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The Effects of Meteorological Factors on Grain Yield of Foxtail Millet (*Setaria italica* Beauv.) under Different Water Supply Conditions

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Abstract: Meteorological factors have significant impacts on crop yield. To account for the impact of meteorological factors on foxtail millet (*Setaria italica* Beauv.) production in different water conditions, a total of 38 collected varieties were grown in nine seasons from 2011 to 2020 (except 2016) under well-watered (WW) and water-stressed (WS) conditions. The results showed that there was a large seasonal variation in GY; the variation ranged from 4.92 t ha^{-1} to 6.95 t ha^{-1} under the WW treatment and from 3.50 t ha^{-1} to 5.77 t ha^{-1} under the WS treatment. The impacts of meteorological factors on foxtail millet under the WW and WS treatments were different; sunshine duration during the whole stage, vegetative stage and reproductive stage had the greatest impact under the WW treatment, while under the WS treatment, sunshine duration and the diurnal temperature range during the whole stage and reproductive stage were the greatest impact factors on grain yield. This work could help us in high-yield foxtail millet cultivation and breeding.

Keywords: foxtail millet; meteorological factor; production

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1. Introduction

Foxtail millet (*Setaria italica* Beauv.) is grown as an annual crop and is the oldest cultivated species in the world [1]. The grain of foxtail millet is rich in dietary fibers, minerals, vitamins, proteins, iron and β-carotene but has a low glycemic index; it is an ideal food for diabetics. Foxtail millet also can produce soft straw for animal feed [2,3]. Furthermore, it has recently been developed as an ideal model system for functional genomics studies of C_4 plants, which will open a new avenue for plant functional studies and crop improvement [4,5].

Foxtail millet is well-adapted to arid and semi-arid areas; compared with other crops, e.g., wheat (*Triticum aestivum*), maize (*Zea mays*) and sorghum (*Sorghum bicolor*), most of the foxtail millet varieties are more drought-tolerant [6]. Foxtail millet originated in China [7,8]; to date, it is one of the most common food crops in the dry part of northern China. It was cultivated on 7.18 × 10^5 ha in 2014, and the total grain production was 1.81 × 10^6 tons [9]. The cultivation area increased to 8.61 × 10^5 ha in 2017 (http://data.chinabaogao.com/nonglinmuyu/2019/0R43PA2019.html, accessed on 18 March 2022).

Meteorological factors such as solar radiation, reference evapotranspiration, precipitation, temperature, etc., are the main determinants of agriculture productivity that directly affect the agriculture sectors. The crop yield is impacted by different meteorological factors, and the effects of these factors are different at diverse growth stages or under different water supply conditions [10–13]. The grain yield of rice was closely related to meteorological factors in different stages after heading, and the yield was severely affected by temperature during the filling stage [12]. The major weather factors affecting winter wheat yield were reference evapotranspiration, diurnal temperature range, sunshine hours, and humidity for winter wheat with irrigation [13]. The yield of cotton increased with the increases in mean diurnal temperature ranging from full bloom to maturity, mean temperature and sunshine hours during the whole growing season, accumulated temperature and days from squaring to anthesis and mean temperature during the reproductive growth stage [14]. Suboptimal meteorological conditions, such as the time and duration of development stages, often increase the risk level of the cultivation of cereal crops due to disturbances of physiological processes induced by abiotic stress, affecting the entire phenology of plants [15]. Thus, a better understanding of the impacts of meteorological factors on crop production is essential for optimizing crop management, improving yield, and adopting reasonable strategies to mitigate climate change [16].

Principal component analysis (PCA) is used to analyze inter-correlated quantitative dependent factors, extract the most important information from the data, compress the size of the data set by keeping only this important information, simplify the description of the data set, and analyze the structure of the observations and the factors [17]. PCA is a powerful statistical tool for evaluating the relationship between crop yield and climatic variables [18]; PCA could determine the leading meteorological factors influencing yield. Han et al. [19] found that the accumulated temperature above 10 °C, the March–October mean temperature and the June–August mean temperature are key meteorological factors which influence the meteorological yield of apple.

From 2011 to 2020, 38 varieties were collected from breeders; some were newly released varieties. The impact of different meteorological factors on grain yields of these varieties is of vital importance to foxtail breeding and cultivation. However, which meteorological factors have the greatest influence on the grain yield under different water supply conditions is not clear. The objective of this study was to assess the effect of meteorological factors on grain yield of foxtail millet in well-watered and water-stressed conditions.

