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Article

Interpreting Variety–Location–Fertilizer Interactions to Enhance Foxtail Millet Productivity in Northern China

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Abstract: Foxtail millet (*Setaria italica* (L.) P. Beauv.) is an important traditional cereal crop in dryland ecological agriculture in China and is widely grown in India, the United States, and Nigeria. It is of significance to understand the variety–location–fertilizer (V–L–F) interaction for highly efficient production. Therefore, a two-year field experiment was conducted with six varieties in five locations, and data were analyzed by combined ANOVA analysis, redundancy analysis (RDA), and additive main multiplicative interaction (AMMI). The results showed that the mean sum of squares was significantly different among years, locations, varieties, fertilizations, and their interactions, except for Y–V and V–F interactions. The contributions of various factors to yield variation varied, location was the largest contributor (38.7%), followed by year (33.6%), and variety and fertilizer contributed 7.1% and 3.2%, respectively. JI25 was widely adapted, and its yield was stable and higher than that of others over diverse environments in two years. The RDA results showed that two principal components explained more than 66.1% of the yield variance, while more than 63.0% of the variances were clustered in the first factor. Excessive single rainfall or total rainfall and air temperature (especially minimum temperature) were significantly associated with the millet yield. The results offered an important reference for variety layout, natural resource potential mining, and formulation of efficient green cultural practices.

Keywords: *Setaria italica*; foxtail millet; variety–location–fertilizer interactions; yield; fertilizer; meteorological factors

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1. Introduction

Foxtail millet (*Setaria italica* (L.) P. Beauv.) is an important cereal crop, which is widely grown in arid and semi-arid areas of China, India, the United States, and Nigeria due to its excellent drought and barren resistance, short growth, and long suitable sowing windows [1,2]. Foxtail millet is rich in protein, folic acid, vitamin E, carotenoid, selenium, and other important nutrients, playing a positive role in maintaining human health [3,4]. In northern China, foxtail millet is a necessary nourishing food for postpartum mothers and daily food for all ages [5,6].

Restrictive factors affecting the yield of foxtail millet include inappropriate planting location [7], unstable climate [8,9], diseases and pests [10], inappropriate variety selection, and improper agronomic measures [11,12]. Some studies showed the main restrictive factor affecting the grain yield is the genotype without ideal trait, while some showed it is selection of planting site (location) [13,14]. In contrast, whether variety, location, or fertilizer were the main restrictive factors affecting grain yield of foxtail millet is not determined. Previous research results defined the suitable variety or fertilization level in a specific location and provided better theoretical guidance for local millet cultivation [15–17]. However, most of the conclusions based on the one-way test in a specific environment are unable to explore the best matching mode of crop varieties, environment, and cultivation measures, or to explain the regulation mechanisms of cultivation measures in environmental factors, variety characteristics, and yield. The field performance of crop varieties is resulted by interaction effect and random error of varieties, environment, and cultivation measures. Crop, environment, and cultivation measures are interrelated and interact with each other to form a farmland crop cultivation system [18,19]. The great majority of studies displayed that environmental effects and interaction effects are closely related to the spatial location and interannual fluctuation of crop planting, accounting for more than 50% of the total variance of variety performance [20,21], and even a higher proportion if the effects of cultivation measures are accumulated [22]. Concurrently, a few studies suggested that environmental effects were lower than the those of varieties [23]. Regarding the importance of cultural practices and varieties in production, there are few research due to the increased difficulty of work and analysis. In addition, the research conclusions vary due to the differences in research objects, environments, and methods. For instance, a study on maize in Ethiopia revealed that cultivation management (plant density) accounted for 37% of yield variation, while varieties only accounted for 6% [22]. Nevertheless, an inconsistent finding was observed in a research on soybean conducted in Argentina, which suggested that the effects of genotype was greater than those of cultivation management (sowing date) [24]. However, given that there are few studies on the interaction mechanism of millet varieties, environment, and cultivation measures, objectives of this study are to (I) evaluate the effects of varieties, location, and fertilization and their interactions, (II) recommend varieties with wide adaptation and high yield, and (III) identify the key soil and meteorological factors influencing fertilization effect.

2. Materials and Methods

2.1. Foxtail Millet Genotypes

Six foxtail millet varieties were selected to evaluate the effects of five different locations and four fertilization treatments. These varieties were the dominant or common ones in the main planting areas of summer millet in China (Table 1).

Table 1. Description of the study varieties.

Variety	Breeding Institutions	Maturity	DTM [1] (Days)	DTB [2] (Days)	DTA [3] (Days)	Height (cm)
JG25	Crop Research Institute of Shandong Academy of Agricultural Sciences	Late	90	44	50	137
JG39	Millet Research Institute of Hebei Academy of Agricultural and Forestry Sciences	Medium	86	41	47	134
JIN21	Institute of Cash Crops, Shanxi Academy of Agricultural Sciences	Late	91	44	49	164
JM1	Chifeng Academy of Agriculture and Animal Husbandry	Early	83	39	46	132
YG35	Henan Anyang Academy of Agricultural Sciences	Early	83	39	46	135
ZG2	Institute of crop science, Chinese Academy of Agricultural Sciences	Medium	88	43	49	130

[1] days from germination to physiological maturity, [2] days from germination to anthesis, and [3] days from germination to booting stage.

2.2. Study Sites

The field experiments were conducted in five locations (as shown in Figure 1) in 2020~2021: Zhengzhou, Zibo, Shijiazhuang, and Handan where were the main summer millet-producing areas in China, and Beijing where was a general summer millet-producing area (Table 2). Previous crop was not found in Beijing, and that in the other 4 places was winter wheat in both years of the research. Soil samples were collected in 0~30 cm before fertilizers to detect the pH value on 1:1 water to soil suspension. After they were treated with 2.0 mol·L^{-1} potassium chloride (KCl), the contents of ammonium nitrogen (AN), nitrate-nitrogen (NN), available phosphorus (P), and available potassium (K) were detected by using an Alliance continuous flow analyzer. The collected soil samples were air-dried, ground, and sieved using a 2.0 mm mesh. The Olen method was employed to test the readily available phosphorus of the soil. K was extracted with 1.0 mol·L^{-1} NH_4OAc and determined by a flame photometry.

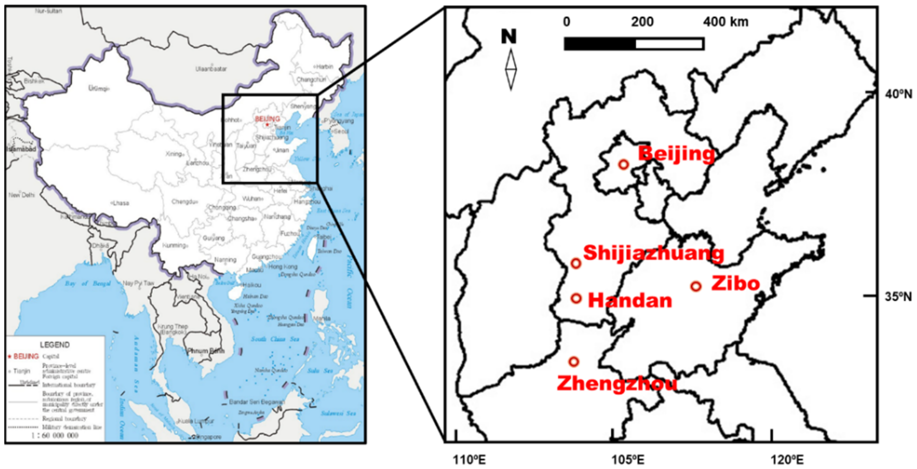

Figure 1. Locations of the study sites.

