Effect of Varying Drip Irrigation Amount on the Quality of Wheat

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Abstract

Drip irrigation is an important water-saving wheat cultivation technology, but little is known on its quality. The aims of this work were to investigate the grain quality under different irrigation amounts, and found out the optimum water condition for obtaining the best grain quality. The irrigation treatments consisted of two varieties (Xinchun6 and Xinchun22) and three water volumes (W1, 3,750 m\textsuperscript{3} hm\textsuperscript{−2}; W2, 6,000 m\textsuperscript{3} hm\textsuperscript{−2}; W3, 8,250 m\textsuperscript{3} hm\textsuperscript{−2}). The plots were irrigated every 10 days during the growing season. The result showed that W1 and W2 resulted in water stress to different degrees, manifesting 40 days and 60 days after wheat emergence, respectively. However, besides for sedimentation being less affected by moisture, W1 obtained the best results for other grain quality measures such as protein content, wet gluten content and starch gelatinization characteristics, whereas protein yield and farinograph parameters were optimized in W2. Therefore, for optimal growth of spring wheat in the arid and semi-arid areas of the in northwestern region of China, grain quality can be maintained if the drip irrigation volume does not exceed 6,000 m\textsuperscript{3} hm\textsuperscript{−2} during the entire growth period. The highest grain yield and relatively better grain quality could be achieved by maintaining soil water potential (SWP) at −61.67 kpa to −61 kpa at the 20 cm–40 cm soil layer 15 cm away from the drip irrigation belt after 40 days of wheat emergence and −39 kpa to −37.67 kpa at the 40 cm–60 cm soil layer. Although the SWP should be appropriately reduced after 60 days of emergence, values of approximately −82 kpa to −67 kpa at the 20 cm–40 cm soil layer and −54 kpa to −53 kpa at the 40 cm–60 cm soil layer should be maintained.

Key words: Wheat, Drip Irrigation, Wheat Grain Quality.

1. Introduction

As a globally important food crop, the area dedicated to wheat cultivation in China is only surpassed by that of rice and corn [17, 24]. Maintaining and increasing global wheat production is strongly linked to food security [1]. With the development of the agricultural economy and the improvement of living standards, increasing attention is being paid to wheat yield and quality [10]. Wheat quality is controlled by not only genetics, but also the ecological environment and cultivation methods. Among the numerous factors to consider within cultivation methods, water is one of the most important affecting wheat growth and development, yield and quality [28]. As one of the most efficient irrigation methods [21], drip irrigation technology has...
demonstrated huge potential for water savings and increased yields for wheat cultivation. In 2009, the 148th Regiment of the 8th Division of Xinjiang harvested a spring wheat yield of 12,090 kg hm⁻² from a 10.6 hm² zone under drip irrigation, in the process setting a national record for the highest wheat yield under large-scale wheat production in an arid and semi-arid region with continental weather conditions [11].

A multitude of studies have focused on the influence of irrigation technology on wheat grain quality. The general conclusion gained from traditional flood irrigation is that the application of an appropriate water supply is conducive to improving the quality of wheat, whereas excessive water leads to poor quality [9]. However, the more specific influence of drought and waterlogging on quality indices such as grain wet gluten content, sedimentation value, water absorption rate, dough shaping time and dough stability time, remains contentious [8, 27, 18, 15, 25]. Few studies have focused on the influence of drip irrigation on wheat quality in the irrigated area of Xinjiang Oasis. Drip irrigation technology has brought revolutionary changes to agriculture in comparison with traditional irrigation techniques [19]. However, further knowledge is needed in regards to the effects of irrigation on wheat cultivation, including:

1) The impact of changes in irrigation methods on wheat quality;
2) Whether the effect of drip irrigation on wheat grain quality is consistent with that under traditional irrigation and;
3) Which model is appropriate for water management to improve wheat quality under drip irrigation? The current study explored the influence of drip irrigation on grain quality of spring wheat by applying different volumes of irrigation. The results could provide a theoretical basis and reference for appropriate water supply to optimize the quality and yields of spring wheat under drip irrigation.

2. Materials and Methods

2.1 Experiment Site and Experiment Design

The field experiment was conducted during the 2014 and 2015 growing seasons at the Shihezi University Agronomy Experiment Station, Xinjiang Province, China (44°19’N, 86°03’E). The site has a dry continental climate with a mean temperature of 8.9 °C. The mean annual precipitation is 180 mm. The mean temperature was 23.5 °C during both wheat growing seasons, whereas precipitation was 45 mm and 75 mm in 2014 and 2015, respectively. The soil is classified as a sandy loam [22].

