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Assessment of suitable cultivation region for Pepino (*Solanum muricatum*) under different climatic conditions using the MaxEnt model and adaptability in the Qinghai–Tibet plateau

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A R T I C L E I N F O

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A B S T R A C T

Pepino (*Solanum muricatum*), a member of the Solanaceae family originating from South America, is cultivated globally. However, the cultivation range and suitable habitat of Pepino have not been extensively studied, which hampers the further development of its cultivation industry. Therefore, we aimed at enrich and expand the planting scope of Pepino. Currently, the main cultivation areas of Pepino in China are the Yunnan–Guizhou Plateau and the Loess Plateau, where the altitude is above 1000 m. In this study, ArcGIS combined with the MaxEnt model was used for prediction, whose area under curve value was 0.949. The main climatic factors affecting the distribution of Pepino are temperature seasonality, annual means temperature, mean temperature of the coldest quarter, elevation, isothermality, and the climate factors, and their cumulative contribution rate of 87.6%. Pepino's main potential distribution areas are located in Yunnan–Guizhou Plateau, Yunnan Province, Hexi Corridor of Loess Plateau, and low altitude areas of Qinghai–Tibet Plateau. The main distribution ranges from 1000 to 2000 m above sea level, and the total suitable area accounts for 20.09% of China's total land area. The prediction results reveal an expanded potential area for Pepino, with no significant migration in the central region of the main potential distribution area by 2050 and 2070. No studies have been conducted on the open-area cultivation of Pepino in northern China. Our findings revealed that the yield and quality in the four experimental sites and final actual cultivation conditions were consistent with the predicted results of MaxEnt. The yiel d per plant in Xunhua and Minhe was significantly different from that in Xining, which was low, and that in Minhe was the highest. Overall, the fruit quality in the Xining region was the lowest among the three regions, which was related to the climatic differences in each region. These results align with the predicted outcomes, indicating that Xining is the least suitable area. Further, these data verify the accuracy of the prediction results. The climate data of the four regions were analyzed simultaneously to elucidate the influence of different climate conditions on the growth of Pepino. Our findings are of considerable

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significance for introducing characteristic horticultural crops in the Qinghai–Tibet Plateau and using the MaxEnt model to predict the cultivation range of crops.

1. Introduction

Pepino (*Solanum muricatum*), belonging to Solanaceae, is closely related to tomato and potato [1] and was only present in South America before the 19th century. The Pepino genetic center of origin presumably lies in southern Colombia [2], from where it expanded to the rest of South America through the Inca Empire, extending from the southern border of Colombia to central Chile just below Santiago [3]. In the last few decades, researchers have investigated Pepino as a potential novel specie to introduce in their markets and envisioned the requirement for breeding programs for crop adaptation to new agroclimatic conditions and fruit organoleptic traits [4]. The Pepino crop currently cultivated in China corresponds to exotic varieties over the years; therefore, there are no registered cultivars. It has been cultivated in southern China and is commonly associated with high altitudes, low relative drought, mild summers, and poor soils [5]. Generally, Pepino is eaten as a fruit, and the mature fruit has a unique fruit aroma; About melon flavor has been mentioned in the previous study, in the previous study analyzed the sensory evaluation and flavor compounds [5], evaluated the soil physical and chemical properties and its influence on metabolites [6], determine the degree of popularity and its nutrients, but also studied the light on the influence of seedling growth [7], and the influence on lateral development, mining the light response lateral transcription factor, and master the TCP gene family plays important functions in the process of regulation and control [8]. All of the above studies have provided scientific and accurate support for the deeper exploration of Pepino [9]. However, some varieties are also considered vegetables [10]. The edible and medicinal significance of Pepino have been studied extensively. Pepino has high water (92% of fresh weight) and low calorie (250 kcal/kg) contents and possesses antioxidant, antidiabetic, anti-inflammatory, and antitumor properties [11–13] which has been popular in recent years. Pepino was introduced into China only 30 years ago, with a short cultivation history, and grown only in the south. Recently, it has gradually expanded to the north due to its psychrophilic properties. However, there is no record of its open-air cultivation in the Qinghai plateau. In Qinghai Province, the average altitude is above 2400 m, and almost no fruit crops grown due to the cool summer. Because of rising temperatures and rainy summers, some plateau crops have been introduced recently. Recently, with rising temperatures and increased summer rainfall, some plateau crops have been introduced. However, there remains a scarcity of fruit crops suitable for altitudes around 2000 m [14,15].

Climatic factors determine the species range, and plants are extremely sensitive to climatic responses. In China, Pepino is primarily cultivated in greenhouses, with open-air cultivation limited to southern Yunnan, characterized by a large diurnal temperature difference, low summer temperatures, and concentrated precipitation [16]. The major plateaus in China is Yunnan–Guizhou, Loess, and Qinghai–Tibet. The average altitude and latitude of the Yunnan–Guizhou Plateau are low, whereas that of the Loess Plateau and Qinghai–Tibet Plateau is intermediate and high, respectively. The Qinghai–Tibet Plateau has a continental climate type characterized by low temperature, large diurnal temperature difference, low and concentrated precipitation, long sunshine hours, and strong solar radiation, with a fragile ecosystem [17]. Moreover, with global warming, the Tibetan plateau also has a substantial climate warming, which promotes the expansion of the arable land area, increasing crop cultivation area throughout the Tibetan plateau [18].

