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GIES Case Study on Zhangzi Big Green Pepper Facility Agriculture

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Abstract: The Zhangzi big green pepper, named after its origin in Zhangzi County, Changzhi City, Shanxi Province, is a representative specialty vegetable of the warm temperate semi-humid basin region. Located at the southwestern edge of the Shangdang Basin, Zhangzi County is one of China's key regions for facility-based pepper cultivation. In recent years, local agricultural production has gradually shifted from traditional open-field farming to a facility-oriented, standardized, and large-scale model dominated by greenhouses and plastic tunnels, forming a multi-season cropping system. The main production areas feature weakly alkaline soils with heavy metal contents far below national limits, enriched with organic matter and various available trace elements. Irrigation water quality is high, with pH and pollutant indicators meeting national standards, ensuring the ecological safety of water sources. The region also has a high vegetation coverage, with farmland accounting for nearly half of the county's total area. The big green pepper fruits are well-shaped, bright in color, thick-fleshed, juicy, and nutritionally rich, containing abundant chlorophyll and vitamin C, and are sold widely both domestically and internationally. The dataset of the GIES (Geographical Indications Environment and Sustainability) case on the Zhangzi big green pepper includes 4 categories: administrative divisions, physical

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geography, varietal and quality characteristics, and production management, comprising 66 files with a total data volume of 48.3 MB.

Keywords: Zhangzi County; big green pepper; facility agriculture; GIES; Case 26

DOI: https://doi.org/10.3974/geodp.2025.03.11

Dataset Availability Statement:

The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at: https://doi.org/10.3974/geodb.2025.09.01.V1.

1 Introduction

Zhangzi County derives its name from Dan Zhu, the eldest son (Zhangzi) of the legendary Emperor Yao, who was enfeoffed in this region in ancient times, and the name has been preserved for thousands of years. Situated on the southwestern side of the Shangdang Basin in southeastern Shanxi Province, Zhangzi lies within the warm temperate semi-humid climatic zone. Influenced by the alternating circulation of cold and warm air masses, the county experiences a mild climate with 4 distinct seasons and a general synchrony of rainfall and temperature. With favorable natural conditions and a long history of vegetable cultivation, the region has nurtured the Zhangzi big green pepper as a high-quality agricultural product with distinctive geographical characteristics. As the largest pepper production base in China[1], Zhangzi County has in recent years achieved a historic transition from open-field to facility-based cultivation, and from single-season to multi- and off-season production, making the big green pepper industry an important pillar of rural revitalization[2].

2 Metadata of the Dataset

The details of the GIES case dataset on Zhangzi big green pepper facility agriculture in warm temperate and semi-humid basin[3], including its name, authors, geographical region, time period, data format, and dataset composition, are presented in Table 1.

3 Dataset Development

3.1 Case Area

The case area covers Zhangzi County, Changzhi City, Shanxi Province (Figure 1), located between 35°53′N–36°15′N and 112°27′E–113°00′E. The county has a total area of 1,029 km^2 and population of 298,700[1]. It administers 9 towns, including Danzhu, Baodian, Shizhe, Nanchen, Dabutou, Cilin, Setou, Nanzhang, and Songcun, as well as 2 townships, Nianzhang and Changzhang. Among these, Shizhe, Nanchen, Dabutou, and Songcun are the main production areas for both open-field and facility-based vegetables, with big green pepper as the dominant crop. The county enjoys convenient transportation: the county is located about 20 km from the municipal center, and the Taijiao Railway, Wari Railway, provincial highway 227, highway 228, and highway 326, together with the Qinglan Expressway, all pass through the area, providing favorable conditions for the transportation of big green pepper.

3.2 Ecological Environment Data

3.2.1 Topography

Zhangzi County is located in the Loess Plateau region at the southwestern edge of the

[1] Changzhi City Seventh National Population Census Bulletin. https://www.changzhi.gov.cn.

Table 1 Metadata summary of the GIES case dataset on Zhangzi big green pepper facility agriculture in warm temperate and semi-humid basin