The current study selected two wheat varieties, Xinchun 6 (XC 6) and Xinchun 22 (XC 22). Three volumes of irrigation water were investigated during the wheat growing season, W1 (3,750 m³·hm⁻²), W2, (6,000 m³·hm⁻²) and W3 (8,250 m³·hm⁻²), with each treatment replicated three times. For each treatment, irrigation water was applied every 10 days after wheat emergence (the specific dripping scheme is shown in Table 1). The irrigated plot area was 12 m² and wheat was planted with an equal spacing of 0.15 m between plants. Seeds were applied in artificial strips of approximately 405 kg hm⁻² and the density of irrigation capillary tubes was set as one tube per four rows. Water movement between the plots was prevented by burying waterproof membranes to a depth of 100 cm below the soil surface between each plot. Soil water potential was measured between rows (the specific distribution show in Figure 1). At the three-leaf stage, cycocel was applied at 3,750 mL hm⁻² to control 1–2 sections of the base. The plot was fertilized using urea (N mass fraction ≥ 46%) of 150 kg hm⁻² and diammonium phosphate (P₂O₅ mass fraction ≥ 48%) of 225 kg hm⁻² as base fertilizer. Urea was applied to the soil surface during the following times: 15% at the three leaf stage, 30% at the jointing stage, 30% at the booting stage, 15% at the flowering stage and 10% at the grain filling stage. The soil physical and chemical properties are shown in Table 2. Other methods used were consistent with standard field management [23].

Figure 1. Sketch map showing the position of the drip tap, the wheat rows and the watermark tensiometers.
### Table 1. The schemes under different water treatment m$^3$/hm$^2$

<table>
<thead>
<tr>
<th>Irrigation frequency</th>
<th>Irrigation time</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>Irrigation interval (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>water emergence</td>
<td>675</td>
<td>675</td>
<td>675</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10 days after emergence</td>
<td>341.4</td>
<td>591.4</td>
<td>841.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>30 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>40 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>50 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>60 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>70 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>80 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>90 days after emergence</td>
<td>341.7</td>
<td>591.7</td>
<td>841.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total (m$^3$/hm$^2$)</td>
<td>3750</td>
<td>6000</td>
<td>8250</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. The soil physical and chemical properties in experiment plots

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>20±1.23</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>35±1.32</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>40±2.27</td>
</tr>
<tr>
<td>PH</td>
<td>7.71±0.43</td>
</tr>
<tr>
<td>Organic matter (mg/kg)</td>
<td>23.41±0.75</td>
</tr>
<tr>
<td>Alkaline N (mg/kg)</td>
<td>59.16±2.57</td>
</tr>
<tr>
<td>Olsen P (mg/kg)</td>
<td>20.94±1.21</td>
</tr>
<tr>
<td>Available K (mg/kg)</td>
<td>143.64±18.21</td>
</tr>
<tr>
<td>Bulk density (g/cm$^3$)</td>
<td>1.25±0.15</td>
</tr>
<tr>
<td>Saturated Volumetric water content</td>
<td>30.6±0.38</td>
</tr>
</tbody>
</table>

#### 2.2. Soil Water Content

The soil moisture content was monitored using tensiometers (200SS-5, USA). The tensiometers were located 15 cm (nearest row from the drip tape, Location 1) and 30 cm (furthest row from drip tape, Location 2) from the drip irrigation belt in the horizontal direction and installed vertically at 20 cm intervals between 0 cm–60 cm (0 cm–20 cm, 20 cm–40 cm and 40 cm–60 cm) soil depth. Soil moisture content was measured before and after irrigation with a tensiometer. The measurement range was 0 cbar to −200 cbar (or 0 KPa to −200 KPa), with 0 cbar and −200 cbar representing saturated soil water and extremely dry soil, respectively.

#### 2.3. Grain Protein Content

Grain protein content was measured using the Danish FOSS 1241 near-infrared grain composition analyzer according to the AACC 39-11 method [12].

#### 2.4. Wet Gluten Content

The wet gluten content (14% moisture base) was determined using the Swedish PERTEN 2200 gluten quantity/mass measurement system according to the method specified in GB/T 5506.2-2008.
2.5. Sedimentation Value

The Zeleny sedimentation value was determined using the BAU-1 sedimentation meter of the China Agricultural University according to the AACC 56-61A method.

2.6. Farinograph Parameters

Farinograph parameters were determined using the German BRABENDER 810110 electronic farinograph according to method GB/T 14614-2006. Farinograph parameters relate to rheological parameters of dough such as dough forming time, stabilization time and water absorption rate.