Currently, climate change experiment (CLIMEX), bioclimatic prediction system (BIOCLIM), generalized linear model (GLM), generalized additive model (GAM), ecological niche model (ENM), ecological niche factor analysis (ENFA), genetic algorithm for rule-set prediction (GARP), and maximum entropy algorithm (MaxEnt) is widely used for evaluating ecological demand, climate factor response, and distribution of potential cultivation areas. Among these, the MaxEnt model is widely preferred for its efficiency, user-friendly interface, performance, and high accuracy. Moreover, the MaxEnt model considers more socioeconomic factors and can identify priority areas, reduce conflict between human activities and natural ecology, and minimize the impact of human activities on species. The model emphasizes the suitability of species distribution based on natural environmental variables such as temperature, precipitation, and soil [19–21]. The MaxEnt model achieves accurate results in ecological prediction, providing a theoretical basis for improving ecological species distribution and clarifying ecological climate change. In addition, it has been successfully applied to predict the suitability of single-season and double-season rice crops [22]. The model has calculated the climate distribution of summer maize in China from 1961 to 2010 [23]to simulate the change in climate suitability of potatoes [24]. The prediction results are objective and accurate and can also effectively avoid the bias caused by model overfitting. Such studies can predict and estimate the potential planting areas of crops and provide a theoretical basis for industrial crop planting. Few studies have also summarized the advantages and disadvantages of the MaxEnt model [25]. In general, MaxEnt has high predictive power and accuracy. The current distribution of many species is increasingly mapped using ENMs. Modeling approaches aim at estimate the ecological suitability of ecosystems relative to environmental variables [26]. Understanding the influence of environmental variables on species occurrence and distribution is crucial [27]. Pepino is an emerging specialty horticultural crop in recent years, highly favored by the public. However, most of the research on it has been focused on greenhouse cultivation, with less attention paid to outdoor cultivation. In past studies, the maximum entropy model (MaxEnt) has only been applied in ecology. With further research, the model has gradually been used in medicinal crops but has not been applied to the Solanaceae family of crops. This study is the first to apply the MaxEnt model to specialty horticultural crops, researching the potential distribution of pepino in Qinghai province. There are few outdoor horticultural crops in Qinghai, making it difficult to determine the suitability of newly introduced crops for cultivation. The application of this method can more efficiently and conveniently determine the potential suitable areas for cultivation of crops.

Therefore, herein, we applied MaxEnt on Pepino to predict its potential distribution in Qinghai Province and combined it with ArcGIS software to classify its suitability class. Further, we elucidated the climatic characteristics and key influencing factors of the

Pepino suitability area. The findings of this study aim to provide insights for optimizing the regional production layout of Pepino and maximizing the utilization of agricultural resources in the region.

2. Material and Methods

2.1. Data sources and processing

The Pepino species selected for this study was SRF (sweet round fruit type); Distribution data for Pepino were collected mainly from the literature and the Global Diversity Information Facility (GBIF) database [28]. A total of 117 sampling points was collected, and their geographic coordinates (latitude and longitude) were converted into an Excel spreadsheet and saved in csv. format. The environmental data were obtained from WorldClim (http://www. Worldclim.org) with 20 environmental variables, including 19 climate factors and elevation data [29], The data were in ASC format for use in the ArcGIS software. The required administrative division map (1:400million) was obtained from the National Basic Geographic Information System website (http://nfgis.nsdi. gov. cn/)) [30].

2.2. Handling of environmental variables

We used the MaxEnt version 3.4.4 and ArcGIS version 10.4.1 in this study. The input MaxEnt data was the geographic coordinates (latitude and longitude) of the sampling points and environmental variables. Highly correlated factors with a small contribution rate were removed to avoid overfitting and improve model accurac [31] The jackknife method in MaxEnt was used to determine the contribution rate of the environmental factors [32–34].

2.3. MaxEnt model operation and parameter setting

We set the parameters by selecting options such as "create response curves" and "do jackknife" to measure variable importance. Replicated run type was set to Bootstrap, test to 25%, training to 75%, and the number of repetitions to 10 to start the run. The prediction accuracy of the MaxEnt model was judged by the area under the receiver operating characteristic (ROC) curve (AUC), which was classified into the following four categories by the natural discontinuity grading method: AUC <0.6 (failure), $0.6 \leq$ AUC <0.7 (poor), $0.7 \leq$ AUC <0.8 (average), and $0.8 \leq$ AUC <0.9 (good). The model was generally considered unstable when the AUC is less than 0.75 [35].

2.4. Appropriate area grade division

By dividing the fitness level through ArcGIS software, the MaxEnt prediction results were exported to asc format and input to ArcGIS. The fitness levels were divided into four levels through the software's reclassification function: high potential, good potential, moderate potential, and least potential. Finally, we obtained the Pepino habitat range prediction map. The map was labeled with different colors and inserted with a compass, legend, and scale.

2.5. Cultivation validation in suitable habitat

The predicted results were used to select four counties with various altitudes in the Huangshui River and Yellow River basin in eastern Qinghai province: Guide (GD, 2211 km), Minhe (MH, 1800 km), Xunhua (XH, 1858 km), and Xining (XN, 2246 km). The final selection of cultivation test sites was based on the predicted results and difficulty of the survey. The four areas were designated as test sites because they had a reasonable natural climate and were within the predicted range, and the survey sampling was convenient.

2.6. Determination of agronomic traits

Fruit weight per fruit and yield per plant was measured using a balance in grams. Vernier calipers were used to measure the transverse and longitudinal diameters of the fruits with an accuracy of 0.01 mm. Six replicates were used for all measurements.

2.7. Measurement of physiological indexes

Each physiological index was measured in triplicates.

(1) Organic acids: measured using high-performance liquid chromatography (HPLC) [36].
(2) Soluble carbohydrates: sucrose, glucose, and fructose were determined to use HPLC [37].
(3) Flavonoids (spectrophotometric method): the sample of Cucumis sativus fruit was dried to constant weight, crushed, passed through a 40-mesh sieve, weighed approximately 0.5 g, added 5 mL of extraction solution, extracted by ultrasonic extraction method (ultrasonic power, 300 W), crushed for 5s, with intermittence of 8 s at 60 °C, and finally extracted for 30 min. The sample was then centrifuged for 10 min at 12,000 rpm and 25 °C. The supernatant was collected and fixed with the extraction solution to 5 mL for measurement. The visible spectrophotometer preheated for more than 30 min, the wavelength was adjusted to 470 nm, and distilled water was adjusted to zero. After mixing the reagent, the sample was kept in a water bath for 45 min at

37 °C and centrifuged at 10,000 rpm for 10min to separate the supernatant. Glass cuvettes of 1 mL were used to determine the absorbance value.