2. Materials and Methods

2.1. Experiment Site

The experiment was conducted in Hengshui Dryland Agricultural Experimental Station (37°13′ N, 114°37′ E; 23 m above sea level) (Figure 1), Hebei province, northern China, from 2011 to 2020 (except 2016). This site is in the semi-arid area of China; the soil was classified as silt loam with a pH of 8.1, soil organic matter of 1.1% and soil bulk density of 1.2 to 1.5 g cm^{-3}.

2.2. Plant Materials

In total, 38 varieties (Table S1) collected from different breeders were used in this study. Some of the varieties were replaced by the newly released ones each season. The control variety, Jigu19, was grown in all nine seasons.

2.3. Experiment Design and Field Management

The experiment field plots were covered with a transparent sun sheet arch shed, with a height of 3.0 m (the lowest side) above the soil surface to exclude the rain precipitation. The shed was controlled automatically under the water-stressed (WS) and well-watered (WW) treatments, and during the whole growth duration, it was open when there was no rain fall; the field plots were only covered with the shed when it was raining to maintain the WS treatment (Figure 2). The experiment design was a randomized block design with three replicates for each variety. The size of each plot was 2 m × 1.5 m, and there was a 0.20 m thick concrete wall which surrounded each plot to avoid water exchange. The depth of each concrete wall was 3.0 m, the top 2 m in each plot was a soil layer, and under the soil layer, there was a 1 m buffer layer. All field managements were the same as those of the local farmers, except that there was no irrigation applied during the growing season under the WS treatment, whereas irrigation was provided for the WW treatment. To promote successful germination, before sowing, the soil under all the treatments was irrigated to ensure that the soil (the top 1 m of the soil profile) moisture was more than 80% of the field capacity. Seeds were sown by hand. The space between rows was 20 cm. In the seedling stage, the seedlings' densities were manually checked and kept at 60 plants m^{-2}. The dates of sowing and harvest are shown in Table S2. The composite chemicals (225 kg ha^{-1} for N, 225 kg ha^{-1} for P_2O_5 and 225 kg ha^{-1} for K_2O) were incorporated into the soil as base fertilizer. During the growing season, no other fertilizer was applied. Irrigation was applied twice during growth stage; one was in the jointing stage, and another was in the grain-filling stage. Each time, 900 m^3 ha^{-1} (i.e., 90 mm ha^{-1}) water was irrigated for the WW treatment, and the amount of irrigation was monitored using a water meter. The dates of irrigation in each year are shown in Table 1. No irrigation was applied under the WS condition during the growing season.

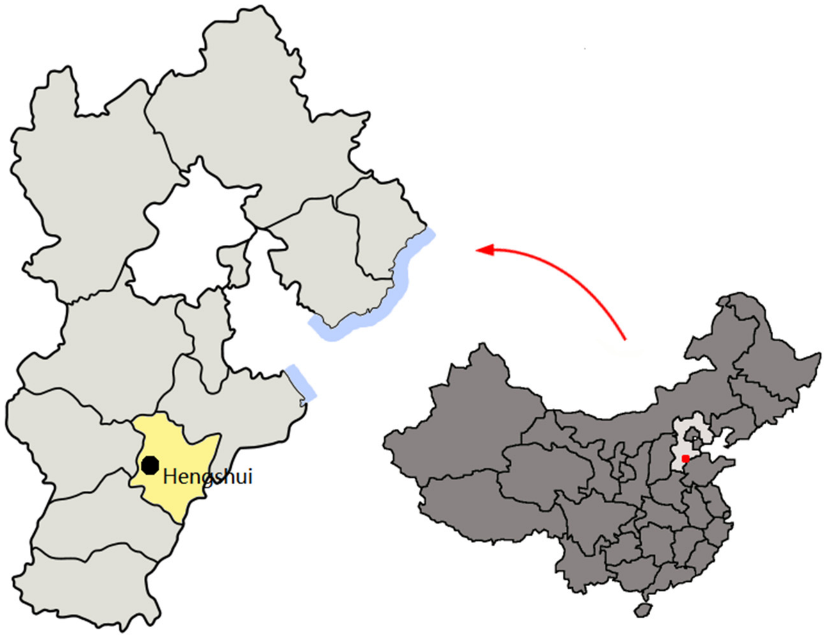

Figure 1. The locations of the trial site (the dark dots in the figure) in northern China.