2.7. Starch Gelatinization

Starch gelatinization characteristics were measured using the Newport Rapid Viscosity Analyzer (RVA-Tec Master) from Australia according to method ABCC 76-21. These measures included peak viscosity, trough viscosity, breakdown and final viscosity and the viscosity unit is Lipo (cp). Upon measuring, 1 mmol L⁻¹ silver nitrate solution was used in place of distilled water to inhibit α-amylase activity and eliminate its effect on starch gelatinization characteristics.

2.8. Statistical Analysis

Data were analyzed using the generalized linear model (GLM) procedure (SPSS 16.0). Differences between means were compared using Fisher’s least significant difference (LSD) test at the 5% probability level.

3. Results

3.1. Measurement of Soil Water Potential

Soil water potential (SWP) is an important indicator of soil dryness and soil water effectiveness on plant growth. The most obvious advantage of using SWP is that it describes the effectiveness of water application on plants. Furthermore, SWP is not influenced by soil texture. Thus, SWP is highly representative of soil moisture and has seen wide-spread application [12]. SWP performance for the three irrigation treatments was W3 > W2 > W1, and significant differences in soil moisture in the horizontal and vertical directions were evident under the different treatments (Figure 2). At the near row, SWP changed drastically before and after irrigation at 0 cm–20 cm depth and SWP below 20 cm generally recovered under all treatments after irrigation. SWP under W1 recovered the least and with no recovery occurring upon irrigation after 40 days of emergence. SWP under W2 showed no recovery after irrigation at 40 cm–60 cm depth after 60 days of emergence. SWP under W3 recovered throughout the wheat growth period. At the far row, SWP at 0 cm–20 cm depth changed less drastically than at the same depth in the near row before and after irrigation, and SWP below 20 cm under the different treatments was generally restored after irrigation, but to a lesser degree than at the same depth in the near line. At the far row, SWP at the 0 cm–20 cm depth in the late stage (approximately 50 days after emergence) for W1 and W2 was not restored after irrigation. In addition, SWP below 20 cm depth did not recover after 40 days of emergence in W1 after irrigation. At 40 cm–60 cm depth, SWP did not recover after 60 days of emergence in W2 after irrigation. However, at 0 cm–60 cm depth, SWP recovered during the growing season and was maintained at a relatively low level. This demonstrated that wheat was not subjected to water stress during the entire growth period in W3, even for plants located at the far row from the drip tape. The fact that SWP did not recover in the near row below 20 cm depth indicates a water deficit. This shows that both W1 and W2 were subjected to a certain degree of water deficit, resulting in different responses to wheat growth and yield. These results suggest that the average SWP values at 20 cm–40 cm and 40 cm–60 cm depths in near row after 40 days of emergence were in the ranges ~137 Kpa to ~84.67 Kpa and ~81 Kpa to ~76 Kpa, respectively, and after 60 days of emergence were ~101 Kpa to ~82 Kpa and ~54 Kpa to ~59 Kpa, respectively, which resulted in differing degrees of water stress upon spring wheat under drip irrigation.
Figure 2. Temporal changes of soil water potential

(A) The data was the average soil water potential of wheat cultivar ‘XinChun 6’ (XC 6) in different irrigation amount during the whole growth and development stage in 2014 and 2015.

(B) The data was the average soil water potential of wheat cultivar ‘XinChun 22’ (XC 22) in different irrigation amount during the whole growth and development stage in 2014 and 2015. The irrigation amounts were 3750 m$^3$/hm$^2$ (W1), 6000 m$^3$/hm$^2$ (W2), 8250 m$^3$/hm$^2$ (W3).

3.2. Measurement of Grain Protein Content and Protein Yield

Table 3 shows that soil water moisture significantly affected grain protein content. The protein content of XC 6 and XC 22 showed a gradual decline with increasing irrigation volume. The W1 treatment achieved the highest wheat protein content among the three treatments. XC 6 in W1 increased by 1.57% and 5.84% in 2014 and 3.09% and 4.33% in 2015 compared with W2 and W3, respectively. XC 22 in W1 increased by 2.05% and 4.11% in 2014 and 7.87% and 9.19% in 2015 compared with W2 and W3, respectively. Each treatment reached a significant or a highly significant level, showing that the low water treatment (W1) favored an increase of wheat grain protein content, whereas excessive irrigation (W3) resulted in a significant decrease in grain protein content. The effect of water on protein yield reached an extremely significant level under all treatments. With
increasing irrigation volume, the protein yields of the two varieties tended to increased and then decline. The protein yield achieved by the W2 treatment was significantly higher than that by W1 and W3. The protein yield of XC 6 under W2 increased by 14.82% and 11.19% in 2014 and 23.89% and 23.63% in 2015 compared with W1 and W3, respectively, whereas that of XC 22 under W2 increased by 24.59% and 8.67% in 2014 and 29.02% and 3.7% in 2015 compared with W1 and W3, respectively. The analyses demonstrated that, among the irrigation treatments, W1 had the highest grain protein content and the lowest grain yield, whereas W3 had the lowest protein yield and relatively low grain yield. W2 had a relatively higher protein yield and the highest grain yield. This demonstrated that a relatively lower SWP increased wheat grain protein content, whereas a relatively higher SWP hindered both protein content and yield. An appropriate SWP could achieve a relatively higher protein yield and the highest grain yield.

