g (%)</th>
<th>Rate of W &gt; 200 g (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>TMP2</td>
<td>3010.6 NS</td>
<td>2831.1 NS</td>
<td>1067.2 b*</td>
</tr>
<tr>
<td></td>
<td>BMP2</td>
<td>2277.0</td>
<td>3178.3</td>
<td>1052.3 b*</td>
</tr>
<tr>
<td></td>
<td>NMP2</td>
<td>2009.4</td>
<td>1957.7</td>
<td>1569.6 a*</td>
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<tr>
<td>2020</td>
<td>BMP0</td>
<td>1266.3 b*</td>
<td>2175.4 NS</td>
<td>1997.8 NS</td>
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<td></td>
<td>BMP2</td>
<td>1401.5 b*</td>
<td>3234.9</td>
<td>1404.6</td>
</tr>
<tr>
<td></td>
<td>NMP0</td>
<td>1461.9 ab*</td>
<td>2841.4</td>
<td>1583.1</td>
</tr>
<tr>
<td></td>
<td>NMP1</td>
<td>1208.1 b*</td>
<td>2290.8</td>
<td>1497.8</td>
</tr>
<tr>
<td></td>
<td>NMP2</td>
<td>3529.1 ab*</td>
<td>1741.9</td>
<td>2034.8</td>
</tr>
<tr>
<td></td>
<td>TMP0</td>
<td>4172.1 a*</td>
<td>3800.0</td>
<td>1708.0</td>
</tr>
<tr>
<td></td>
<td>TMP2</td>
<td>1417.4</td>
<td>2739.8</td>
<td>1710.7</td>
</tr>
</tbody>
</table>

NS: difference between different treatments was not significant according to F-test ($p > 0.05$). * Difference between treatments was significant according to F-test ($p < 0.05$). Values in a column with the same letter were statistically similar according to Duncan’s multiple range test ($p > 0.05$).

The effects of different mulch treatments on the potato tuber grade (10 plants) were not consistent in 2019 and 2020. In 2019, mulching had significant effects on potato tuber weights at $200 \geq W > 150$ g, $150 \geq W > 100$ g, and $W \leq 50$ g. The NM treatment had significantly more super large potato tubers ($200 \geq W > 150$ g) than the BM and TM treatments, but the NM treatment had significantly more large potato tubers ($150 \geq W > 100$ g) than the TM treatment. In 2020, mulching had significant effects on potato tuber weights at $W > 300$ g, $150 \geq W > 100$ g, $100 \geq W > 75$ g, and $W \leq 50$ g. The NM treatment had significantly more large potato tubers ($150 \geq W > 100$ g) and medium potato tubers...
(100 ≥ W > 75 g) than the BM and TM treatments, but the TM treatment had significantly more super jumbo potato tubers (>300 g) than the BM treatment.

3.5.2. Effect of Mulching and Soil Wetted Percentage on Potato Yield

The soil wetted percentage had an extremely significant effect on potato yield (Figure 6). In 2020, the P2 treatment had a significantly higher potato yield than the P0 treatment, but the P1 and P3 treatments did not show significant differences compared with the P0 treatment. For the mulching treatment, the potato yield in TMP2 (69,550.7 kg/ha) was 17.0% that of TMP0 (59,469.3 kg/ha), and BMP2 (66,811.3 kg/ha) was 16.0% higher than that of BMP0 (57,596.3 kg/ha). For the no mulching treatment, the potato yield in NMP1 (62,953.7 kg/ha), NMP2 (67,920.7 kg/ha), and NMP3 (62,673.5 kg/ha) was 15.8%, 24.9%, and 15.3% higher than that of NMP0 (54,369 kg/ha), respectively. The mulching treatment showed no significant effect on potato yield. The potato yield difference between TMP2 and NMP2 was only 2.3%. The potato yield was positively correlated with the soil water content and plant height, negatively correlated with temperature in tuber bulking and maturation and stem thickness, and approximately uncorrelated with the potato commercial rate (Figure 7).