(4) Total phenol (spectrophotometric method):the samples of Pepino was dried to constant weight, crushed, passed through a 40-mesh sieve, weighed approximately 0.2 g, added 5 mL of extraction solution, extracted using ultrasonic extraction method (ultrasonic power 300 W, crushing 5 s, intermittent 8 s, 60 °C, extraction 30 min). The samples were then centrifuged at 12,000 rpm and 25 °C for 10 min, and the supernatant was collected and fixed with extraction solution to 5 mL for measurement. The spectrophotometer preheated for more than 30 min, and the wavelength was adjusted to 760 nm. The reagents were mixed and left to stand for 10 min at room temperature. The absorbance values were measured using a 1 mL glass cuvette.

2.8. Statistical analysis

The "vegan" package of the R software was used for statistical analysis [38]. Redundancy analysis (RDA) was performed to assess the correlation between climate and quality. The "ggcorrplot" package [39] of the R software was used to plot intergroup correlations to describe the effects of the main environmental factors on quality and yield. The "factoextra" package was used for the principal component analysis (PCA).

3. Results and analysis

3.1. Model accuracy evaluation

In the model prediction, The area under the receiver operating characteristic (ROC) curve (AUC) was used to evaluate the model prediction accuracy. A larger AUC value indicates stronger reliability. The evaluation criteria were as follows: 0.5 < AUC ≤0.6, the model is unreliable; 0.6 < AUC ≤0.7, the model is less reliable; 0.7 < AUC ≤0.8, the model is generally reliable; 0.8 < AUC ≤0.9, the model is more reliable; and 0.9 < AUC ≤1, the model is excellent. The AUC value close to 1 indicates more correlation between the geographical distribution of species and environmental variables and the model prediction results more accurate. In this prediction process, after ten calculations, the AUC value was 0.949, which was higher than 0.9 (Fig. 1), indicating that the prediction results were reliable and can provide an accurate judgment for the subsequent analysis.

3.2. Environmental factor screening results

A total of 20 environmental variables was selected (Table 1), and the significance of each environmental variable on the model accuracy was examined according to the environmental factor correlation and jackknife procedure. The following environmental variables were selected according to their contributions:Among the 19 environmental factors (Fig. 2B) used to predict the MaxEnt model, the results demonstrated that, when only using a single environmental factor, the four environmental factors that had the greatest impact on the normalized training gain were bio4 (Temperature Seasonality), bio1 (Annual mean temperature), bio11 (Mean temperature of the coldest quarter), and bio 3 (Isothermality). From all environmental variables, the gain value of the model decreased

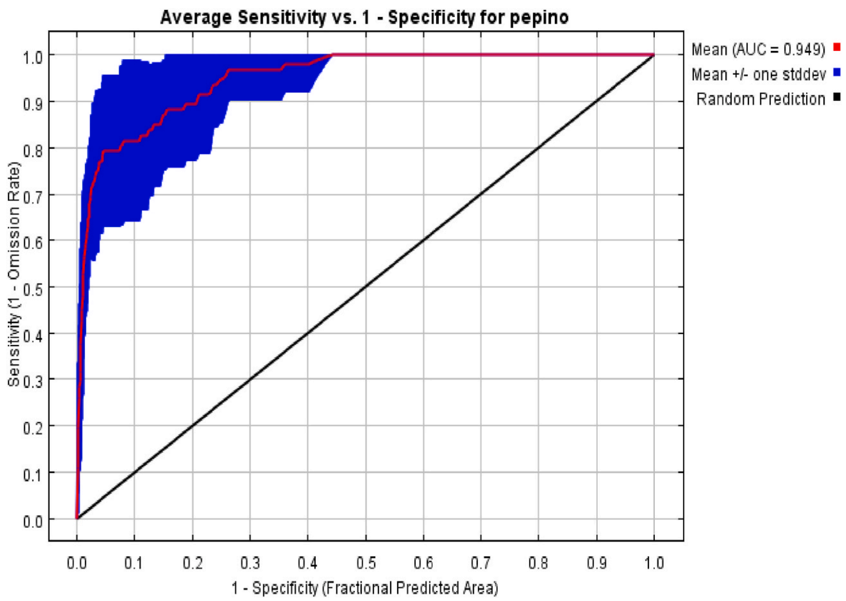

Fig. 1. Reliability test of the distribution model created for Pepino.

Table 1
Environmental variables used in the study.

Abbreviation	Climate variables	Unit
bio1	Annual mean temperature	°C
bio2	Mean diurnal range	°C
bio3	Isothermality	°C
bio4	Temperature Seasonalit	°C
bio5	Max temperature of warmest month	°C
bio6	Min temperature of coldest month	°C
bio7	Temperature annual range	°C
bio8	Mean temperature of wettest quarter	°C
bio9	Mean temperature of driest quarter	°C
bio10	Mean temperature of warmest quarter	°C
bio11	Mean temperature of coldest quarter	°C
bio12	Annual precipitation	mm
bio13	Precipitation of wettest month	mm
bio14	Precipitation of driest month	mm
bio15	Coefficient of variation of precipitation Seasonality	mm
bio16	Precipitation of wettest quarter	mm
bio17	Precipitation of driest quarter	mm
bio18	Precipitation of warmest quarter	mm
bio19	Precipitation of coldest quarter	mm
elev	Elevation	m