Table 2. Description of the study sites.

Location Name	Region	Soil Parameters (0~30 cm)						Sowing and Harvesting Date	
		Type	pH	P *	K *	AN *	NN *	2020	2021
Zhengzhou (ZZ)	Henan Province, China	Loamy clay	8.11	29.14	126.67	17.88	39.74	18 June, 16 September	11 June, 9 September
Zibo (ZB)	Shandong Province, China	Sandy clay	7.97	6.39	138.00	9.39	10.66	19 June, 21 September	19 June, 17 September
Beijing (BJ)	Beijing, China	Silty clay	8.26	25.22	97.11	9.25	24.66	6 June, 20 September	10 June, 21 September
Shijiazhuang (SJZ)	Hebei Province, China	Loamy clay	7.81	22.21	98.00	7.89	4.17	22 June, 20 September	23 June, 21 September
Handan (HD)	Hebei Province, China	Silty clay	8.05	17.49	308.00	8.32	23.08	12 June, 10 September	2 July, 30 September

* mg/kg.

The climatic conditions were obviously different in rainfall, sunshine hours, air temperature, and air humidity in these five places with fluctuations among years (Figure 2). For example, the rainfall and air humidity in Handan were the highest, and the sunshine hours in Zibo were significantly more than others in 2020.

2.3. Experimental Design and Filed Management

The four fertilization treatments were set and applied as a basal dressing: no fertilization (F_0), low fertilization (N 75, P 20, and K 21 kg·ha^{-1}, F_1), medium fertilizer (N 150, P 41, and K 42 kg·ha^{-1}, F_2), and high fertilizer (N 300, P 82, and K 83 kg·ha^{-1}, F_3). N, P, and K fertilizers were derived from urea (46% N), calcium superphosphate (7% P) and potassium sulfate (41% K), respectively. The basis for setting the fertilization amount of F_1, F_2, and F_3 was listed below: arranging data of 12 published research papers about foxtail millet fertilization, extracting and summarizing the best fertilization amount data of each paper, and obtaining the range and median of the best fertilization amount. The median was undertaken as the medium fertilization amount data (F_2). Once range of the best fertilization amount was referred to, the fertilization amounts of F_1 and F_3 were 0.5 times and 2 times of F_2, respectively.

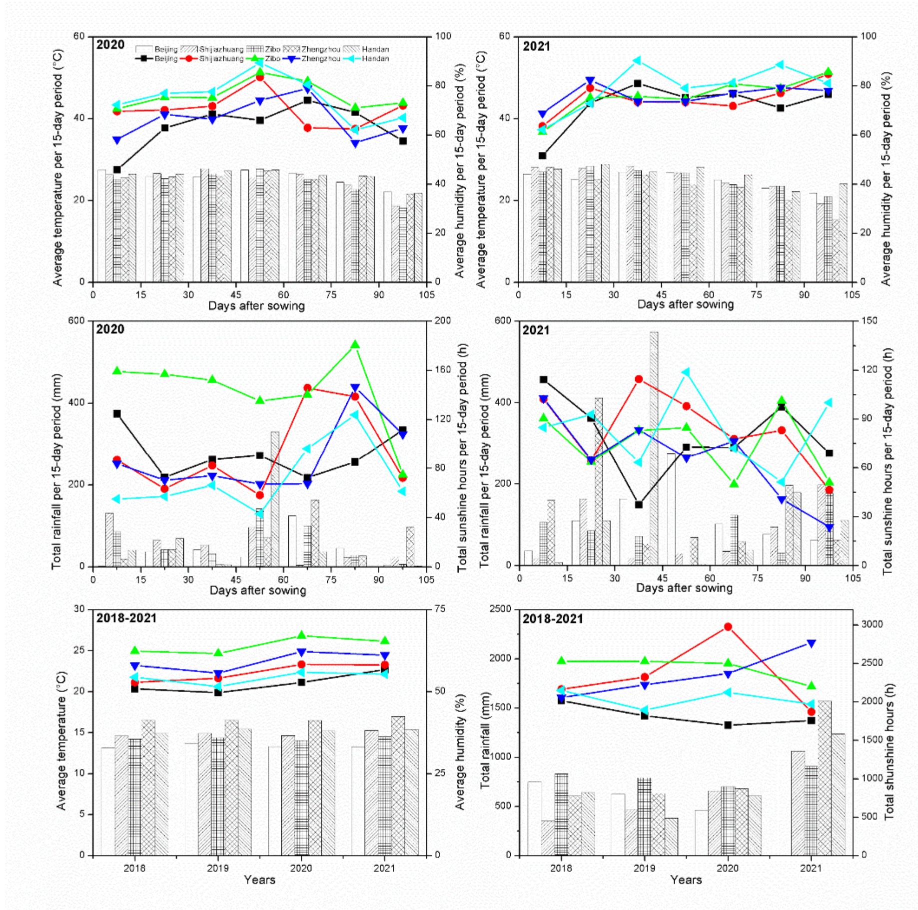

Figure 2. Air temperature (vertical bars), rainfall (vertical bars), sunshine hours (scatter and line), and humidity (scatter and line) in five sites in 2018–2021.

A split-plot design was adopted in the experiment. Four fertilization treatments were undertaken as the main plots, with 18 split plots each, which were composed of 6 varieties with 3 repetitions. Plots at 10~15 m^2 in size were used in five locations, with a row spacing of 0.40 m. At the 5~6 leaves stage of foxtail millet, inter-tillage was carried out to ensure 0.6 million plants per hectare.

The growth period was recorded, including the seedling emergence stage, booting stage, flowering stage, and mature stage. At flowering and maturity, 6 plants were randomly sampled from each plot and assessed for average height and hand harvesting. All plants were divided into leaves, stems, ears, dried, and weighed. At maturity, a quadrat was harvested to determine the yield of each plot, where each quadrat was manually harvested in an area of 3.96 m^2, converted to yield per hectare. At the maturity stage, 10 spike were randomly collected from each plot to evaluate the average spike length and width. After natural air-drying, the average spike weight per plant was obtained by weighing, and after threshing, the average grain weight per spike was obtained.

2.4. Statistical Analysis

Combined ANOVA, biplots of AMMI model, and all the genetic and environmental variability parameters for each factor were calculated in Data Procession System V14.10 [25]. Least significance difference (LSD) at 0.05/0.01/0.001 probability were adopted to estimate the significance between the independent variables and dependent variables. Redundancy analysis (RDA) was performed to identify the edaphic factors that influenced yield using the statistical program Canoco ver. 5. Histogram, scatter plot, and Pearson correlation analysis were carried out in OriginPro ver. 2022 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Mean Performance of Subjects and Analysis of Variance

The combined ANOVA on all tested environments showed that all trait variations were very significant in location, variety, and fertilization, except height in fertilization (Table 3). Spike length (SL), spike width (SW), grain weight (GWE), and yield were mainly affected by location. The plant height and spike weight (SWE) were mainly affected by varieties and interaction of year and location, respectively.