The soil wetted percentage had an extremely significant effect on IWUE, while mulching did not significantly affect IWUE (Table 4). The NMP1 and NMP2 treatments had 83.4% and 81.0% significantly higher IWUE than the NMP3 treatment. Excessive irrigation resulted in low IWUE. This was because too much irrigation was detrimental to the potato roots’ aerobic respiration and harmful to potato tuber growth.

3.5.3. Effect of Mulching and Soil Wetted Percentage on Potato Quality

The soil wetted percentage had a significant effect on potato starch content (Table 5). With the same mulching treatment, the potato starch content was ranked P0 > P2 > P3 > P1. Irrigation caused potato starch content reduction, but only the P1 and P3 treatments reached significant differences. Neither mulching nor soil wetted percentage, nor their interaction, had a significant effect on vitamin C and crude protein content in the potatoes.
Table 4. Potato yield and IWUE for different treatments: black mulch with soil wetted percentage of 50% (BMP2), transparent mulch with soil wetted percentage of 50% (TMP2), non–mulched check with soil wetted percentage of 50% (NMP2) in 2019 and black mulch without irrigation (BMP0), black mulch with soil wetted percentage of 50% (BMP2), transparent mulch without irrigation (TMP0), transparent mulch with soil wetted percentage of 50% (TMP2), non mulch without irrigation (NMP0), no mulch with soil wetted percentage of 25% (NMP1), no mulch with soil wetted percentage of 50% (NMP2), and no mulch with soil wetted percentage of 75% (NMP3) in 2020.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Yield (kg/ha)</th>
<th>IWUE (kg/ha/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>TMP0</td>
<td>59,469.3 ± 3604.9 b**</td>
<td>377.1 a**</td>
</tr>
<tr>
<td></td>
<td>TMP2</td>
<td>69,550.7 ± 3410.5 a**</td>
<td>377.1 a**</td>
</tr>
<tr>
<td></td>
<td>BMP2</td>
<td>57,595.3 ± 3462.0 b**</td>
<td>243.83 a**</td>
</tr>
<tr>
<td></td>
<td>NMP0</td>
<td>66,811.3 ± 3417.9 a**</td>
<td>366.0 a**</td>
</tr>
<tr>
<td></td>
<td>NMP1</td>
<td>54,369.0 ± 3777.5 b**</td>
<td>361.3 a**</td>
</tr>
<tr>
<td></td>
<td>NMP2</td>
<td>62,953.7 ± 240.8 ab**</td>
<td>199.6 b**</td>
</tr>
<tr>
<td></td>
<td>NMP3</td>
<td>62,673.5 ± 3269.5 ab**</td>
<td>199.6 b**</td>
</tr>
<tr>
<td>2020</td>
<td>TMP0</td>
<td>50,868.2 ± 2583.6 a</td>
<td>314.0 a</td>
</tr>
<tr>
<td></td>
<td>BMP2</td>
<td>50,110.0 ± 5410.7 a</td>
<td>300.1 a</td>
</tr>
<tr>
<td></td>
<td>NMP0</td>
<td>44,294 ± 4715.4 a</td>
<td>285.8 a</td>
</tr>
<tr>
<td></td>
<td>NMP1</td>
<td>62,953.7 ± 240.8 ab**</td>
<td>199.6 b**</td>
</tr>
<tr>
<td></td>
<td>NMP2</td>
<td>67,920.7 ± 4791.8 a**</td>
<td>361.3 a**</td>
</tr>
<tr>
<td></td>
<td>NMP3</td>
<td>67,920.7 ± 4791.8 a**</td>
<td>361.3 a**</td>
</tr>
</tbody>
</table>