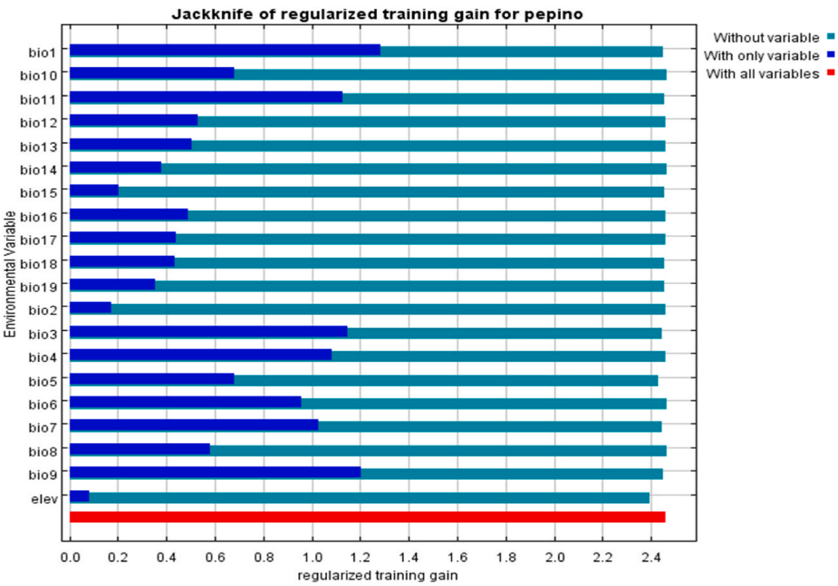

Fig. 2. Importance of environmental variables in Pepino growth using jackknife analysis.

Table 2
Environmental factor contribution rate. Note: The different climatic factors are listed in a contribution order from largest to smallest.

Environmental variable	Percent c on tribute	Environmental variable	Percent contribute
bio4	34.4	bio 10	1
bio1	21	bio 2	1
bio11	17.8	bio 6	0.6
elev	7.8	bio12	0.3
bio3	6.6	bio14	0.2
bio17	4.2	bio9	0.2
bio13	1.2	bio19	0.2
bio7	1.1	bio15	0.1
bio 5	1.1	bio16	0.1
bio18	1	bio8	0

the most in the absence of Elev, indicating that elev has information that is absent in other variables and has an irreplaceable effect on the model accuracy (Fig. 2). Each environmental variable contributed more than 5%, with a cumulative contribution of 87.6%. Bio4 contributed 34.4%, bio1 21%, bio11 17.8%, Elev 7.8%, and bio3 6.6%.bio4 contributed the most to the model and was an important environmental variable (Table 2). Our results indicate that temperature and altitude is extremely important for Pepino growth. Moreover, Pepino has strong suitability on the Tibetan plateau; however, the excessively high altitude will be a threat to its survival. Overall, the main environmental factors affecting the potential distribution of Pepino were temperature factor and Elevation.

3.3. Prediction of the suitable habitat of pepino

The fitness level of Pepino was divided into four levels according to the natural breakpoint method: high potential, good potential, moderate potential, and least potential (Fig. 3). In China, high potential Pepino is mainly distributed in Yunnan Plateau, Southern Tibetan Plateau, and Qaidam Basin, consistent with the adaptive growth characteristics of Pepino at high altitudes. High potential accounted for 3.64%, whereas good potential accounted for 16.45% of the total area in China (Fig. 3a). Within the distribution range of each province and city, Qinghai Province revealed high and good potentials, with high potential in the Qaidam Basin, covering 4.89% of the total area of Qinghai Province, and good potential in the periphery of the Qaidam Basin and parts of eastern Qinghai, covering 12.43% of the total area of Qinghai Province (Fig. 3b). The suitable areas included Qinghai Province, Yunnan Province, and Taiwan, which are at different latitudes, with Qinghai Province at a higher and Taiwan and Yunnan Province at lower latitudes. However, each area has the climatic characteristics of highland mountains, with sufficient precipitation and long sunshine hours in summer, which are suitable for the growth of Pepino. According to Chinese domestic production data, Yunnan Province is currently the main region for open-air cultivation of Pepino in China (Fig. 3b).

3.4. Environmental factor response curve analysis

The environmental factor response curves represent the probability of species survival under each environmental condition (Fig. 4). When the survival probability reaches 0.5 or higher, the environment is considered suitable for the species to grow, and the species is judged as the best environment for survival. According to the curve in Fig. 4, the survival probability of Pepino increased with increasing bio1; The maximum survival probability of Pepino exceeded 0.7 when bio1 ranged from 10 to 20 °C, indicating that Pepino thrives under these temperature conditions. However, the probability of Pepino survival sharply declined outside the optimal temperature range, indicating unsuitability for growth (Fig. 4a). When the probability of Pepino survival was 90%, bio3 was 0.8, confirming that this condition promotes Pepino growth (Fig. 4b). When bio4 was greater than 0, the probability of Pepino survival gradually increased and reached a maximum value of 1. The survival probability then gradually decreased with increasing standard deviation (Fig. 4d). Further, bio11 was also a key factor influencing the suitability of Pepino. The survival probability of Pepino was above 0.7 when the temperature ranged from 0 to 10°C and then decreased with increasing temperature (Fig. 4e). Elev had an irreplaceable influence on Pepino growth; its survival probability was above 0.6 when Elev was 2000–3000 m, confirming that high altitude is suitable for Pepino growth, consistent with its geographical characteristics of origin (Fig. 4c).