Figure 2. The foxtail millet experiment. Left is experiment site. Right is the foxtail millet under water-stressed (WS) and well-watered (WW) treatments.

Table 1. The dates of irrigation in each year.

Year	Irrigation before Sowing	Irrigation in Jointing Stage	Irrigation in Grain-Filling Stage
2011	14 June	24 July	22 August
2012	15 June	26 July	24 August
2013	17 June	26 July	23 August
2014	14 June	18 July	23 August
2015	16 June	28 July	25 August
2017	13 June	21 July	19 August
2018	12 June	13 July	11 August
2019	10 June	27 July	23 August
2020	16 June	18 July	22 August

2.4. Measurements and Calculations

The dates of sowing, harvest, and the occurrence of the major growth stages for each growth season and for each variety were recorded. During the growth seasons, there were no diseases that needed treatments in all those years. Weeds were controlled by hand. The only insect that needed control was spider mite, and it was controlled by spaying lambda-cyhalothrin when it was necessary. At harvest, 100 plant individuals were randomly selected from each plot for measurements of grain weight per panicle and panicle weight per plant. Abortive grain rate (AGR) is defined as: 1 − (grain weight per panicle/panicle weight per plant). The individual plot was harvested manually, and the grain and straw were dried to a constant weight at 80 °C to evaluate grain yield (GY) and straw yield (SY). The harvest index was calculated as: Harvest index (HI) = GY/(GY + SY). Thousand grain weight (TGW) was measured by two weights of 500 grains each. Daily meteorological data, including daily maximum temperature (Tmax), minimum temperature (Tmin), accumulative temperature (AT), relative humidity (RH), and sunshine duration (Shr), were collected at the national basic weather stations at the experimental site during the study period. The diurnal temperature range (DTR) was calculated by subtracting the daily Tmin from the daily Tmax. The reference evapotranspiration (ET_0) was calculated with the crop-water program developed by FAO using the FAO Penman–Monteith equation [20] with the daily weather data. AT, Shr, RH, DTR, Tmin, Tmax and ET_0 during the whole growth stage (WhS), vegetative stage (VS) and reproductive stage (RS) were processed, respectively. VS was from the sowing date to the start date of the booting stage, and RS was from the start date of the booting stage to the harvest date; the dates are shown in Table S2. The booting and harvest dates were the dates when more than 50% of plants were in the booting stage or were harvested.

2.5. Data Analysis

Principal Component Analyses (PCAs) were performed in SPSS 16.0.

3. Results

3.1. The Variation of Grain Yield and Related Traits

The average GY, AGR, TGW and HI of all the foxtail millet varieties tested for each season under the two water treatments varied from 2011 to 2020 (Figure 1). The average GY and TGW under the WW treatment were higher than those under the WS treatment in each year. However, for the average AGR and HI, the patterns were different from the pattern for the average GY and TGW. The average values of AGR under the WW treatment in 2013, 2014, 2018 and 2020 were higher than those under the WS treatment, and in other growth seasons, the opposite result was shown. The average values of HI under the WW treatment in 2011, 2013, 2014, 2017, 2019 and 2020 were higher than those under the WS treatment, while in 2012 and 2015, the average HI was lower under the WW treatment than that under the WS treatment.

The lowest average GY under the WW (4.92 t ha^{-1}) and WS (3.50 t ha^{-1}) treatments were obtained in 2012 and 2018, respectively; the highest average GY was obtained in 2020 under both the WW and WS treatments, and it was 6.95 t ha^{-1} and 5.77 t ha^{-1} under the WW and WS treatment, respectively (Figure 3, Table 2). Under both the WW and WS treatments, the lowest average TGWs were observed in 2018 (2.51 g and 2.46 g under the WW and WS treatment, respectively), and the highest average TGWs were observed in 2020 (2.99 g and 2.96 g under the WW and WS treatment, respectively) (Figure 3, Table S3).

The lowest average AGR was obtained in 2019 (11.93%) under the WW treatment and in 2020 (10.6%) under the WS treatment, and the highest average AGRs were obtained in 2017 under both the WW (23.14%) and WS (24.24%) treatments (Figure 3, Table S4). For HI, the lowest average value was obtained in 2015 (0.43), and the highest average value was obtained in 2013 (0.54) and 2020 (0.54) under the WW treatment, while under the WS treatment, the lowest average value was obtained in 2019 (0.40), and the highest value was obtained in 2012 (0.53) (Figure 3, Table S5).