Items	Description
Dataset full name	GIES case dataset on Zhangzi big green pepper facility agriculture in warm temperate and semi-humid basin
Dataset short name	ZhangziPepperCase26
Authors	Liu, W. B., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, liuwb@igsnrr.ac.cn Zhang, H. J., Zhangzi County People's Government, liufuhu@yeah.net Liu, F. H., Zhangzi County Bureau of Agriculture and Rural Affairs, liufuhu@yeah.net Zhang, H. J., Zhangzi County Bureau of Agriculture and Rural Affairs, zzxnwcyb@163.com Zhang, H. L., Zhangzi County Development and Reform and Science and Technology Bureau, zzxfgj@163.com Feng, G. L., Zhangzi County Bureau of Agriculture and Rural Affairs, 344782703@qq.com Shi, Y. J., Zhangzi County Bureau of Agriculture and Rural Affairs, zzxnwcyb@163.com Duan, X. L., Zhangzi County Development and Reform and Science and Technology Bureau, zzxfgj@163.com Lian, L. J., Zhangzi County Development and Reform and Science and Technology Bureau, zzxfgj@163.com Shen, L. X., Taiyuan University of Technology, shenlixia@tyut.edu.cn Li, Q., Zhangzi County Danxi Longxin Agricultural Technology Co., Ltd., dlclq1973@163.com Miao, H. B., Zhangzi County Bureau of Natural Resources, zzxgtj@163.com Yang, M., Zhangzi County Water Conservancy Bureau, 248117868@qq.com Zhang, P. P., Zhangzi County Bureau of Agriculture and Rural Affairs, zzxnwcyb@163.com Li, L. X., Zhangzi County Bureau of Agriculture and Rural Affairs, zzxnwcyb@163.com Ren, Q., Zhangzi County Bureau of Agriculture and Rural Affairs, tianqu118@163.com Chai, P. S., People's Government of Danzhu Town, Zhangzi County, 13467000177@163.com Han, Z., People's Government of Songcun Town, Zhangzi County, scxzf123@163.com Li, L. L., People's Government of Dabutou Town, Zhangzi County, 1636941591@qq.com Li, P., People's Government of Nanchen Town, Zhangzi County, 1019114970@qq.com Chen, Z. Z., People's Government of Nanzhang Town, Zhangzi County, 109512008@qq.com Li, X. Y., People's Government of Changzhang Township, Zhangzi County, 36519969@qq.com Wang, X. Z., People's Government of Baodian Town, Zhangzi County, 449133557@qq.com Tian, N., People's Government of Nianzhuang Township, Zhangzi County, yuhan7122@qq.com Tan, M. H., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, tanmh@igsnrr.ac.cn Wang, T. T., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, wangtt@igsnrr.ac.cn Zhang, X. X., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 13998551325@163.com Zhang, R. H., Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 19861601971@136.com
Geographical area	Zhangzi County, Shanxi Province, 35°53′N–36°15′N, 112°27′E–113°00′E
Year	2023, 2024
Data format	.xlsx, .shp, .tif, .jpg, .docx, .txt
Data size	48.3 MB
Data files	(1) geographic boundaries data; (2) physical geography data; (3) quality characteristics of pepper; (4) management and historical culture information
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	(1) *Data* are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use *Data* subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute *Data* subject to written permission from the GCdataPR Editorial Office and the issuance of a *Data* redistribution license; and (4) If *Data* are used to compile new datasets, the "ten percent principal" should be followed such that *Data* records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[4].
Communication and searchable system	DOI, CSTR, Crossref, DCI, CSCD, CNKI, SciEngine, WDS, GEOSS, PubScholar, CKRSC

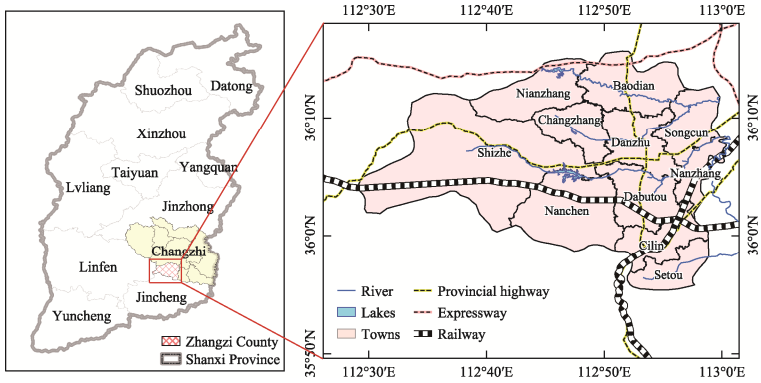

Figure 1 Map of geo-location of the case area

Shangdang Basin, bordering the Taihang Mountains in the east, the Lvliang Mountains in the west, the Fen River in the south, and the Datong Basin in the north. The overall topography slopes from west to east, forming a three-tier geomorphic structure (Figure 2). The western part is dominated by the Fajiu Mountain range with noticeable elevation differences, the central and southern parts are characterized by gently undulating mountains interlaced with rivers and hills, while the northeastern part is relatively flat. Based on topographic data derived from ASTER GDEM[2], the elevation of the county ranges from 865 to 1,645 m, with an average elevation of 929.8 m, and most areas lying between 900 and 1,000 m. The landform is typical of low to mid-mountain and hilly terrain. The slope is generally gentle, with most areas below 3° (Figure 3), providing suitable topographic conditions for the construction and spatial planning of facility agriculture.