Table 3. Effect of different water treatment on protein content and protein yield of wheat

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Protein (%)</th>
<th>Protein Yeard (kg/hm²)</th>
<th>Protein (%)</th>
<th>Protein Yeard (kg/hm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XC 6</td>
<td></td>
<td></td>
<td>XC 22</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>W1</td>
<td>14.83±0.12A</td>
<td>953.78±7.42Cc</td>
<td>14.56±0.12Aa</td>
<td>748.72±5.93Cc</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>14.6±0.1Ab</td>
<td>1119.82±7.67Aa</td>
<td>14.26±0.12Ab</td>
<td>992.96±8.03Aa</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>13.96±0.06Bc</td>
<td>994.42±4.11Bb</td>
<td>13.96±0.06Bc</td>
<td>819.84±3.38Bb</td>
</tr>
<tr>
<td>2015</td>
<td>W1</td>
<td>16.13±0.06Aa</td>
<td>688.89±2.47Bb</td>
<td>17.76±0.05Aa</td>
<td>586.3±1.90Cc</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>15.63±0.06Bb</td>
<td>905.17±3.34Aa</td>
<td>16.36±0.06Bb</td>
<td>826.02±2.95Aa</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>15.43±0.12Bc</td>
<td>682.15±5.1Bb</td>
<td>16.13±0.05Cc</td>
<td>795.42±2.80Bb</td>
</tr>
</tbody>
</table>

Values are the mean±SE, the SE was calculated across three replicates for each year.
† Value within columns followed by different uppercase letters are significantly different at p<0.01 according to least-significant-different
‡ Value within columns followed by different lowercase letters are significantly different at p<0.05 according to least-significant-different

3.3. Measurement of Wheat Grain Flour Quality

Wet gluten contains a certain amount of water and has not been dried. The quantity and quality characteristics of gluten are important factors determining the processing quality of flour. Better flour quality is achieved by higher contents of wet gluten. Wet gluten content decreased as the amount of water increased (Figure 3). Among the water treatments, W1 exhibited the highest wet gluten content, significantly higher than that of W2 and W3. Wet gluten contents of XC 6 under W1 increased by 2.17% and 4.98% in 2014 and 4.63% and 8.1% in 2015 compared with W2 and W3, respectively, whereas that of XC 22 under W1 increased by 5.76% and 11.62% in 2014 and by 7.1% and 10.6% in 2015 compared with W2 and W3, respectively. For all treatments, the wet gluten of XC 6 was significantly higher than that of XC 22. In W1, the wet gluten content of XC6 was 6.7% and 6.12% higher than that of XC22 during 2014 and 2015, respectively. The analyses showed that a lower SWP was beneficial to higher wet gluten content under drip irrigation, and an increased SWP resulted in decreased wet gluten content.

Figure 3. Effect of different water treatment on wet gluten content
The W1, W2 and W3 indicates the irrigation amount, respectively 3750 m$^3$/hm$^2$ (W1), 6000 m$^3$/hm$^2$ (W2), 8250 m$^3$/hm$^2$(W3) in 2014 and 2015. Vertical bars represent SE of mean, the SE was calculated across three replicates for each year. Values of different treatments followed by the same letter indicate no significant differences (P<0.01) according to least-significant-difference test.