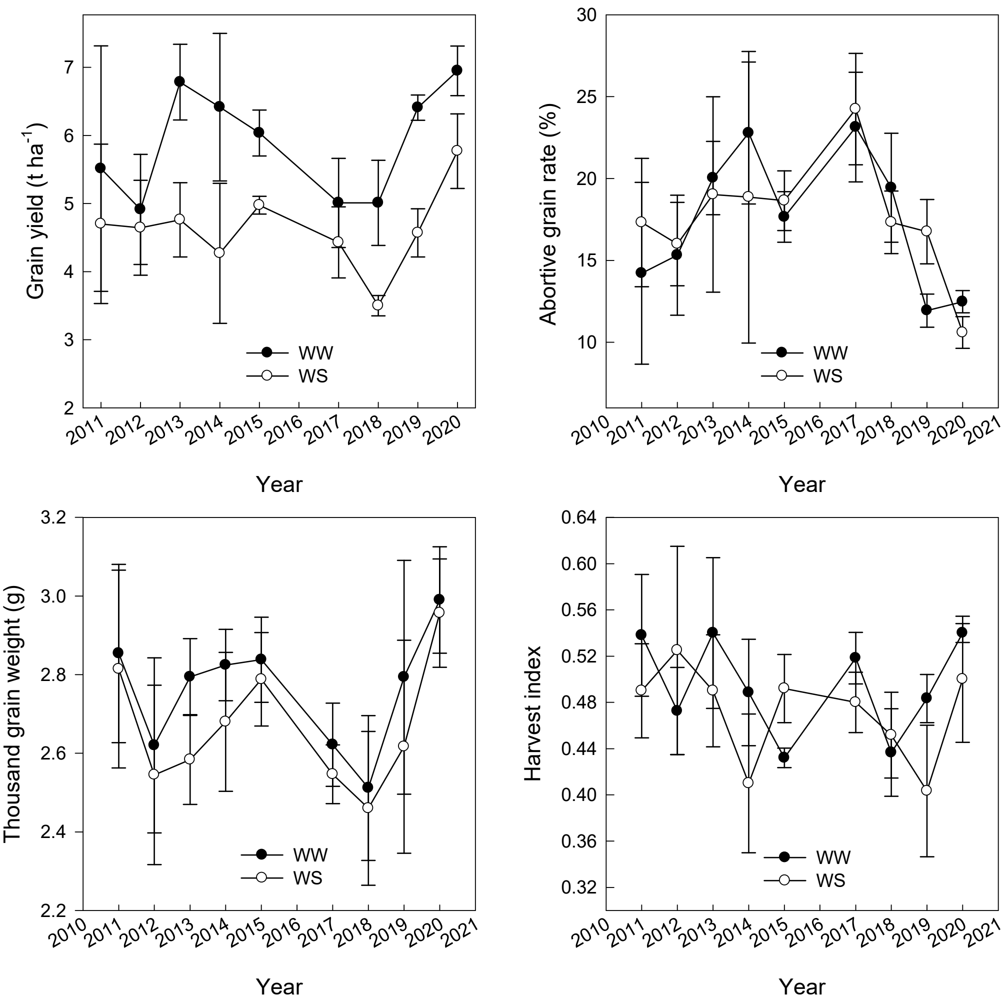

Figure 3. The variation in average grain yield, thousand grain weight, harvest index and abortive grain rate of the varieties under well-watered (WW) and water-stress (WS) treatments from 2011 to 2020. Error bar: standard deviation.

Table 2. The maximum, minimum, mean and coefficient of variation of grain yield of different varieties in nine seasons.

Treatment	Year	Maximum	Minimum	Mean	Coefficient of Variation (%)
WW	2011	7.51	3.43	5.51	32.70
	2012	5.73	3.83	4.92	16.44
	2013	7.72	6.33	6.78	8.18
	2014	8.07	4.86	6.42	16.89
	2015	6.32	5.46	6.04	5.58
	2017	5.64	3.89	5.01	13.06
	2018	5.56	4.00	5.01	12.49
	2019	6.60	6.22	6.41	2.89
	2020	7.36	6.37	6.95	5.23
WS	2011	6.10	3.23	4.70	24.89
	2012	5.49	3.82	4.65	15.00
	2013	5.59	4.16	4.76	11.45
	2014	6.07	3.16	4.27	24.10
	2015	5.14	4.80	4.98	2.61
	2017	5.23	4.04	4.43	11.78
	2018	3.67	3.30	3.50	4.26
	2019	4.86	4.11	4.57	7.75
	2020	6.19	4.76	5.77	9.50