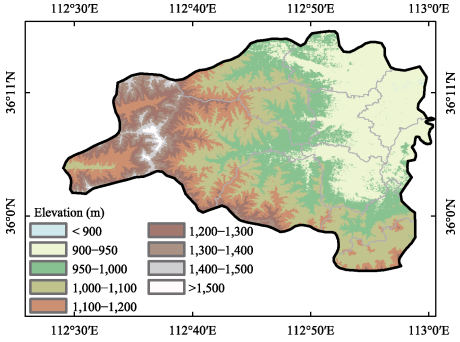

Figure 2 Map of elevation of Zhangzi County

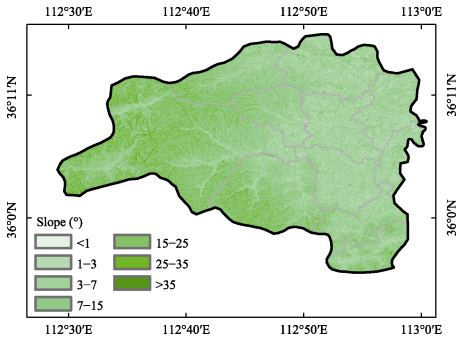

Figure 3 Map of land slope of Zhangzi County

3.2.2 Land Use and Vegetation Coverage

To reveal the characteristics of land use and vegetation coverage in Zhangzi County, the Google Earth Engine (GEE) remote sensing platform was used, and cloud-free Sentinel-2 satellite imagery[3] for 2023 was analyzed to obtain the Normalized Difference Vegetation Index (NDVI) and land-use spatial distribution data (Figure 4). The results show that land use in Zhangzi County mainly includes farmland, forest, grassland, water bodies, artificial surfaces, etc. (Table 2, Figure 5). Farmland occupies the largest share, accounting for nearly half of the county's total area and serving as the main zone for agricultural production and vegetable cultivation. This is followed by forest and grassland, which are mainly distributed in the western and southwestern mountainous areas and together account for 39.57% of the

[2] NASA, NIMA. https://earthexplorer.usgs.gov/.

[3] ESA. Sentinel-2. https://dataspace.copernicus.eu/.

total county area. Except for artificial surfaces, most regions exhibit high vegetation coverage (Figure 4), with NDVI values generally above 0.5, indicating good vegetation growth conditions.

Major vegetables such as big green pepper are cultivated through both open-field and facility-based methods on the farmland. The production bases are mainly located in areas with favorable ecological conditions and clean environments, intentionally avoiding industrial and mining zones as well as main railways and highways to minimize the potential impact of pollution sources on agricultural production.

Table 2 Proportion of land use types in Zhangzi County

Type	Farmland	Forest	Grassland	Water	Artificial surface	Barren land
Area (%)	47.72	9.69	29.88	0.47	12.24	0.001

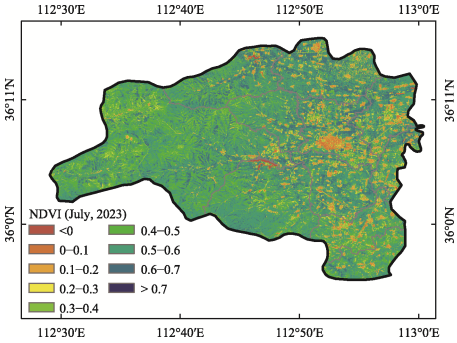

Figure 4 Map of the NDVI of Zhangzi County

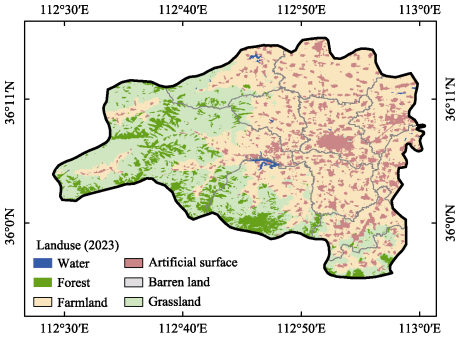

Figure 5 Map of the land use of Zhangzi County

3.2.3 Climate

Zhangzi County has a warm temperate, semi-humid continental monsoon climate, characterized by 4 distinct seasons and mild temperatures, with neither severe cold in winter nor extreme heat in summer. Rainfall and high temperatures occur in the same period (Figures 6 and 7). Based on daily surface climate data from the China Meteorological Data Service Center (V3.0)[4], data from the nearest meteorological station in Changzhi (Station No. 53882; 36.05°N, 113.07°E; elevation 988.59 m) was analyzed. From 1990 to 2020, annual precipitation ranged from 330.57 to 915.84 mm, with a multi-year average of 665.15 mm. The mean annual temperature was 10.22 ℃, with an extreme maximum of 31.08 ℃ and an extreme minimum of −13.7 ℃. The annual effective accumulated temperature above 10 ℃ was between 3,076.43–3,213.24 ℃, with a total accumulated temperature of 3,148.21 ℃. The mean annual temperature of the 0–20 cm soil layer was 11.05 ℃, which is 1.85 ℃ higher than the mean air temperature. The average annual sunshine duration was 2,556.5 h, with the maximum

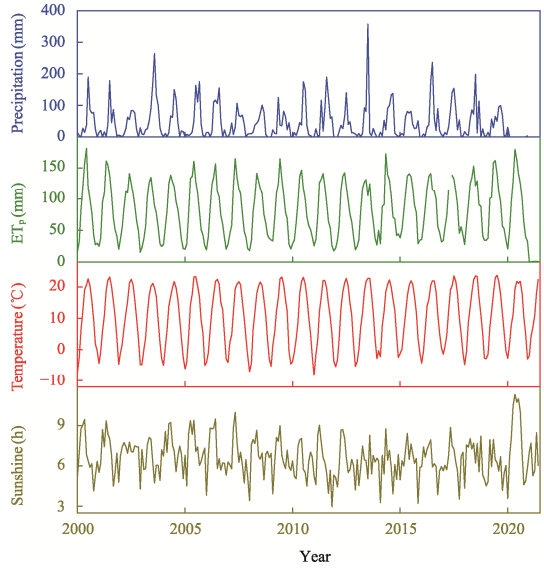

Figure 6 Inter-annual characterization of climate in Zhangzi County

[4] National meteorological center of CMA. http://www.nmc.cn/f/p-2027.

occurring from April to June, and the average frost-free period ranged from 143 to 196 days.