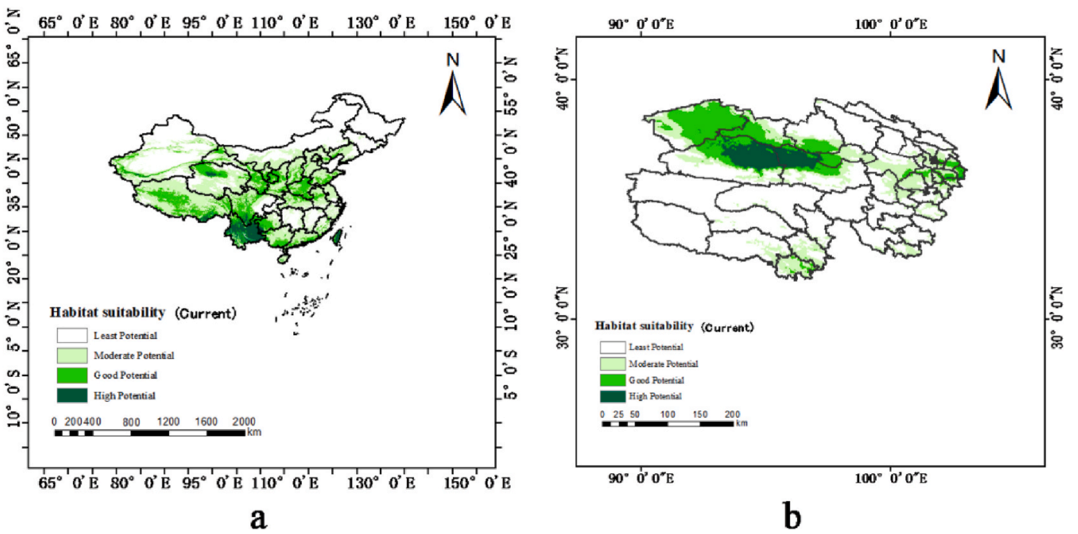

Fig. 3. Current climate conditions potential distribution area of Pepino. a: Distribution area of Pepino in China; b: Distribution area of Pepino in Qinghai province. Blank indicates a low suitable growth area, and dark green indicates a high suitable growth area.

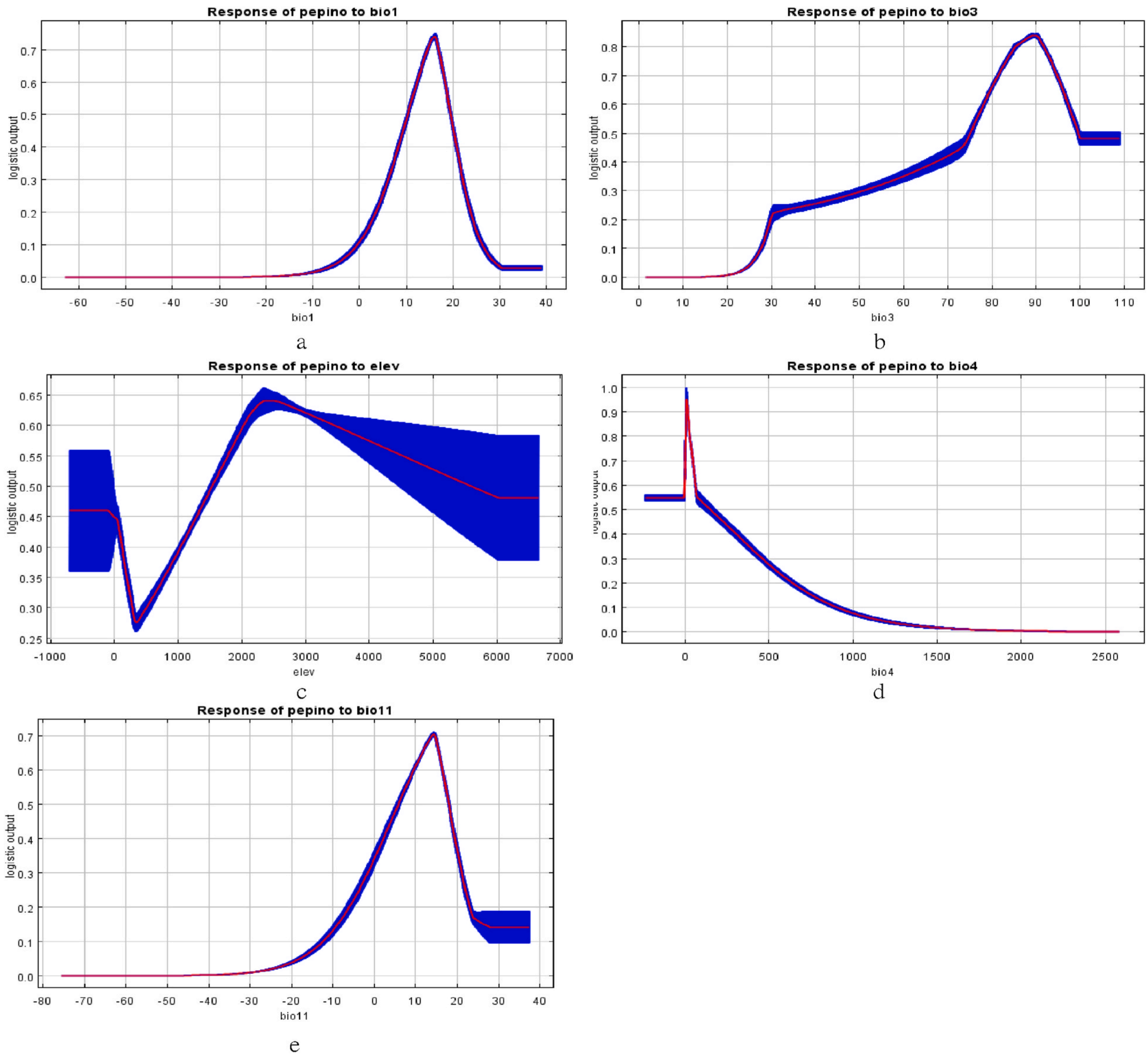

Fig. 4. Environmental factor response curve. a: bio1 (Annual mean temperature); b: bio3 (Isothermality); c: Elev (Elevation); d: bio4(Temperature Seasonality); e: bio11 (Mean temperature of the coldest quarter).