Table 3. Interaction effect of year, location, variety and fertilization on yield traits of foxtail millet.

Treatment	SL (cm)	SW (cm)	SWE ($g \cdot plant^{-1}$)	GWE ($g \cdot plant^{-1}$)	Height (cm)	Yield ($kg \cdot ha^{-1}$)
Year						
2020	19.4 b	2.4 a	16.6 a	13.2 a	140.1 a	3720.5 b
2021	19.8 a	2.3 b	16.8 a	13.2 a	137.7 b	4973.5 a
Location						
Beijing	20.7 a	2.8 a	18.4 a	15.2 a	148.2 a	3862.6 d
Shijiazhuang	19.7 b	2.0 e	15.1 c	11.0 d	138.0 b	4442.3 b
Handan	19.6 b	2.3 c	17.3 b	12.6 c	131.2 c	4865.1 a
Zibo	19.9 b	2.5 b	17.1 b	14.5 b	139.0 b	4187.2 c
Zhengzhou	18.1 c	2.2 d	15.5 c	12.9 c	137.9 b	4378.8 b
Variety						
ZG2	19.6 c	2.3 d	16.5 bc	13.1 c	130.1 e	4281.7 d
YG35	20.0 b	2.4 bc	16.7 bc	13.6 bc	135.2 bc	4552.3 c
JIN21	20.4 a	2.2 e	16.2 c	11.9 d	164.1 a	4652.8 b
JI39	18.9 d	2.3 cd	16.8 b	13.9 b	134.5 c	4882.2 a
JI25	20.6 a	2.4 b	18.5 a	14.4 a	136.9 b	3755.1 f
JM1	18.2 e	2.5 a	15.4 d	12.4 d	132.4 d	3959.9 e
Fertilizer						
F0	19.3 b	2.3 b	16.0 c	12.7 c	137.5 b	4644.7 b
F1	19.5 b	2.4 a	17.0 ab	13.6 a	138.7 ab	3896.1 d
F2	19.8 a	2.4 a	16.6 b	13.1 bc	139.2 ab	4805.2 a
F3	19.9 a	2.4 a	17.1 a	13.5 ab	139.7 a	4042.9 c
F-value and significance						
Year (Y)	10.3 **	114.1 ***	1.0 ^{NS}	0.1 ^{NS}	22.4 ***	678.0 ***
Location (L)	54.4 ***	289.3 ***	53.9 ***	105.6 ***	114.9 ***	779.6 ***
Variety (V)	42.2 ***	21.7 ***	26 ***	27.1 ***	412.8 ***	142.6 ***
Fertilizer (F)	5.6 ***	8.4 ***	8.5 ***	7.4 ***	2.5 ^{NS}	64.4 ***
Y × L	16.6 ***	20.4 ***	84.7 ***	67.6 ***	40.8 ***	293.2 ***
Y × V	12.2 ***	9.5 ***	7.6 ***	5.0 ***	2.8 *	2.0 ^{NS}
Y × F	2.2 ^{NS}	3.2 *	1.5 ^{NS}	2.1 ^{NS}	1.7 ^{NS}	2.7 *
L × V	5.1 ***	4.0 ***	7.5 ***	7.7 ***	5.7 ***	20.4 ***
L × F	8.8 ***	13.6 ***	17.2 ***	14.4 ***	7.5 ***	11.0 ***
V × F	1.4 ^{NS}	2.3 **	2.6 ***	3.0 ***	1.3 ^{NS}	1.6 ^{NS}
Y × L × V	6.1 ***	5.1 ***	2.5 ***	3.1 ***	3.0 ***	12.6 ***
Y × L × F	2.3 **	5.6 ***	6.4 ***	6.2 ***	5.4 ***	2.0 *
Y × V × F	1.1 ^{NS}	0.8 ^{NS}	1.5 ^{NS}	1.4 ^{NS}	0.7 ^{NS}	2.3 **
L × V × F	1.8 ***	1.6 **	0.9 ^{NS}	1.1 ^{NS}	0.8 ^{NS}	1.6 **
Y × L × V × F	2.0 ***	1.3 ^{NS}	1.2 ^{NS}	1.2 ^{NS}	0.7 ^{NS}	1.5 *

SL: spike length; SW: spike width; SWE: spike weight; GWE: grain weight; Height: plant height, Yield: yield per hectare. Means in a column followed by different lowercase letters are significantly different at $p < 0.05$ according to LSD test. * means $p < 0.05$, ** means $p < 0.01$, *** means $p < 0.001$, and ^{NS} means non-significant.

All trait' variations were very significant in location, variety, and fertilization, except dry matter accumulation after anthesis (DMAA) and dry matter harvest index (DMHI) in fertilization (Table 4). Matured straw (MST) and matured dry matter were mainly affected by year. Matured spike (MSP), flowered spike (FSP), and DMHI were mainly affected by location. Flowered straw (FST) and flowered dry matter (FDM) were mainly affected by variety. MST and FST were mainly affected by year. DMAA was mainly affected by interaction of year and location.

Table 4. Interaction effect of year, location, variety and fertilization on agronomic traits of foxtail millet.