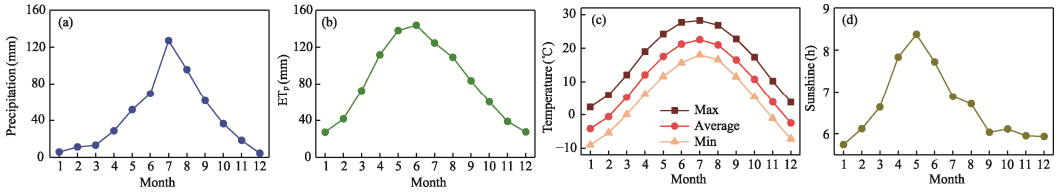

Figure 7 Intra-annual characteristics of climate in Zhangzi County

3.2.4 Water Conditions Data

Zhangzi County possesses abundant water resources and enjoys favorable irrigation conditions. The main rivers within the county include the Zhuozhang, Lan, Yong, Taoqing, and Dan Rivers, all of which flow eastward into the Zhangze Reservoir in Changzhi City, while the Wangyu and Hengshui Rivers flow westward into the Qin River. According to the Second water resources assessment report of Changzhi City[5], the total water resources of Zhangzi County amount to 122 million m^3. Among these, surface water resources total 86.93 million m^3, with 65.19 million m^3 available for use, and groundwater resources total 66.19 million m^3, of which 36.12 million m^3 are exploitable. The county has 6 medium- and small-sized reservoirs with a combined storage capacity of 51.45 million m^3, including 19.64 million m^3 available for irrigation and 26.45 million m^3 reserved for flood control.

In accordance with the Standard for irrigation water quality (GB 5084—2021)[5], 23 sampling points (P1–P23) were established in the main big green pepper production areas, where P3 and P21 represent surface water and the remaining points groundwater (Figure 8). 15 parameters of irrigation water quality were measured (Table 3). The results show that pH ranged from 7.5 to 8.4, meeting the standard range of 5.5 to 8.5. Suspended solids (3–32 mg/L), biochemical oxygen demand (1.9–11.4 mg/L), and chemical oxygen demand (5–17 mg/L) were all well below the permissible limits. Total dissolved solids in the 21 groundwater samples were below 1,000 mg/L, while the 2 surface water samples slightly exceeded this value but still satisfied the dryland irrigation standard of not more than 2,000 mg/L. Heavy metals (Pb, Cd, Cr^{6+}, Hg, As) were either undetected or significantly lower than the standard thresholds. Anionic synthetic detergents and sulfides were not detected. Indicators of thermotolerant coliform bacteria and helminth eggs also met the limits (≤40,000 MPN/L and ≤20/10L, respectively), indicating that irrigation water in Zhangzi County is free from significant biological contamination and meets the environmental safety requirements for agricultural production.

3.2.5 Soil Conditions Data

According to the Soil environmental quality risk control standard for soil contamination of agricultural land (Trial) (GB 15618—2018)[6], 9 soil indicators were measured at 21 sampling sites across Zhangzi County (Figure 8, Table 4). The results show that soil pH range from 7.60 to 8.36, indicating a weakly alkaline environment suitable for the cultivation of facility vegetables such as big green pepper. The concentrations of heavy metals in the surface soil layer (0–20 cm) were all well below the standard thresholds, suggesting minimal pollution risk and compliance with national environmental safety requirements for agricultural land. In addition, the levels of trace elements met the classification standards for available soil micronutrients in China, ensuring adequate nutrient supply for essential physiological processes in crops, including enzymatic reactions, photosynthesis, and material transport.

[5] Changzhi Water Authority. Second water resources assessment report of Changzhi City.