3.5. Prediction of the future habitat of pepino

The 2050 forecast map shows that the proportion of high and good potential areas are 4.31% and 10.36% nationwide. These values represent a 0.67% increase and a 6.09% decrease when compared to the current fitness range (Fig. 5a). The proportion of high and good potential areas within Qinghai Province was 7.28% and 16.16%, with an increase of 2.39% and 3.73%, respectively (Fig. 5b). According to the 2070 forecast map, the national high and good potential areas are 4.15% and 10.25%, which are 0.51% and 6.20% more than the current projection, respectively (Fig. 5c). In Qinghai Province, the high and good potential areas were 7.03% and 16.09%, which were 2.14% and 3.66% more than the current projection, respectively (Fig. 5d).

3.6. Selection of cultivation sites

We selected the following four sites in the Yellow River and Huangshui River basins for cultivation trials in this experiment: Xining, Guide, Xunhua, and Minhe. The two river basins have a relatively mild climate, long sunshine, abundant precipitation, and a good natural environment for the plant growth. Meanwhile, the four areas are located near the Qinghai Academy of Agriculture and Forestry, which was convenient for survey records. Importantly, all four sites fall within the projected fitness range, enabling more precise validation results to be obtained (Fig. 6). Huangshui River basin has a continental climate with large topographic differences

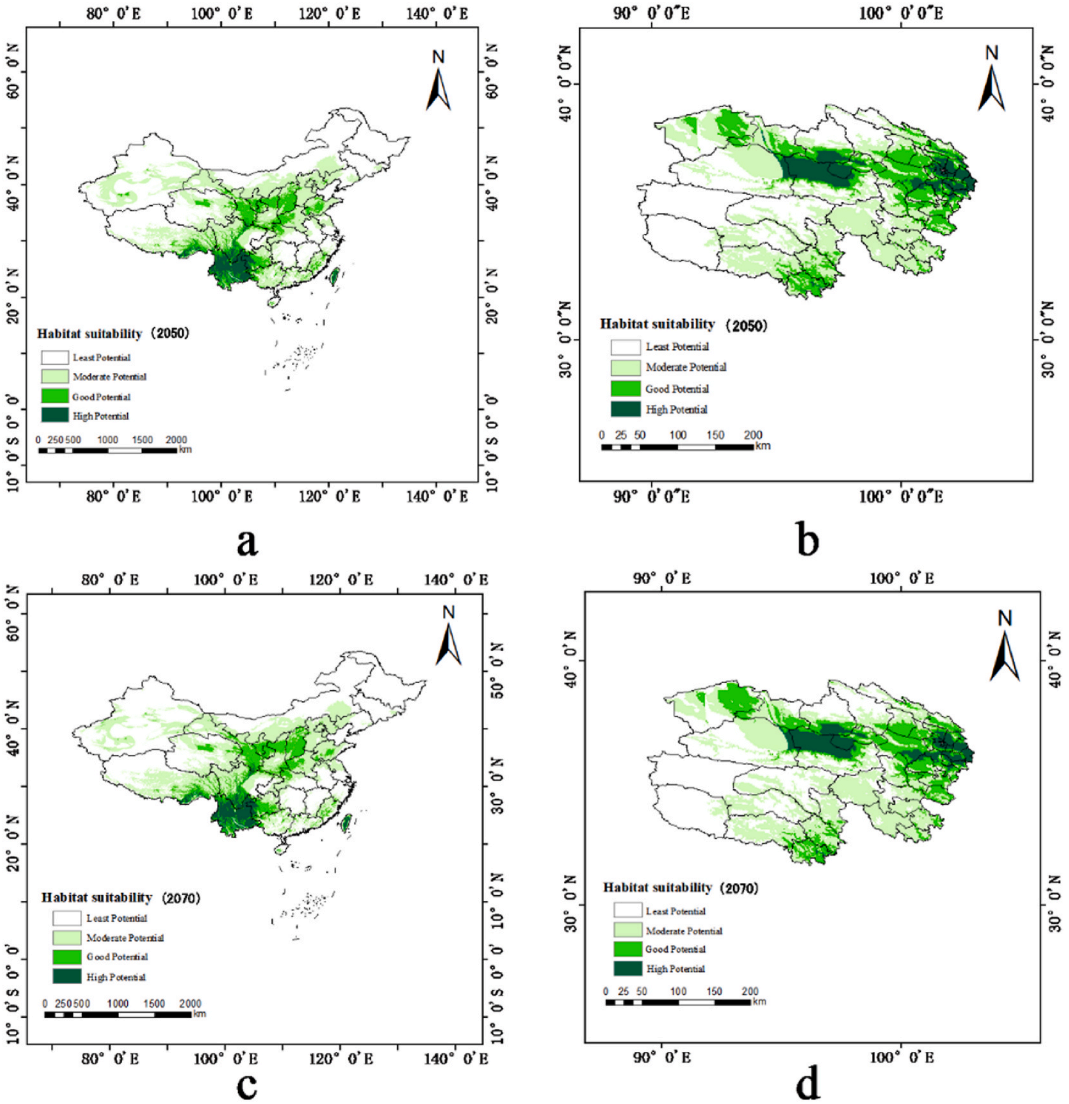

Fig. 5. Conditions for potential distribution area of Pepino under future climate. a: Projected range of suitable growing areas for cucumber and eggplant in China in 2050. b: Projected range of suitable growing areas for cantaloupe in Qinghai Province in 2050. c: Projected range of suitable growing areas for cucumber and eggplant in China in 2070. d: Projected range of cantaloupe aptitude zones in Qinghai Province in 2070.

and temperature variations. Huangshui River basin has high terrain and low temperature, and precipitation increases with elevation. Huangshui River is a major tributary of the upper reaches of the Yellow River, having strong solar radiation, sufficient light, the precipitation concentration, the temperature difference, and other climatic characteristics. These climatic characteristics are suitable for Pepino growth, as obtained in the forecast.