Treatment	**MSP ($g \cdot plant^{-1}$)**	**MST ($g \cdot plant^{-1}$)**	**FSP ($g \cdot plant^{-1}$)**	**FST ($g \cdot plant^{-1}$)**	**MDM ($g \cdot plant^{-1}$)**	**FDM ($g \cdot plant^{-1}$)**	**DMAA ($g \cdot plant^{-1}$)**	**DMHI ($g \cdot g^{-1}$)**
Year								
2020	15.0 a	12.8 a	2.0 a	11.3 a	27.8 a	13.3 a	14.6 a	5.4×10^{-1} b
2021	14.0 b	11.2 b	2.0 a	10.5 b	25.2 b	12.5 b	12.7 b	5.5×10^{-1} a
Location								
Beijing	13.3 c	13.9 a	2.1 b	11.9 a	27.1 b	14.0 a	13.3 c	4.9×10^{-1} e
Shijiazhuang	12.3 d	11.5 c	2.0 b	10.5 c	23.8 d	12.5 cd	11.3 d	5.2×10^{-1} d
Handan	16.3 a	12.1 b	1.8 c	10.2 c	28.4 a	12.0 d	16.3 a	5.8×10^{-1} b
Zibo	15.1 b	10.3 d	2.3 a	10.6 c	25.4 c	12.9 bc	12.6 c	5.9×10^{-1} a
Zhengzhou	15.6 b	12.2 b	1.8 c	11.3 b	27.8 ab	13.1 b	14.7 b	5.6×10^{-1} c
Variety								
ZG2	14.6 b	11.3 c	2.1 a	11.0 b	25.9 c	13.2 b	12.8 d	5.6×10^{-1} b
YG35	14.8 b	11.1 c	2.0 b	9.7 c	25.9 c	11.7 c	14.2 ab	5.7×10^{-1} b
JIN21	13.5 c	14.4 a	2.0 b	13.1 a	28.0 ab	15.1 a	12.9 cd	4.8×10^{-1} e
JI39	14.6 b	12.4 b	1.9 b	11.0 b	27.0 b	13.0 b	14.1 bc	5.4×10^{-1} d
JI25	15.8 a	12.7 b	1.9 b	11.4 b	28.6 a	13.2 b	15.3 a	5.5×10^{-1} c
JM1	13.8 c	9.9 d	2.1 a	9.1 d	23.7 d	11.19 c	12.5 d	5.8×10^{-1} a
Fertilizer								
F0	13.9 b	11.5 c	1.8 c	10.3 b	25.4 c	12.1 c	13.2 b	5.5×10^{-1} ab
F1	14.5 a	11.8 bc	2.0 b	10.9 a	26.3 b	12.8 b	13.5 ab	5.5×10^{-1} a
F2	14.7 a	12.1 b	2.1 ab	11.2 a	26.8 ab	13.2 ab	13.5 ab	5.5×10^{-1} ab
F3	14.2 c	12.6 a	2.1 a	11.2 a	27.6 a	13.3 a	14.3 a	5.4×10^{-1} b
F-value and significance								
Year(Y)	29.2 ***	114.5 ***	0.1 ^{NS}	17.2 ***	72.7 ***	18.4 ***	30.4 ***	28.3 ***
Location(L)	62.0 ***	60.7 ***	35.7 ***	13 ***	30.0 ***	15.5 ***	27.1 ***	224.2 ***
Variety(V)	12.6 ***	73.4 ***	5.5 ***	45.1 ***	21.5 ***	45.4 ***	6.8 ***	115.1 ***
Fertilizer(F)	6.5 ***	9.7 ***	23.6 ***	5.4 **	9.2 ***	10.5 ***	1.8 ^{NS}	1.8 NS
Y × L	49.3 ***	67.2 ***	23.3 ***	17.9 ***	62.0 ***	19.0 ***	31.2 ***	23.2 ***
Y × V	6.3 ^{NS}	1.8 ^{NS}	4.9 ***	1.4 ^{NS}	4.7 ***	2.4 *	3.4 **	6.1 ***
Y × F	0.5 ^{NS}	0.3 ^{NS}	0.4 ^{NS}	0.9 ^{NS}	0.1 ^{NS}	1.3 ^{NS}	0.5 ^{NS}	2.9 *
L × V	3.3 ***	4.2 ***	10.4 ***	3.5 ***	3.6 ***	5.9 ***	1.9 **	4.3 ***
L × F	11.3 ***	7.2 ***	9.5 ***	2.4 **	11.2 ***	4.1 ***	7.0 ***	3.1 ***
V × F	0.5 ^{NS}	0.7 ^{NS}	1.5 ^{NS}	1.0 ^{NS}	0.4 ^{NS}	1.3 ^{NS}	0.9 ^{NS}	1.3 ^{NS}
Y × L × V	4.2 ***	5.9 ***	3.6 ***	1.2 ^{NS}	5.4 ***	1.7 *	4.9 ***	5.2 ***
Y × L × F	2.5 **	2.5 ***	2.6 ***	2.0 *	2.7 **	2.9 ***	1.3 ^{NS}	1.9 *
Y × V × F	1.0 ^{NS}	1.2 ^{NS}	0.6 ^{NS}	0.3 ^{NS}	1.1 ^{NS}	0.4 ^{NS}	0.9 ^{NS}	1.0 ^{NS}
L × V × F	1.0 ^{NS}	0.7 ^{NS}	2.1 ***	1.0 ^{NS}	0.8 ^{NS}	1.4 ^{NS}	1.1 ^{NS}	1.1 ^{NS}
Y × L × V × F	1.0 ^{NS}	1.0 ^{NS}	0.7 ^{NS}	0.4 ^{NS}	1.0 ^{NS}	0.6 ^{NS}	0.9 ^{NS}	0.7 ^{NS}

FSP: spike weight at flowering stage; FST: straw weight at flowering stage; FDM: total weight at flowering stage; MSP: spike weight at maturity stage; MST: straw weight at maturity stage; MDM: total weight at maturity stage; DMAA: dry matter accumulation after anthesis; DMHI: dry matter harvest index. Means in a column followed by different lowercase letters are significantly different at $p < 0.05$ according to LSD test. * means $p < 0.05$, ** means $p < 0.01$, *** means $p < 0.001$, and ^{NS} means non-significant.

The combined ANOVA (Table 5) of all tested environments in two years indicated extremely significant yield variability. The mean sum of squares showed a significant variation among year, location, variety, fertilization, and their interaction, except Y–V interaction and V–F interaction. Grain yield displayed that 38.7% of the variations was contributed by location, whereas 33.6%, 7.1%, and 3.2% were contributed by year, variety, and fertilizer, respectively. Among all the interactions, the proportion of Y–L interaction was the highest.

Table 5. ANOVA for yield traits studied along with its contribution toward total variation among six varieties of foxtail millet at five study sites with four fertilizer treatments.

Factor	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Variation Contribution
Year (Y)	1.0×10^8	1	1.03×10^8	678.01 ***	33.62%
Location (L)	4.7×10^8	4	1.18×10^8	779.60 ***	38.66%
Variety (V)	1.1×10^8	5	2.16×10^7	142.61 ***	7.07%
Fertilizer (F)	2.9×10^7	3	9.76×10^6	64.42 ***	3.19%
Y × L	1.8×10^8	4	4.44×10^7	293.22 ***	14.54%
Y × V	1.5×10^6	5	2.99×10^5	1.97 NS	0.10%
Y × F	1.2×10^6	3	4.02×10^5	2.65 *	0.13%
L × V	6.2×10^7	20	3.09×10^6	20.38 ***	1.01%
L × F	2.0×10^7	12	1.67×10^6	11.04 ***	0.55%
V × F	3.6×10^6	15	2.39×10^5	1.57 NS	0.08%
Y × L × V	3.8×10^7	20	1.92×10^6	12.64 ***	0.63%
Y × L × F	3.6×10^6	12	2.98×10^5	1.96 *	0.10%
Y × V × F	5.2×10^6	15	3.50×10^5	2.31 **	0.11%
L × V × F	1.5×10^7	60	2.46×10^5	1.63 **	0.08%
Y × L × V × F	1.4×10^7	60	2.30×10^5	1.52 *	0.08%
Residual	7.3×10^7	480	1.52×10^5		0.05%
Total	1.1×10^7	719			

* means $p < 0.05$, ** means $p < 0.01$, *** means $p < 0.001$, and NS means non-significant.

The combined ANOVA for all the test locations revealed the presence of highly significant variation for yield (Table 6). The mean sum of squares showed a significant variation among year, variety, fertilizer, and Y–V interaction. In addition, interactions among the five locations are different. For example, the V–F interaction was highly significant in Beijing, Shijiazhuang, and Handan, indicating that the effects of fertilization and varieties were bidirectional and mutual, and yield could be further improved through appropriate cultivar selection and fertilization management. The V–F interaction was not significant in Zibo and Zhengzhou, suggesting the responses of all varieties to fertilization pattern were relatively consistent.