NS: difference between different treatments was not significant according to F-test (p > 0.05). ** Difference between different treatments was significant according to F-test (p < 0.0). Values in a column with the same letter were statistically similar according to Duncan’s multiple range test (p > 0.05).
Table 5. Potato nutrient composition (starch content, vitamin C, and crude protein) under different treatments: black mulch without irrigation (BMP0), black mulch with soil wetted percentage of 50% (BMP2), transparent mulch without irrigation (TMP0), transparent mulch with soil wetted percentage of 50% (TMP2), no mulch without irrigation (NMP0), no mulch with soil wetted percentage of 25% (NMP1), no mulch with soil wetted percentage of 50% (NMP2), and no mulch with soil wetted percentage of 75% (NMP3) in 2020.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Starch Content (%)</th>
<th>Vitamin C (mg/kg)</th>
<th>Crude Protein (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMP0</td>
<td>12.94 ± 0.35 a*</td>
<td>239.25 ± 19.80 a</td>
<td>1.48 ± 0.44 a</td>
</tr>
<tr>
<td>BMP2</td>
<td>12.52 ± 0.50 ab*</td>
<td>237.33 ± 13.12 a</td>
<td>1.13 ± 0.13 a</td>
</tr>
<tr>
<td>TMP0</td>
<td>14.35 ± 0.34 a*</td>
<td>245.50 ± 4.92 a</td>
<td>1.28 ± 0.39 a</td>
</tr>
<tr>
<td>TMP2</td>
<td>11.82 ± 0.44 ab*</td>
<td>234.00 ± 11.05 a</td>
<td>1.13 ± 0.09 a</td>
</tr>
<tr>
<td>NMP0</td>
<td>14.23 ± 0.59 a*</td>
<td>235.33 ± 11.44 a</td>
<td>1.64 ± 0.09 a</td>
</tr>
<tr>
<td>NMP1</td>
<td>12.11 ± 1.05 b*</td>
<td>240.33 ± 19.70 a</td>
<td>1.11 ± 0.17 a</td>
</tr>
<tr>
<td>NMP2</td>
<td>13.50 ± 1.31 ab*</td>
<td>232.67 ± 9.39 a</td>
<td>1.47 ± 0.34 a</td>
</tr>
<tr>
<td>NMP3</td>
<td>12.37 ± 0.37 b*</td>
<td>242.00 ± 13.00 a</td>
<td>1.06 ± 0.09 a</td>
</tr>
</tbody>
</table>

Film mulching NS NS NS
Wetted percentage * NS NS NS
Film mulching × Wetted percentage NS NS NS

NS: difference between different treatments was not significant according to F-test (p > 0.05). * Difference between different treatments was significant according to F-test (p < 0.05). Values in a column with the same letter were statistically similar according to Duncan’s multiple range test (p > 0.05).

4. Discussion

Mulching and irrigation influence the soil hydrothermal environment and crop growth [31,32]. In this study, soil temperature was increased by mulching during the early potato growth stage and the warming effect of TM was better than that of BM, with a soil temperature increase up to 1.4 to 2.6 °C. During the later growth stage, the mulching effect on soil temperature was not obvious, with the TM treatment increasing the temperature by about 0.1 to 0.4 °C and the BM treatment decreasing it by 0.1 to 0.6 °C. The potato leaves became denser with the growth of plants, which played a shielding role on the ground and weakened the influence of sunlight and radiation on soil temperature. The results of this study that mulching had a warming effect during the early growth stage and a less significant warming effect during the later growth stage were consistent with the findings of Zhao et al. [33,34]. The finding that BM had a relative cooling effect in the later growth stages was found by Zhang et al. [18]. This may be due to the fact that TM had higher solar radiation transmissivity than BM and it was more effective in the season when the air temperature was low [7,35]. The solar radiation transmission of the transparent film was 85–95% higher than that of black film, which was more conducive to the absorption of thermal radiation by soil in the early stage as well as without film [11].

The effect of irrigation on soil temperature was more pronounced than that of mulching. This study found that irrigation could reduce the soil temperature by 0.4 to 3.0 °C in the early potato growth stage. Irrigation could also serve to reduce the soil temperature by 0.4 to 1.4 °C in the late potato growth stage, when air temperatures were higher. This study concludes that there is a coupling effect between soil water and soil temperature. Irrigation caused a lower soil temperature in the irrigation treatment than in the non-irrigation treatment. This result is similar to previous studies, which showed that irrigation can reduce the soil temperature and benefit crop growth and development [36–38]. Due to the influence of seasonal rainfall (June and July are the rainy seasons in the experimental location), the frequency and amount of irrigation would not increase without film mulching, nor would they cause excessive drying of the soil [39].