3.7. Melon and eggplant quality and climate correlation

RDA was used to analyze the correlation between Pepino fruit quality yield and environmental factors., with the first two coordinate axes cumulatively explaining 80.54% of the variation in the Pepino fruit quality and yield. The correlation between environmental factors and fruit quality was indicated by the angle between the two, with a positive correlation at $<90^\circ$ and a negative correlation at $>90^\circ$; the smaller the angle, the higher the correlation. According to the length of the arrow, determine four main environmental factors: average temperature average wind speed relative humidity and ground pressure，The single plant yield was positively correlated with average wind speed, relative humidity, and precipitation, Except for citric acid, single fruit weight, flavonoids, cross diameter, total phenols, fructose, and longitudinal diameter were all positively correlated with mean temperature, ground pressure. Glucose and sucrose displayed positive correlations with short-wave radiation intensity and sunshine hours. Conversely, evapotranspiration exhibited a negative correlation with each quality index(Fig. 7).

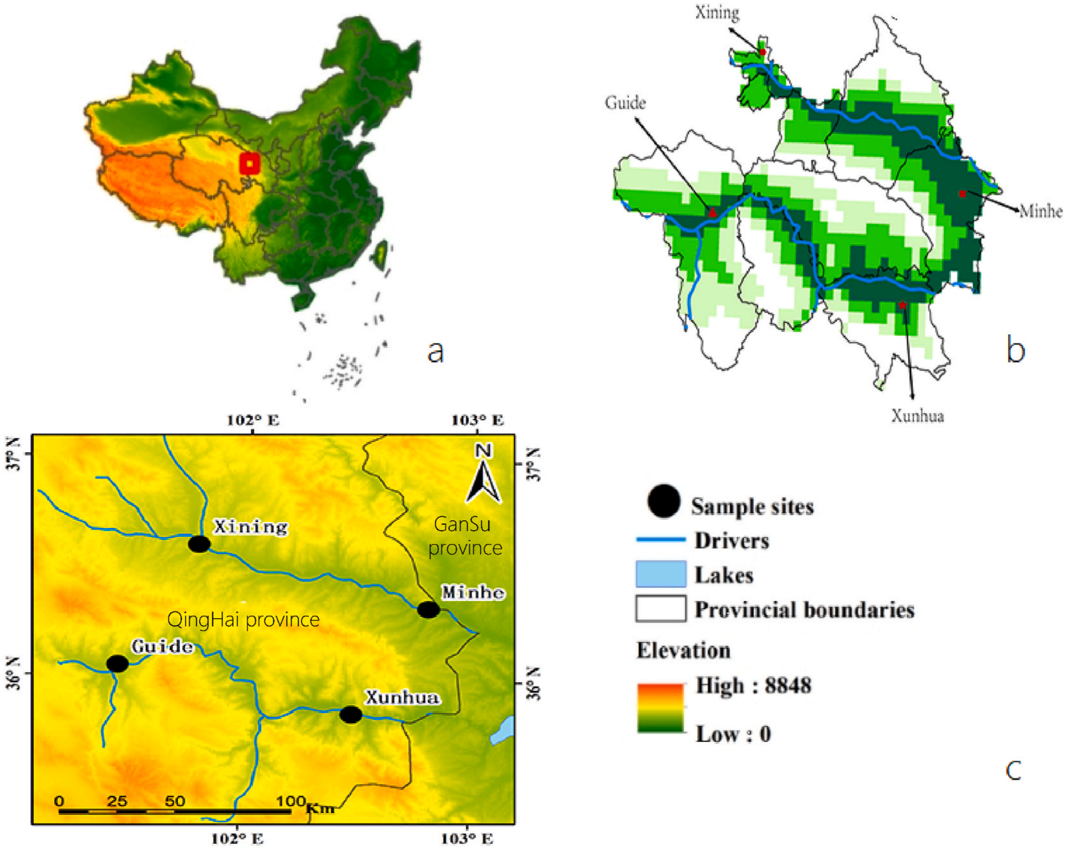

Fig. 6. National topographic map and geographical location of cultivation sites. a: Topographic map of China. b: Distribution map of cultivation points in suitable growing areas: ▲Guide, ★Xunhua, ■Minhe, ●Xining; c: Geographical location of the four cultivation sites according to the terrain.

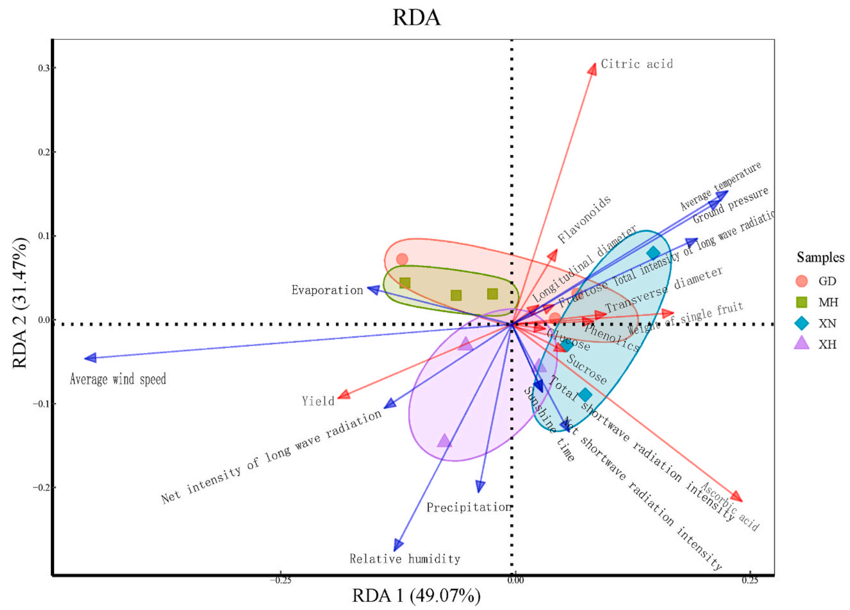

Fig. 7. RDA of climatic factors and fruit quality in different regions.