3.2. Mean Yield

Yield varied widely among genotypes, environments, and fertilization (Figure 3). The yield in 2020 (4725 kg·ha^{-1}) was higher than that in 2021 (3969 kg·ha^{-1}) (Figure 3a). The highest yield was observed in Zibo, followed by Zhengzhou and Handan, which were 5744 kg·ha^{-1}, 4491 kg·ha^{-1}, and 4326 kg·ha^{-1}, respectively. The large variations in average yield among the varieties were observed in Beijing and Zhengzhou due to the larger range of scatter plots (Figure 3b). The average yields of varieties JI24 and YG35 were higher than those of other varieties across five locations. Additionally, the large variations in yield among the fertilizer treatments were observed in JM1 and JI39 due to the larger range of the scatter plots (Figure 3c). Compared with other fertilization treatments, the average yield of F_2 treatment was the highest.

Table 6. ANOVA for yield traits studied along with its contribution toward total variation among six varieties of foxtail millet with four fertilizer treatments.

Factor	df	Beijing		Shijiazhuang		Handan		Zibo		Zhengzhou	
		MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value	MS	F-Value
Year (Y)	1	5.0×10^7	294.71 ***	3.9×10^7	392.7 ***	1.0×10^8	1049.87 ***	7.4×10^6	35.38 ***	8.2×10^7	445.96 ***
Variety (V)	5	1.5×10^7	90.40 ***	8.1×10^5	8.07 ***	4.5×10^6	46.57 ***	9.6×10^6	46.11 ***	3.8×10^6	20.73 ***
Fertilizer (F)	3	4.7×10^6	28.25 ***	4.0×10^6	40.48 ***	5.8×10^5	5.94 ***	1.3×10^6	6.35 ***	5.8×10^6	31.36 ***
Y × V	5	7.0×10^5	4.19 **	1.6×10^6	15.59 ***	2.3×10^6	23.44 ***	2.2×10^6	10.34 ***	1.3×10^6	6.85 ***
Y × F	3	4.6×10^5	2.76 *	3.7×10^4	0.37 NS	7.1×10^4	0.73 NS	2.6×10^5	1.26 NS	7.6×10^5	4.11 **
V × F	15	3.6×10^5	2.17 *	2.1×10^5	2.12 *	2.4×10^5	2.46 **	1.7×10^5	0.81 NS	2.4×10^5	1.31 NS
Y × V × F	15	3.6×10^5	2.12 *	5.3×10^4	0.53 NS	2.9×10^5	2.96 ***	2.9×10^5	1.39 NS	2.8×10^5	1.53 NS
Residual	96	1.7×10^5		1.0×10^5		9.8×10^4		2.1×10^5		1.8×10^5	
Total	143										

* means $p < 0.05$, ** means $p < 0.01$, *** means $p < 0.001$, and NS means non-significant.

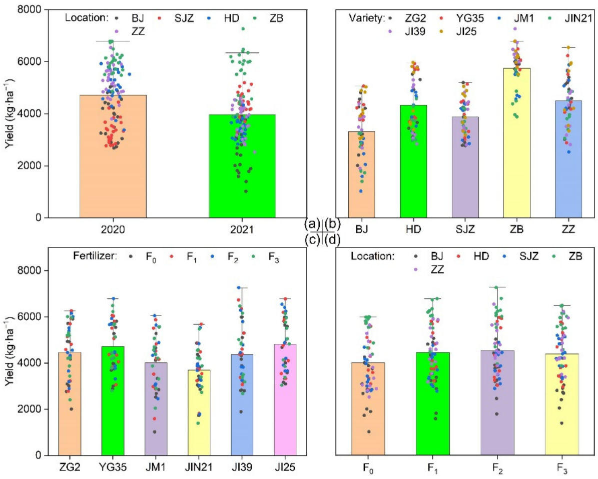

Figure 3. Foxtail yield variation among year (**a**), locations (**b**), varieties (**c**), and fertilizer (**d**) in the year 2020–2021 cropping seasons in China. The histogram represents the average yield, the scatter represents the yield data of all samples, and the median ± interquartile range (IQR) with bars represents the range within 1.5 IQR. The scatter of different colors represents different treatment methods (such as location, variety, and fertilization).

3.3. Variety and Its Adaptability

When the Shukla model was adopted to calculate the high-yield performance and stability of varieties, only three factors (years, locations, and varieties) were included, with the exclusion of fertilization treatment. Before the Shukla model was operated, the yield values per 4 fertilization patterns in the same repetition were averaged. Table 7 revealed that the JI25 showed the highest mean yield, followed by YG35, ZG2, JI39, JM1, and JIN21. The JM1 showed the largest Shukla's stability variance, followed by JI39, JIN21, YG35, JI25, and ZG2. The mean yields of JI25 and YG35 were ranked forefront, with low Shukla's stability variation and very good comprehensive evaluation. The mean yields of JIN21 and JM1 were ranked backward, with high Shukla's stability variation and poor/general comprehensive evaluation.

Table 7. Analysis of high yield and stability of varieties.

Varieties	High Yield Parameters		Shukla's Stability Parameters		Adaptation Area	Comprehensive Evaluation
	Yield (kg·ha^{-1})	Effect Size	Variance	Degree of Variation		
JI25	4813.9	466.6	38,885.6	4.1	All five places	Very good
YG35	4721.2	373.8	58,238.5	5.1	All five places	Very good
ZG2	4467.4	120.0	21,094.9	3.3	All five places	Good
JI39	4366.5	19.1	188,664.7	9.9	All five places	Fairly good
JM1	4013.2	−334.2	209,438.8	11.4	All five places	General
JIN21	3701.9	−645.4	126,973.9	9.6	All five places	Poor

AMMI biplot was utilized to visually represent the yield potential, comprising the variety, stability level, and association of test environments. Figure 4 depicts the relationship between summer millet genotypes and environments. The AMMI biplot was constructed between the first two principal components that explained 76.5% of V–L interaction, in which IPCA1 and IPCA2 contributed 49.5% and 27.0%, respectively. The perpendicular projection from the genotype to the environmental vector reflected the amount of interaction with the environment. Meanwhile, the length of the vector of an environment from the biplot origin meant that it was proportional to the amount of L–V interaction. Apart from that, strong interactive forces were elicited by the environments with longer vectors, whereas weak interactive forces were triggered by those with shorter vectors. With respect to the environment in Beijing, the strongest interactive forces were witnessed, followed by Zibo and Zhengzhou. On the contrary, the weakest interactive forces were observed in Handan. Since the clustered genotypes behaved similarly across environments, almost analogous yield performances were presented amid the variety YG35, JI25, and ZG2. Additionally, given that the genotype and the environment with markers in the same direction from the origin presented a positive interaction, a negative and a small interaction was displayed in those with makers in opposite directions and at right angles individually. The genotype JI39 presented a positive L–V interaction with environment in Zibo, and genotypes YG35, JG25, and ZG2 had the positive L–V interactions with environment in Beijing. Similarly, genotypes ZG2 and JIN21 displayed negative L–V interactions with Beijing and Shijiazhuang, respectively. Albeit dispersion of varieties in biplot indicated that they were different to diverse locations, an acute angle between Handan and Zibo vectors revealed a positive correlation, while the obtuse or nearly right angle of Beijing with Zhengzhou, Handan, Shijiazhuang, and Zibo, and Zhengzhou to Zibo suggested no correlation (Figure 4).