Table 3 Statistical testing results of water samples in the case area

	pH	SS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	Anionic Synthetic Detergents (mg/L)	Cl^- (mg/L)	S^{2-} (mg/L)	Total Salinity (mg/L)	Pb (mg/L)	Cd (mg/L)	Cr^{6+} (mg/L)	Hg (mg/L)	As (mg/L)	Thermotolerant Coliform Bacteria (MPN/L)	Helminth Eggs (Counts/10L)
P1	7.8	6	2.8	7	ND	11.3	ND	368	ND	ND	ND	ND	ND	ND	ND
P2	7.5	3	2.2	5	ND	13.4	ND	522	ND	ND	ND	0.0001	ND	ND	ND
P3	8.4	18	2.3	6	ND	317	ND	1,209	0.010,63	0.000,14	ND	ND	ND	ND	ND
P4	8.1	16	1.9	5	ND	20.4	ND	335	ND	ND	ND	ND	ND	ND	ND
P5	7.6	5	2.0	5	ND	39.0	ND	806	ND	ND	ND	ND	ND	ND	ND
P6	7.8	8	2.1	5	ND	17.7	ND	445	ND	ND	ND	ND	ND	ND	ND
P7	8.4	8	2.8	7	ND	9.22	ND	302	ND	ND	ND	ND	ND	ND	ND
P8	7.9	7	2.0	5	ND	78.7	ND	903	ND	ND	ND	ND	ND	ND	ND
P9	7.9	11	2.1	5	ND	14.9	ND	354	ND	ND	ND	ND	ND	ND	ND
P10	8.0	7	2.2	5	ND	34.7	ND	681	ND	ND	ND	ND	ND	ND	ND
P11	8.0	1	2.1	5	ND	40.1	ND	620	ND	ND	ND	ND	ND	ND	ND
P12	7.8	6	2.1	5	ND	40.1	ND	877	ND	ND	ND	ND	ND	ND	ND
P13	8.0	8	2.0	5	ND	21.3	ND	680	ND	ND	ND	ND	ND	ND	ND
P14	8.3	10	2.1	5	ND	17.7	ND	466	ND	ND	ND	ND	ND	ND	ND
P15	8.2	2	6.7	11	ND	15.7	ND	416	ND	ND	ND	ND	ND	ND	ND
P16	7.7	0	8.2	14	ND	15.6	ND	579	ND	ND	ND	ND	ND	ND	ND
P17	7.8	32	11.4	17	ND	28.4	ND	560	ND	ND	ND	ND	ND	ND	ND
P18	7.8	7	2.1	5	ND	9.93	ND	381	ND	ND	ND	ND	ND	ND	ND
P19	8.0	4	3.3	7	ND	11.6	ND	298	ND	ND	ND	ND	ND	ND	ND
P20	8.3	6	2.3	5	ND	76.6	ND	789	ND	ND	ND	ND	ND	490	ND
P21	7.9	7	3.2	7	ND	20.6	ND	1,317	0.00011	ND	ND	ND	ND	ND	ND
P22	7.9	0	2.8	6	ND	11.5	ND	365	ND	ND	ND	ND	ND	460	ND
P23	8.0	0	2.3	5	ND	4.96	ND	308	ND	ND	ND	ND	ND	ND	ND
Limit	5.5–8.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Note: "ND" stands for "Not Detected".

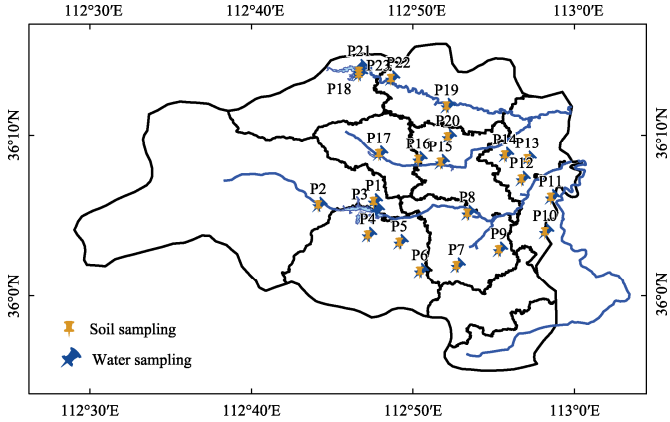

Figure 8 Distribution map of water and soil sampling sites

Table 4 Statistical testing results of soil environmental indicators

	pH	Cd (mg/kg)	Hg (mg/kg)	As (mg/kg)	Pb (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Zn (mg/kg)
P1	7.90	0.13	0.041,2	11.6	24.0	65	28	30	108
P2	7.60	0.10	0.019,5	9.84	19.5	56	28	23	122
P4	8.26	0.09	0.060,5	7.51	20.4	55	26	23	92
P5	8.19	0.09	0.034,5	8.10	20.4	50	15	23	99
P6	8.17	0.11	0.027,3	15.8	20.6	51	28	24	101
P7	8.34	0.09	0.031,9	11.8	19.1	59	28	29	98
P8	8.10	0.11	0.022,5	13.2	23.1	50	26	24	96
P9	8.23	0.13	0.038,7	12.0	21.8	54	28	28	85
P10	8.03	0.20	0.078,3	11.9	24.2	78	79	26	141
P11	8.16	0.13	0.046,5	11.8	21.2	63	35	26	88
P12	8.29	0.12	0.072,6	13.7	21.2	51	32	24	111
P13	8.36	0.08	0.034,6	15.6	20.5	50	33	29	105
P14	8.20	0.17	0.047,5	16.9	21.1	48	35	30	98
P15	8.33	0.08	0.032,1	12.9	18.8	47	31	28	84
P16	8.25	0.10	0.062,4	16.4	20.0	53	32	29	99
P17	8.11	0.12	0.043,2	13.4	21.3	51	28	29	86
P18	8.21	0.13	0.034,0	14.2	20.2	54	27	28	80
P19	8.23	0.07	0.025,4	6.82	23.0	52	27	27	79
P20	8.08	0.08	0.028,6	14.1	16.5	45	27	27	73
P22	8.19	0.10	0.039,1	15.6	18.8	51	28	26	78
P23	8.24	0.13	0.052,3	9.46	21.6	49	27	23	96
Limit	–	–	–	–	–	–	–	–	–

Note: P3 and P21 are designated as rivers, therefore, soil sampling was omitted.