Sedimentation value reflects wheat gluten content and quality, and is a comprehensive indicator for evaluating the quantity and quality of flour protein. Figure 4 shows the sedimentation value decreased as the amount of water increased, with sedimentation value decreasing in the order W1 > W2 > W3 in both cropping seasons; however, no significant difference was evident between treatments. W1 exhibited the highest sedimentation value in the two varieties. Sedimentation of XC 6 under W1 was 30.3 mL and 31.7 mL in 2014 and 2015, respectively, higher by 0% and 1% in 2014 and 3.1% and 2.1% in 2015 than that under W2 and W3, respectively. Sedimentation of XC 22 under W1 was 32.3 mL and 35.3 mL in 2014 and 2015, respectively, 3% and 4% higher in 2014 and 0.9% and 0.9% higher in 2015 compared to that of W2 and W3, respectively. In each treatment, the sedimentation value of XC 22 was higher than that of XC 6. These results suggest that irrigation volume has no effect on sedimentation value under drip irrigation, i.e., the fluctuation in SWP has little effect on sedimentation value.

Figure 4. Effect of different water treatment on sedimentation value

The W1, W2 and W3 indicates the irrigation amount, respectively 3750 m$^3$/hm$^2$(W1), 6000 m$^3$/hm$^2$ (W2), 8250 m$^3$/hm$^2$(W3) in 2014 and 2015. Vertical bars represent SE of mean, the SE was calculated across three replicates for each year. Values of different treatments followed by the same letter indicate no significant differences (P < 0.05) according to least-significant-difference test.

3.4. The Influence on Farinograph Parameters

The water absorption rate, dough developing time and dough stability time of the two varieties showed a trend of rising first and then decreasing in both cropping seasons (Table 4). The water absorption rate of dough was highest in W2, and extremely significantly higher than those of W1, W3. However, different trends were evident for all treatments between the two varieties. The trends in water absorption rate for XC 6 and XC 22 for the treatments were W2 > W1 > W3 and W2 > W3 > W1, respectively. The dough developing time and dough stability time trends for the treatments were both W2 > W3 > W1, and the difference between treatments were significantly different. The dough developing time was longest in W2 in the two varieties. The dough developing time of XC 6 under W2 was 0.26 min and 0.2 min longer in 2014 and 2015 compared with that under W1 and W3, respectively. The dough developing time of XC 22 under W2 was 1.43 min and 0.43 min longer in 2014 and 2015 and 0.77 min longer in 2015 compared with that under W2 and W3, respectively. The dough developing time of XC 22 under W2 was 0.67 min and 0.5 min longer in 2014 and 2015 compared with that under W2 and W3, respectively. The dough stability time was longest under W2 for the two varieties. Dough stability time of XC 6 under W2 was 0.67 min and 0.5 min longer in 2014 and 2015 compared with that under W2 and W3, respectively. Dough stability time of XC 22 under W2 was 3.3 min and 1.57 min longer in 2014 and 2015 compared with that under W2 and W3, respectively. These results indicated that the farinograph parameters of the two varieties were optimized under W2, and lower and higher values of SWP were both unfavorable for farinograph parameters under drip irrigation.
According to least
characteristics.

Higher than those of W2 and W3. According to the analysis, W1 was most beneficial to improved starch
then increased upon in
superior to that of XC22. The same trends were evident in the two varieties: values showed an initial decline and
significantly higher than those of XC 6 were
2015 compared with that under W2, respectively. The peak viscosity and the breakdown values of XC
and final viscosity increased by 2.3%, 1.6%, 3.5% and 2.3% in 2014 and
15%, 23.6%

Trough viscosity, breakdown and final viscosity showed gradual declines with the increase of irrigation volume and the order was W1> W2> W3. Peak viscosity, trough viscosity, breakdown and final viscosity increased by 5%, 6.6%, 4.8% and 4.2% in 2014 and
15%, 23.6%