3.2. The Effect of Meteorological Factors on Grain Yield of Foxtail Millet

PCA has shown the diversity of the meteorological factors, which are shown in Table S6, and GY-related traits under both the WW and WS treatment (Table 3). The first five components with Eigen values of >1.0 explained 95.440% of the total variance under the WW treatment and 95.644% of the total variance under the WS treatment. PC1 showed 41.794% and 42.628% and PC2 showed 18.762% and 17.797% of the total variance under the WW and WS treatment, respectively.

Table 3. Eigen value and percentage of total variation for the principal component axes under well-watered (WW) and water-stressed (WS) treatments.

Treatments	Principal Components	1	2	3	4	5
WW	Eigen values	10.031	4.503	3.929	2.899	1.544
	% of Variance	41.794	18.762	16.369	12.080	6.435
	Cumulative %	41.794	60.556	76.925	89.005	95.440
WS	Eigen values	10.231	4.271	3.934	2.711	1.808
	% of Variance	42.628	17.797	16.393	11.294	7.533
	Cumulative %	42.628	60.425	76.818	88.111	95.644

PC1 was highly related to Shr-Whs, Shr-VS and Shr-RS under the WW treatment (Table S7 and Figure 4) and was highly related to Shr-WhS, Shr-RS, DTR-WhS and DTR-RS under the WS treatment (Table S8 and Figure 5). PC2 was highly related to AT-RS, Tmin-Whs, Tmin-RS and Tmax-RS under the WW treatment (Table S7 and Figure 4) and highly related to AT-VS, ET_0-VS, Tmin-VS and Tmax-VS under the WS treatment (Table S8 and Figure 5).

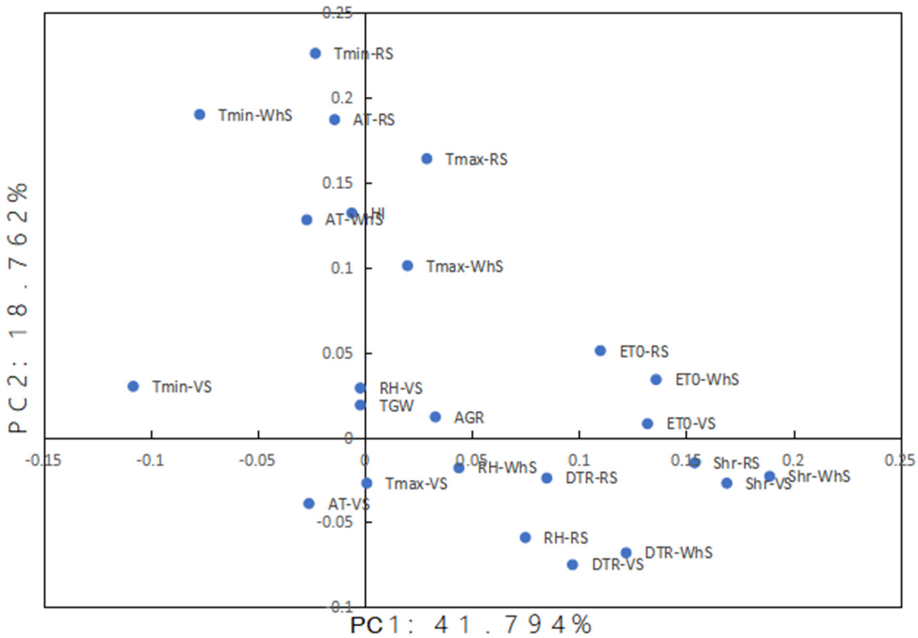

Figure 4. Principal component biplot of yield traits and meteorological factors under well-watered (WW) treatments for the year 2011–2020. TGW, though grain weight; AGR, abortive growth rate; HI, harvest index; AT, average temperature; ET_0, the reference evapotranspiration; Shr, sunshine duration; RH, relative humidity; DTR, the diurnal temperature range; Tmin, daily minimum temperature; Tmax, daily maximum temperature; WhS, whole growth stage; VS, vegetative stage; RS, reproductive stage.