3.3 Product Quality Data

3.3.1 Varieties and Characteristics

The Zhangzi big green pepper exhibits considerable varietal diversity. In the early stage of cultivation, the main varieties included Qiemen and Zhongjiao No.4, while later introductions featured Fuli No.1, Fuli No.2, 5029, 5018, and Victoria[7]. The fruits are generally large and uniform in shape, with smooth surfaces, bright green color, firm texture, full cavities, and thick, juicy flesh. They are crisp, tender, and aromatic, suitable for a wide range of cooking methods[8]. Owing to their large size, thick flesh, and strong storage and transport qualities, Zhangzi big green peppers are highly competitive in both domestic and international markets.

3.3.2 Quality Testing Data

Test results show that the Zhangzi big green pepper contains higher levels of chlorophyll and vitamin C than the reference values, indicating strong photosynthetic capacity, high nutritional value, and notable antioxidant properties. The protein content was slightly higher than the reference, while the iron content was essentially consistent with it (Table 5).

In terms of food safety, concentrations of heavy metals (Cd, Hg, total As, Cr), pesticide residues (23 items including carbofuran and chlorpyrifos, etc.), and microbiological indicators (5 items) were all undetected or far below the limits specified in China's national food safety standards (GB 2762—2022 and GB 2763—2021)[9,10] (Table 6). These results demonstrate that the Zhangzi big green pepper is not only of high quality but also fully compliant with national food safety requirements.

Table 5 Quality testing results of Zhangzi big green pepper

Items	Result	Reference	Conclusion
Chlorophyll (mg/g)	0.153	0.091	Higher than the reference
Vc (mg/100g)	114.01	76.06	Higher than the reference
Fe (mg/100g)	0.40	0.27	Higher than the reference
Protein (g/100g)	1.05	1.0	Higher than the reference

Table 6 Statistical testing results of safety and hygiene indicators of Zhangzi big green pepper

	Cd	Hg	As	Cr	Other 25 items
Sample 1	0.075 mg/kg	ND	ND	0.73 mg/kg	ND or below the risk threshold
Sample 2	0.02 mg/kg	ND	ND	0.31 mg/kg	ND or below the risk threshold

Note: Microbiological indicators (5 items): Total Bacterial Count, Coliforms, Molds and Yeasts, Salmonella, Staphylococcus aureus. Pesticide residues (23 items): Cypermethrin, Triadimefon, Carbendazim, Procymidone, Chlorpyrifos, Lambda-cyhalothrin, Imidacloprid, Carbofuran, Fipronil, Omethoate, Methamidophos, Triazophos, Aldicarb, Abamectin, Beta-cyfluthrin, Profenofos, Emamectin benzoate, Myclobutanil, Pyrimethanil, Dimethomorph, and Methyl isofenphos.

4 Management of Zhangzi Big Green Pepper Industry

According to the 2024 statistical data, the gross domestic product (GDP) of Zhangzi County reached 26.819 billion CNY, including 1.78 billion CNY from the primary industry. The total annual fiscal revenue was 6.795 billion CNY, of which 2.652 billion CNY came from the general public budget and 1.848 billion CNY from tax revenue. The county had a permanent population of 284,000, including 169,700 rural residents, with a per capita disposable income of 23,400 CNY for rural households. With the continuous development of the rural economy, the vegetable industry has gradually become a key driver of farmers' income growth and rural revitalization.

Vegetable cultivation in Zhangzi County had already achieved a considerable scale by the 1990s and reached its peak in 1995, when the total planting area exceeded 6,666.67 ha, including more than 4,000 ha devoted to peppers. By the end of 2017, the cultivation of Zhangzi big green pepper had expanded to more than 300 villages, covering an area of over 4666.67 ha with an annual output exceeding 60 million kg[14]. In 2022, the Danxi Longxin Modern Agricultural Demonstration Park adopted an integrated operational framework that linked enterprises, cooperatives, and farming households. Through this coordinated mechanism, more than 20 cooperatives and numerous farmers jointly managed over 180 greenhouses, producing more than 2,000 tons of peppers annually[15]. As the cultivation area continued to expand, the big green pepper industry became a central pillar of Zhangzi County's characteristic agriculture, significantly increasing farmers' cash income, strengthening village collective economies, and promoting local employment.

4.1 Pepper Cultivation Techniques

(1) Planting environment. Facility bases should be located in areas with flat terrain, stable water supply, and good irrigation and drainage conditions. The soil should be sandy loam with a deep plow layer, loose texture, good aeration, and rich organic matter. In greenhouses, daytime temperature should be maintained at 25–28 ℃, nighttime temperature at 12–15 ℃, and relative humidity at 40%–45%. The extreme temperature should be controlled between 10–35 ℃. When the outside temperature remains above 15 ℃, the facilities should be kept well ventilated to ensure proper air circulation and humidity balance.

(2) Pre-sowing preparation. Plastic tunnels, solar greenhouses, or multi-span greenhouses can be used for seedling raising. Weeds and debris inside and outside the facilities should be

removed, drainage channels dredged to prevent water logging, and seedling tools, trays, and substrate preparation areas thoroughly disinfected. The substrate should be leveled and lightly compacted, with holes drilled to a depth of 0.8–1.0 cm.