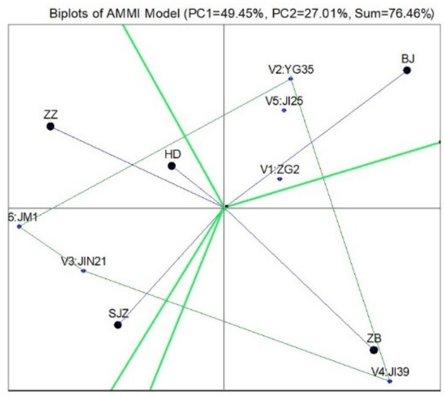

Figure 4. Polygon view of the AMMI biplot for 6 varieties evaluated across 5 study sites in 2020–2021. ZZ, SJZ, BJ, ZB, and HD represent 5 study sites. JIN21, JI25, JI39, YG35, JM1, and ZG2 represent 6 varieties.

The varieties farthest from each direction were connected to green straight lines, such as JI39, JM1, YG35, and JIN21, to form a quadrilateral and four vertical lines (green dotted lines) on the four sides through the center, dividing the diagram into four sectors and the environment into three sectors. Zhengzhou, Handan, and Shijiazhuang were in a group, while Zibo and Beijing were in the other group. The varieties located at the top corner of the quadrilateral were with the highest yields in each environment in the sector. For example, YG35 witnessed the highest yield in Beijing, while ZG2 showed the lowest yield.

3.4. Location and Year

Yields varied widely among year and location (Figure 5). A higher mean yield in 2020 (3347~5970 kg·ha^{-1}) was observed than that in 2021 (2721~5518 kg·ha^{-1}). The average yield of five locations decreased in 2020~2021, except Shijiazhuang; specifically, the highest yield was achieved in two years in Zibo, and yields at other locations (e.g., Handan, Zhengzhou, and Shijiazhuang) varied greatly from year to year.

Both year and location were environmental factors, and they showed strong interaction (Table 8). Therefore, the year and location were integrated into a comprehensive environmental factor (or CE, for short), then an analysis of variance for CE and varieties was carried out. The effect of CE and the effect of variety had a very significant impact on yield. The yield of JG39 in Zibo in 2021 was the highest, reaching 6518 kg·ha^{-1}, which was 41.3% higher than the lowest yield at the same place in the same year (JM1 4612 kg·ha^{-1}). The current results clearly indicated that Zibo provided optimum environmental conditions for the cultivation of summer millet, and the average yield of summer millet in Zibo was 27.9~73.6% higher than that in the other four locations. Grain yield displayed that 77.6% of the variation was contributed by year and location, whereas 20.0% of that was contributed by variety.

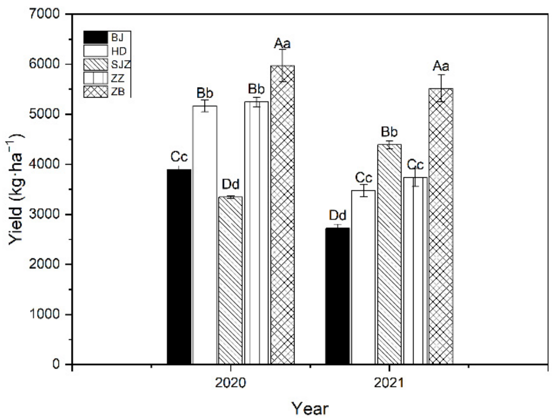

Figure 5. Effects of year and location on yield. Different lowercase and uppercase letters on columns suggest the differences are statistically significant at $p < 0.05$ and $p < 0.001$ according to LSD test, respectively.

Table 8. ANOVA for yield traits studied along with its contribution toward total variation among 6 varieties of foxtail millet with ten year and location treatments.

Year and Location	JM1	JI25	JG39	JIN21	YG35	ZG2
2020BJ	2877 Cc	4690 Aa	3897 Bb	3021 Cc	4426 Aa	4458 Aa
2020HD	4762 Bc	5785 Aa	5305 Ab	3995 Cd	5787 Aa	5363 Ab
2020SJZ	3062 Bc	3505 ABab	3263 ABbc	3718 Aa	3457 ABabc	3079 Bc
2020ZZ	5468 Bbc	6011 Aa	4646 CDd	4513 Dd	5672 ABab	5168 BCc
2020ZB	5675 BCbc	6239 Aa	6291 Aa	5391 Cc	6289 Aa	5940 ABab
2021BJ	1779 Cc	3547 Aa	2945 Bb	1683 Cc	3668 Aa	2709 Bb
2021HD	3767 Aa	3686 ABab	3085 Cc	3189 BCc	3798 Aa	3353 ABCbc
2021SJZ	4270 BCb	4845 Aa	4460 ABab	3761 Cc	4492 ABab	4518 ABab
2021ZZ	3860 Aab	3807 Aab	3256 Bc	3572 ABbc	3890 Aab	4038 Aa
2021ZB	4612 Cc	6025 ABb	6518 Aa	4176 Cd	5732 Bb	6047 ABb
ANOVA	df	Mean square	F-value	p	Variation contribution%	
Year and location (CE)	9	20,919,435.5	342.6	<0.001	77.63%	
Variety	5	5,403,222.0	88.5	<0.001	20.05%	
(CE) × Variety	45	564,220.5	9.2	<0.001	2.09%	

Means in a column followed by different lowercase and uppercase letters are significantly different at $p < 0.05$ and $p < 0.001$ according to LSD test, respectively.

3.5. Fertilization

Proper nutrient management was very important to improve crop yields and maintain a balanced farmland system. Fertilizer improved grain yields in the present study, and the response of foxtail millet yield to fertilizer level for an individual variety grown at a particular location was mostly curvilinear (Figure 6). When only considering the effects of fertilization treatment and year, the mean yield increased first and then decreased from F_0 to F_3, and the mean yield of F_2 treatment was the highest, and the response trends of yield to fertilization were similar in 2020 and 2021, and the overall yield in 2021 was significantly lower than that in 2020 (Figure 6a). When only considering the effects of fertilization treatment and location, the effects of fertilization on yield were changeable due to different locations. Specifically, yield increased first and then decreased curvilinearly from F_0 to F_3 in Beijing, Handan, Zibo, and Zhengzhou. However, the yield increased nearly linearly from F_0 to F_3 in Shijiazhuang. F_2 treatment in Handan, Zibo, and Zhengzhou showed the highest yield, F_1 treatment in Beijing, and F_3 treatment in Shijiazhuang showed the highest yields (Figure 6b).

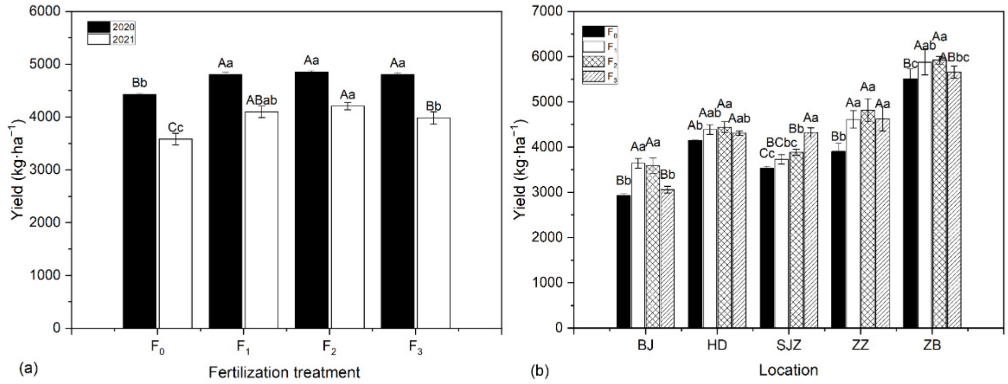

Figure 6. Effects of fertilizer–year (**a**) and fertilizer–location (**b**) on yield. Different lowercase and uppercase letters on columns indicate the results are significantly different at $p < 0.05$ and $p < 0.001$ according to LSD test, respectively.