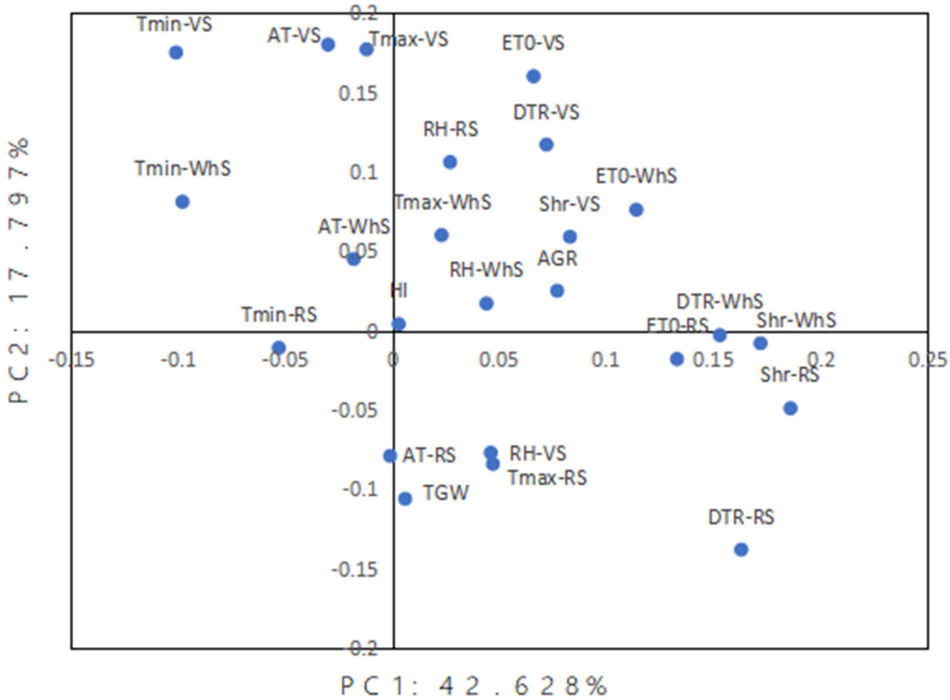

Figure 5. Principal component biplot of yield traits and meteorological factors under water-stress (WS) treatments for the year 2011–2020. TGW, though grain weight; AGR, abortive growth rate; HI, harvest index; AT, average temperature; ET_0, the reference evapotranspiration; Shr, sunshine duration; RH, relative humidity; DTR, the diurnal temperature range; Tmin, daily minimum temperature; Tmax, daily maximum temperature; WhS, whole growth stage; VS, vegetative stage; RS, reproductive stage.

PC3 was highly related to AT-VS, Tmin-VS and Tmax-VS under the WW treatment and AT-RS, Tmin-Whs (Table S7), Tmin-RS and Tmax-RS under the WS treatment (Table S8). PC4 was highly related to RH-Whs and RH-VS under the WW treatment (Table S7) and Shr-VS, and RH-VS under the WS treatment (Table S8). PC5 was highly related to ET_0-VS, Shr-VS, RH-WhS, RH-RS, DTR-RS and Tmin-RS under the WW treatment (Table S7) and ET_0-VS, RH-WhS, RH-VS and RH-RS under the WS treatment (Table S8).

4. Discussion

4.1. Variation in Grain Yield

Foxtail millet is a healthy food for people in the world; it is cultivated in 26 countries and ranks fourth among all millets [21]. Meteorological factors and water supply condition influence the grain yield of foxtail millet [22,23]. In this study, a large seasonal variation in GY was observed under both the WW and WS treatments, which ranged from 4.92 t ha^{-1} to 6.95 t ha^{-1} under the WW treatment and from 3.50 t ha^{-1} to 5.77 t ha^{-1} under the WS treatment. Meteorological factors had a large influence on foxtail millet grain production, and drought evidently reduced the GY. TGW, AGR and HI are important traits associated with GY, the variation trend of TGW was consistent with the variation trend of GY, the consistency of the variation trend of AGR, HI and GY was weak, and the variation trend of AGR was nearly opposite to the trend of GY, which is consistent with previous research [23].