Effect of different water treatment on starch pasting properties
shows that water plays an important role in regulating starch
gelatinization characteristics of spring wheat under drip irrigation. The gelatinization characteristics of the two
wheat varieties were highest in W1. However, the trends in peak viscosity, trough viscosity, breakdown and
final viscosity under the different irrigation treatments were different for both varieties. In XC 6, the values
showed gradual declines with the increase of irrigation volume and the order was W1> W2> W3. Peak viscosity,
trough viscosity, breakdown and final viscosity increased by 5%, 6.6%, 4.8% and 4.2% in 2014 and
15%, 23.6%, 15.6% and 17% in 2015 compared with that under W3, respectively. In XC 22, trends in peak
viscosity, trough viscosity, breakdown and final viscosity showed initial declining trends and then increased
upon increased irrigation, the order of which was W1> W3> W2. Peak viscosity, trough viscosity, breakdown and
final viscosity increased by 2.3%, 1.6%, 3.5% and 2.3% in 2014 and 13.6%, 17.6%, 13.3% and 13.2% in
2015 compared with that under W2, respectively. The peak viscosity and the breakdown values of XC 6 were
significantly higher than those of XC22, indicating that the starch gelatinization characteristics of XC 6 were
superior to that of XC22. The same trends were evident in the two varieties; values showed an initial decline and
then increased upon increased irrigation, and the order was W1> W3> W2, with the values of W1 significantly
higher than those of W2 and W3. According to the analysis, W1 was most beneficial to improved starch
gelatinization characteristics under drip irrigation; therefore, lower SWP improved starch gelatinization
characteristics.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>XC 6</th>
<th>XC 22</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water absorption (%)</td>
<td>Dough developing time (min)</td>
<td>Dough stability time (min)</td>
</tr>
<tr>
<td>2014</td>
<td>W1</td>
<td>61.8±0.3b</td>
<td>3.97±0.058Bb‡</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>62.23±0.058a</td>
<td>4.23±0.058Aa</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>61.46±0.158b</td>
<td>4.03±0.057Bb</td>
</tr>
<tr>
<td>2015</td>
<td>W1</td>
<td>66.73±0.058Cc</td>
<td>3.53±0.058Bb</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>67.0±0.1Aa</td>
<td>3.93±0.058Aa</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>66.23±0.058Bb</td>
<td>3.8±0.01Ab</td>
</tr>
</tbody>
</table>

Values are the mean±SE, the SE was calculated across three replicates for each year.
†Value within columns followed by different uppercase letters are significantly different at p<0.01
according to least-significant-different
‡ Value within columns followed by different lowercase letters are significantly different at p<0.05
according to least-significant-different

3.5. The Influence of Starch Gelatinization Characteristics

Starch gelatinization characteristics are an important indicator of starch quality, and exert a strong
influence on the food quality of noodles. Table 5 shows that water plays an important role in regulating starch
gelatinization characteristics of spring wheat under drip irrigation. The gelatinization characteristics of the two
wheat varieties were highest in W1. However, the trends in peak viscosity, trough viscosity, breakdown and
final viscosity under the different irrigation treatments were different for both varieties. In XC 6, the values
showed gradual declines with the increase of irrigation volume and the order was W1> W2> W3. Peak viscosity,
trough viscosity, breakdown and final viscosity increased by 5%, 6.6%, 4.8% and 4.2% in 2014 and
15%, 23.6%, 15.6% and 17% in 2015 compared with that under W3, respectively. In XC 22, trends in peak
viscosity, trough viscosity, breakdown and final viscosity showed initial declining trends and then increased
upon increased irrigation, the order of which was W1> W3> W2. Peak viscosity, trough viscosity, breakdown and
final viscosity increased by 2.3%, 1.6%, 3.5% and 2.3% in 2014 and 13.6%, 17.6%, 13.3% and 13.2% in
2015 compared with that under W2, respectively. The peak viscosity and the breakdown values of XC 6 were
significantly higher than those of XC22, indicating that the starch gelatinization characteristics of XC 6 were
superior to that of XC22. The same trends were evident in the two varieties; values showed an initial decline and
then increased upon increased irrigation, and the order was W1> W3> W2, with the values of W1 significantly
higher than those of W2 and W3. According to the analysis, W1 was most beneficial to improved starch
gelatinization characteristics under drip irrigation; therefore, lower SWP improved starch gelatinization
characteristics.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cultivar</th>
<th>Treatment</th>
<th>Peak viscosity (cp)</th>
<th>Trough viscosity (cp)</th>
<th>Break down (cp)</th>
<th>Final viscosity (cp)</th>
<th>Setback (cp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>XC 6</td>
<td>W1</td>
<td>3419.33±5.81A†</td>
<td>1963.33±2.17A</td>
<td>1456.33±4.04A</td>
<td>3218.67±5.59A</td>
<td>1255±4.35A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2</td>
<td>3285.33±4.31B</td>
<td>1898.33±5.78B</td>
<td>1413±4.58B</td>
<td>3142.67±4.67B</td>
<td>1244.33±1.15B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W3</td>
<td>3246.66±5.30B</td>
<td>1835.67±5.75C</td>
<td>1387±3.61C</td>
<td>3082.33±6.65B</td>
<td>1248.67±2.89B</td>
</tr>
<tr>
<td></td>
<td>XC 22</td>
<td>W1</td>
<td>2876.67±4.67A</td>
<td>1794.67±5.57A</td>
<td>1083.33±7.02A</td>
<td>3255±5.12A</td>
<td>1460.67±2.88A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2</td>
<td>2810.67±2.75B</td>
<td>1765.33±7.78C</td>
<td>1045.33±5.77B</td>
<td>3178.67±4.57C</td>
<td>1413.33±4.15C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W3</td>
<td>2825.67±2.15B</td>
<td>1772.67±2.82B</td>
<td>1053±2.13B</td>
<td>3195±1.45B</td>
<td>1422.33±2.52B</td>
</tr>
<tr>
<td>2015</td>
<td>XC 6</td>
<td>W1</td>
<td>2996±5.57A</td>
<td>1879±4.9A</td>
<td>1321±4.58A</td>
<td>2954±6.77A</td>
<td>1080.33±3.86A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2</td>
<td>2785.67±6.65B</td>
<td>1539±5.56B</td>
<td>1238±7B</td>
<td>2539±4.58B</td>
<td>1005.33±5.5C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W3</td>
<td>2742.67±5.91C</td>
<td>1435±5.81C</td>
<td>1114.67±7.63C</td>
<td>2452.67±8.6C</td>
<td>1035±3±5.01B</td>
</tr>
<tr>
<td></td>
<td>XC 22</td>
<td>W1</td>
<td>2655.33±7.37A</td>
<td>1721±8.7A</td>
<td>1015.67±6.11A</td>
<td>3015±9.5A</td>
<td>133±3.5A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2</td>
<td>2294±4.51B</td>
<td>1417.67±9.21C</td>
<td>880.67±7.01C</td>
<td>2617.33±8.5C</td>
<td>1205.33±5.59C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W3</td>
<td>2637.33±6.50A</td>
<td>1635±8.18B</td>
<td>954±3.65B</td>
<td>2948.67±8.5B</td>
<td>1298±3.52B</td>
</tr>
</tbody>
</table>