3.6. RDA Analysis of Yield vs. Climate and Soil Factors

From the date of seed sowing to the end of maturity, every 15 days was marked as a growth stage of foxtail millet, and there were seven stages in total. The maximum, minimum, mean, or sum of air temperature, rainfall, humidity, and sunshine hours in each stage was obtained, and 77 meteorological factors were finally gathered. A total of 25 important meteorological factors were clarified after the correlation coefficient between yield and 77 meteorological factors, and their significant difference was compared. The clarified factors, along with five soil factors and yield, were analyzed based on distance redundancy analysis (Figure 7). The RDA results showed that solely two RDA components explained more than 66.1% of the yield variance, while more than 63.0% of the variance was clustered in the first factor. In addition, the correlation between five soil nutrient factors and yield was different. Soil available phosphorus and soil pH value were significantly negatively correlated with yield, and soil K, AN, and NN were slightly negatively correlated with the yield. In general, the correlation coefficient between yield and climate factors was higher than that with soil nutrients. Yield showed a strong positive correlation with 5Hn, 6Tx, 3St, 6St, 4Hn, 5H, 4T, 6T, 3S, etc., and a strong negative correlation with 2Rx, 6Rx, 3Rx, 3Tn, 6Rt, etc. Zibo, with the highest yield, showed a strong positive correlation with 4Hn, 5H, 5Hx, 6S, 5Rt, 2St, 5Hn, and 4H; while Beijing, with the lowest yield, showed a strong negative correlation with 3Tx, 2T, and 6Tx.

3.7. Time Sequence of Meteorological Factors Affecting Summer Millet Growth

According to RDA results of yield, climate, and soil factors (3.6), a picture (Figure 8) in which the key meteorological factors affected summer millet yield was made. The conditions favorable to grain yield are described below. During the period from 4/5 leaves to the mid-flowering stage and mid-grouting stage, sufficient sunshine would promote the accumulation of photosynthetic products. Apart from that, the high temperature at jointing~booting and mid-grouting stage was beneficial to growing, heading, and flowering of crops, and high humidity at emergence~3/4 leaves stage, heading~maturity except mid-grouting could help to protect seedlings from drought stress and protect pollen and stigma from a high-temperature burn. Ample rainfall at flowering~maturity except mid-grouting was conducive to nutrient absorption and substance assimilation.

The conditions unfavorable to grain yield are described below. During the period from seed emergence to 3/4 leaves, it was a daunting task for young seedlings to withstand high air temperature. From the 4/5 leaf stage to jointing, however, it would not only weaken the photosynthesis of seedlings but also lead to unstable rooting and lodging of plants if a single rainfall was excessive. Moreover, during jointing and booting, high temperature at night could cause stem cells to elongate faster and thinner, and the plants were not resistant to lodging, susceptible to late spring coldness, and thus the spike differentiation time was shortened. During the mid-grouting period, excessive rainfall would weaken the accumulation of photosynthetic products.

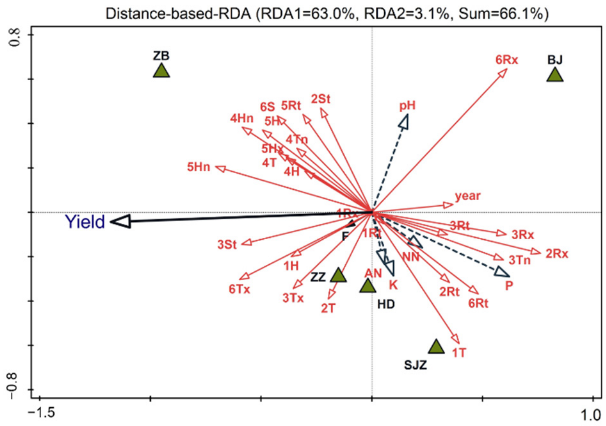

Figure 7. RDA analysis of yield, climate, and soil factors (2020–2021). ZZ, SJZ, BJ, ZB, and HD represent 5 study sites; pH, AN, NN, K, and P represent soil pH, ammonium nitrogen, nitrate-nitrogen, available potassium, and available phosphorus, respectively; The capital letters R, S, T, and H represent the average values of rainfall, sunshine time, air temperature, and air humidity, respectively. When the capital letter is followed by the small letters x, n, and t, they represent the maximum, minimum, and total values of the climate factors, respectively. The numbers in front of the uppercase letters represent the stages after seed germination. For example, 6Tn represents the minimum temperature in the 6th stage after seed germination, and 7S represents the average sunshine time in the 7th stage.

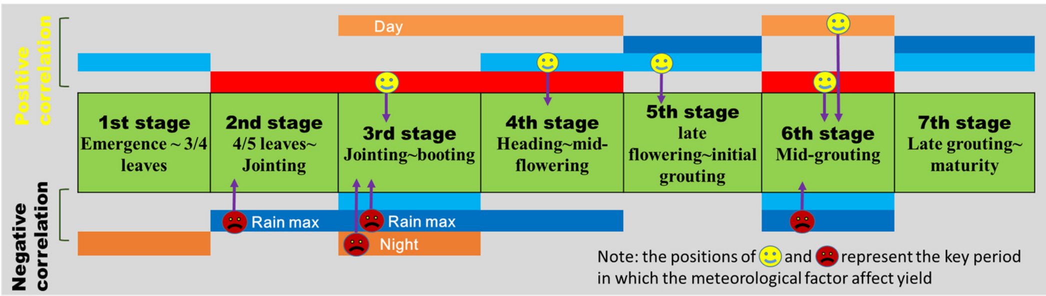

Figure 8. The period and meteorological factors that affect summer millet yield. The green squares represent the growth period of summer millet, with the factors positively related to yield shown above the green squares and the factors negatively related to yield displayed below the green square. Red, orange, light blue, and dark blue bars represent sunshine time, air temperature, air humidity, and rainfall, respectively, and the positions of the face symbol represent the key period in which the meteorological factor affects yield.

4. Discussion

4.1. Location-Variety Interaction and Variety Selection

The variety effect was only next to environment in the contribution to the yield, and significant genetic variations among the varieties and significant V–L interaction were popular [20,21], indicating it was of significance to select a suitable variety in a specific environment. Some extreme factors in growing environments (e.g., high temperatures that surpassed historical records at any time) could affect the growth and development of foxtail millet greatly in summer seasons, so resistance to high temperature was very important. In our other studies, JI25 and YG35 showed stronger resistance to high temperature than the other four varieties. When the night temperature increased by 2 °C in an artificial climate box, the booting days of ZG2, JG39, JM1, and JIN21 were significantly reduced, and the spike weight decreased significantly, while the booting days of JI25 and YG35 were not significantly shortened and the spike weight decreased slightly (unpublished). Because the growth period of summer millet spanned all summer, identifying high-yielding cultivars with stable booting days was one of the best means to tackle unpredictable growing conditions.