4.2. Meteorological Factors Play an Important Role in Grain Yield

Meteorological factors, such as temperature, humidity and sunshine duration, can affect crop growth and development and influence crop yield [11,12,24]. Ming et al. [25] found GY was closely correlated with various meteorological factors in different growth stages. In our study, seven factors (AT, Tmin, Tmax, ET_0, DTR and RH) were observed, and we separated the whole growth stage (WhS) into the vegetative (VS) and reproductive stages (RS). PCA is an effective means of collecting information from complex, multiple factors that are highly correlated; furthermore, it is valuable for extracting underlying factors for traits by dimension reduction, and it can be used for the measurement of the independent impact of a particular factor to the total variance, whereas each coefficient of proper vectors indicates the degree of contribution of every original variable with which each principal component is associated [26]. Han et al. [19] evaluated the impact of different meteorological conditions on apple yield in Yantai City; they found that the cumulative contribution of the five principal components reached 90.076%, and these five components could represent the twelve meteorological factors. In this study, five principal components explained 95.440% and 95.644% of the total variance under the WW and WS treatment, respectively, which were higher than the requirement of a cumulative contribution of >85% for a principal component analysis [19], and most of the information in the original data has been extracted at this point.

PC1 and PC2 from principal component analysis would provide the highest possible percentage of the explained variance. In this study, PC1 showed 41.794% and 42.628% and PC2 showed 18.762% and 17.797% of the total variance under the WW and WS treatment, respectively. PC1 was composed of Shr during the WhS, VS and RS under the WW treatment and Shr and DTR during the WhS and RS under the WS treatment. This indicated that Shr during the WhS and VS and RS were the greatest impact factors if foxtail millet was supplied well with water/irrigation. If foxtail millet suffered water stress, Shr and DTR during the WhS and RS had the greatest effect on grain yield, probably because the plots were watered before sowing. Water stress during the VS was not significant; during the RS, the stress became more and more serious, and the variation in Shr and DTR during the RS were the main factors which could work with water stress to impact the GY of foxtail millet. Furthermore, AT, Tmin and Tmax during the RS (PC2) also had large impacts on grain yield under the WW treatment, while AT, Tmin, Tmax and ET_0 during the VS (PC2) had large impacts on grain yield under the WS treatment. In the water supply condition, AT, Tmin and Tmax could impact grain filling during the RS, which finally influenced the grain yield. Meanwhile, in the water stress condition, AT, Tmin and Tmax affected the grain yield, probably by influencing photosynthates' formation during the VS. Tmin and Tmax are two main parameters used to calculate ET_0 [27]; when foxtail millet cannot be irrigated or precipitated, ET_0 during the VS could also be the key factor. Therefore, water supply could impact the influence of meteorological factors on the grain yield of foxtail millet, and the influences are different in vegetative and reproductive stages. However, the results in this study were only from Hengshui city, the effect of meteorological factors on grain yield of foxtail millet were complicated, the effect could be different in other areas, more research in different places could be considered, and more meteorological factors could be added. In addition, more research, such as on the effect of meteorological factors on physiological characters of foxtail millet, etc., could be studied in future studies.

5. Conclusions

The effects of meteorological factors on the grain yield of foxtail millet were related to the water supply condition and growth stage. Under the irrigation condition, sunshine during the whole growth stage, vegetative and reproductive stages was the key meteorological factor, while without irrigation and precipitation, sunshine and diurnal temperature range during whole growth stage and reproductive stage were the key meteorological factors. The findings in this study could help us in foxtail millet cultivation and breeding in the North China Plain.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/crops3010006/s1, Table S1: The information of 38 varieties; Table S2: The recorded dates of sowing, booting and harvest; Table S3: The maximum, minimum, mean and coefficient of variation of thousand grain weight of different varieties in nine seasons; Table S4: The maximum, minimum, mean and coefficient of variation of abortive grain rate weight of different varieties in nine seasons; Table S5: The maximum, minimum, mean and coefficient of variation of harvest index of different varieties in nine seasons; Table S6: The major meteorological factors during the nine seasons at different growing stages of foxtail millet; Table S7: Component matrix for the principal component axes under well-watered (WW) treatment; Table S8: Component matrix for the principal component axes under water-stress (WS) treatment.

Author Contributions: Conceptualization, W.Z.; methodology, B.W., B.L. and Z.C.; formal analysis, Y.G.; resources, W.Z. and G.L.; data curation, W.Z. and B.W.; writing—original draft preparation, Y.G.; writing—review and editing, Y.G. and C.B.; supervision, W.Z.; funding acquisition, W.Z. All authors have read and agreed to the published version of the manuscript.

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