Values are the mean±SE, the SE was calculated across three replicates for each year.
†Value within columns followed by different uppercase letters is significantly different at p < 0.01
according to least-significant-different.
4. Discussion

Irrigation amount had a significant influence upon the grain protein content of wheat. The results indicated that water stress was of benefit to increased grain protein content, but also led to decreased grain yield under drip irrigation. The larger volume of irrigation resulted in the lowest protein content and decreased grain yield due to starch dilution. Therefore, drip irrigation under the lowest and highest irrigation volume was unfavorable to increasing protein yield. These results are consistent with those of most studies on the influence of water on protein content and protein yield under traditional irrigation conditions [4, 15]. However, the study of winter showed that water stress reduced wheat protein content. In addition, Xu found that both a severe water deficit of soil and excessive irrigation resulted in reduced protein content during the late filling stage [26]. In the aforementioned study, the applied irrigation volume was 1,200 m³ ha⁻¹ during the entire growth period, which could be classified as extreme water deficit. However, in the present study, the applied irrigation level resulted in a water deficit for wheat to a certain degree, but did not reach the same level of extreme water deficit. Therefore, the investigated irrigation volumes in the present study did not result in reduced protein content under water deficit. The W2 treatment in the present study succeeded in achieving the highest grain yield and protein yields and higher protein content. Therefore, we could conclude that drip irrigation could achieve the highest grain and protein yields and relatively higher protein content, with an average SWP of −61.67 kPa −61 kPa at 20 cm–40 cm depth at a distance of 15 cm from the drip tape after 40 days of wheat emergence.

The effect of water on the content of wet gluten remains controversial. The studies suggested that water stress reduced the content of wet gluten in spring wheat under a drought condition [27]. Wang and Mei suggested that water stress increased the content of wet gluten [23, 14]. Fan found that the content of wet gluten varied in different types of wheat grain was significantly improved under drought conditions [6], whereas waterlogging had different effects on different varieties. Wei demonstrated that wet gluten content of winter wheat showed an increasing and then decreasing trend with increased irrigation volume under drip irrigation [25]. In addition, the results of the present study showed that water stress under drip irrigation resulted in a significant increase of wet gluten content, and wet gluten content gradually decreased with an increase of SWP. It can be concluded that the first reason for the difference between the results of the present study and those of previous studies is that the water deficit levels attained in the present study were not as severe. Therefore, the wet gluten content reached in the present study did not decrease under lower water treatment. An additional reason for the discrepancies in the results is due to use of the different wheat varieties. The present study found that reducing SWP under drip irrigation could lead to a significant increase in wet gluten content for XC 6 and XC 22.

Views regarding the effect of water on sedimentation remain divided. In the present study, the sedimentation value decreased with the increase of irrigation volume; however, there was no significant difference between the two varieties under different treatments during the two-year test, which indicated that SWP had little effect on sedimentation value under drip irrigation. We may infer that drip irrigation based on multiple irrigation volumes may likely mitigate the influence of water on sedimentation value to a certain degree.