Irrigation and mulching can also have an impact on the growth, yield, and quality of potatoes. This study found that the irrigation treatment could significantly increase the potato plant height and stem thickness, which is consistent with the plant growth mechanism [40] and the previous study [18]. In this study, irrigation could significantly
increase the potato yield with or without mulching, while mulching did not significantly affect the potato yield. The P2 treatment had the highest potato yield and the yield could be increased by 16% to 17% with the mulched treatment and by 24.9% with the no mulching treatment. This conclusion was the same as that of Yang et al. [41]. This study found that irrigation had a significant effect on IWUE, with P1 and P2 significantly increasing IWUE. However, too much irrigation had a negative impact on the potato yield and IWUE. A large amount of irrigation can maintain a high level of soil wetted percentage, but the soil being full of water would also reduce the air in the soil, making the potato experience anaerobic respiration and root rot and then reduce production. When the plastic film was covered, excessive rainwater in the soil during the rainy season was not easy to discharge, and it might also cause harm. The soil wetted percentage of P2 was preferable for potato growth, which was similar to the findings of Badr et al. [27] and Meng et al. [42] who found that moderate irrigation increases IWUE. According to principal component analysis (Figure 7), soil moisture also scored higher in potato growth than temperature, and the correlation was stronger. This study did not find a significant effect of mulching on potato yield, which differs from the results of Zhang et al. [43], but is consistent with Rykbost and Cetas [44], Wang et al. [45], and Hou et al. [46] who found no significant effect on potato yield with or without mulching. The reason for this result might be that the potato growth during the early growth stage did not suffer from low soil temperature stress and the warming effects of film mulching on potato growth were not significant.

The main function of plastic film mulching was to increase the soil temperature and preserve the soil moisture. However, in the potato planting season in eastern China, sufficient sunshine and gradually increasing the air temperature weakened the warming effect of the plastic film. The irrigation in the early growth stage and the rainfall in the middle and late growth stages also made the effect of the soil moisture conservation of plastic film insignificant. Even in the rainy season, the reduction in soil moisture evaporation using a plastic film could lead to a potato yield reduction. This study found that the effect of increasing the potato yield could only be achieved through the use of drip irrigation in northern China. The reduction in using plastic film could reduce the possible harm caused by the residual plastic film in the soil in the future. However, due to the limitations of experimental conditions, this experiment lacked the determination of leaf area, leaf photosynthetic rate, transpiration rate, and other indicators that reflect crop growth. The consideration of crops was mainly focused on the yield. Moreover, the amount of soil residual film was not measured, and the reduced residual film harm could not be calculated.

5. Summary and Conclusions

Irrigation could reduce soil temperature by 0.4 °C to 3.0 °C. In the season of high temperatures, irrigation could be used to avoid high soil temperature causing harm to potato growth. Irrigation could significantly increase plant height, stem thickness, and potato yield. The potato yield in the irrigation treatment could be 16.0–24.9% greater than in the non-irrigation treatment. The best yield increase was achieved when the drip irrigation soil wetted percentage was P2. Moreover, the highest IWUE for potatoes was achieved under drip irrigation soil wetted percentage P1 and P2. The NMP1 and NMP2 treatments had 83.4% and 81.0% significantly higher IWUE than the NMP3 treatment. Irrigation had a significant effect on potato growth, while mulching did not.

Considering environmental protection, resource conservation, and economic efficiency, drip irrigation without mulching under soil wetted percentage P2 was suitable for potato cultivation in eastern China.

Author Contributions: Conceptualization, Y.Z.; Methodology, Y.Z.; Validation, S.F.; Formal analysis, Y.Z. and Y.T.; Investigation, W.K.; Data curation, Y.T. and W.K.; Writing—original draft, Y.T.; Writing—review & editing, Y.Z. and Y.T.; Visualization, Y.T.; Supervision, Y.Z., S.F. and F.W.; Project administration, Y.Z. and F.W.; Funding acquisition, Y.Z. All authors have read and agreed to the published version of the manuscript.
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