(3) Sowing. Sowing time should be determined according to transplanting schedules, generally 60–70 days in advance for winter-spring seedlings and 40–45 days in advance for summer-autumn seedlings. Seeds should be disinfected, rinsed, and sown into trays, then covered with perlite, watered thoroughly, and sealed with a white plastic film for moisture retention. The film should be removed when more than 60% of cotyledons have expanded. During seedling growth, temperature should be kept at 30–32 ℃ with relative humidity around 90%.

(4) Seedling management. Water and nutrients should be supplied according to seedling growth stages, with longer intervals during cool or rainy weather. For greenhouse transplanting, seedlings should be transported under controlled temperature. For plastic tunnel transplanting, ventilation and cooling should start 3 to 5 days in advance to harden seedlings. For open-field transplanting, seedlings should be gradually acclimated 7 to 10 days prior to transplanting.

(5) Cultivation techniques. Prior to transplanting, clean the field and form ridges covered with plastic mulch. Adopt the method of planting double rows with single plants on top of the ridges. After the seedling recovery phase, initiate a hardening-off period by controlling water for approximately 20 days. This practice promotes root system development and suppresses excessive vegetative growth. Following transplanting, enhance shading and implement scientific fertilization. During the mid to late growth stages, promptly remove non-fruiting branches to ensure balanced fruit development.

(6) Water and fertilizer management. A thorough irrigation should be applied before transplanting, followed by controlled watering during seedling establishment. When 70% of plants in the facility reach harvest readiness, the first irrigation should be applied, combined with balanced fertilization. Generally, irrigation is performed every 10–15 days, with water depth reaching half the depth of furrows, avoiding flood irrigation to maintain soil moisture. A “two irrigations, one fertilization” approach is recommended, applying 150–225 kg of compound fertilizer and 75–105 kg of diammonium phosphate per ha. Fertilizer application should stop 30 days before harvest to ensure fruit quality.

(7) Pest and disease control. For pest and disease management, the principle of “prevention first and integrated control” should be followed, giving priority to agricultural, physical, and biological measures, while chemical control should only serve as a supplement. Resistant varieties should be selected, and insect-proof nets and shading nets should be used during summer seedling raising to reduce pest and disease incidence.

(8) Packaging, labeling, and transportation. Peppers in the same package must be of the same variety, batch, and grade, and should be free from impurities or contaminants. Outer packaging should indicate the variety, origin, and grade. For long-distance transportation, cold-chain logistics at 8–13 ℃ should be adopted, while insulated transport may be used for short-distance delivery to ensure freshness and marketability.

4.2 Standardized Management

Standardized cultivation is an important means of improving the yield and quality of Zhangzi big green pepper and maintaining orderly market production. On the basis of scientific and regulated farming practices, dedicated personnel should be assigned to carry out full-cycle management of cultivation. Combined with technical training and on-site guidance provided by agricultural experts, a standardized production technology system adapted to local conditions has been gradually established for Zhangzi big green pepper (Table 7).

Table 7 Technical specifications for standardized production of pepper in Zhangzi County

	Name of standard and technical specification	Types
1	Technical regulations for pepper seedling production (DB1404/T 25—2022)	Local standard
2	Field pepper production technical regulations (DB1404/T 26—2022)	Local standard
3	Greenhouse pepper production technical regulations (DB1404/T 27—2022)	Local standard
4	Zhangzi green pepper standards system, Part 1: production environment (T/ZZQJ005—2023)	Local standard
5	Zhangzi green pepper standards system, Part 2: seedling production regulations (T/ZZQJ006—2023)	Local standard
6	Zhangzi green pepper standards system, Part 3: cultivation technical regulations (T/ZZQJ007—2023)	Local standard
7	Zhangzi green pepper standards system, Part 4: quality grading and classification (T/ZZQJ008—2023)	Local standard
8	Zhangzi green pepper standards system, Part 5: raw material acceptance and finished product inspection (T/ZZQJ009—2023)	Local standard
9	Zhangzi green pepper standards system, Part 6: storage and transportation technical Regulations (T/ZZQJ010—2023)	Local standard
10	Zhangzi green pepper standards system, Part 7: dehydrated green pepper (T/ZZQJ011—2023)	Local standard
11	Zhangzi green pepper standards system, Part 1: production environment (T/ZZQJ005—2023)	Local standard
12	Zhangzi green pepper standards system, Part 2: seedling production procedures (T/ZZQJ006—2023)	Local standard

4.3 Industry Chain Expansion

Relying on its characteristic vegetable industry, Zhangzi County has promoted facility agriculture and large-scale cultivation of big green pepper, gradually forming a complete industrial chain that integrates intensive seedling cultivation, pepper production, storage, processing, and marketing.

(1) Intensive seedling cultivation. Seedling production provides the foundation for the expansion of the big green pepper industry. The county has 6 vegetable seedling centers with a total area of 31,100 m^2, offering a capacity of over 5 million seedlings. The annual seedling output reaches 88.4 million plants, sufficient to support the cultivation of approximately 1,933 ha of peppers.