Xu suggested that irrigation after flowering would significantly reduce dough quality [26], which in turn would influence dough quality. Zhao showed that dough formation and stabilization times increased with decreasing irrigation frequency, whereas yield was affected adversely [27]. The above results indicate that during the late stage of wheat growth, wheat quality can deteriorate under increasing irrigation frequency and waterlogging, whereas a drought treatment can improve wheat quality [22], through a study that investigated the effect of irrigation volume on grain in the arid region of western Henan, found that one-time irrigation after flowering did not result in a significant decline in wheat quality, with some quality performances improving to varying degrees, whereas irrigation applied at a frequency of twice or more resulted in some quality traits dropping significant. Jia proposed that increasing irrigation frequency in arid or extremely arid years could enhance wheat yield while maintaining or even improving quality. The present study found that the water absorption rate was highest under the W2 treatment; however, differences between varieties were evident. With increasing irrigation amount, both dough formation time and dough stabilization time showed trends of increasing and then decreasing with the increase of SWP, indicating that both water deficit and excessive irrigation resulted in the decline of dough quality. Drip irrigation frequency performed in the present study was approximately five applications after flowering, which is more frequent compared with that of traditional irrigation; however, the increase of irrigation frequencies did not result in reductions in the values of parameters related to flour quality, and instead these values increased within a certain irrigation amount. This proved that high frequency irrigation based on drip irrigation technology could promote an improvement of farinograph parameters. Therefore, optimal farinograph parameters under drip irrigation in arid and semi-arid areas could be obtained when the average SWP at the 20 cm–40 cm soil layer 15 cm away from the drip tape is maintained in the range of −61.67 kPa to −61 kPa after 40 days of wheat emergence. In addition, the water absorption rates of different varieties showed different responses to SWP.
The peak viscosity and breakdown value are two important indices of starch gelatinization. It has been shown that superior quality noodles are manufactured from wheat of high peak viscosity [3, 16]. In addition, noodle quality characteristics such as texture and taste can be improved by increasing the breakdown value of wheat flour [13, 20]. As medium and medium-strong gluten wheat varieties respectively, XC6 and XC22 achieved the best peak viscosity and breakdown values under the W1 treatment. Therefore, it is clear that under drip irrigation, optimal starch gelatinization is achieved with an average SWP in the range of −84.67 kPa to −82.33 kPa at the 20–40 cm soil layer 15 cm away from the drip tape after 40 days of wheat emergence. The results of the present study showed that changes to the different starch gelatinization characteristics depended on the different irrigation volumes and wheat varieties. There should be some threshold which may vary with regard to range for different varieties. These thresholds are a topic of future studies.

5. Conclusions

Under the condition of dryland farming and water-saving agriculture, wheat yield as well as wheat quality should be considered in wheat production. The present study found that following the application of drip irrigation technology to spring wheat in arid and semi-arid areas in the inland northwestern regions of China, grain quality showed no significant drop as long as irrigation over the entire growth period did not exceed 6,000 m³ hm⁻², despite the fact that the frequency of drip irrigation was increased compared with traditional irrigation. The highest grain yield and a relatively better grain quality could be achieved by maintaining SWP at −61.67 kPa to −61 kPa at the 20 cm–40 cm soil layer 15 cm away from the drip tape after 40 days of wheat emergence, −39 kPa to −37.67 kPa at the 40 cm–60 cm soil layer, and appropriately reducing SWP to −82 kPa to −67 kPa at the 20 cm–40 cm soil layer and −54 kPa to −53 kPa at the 40 cm–60 cm soil layer after 60 days of emergence. To further increase protein content and wet gluten content and improve starch gelatinization characteristics, the irrigation volume should be reduced to further decrease SWP; however, the SWP should be maintained above a certain threshold to avoid extreme water deficit which would not improve wheat quality. Therefore, after 40 days of emergence, the SWP value should be no lower than −84.67 kPa at the 20 cm–40 cm soil layer 15 cm away from the drip tape, no less than −86 kPa at the 40 cm–60 cm soil layer and after 60 days of emergence, no less than −119 kPa at the 20 cm–40 cm soil layer and no less than −138 kPa at the 40 cm–60 cm soil layer. Although it should be noted that a reduction of SWP within this range would help improve grain quality, it would also inevitably result in reduced grain yield, protein yield and farinograph parameters. Thus, a balance between yield and quality should be maintained based on actual production to enhance water efficiency and improve wheat quality by reasonably reducing the irrigation quota on the basis of yield fulfillment.

Acknowledgements

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References