Varieties with yield stability were not necessarily high-yielding. If any variety performed well in a specific environment, it could be recommended for that specific environment to maximize its genotypic potential. Varieties with lower Shukla's variance values and higher mean values indicated stable responsiveness to the environment and higher mean performance, whereas those with high Shukla's variance values and low mean values suggested high responsiveness to the environment and below-average performance. These varieties with high Shukla's variance values and low mean values would not be recommended for general cultivation but showed suitable discrimination of environment because of being highly sensitive. JI39, with high Shukla's variance and high mean values of yield, was very productive under favorable conditions, and thus JI39 could be recommended for cultivation in places with fewer sunshine hours and more cloudy days. In areas with overproduction, it should focus on the stability of varieties rather than high yield. Farmers required high-yield varieties that were particularly suitable for the area with suitable environmental conditions. However, under general conditions, breeders and sellers often prefer a variety to be relatively stable in various environments, and its yield is not lower than the average yield. Such a variety should have a higher yield and relative degree of stability.

4.2. Key Environment Factors Affecting Yield

In general, summer millet in rain-fed agroecosystems completes its life cycle by being exposed to multiple and unpredictable abiotic stresses (e.g., high rainfall conditions and high temperatures within the same planting season). It was difficult to know why Zibo could become a suitable environment simply based on Figure 2 since the meteorological factors were conventional, and only the average or sum of meteorological factors were displayed. The effects of average temperature, rainfall, humidity, and light on crop yield have been studied many times [20,26,27]. However, it was difficult to find out which meteorological factors really affected the development of crops if no more detailed climate discrimination and smaller date intervals were provided to interpret the influence of meteorological factors more comprehensively and accurately on crop growth or yield. Therefore, when these were added in this study, yield showed a different correlation with temperature on 31~45 days (3T).

Previous studies have shown that increased temperature reduces the yield of the crop. Heat stress after heading significantly reduced the kernel weight, seed setting rate, and grains per spike of malt barley [28]. Paddy yields of six common rice varieties from Arkansas were reduced by 6.2% after the temperature increased by 1 °C in the average growing season temperature [29]. Studies on foxtail millet have shown that the appropriate average temperature was 19.3~22.7 °C from emergence to jointing. When the temperature increased by 1 °C, the interval days would be shortened by about 3 days [30]. A study in rice cropping systems showed that nighttime warming of less than 1 °C shortened the length of the crop's pre-flowering phase and prolonged the length of the post-flowering phase, resulting in a great reduction in the length of the crop [31]. In the current study, air temperature (especially minimum temperature) from jointing to booting was negatively associated with days to booting and flowering, which proved that the increased night temperature led to the early termination of booting and the beginning of flowering. The negative correlation between temperature and grain spike width increased the reliability concluded in this study. In other words, the shortened interval days caused by temperature increase reduced the time of young panicle differentiation, finally resulting in decline of the grain yield.

Excessive rainfall could positively or negatively affect crop yields and vary by region and season. An experiment in Scotland found a strong positive relationship between growing season rainfall and simulated yield and underscored that rainfall was more essential than the temperature for spring barley production [32]. One of the reasons explaining the increased grain yield with rainfall was that the lower number of females/inflorescence was significantly positively correlated with the average monthly rainfall during the first three months of the corresponding inflorescence opening [33]. Excessive rainfall could significantly reduce the maize yield in cool regions and in poorly drained soils. This yield loss was exacerbated under high preseason soil water storage [34]. This study revealed that the damage of extreme rainfall at the seedling~booting stage is mainly sourced from excess water rather than total rainfall. Foxtail millet was weak and thin at the seedling stage, with difficulty withstanding the impact of high-intensity rainfall. Poor soil drainage leading to deficit oxygen, instability, and difficulty in nutrients absorbing of root also aggravated the plight of crops.

The interception of irradiation by cloud cover associated with rainfall events has become an increasingly important limiting factor in crop production in China [35]. This study found that there was a positive correlation between sunlight time and yield due to different growth periods, and the effects of sunshine hours on yield mainly occurred at the late jointing to booting stage. The main reason for yield loss caused by shading was the reduction in grain number, and the yield declines of various varieties were different [36].

4.3. Fertilization in Foxtail Millet

It was believed that when the amount of fertilization exceeded the threshold, the yield would no longer increase significantly, and many adverse environmental events may occur, such as changes in soil pH, accumulation of soil nitrogen, and pollution of groundwater [12]. In this study, yields in Beijing, Zibo, and Zhengzhou increased first and then decreased curvilinearly with the increase in fertilization amount, so the F_1 pattern was recommended as a reasonable fertilization amount with a high yield; In Shijiazhuang, the yield increased nearly linearly with the increase in fertilization amount, so F_3 pattern was recommended, and in Handan, the yield was hardly affected by the fertilization amount, so F_1 pattern was recommended.

Several factors should be considered to improve fertilization efficiency. Fertilization could interact with varieties and location, so it was better to understand the effect of related factors to optimize the fertilization protocol. Variety adaptability difference was one of the main reasons that affected the fertilization efficiency. Fertilization efficiency in Shijiazhuang and Zhengzhou was much higher than that of variety, and that in Zhengzhou and Handan was the opposite. The large variation of variety performance due to adaptability difference increased the interpretation of variety's effect on yield while weakening the interpretation of the fertilization effect in both Zhengzhou and Handan. In this study, the yield among the fertilizer treatments showed a great difference in JM1 and JI39 compared to other varieties, indicating that it was feasible to improve the yield of the two varieties through fertilization measures.

Soil nutrient difference was another main reason that affected fertilization efficiency. Shijiazhuang showed low soil fertility, which was easily affected by fertilization. The negative correlation between soil available phosphorus and grain yield was stronger than that of other soil nutrients. Because the soil phosphorus content in the test site was high, and the yield of summer millet did not increase significantly after fertilization. Similarly, there was a negative correlation between soil nitrate-nitrogen and yield, which was due to the excessive accumulation of soil nitrate-nitrogen caused by the abuse of nitrogen fertilizer. The above results showed that in the summer valley area, the input of phosphorus fertilizer and nitrogen fertilizer should be reduced to ensure that the fertilizer was not wasted and the grain yield was considerable.

Climate was the third reason that affected fertilization efficiency. Compared with the situation in 2020, the yield in Beijing in 2021 dropped significantly due to increased rainfall, lower temperature, and insufficient light time during the critical periods (jointing~booting stages), which greatly affected the yield and fertilizer utilization. It was found in this study that the yield was strongly affected by rainfall in the early growth stages because the surface runoff and leaching weakened the fertilization effect.

5. Conclusions

The large sum of squares and the significant impact of V–L interaction confirmed the role of the environment in the performance of varieties. The mean sum of squares showed significant variation among year, location, variety, fertilization, and their interaction, except for Y–V interaction and V–F interaction. Grain yield suggested that the location and year contributed up to 38.7% and 33.6% of the variation, respectively, whereas only 7.1% and 3.2% of the variation existed in variety and fertilizer, respectively. JI25 was widely adapted, and its yields was stable and the highest for two years. AMMI and Shukla analysis provided similar results, identifying the best matching varieties and environments. Excessive single rainfall or total rainfall and air temperature (especially minimum temperature) were significantly associated with the production of summer millet.

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