(2) Cold-chain logistics. The county has continuously improved its cold-chain logistics system, significantly enhancing its capacity for long-distance distribution. At present, there are 10 pre-cooling warehouses with capacities exceeding 1,500 m^3, including 6 ammonia-based and 4 water-cooled systems, with a total storage capacity of 63,500 m^3 and an annual turnover exceeding 100,000 tons. In addition, 21 constant-temperature storage facilities provide a total capacity of 56,000 m^3, with a storage capacity of 5,200 tons and an annual turnover of more than 400,000 tons.

(3) Processing and marketing. Processing has extended and strengthened the big green pepper industrial chain. At present, 3 large-scale vegetable processing enterprises operate in the county. Haorun Food Co., Ltd. primarily produces dehydrated peppers, red peppers, carrots, and dandelions, supporting more than 200 ha of vegetable bases. Huafeng Technology and Xinan Agribusiness Cooperative focus on chopped-pepper processing, with an annual output of about 10,000 tons, supporting more than 2,000 ha of red-pepper cultivation in Zhangzi, Tunliu, and nearby areas. Their products are supplied to well-known enterprises such as “Lao Gan Ma” in Guizhou and “Xiangjuming” in Shanghai.

4.4 Brand Building

The Zhangzi big green pepper has a strong brand foundation. Since being recognized as the “Hometown of Chinese Green Pepper” in 1998, Zhangzi County has received a series of

national honors, including "Geographical Indication Agricultural Product" (2008), "Top Ten Counties of Pollution-Free Fruits and Vegetables in China" (2009), "National Demonstration County for Agricultural Standardization (Vegetables)" (2011), and "National Agricultural Product Quality and Safety County" (2019). It was also included in the National Catalogue of Special and Excellent Agricultural Products in 2019 and was designated as a National Demonstration Base for the standardization of the whole agricultural industry chain in 2023.

Established in 2020, Zhangzi Danxi Longxin Agricultural Technology Co., Ltd. has promoted the development of the "Zhangzi Green Pepper" brand toward higher levels of standardization and diversification through the construction of a modern agricultural industrial park covering about 33 ha with a total investment of 50 million CNY. The park is equipped with a 2,800 m^2 multi-span seedling greenhouse and 23.33 ha of high-standard greenhouses, producing approximately 1,100 tons of peppers annually. The company has introduced 21 high-quality new varieties from China Agricultural University for demonstration planting and has expanded its cultivation area to more than 133.33 ha through cooperative and contracted farming. The annual output value has reached 40 million CNY, benefiting more than 2,000 households and ensuring stable income growth for farmers.

4.5 Near Real-time Monitoring System

An automatic *in-situ* observation station for Zhangzi big green pepper has been established in the Danxi Longxin Modern Agricultural Demonstration Park of Zhangzi County. Based on low-power Internet of Things (IoT) technology, the station enables real-time image transmission and simultaneously monitors and automatically records air temperature and humidity, atmospheric pressure, soil temperature and moisture, and vegetation indices such as NDVI. This system ensures the integrity and spatiotemporal consistency of the data. It is also equipped with data processing and analysis functions that support the extraction of phenological characteristic curves, extended index calculations, and dual local-cloud storage. These capabilities provide reliable technical support for precise environment monitoring and scientific research related to big green pepper cultivation.

5 Discussion and Conclusion

The Zhangzi big green pepper holds unique and irreplaceable geographical advantages as a premium agricultural product in Shanxi Province and across China. The fruits are bright green, large, thick-fleshed, smooth-skinned, crisp, and juicy, with excellent storability and transportability, earning the reputation of being the "No.1 sweet pepper in the world". Future research and development should focus on several aspects: (1) strengthening ecological and environmental protection, improving soil conditions, reducing the use of chemical fertilizers and pesticides, and promoting sustainable industrial development; (2) improving standardized production and management systems to stabilize and enhance product quality; (3) extending and optimizing the entire industrial chain that integrates intensive seedling cultivation, planting, storage, processing, and marketing to increase added value and brand influence; and (4) expanding marketing channels through e-commerce platforms to ensure efficient product distribution, reduce production costs, and increase farmers' income. Through these measures, the Zhangzi big green pepper industry, along with the regional vegetable sector, can achieve high-quality and sustainable development.

Author Contributions

Liu, W. B., Liu, F. H., Tan, M. H. and Wang, T. T. completed the overall design of the case study; Zhang, H. J., Zhang, H. J., Zhang, H. L., Feng, G. L., Shi, Y. J., Duan, X. L., Lian, L. J., Miao, H. B., Yang, M., Zhang, P. P., Li, L. X., Ren, Q, Li, Q., Chai, P. S., Han, Z., Li, L.

L., Li, P., Chen, Z. Z., Li, X. Y., Wang, X. Z., Tian, N., Tan, M. H., Wang, T. T., Zhang, X. X. and Zhang, R. H. participated in field research and sampling, providing or collecting relevant data for the case; Shen, L. X., Zhang, H. J. and Zhang, H. L. provided guidance for the case study; Liu, W. B. Wang, T. T., Tan, M. H., Zhang, X. X. and Zhang, R. H. completed the compilation of the dataset, mapping, and writing of the paper.

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Conflicts of Interest

The authors declare no conflicts of interest.

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