3.8. Quality analysis of each region based on PCA

The fruit quality in each region was evaluated comprehensively by PCA (Fig. 8). PCA revealed differences in fruit quality among regions. This high repeatability within groups, indicating similar sample data, instills confidence in the findings. The combined score of the principal component 1 and 2 was 35.64% and 21.05%, respectively, and the cumulative combined score of the two principal components was 56.69%. In principal component 1, GD and XH showed less variability in fruit quality, which was relatively similar. While XN and MH had more variability in fruit quality, in principal component 2, GD had more variability than the other three regions, which was closely related to the climatic conditions in different regions (Fig. 8).

3.9. Climate data correlation for regional quality and model application

To identify the environmental factors that drive compositional differences in the Pepino phenotypic-physiological indicators, a Mantel test was performed to identify a possible correlation between fruit quality, yield, and environmental factors (Fig. 9). The correlations between quality and yield in the four regions and the main climatic factors in the model predictions were analyzed together and judged based on p and r values. Overall, bio1, bio4, and bio11 are the main environmental factors affecting Pepino quality and yield. The significance between bio4 and yield per the plant level was $p = 0.002 < 0.01$, indicating a highly significant correlation; at this level of significance, $r = 0.64 > 0.4$, indicating the strongest correlation between the two. The correlation between bio1 and citric acid ($p = 0.016$, $r = 0.32$) and longitudinal diameter ($p = 0.007$, $r = 0.39$) was similar at different levels of significance. The correlation between bio4 and longitudinal path was $p = 0.033$, $r = 0.30$. The correlation between bio11 and longitudinal path was $p = 0.03$, $r = 0.34$. The correlation between bio3 and Elev was not significant ($p = 0.016$, $r = 0.39$) (Fig. 9). The above results show that temperature change is the main environmental factor affecting the quality and yield of melon and eggplant, and plays an important role in its growth and development.

Margin widths correspond to r values and margin colors indicate statistical significance. Only significant correlations between Pepino fruit quality and environmental variables are shown. The color gradient indicates Spearman's rank correlation coefficient between the environmental variables.

4. Discussion

Model prediction of suitable habitat has been developed as an effective way to protect and evaluate crop suitability. Moreover, analyzing the correlation between climate change and crop distribution areas is crucial. Pepino is an emerging plant used as both fruit and vegetable; therefore, it is essential to expand its production. To the best of our knowledge, this study is the first to use the MaxEnt model to explore the effects of global climate change on the geographic range and environmentally-suitable habitat for Pepino.

The MaxEnt model is an ideal tool for studying the geographic distribution of species [25], which uses species distribution and environmental data to analyze species distribution patterns. The model is widely used in ecological studies and has unique advantages and wide applications in ecology [40]. Current MaxEnt model studies mainly consider the effects of natural factors such as climate and altitude [41]. In recent years, the model has emerged for predicting the distribution of herbs, flowering plants, and gramineous crops [31,42–46]. MaxEnt has remarkably higher prediction accuracy than other models for various ecological crops and gramineous plants [19,22,47]. The MaxEnt model can predict the range of fitness zones and examine the relationship between species migration and climate change [48].

In species distribution prediction, the distribution of fitness zones at high altitudes is similar to the geographic characteristics of the northern foothills of the Andes, where Pepino originates [10]which is the origin of Pepino. Nineteen bioclimatic variables, including elevation, were included in this study to model potential species distributions, as elevation plays a unique role in the adaptive distribution of Pepino [45]. The minimum distance between species distribution data points selected for this study was 10 km, for a total of 117, to avoid duplication of sample records and reduce the inherent bias associated with collecting data [48]. Model prediction accuracy was evaluated, the AUC was 0.949, confirming that the results were extremely reliable and accurate, further supporting the applicability of the ArcGIS-based MaxEnt model for predicting the potential distribution of species, consistent with other studies [49]. The MaxEnt model has also been applied to the Tibetan Plateau region for barley (Hordeum vulgare var. coeleste Linnaeus) to predict its suitable habitat. The results revealed daily minimum temperature and annual precipitation in the coldest month as the two most important environmental variables for predicting barley habitat distribution. Barley grown in the southeastern and northeastern plateau valleys, where moderate and optimal suitable habitat areas were concentrated, with a potential mid-to late-21st century. The contraction of suitable habitat areas may occur in the middle and late 21st century [50]. Future climate changes will expand, contract, or alter the climatic ecological niche of many species, which may lead to changes in the geographic range of crops. Therefore, global climate change scenarios regarding the potential distribution of species must be evaluated [51].

In this study, correlation analysis was conducted on environmental variables. Some studies have not considered the redundant information introduced by highly correlated variables in the modeling process, which negatively affects the reliability of the prediction results [52]. We screened five climatic factors having a strong influence on Pepino cultivation, namely, bio 4 (Temperature Seasonality), bio 1 (Annual mean temperature), bio 11 (Mean temperature of the coldest quarter), elevation (Elevation), and bio 3 (Isothermality). All of them, except elevation, were correlated with temperature, which varies with different plant types, developmental stages, and other factors. Temperature variation can be effectively used to predict crop distribution areas and growing seasons. Researchers can satisfactorily predict plant growth rates and production potential through temperature variations [49]. Pepino belongs to the Solanaceae family and is more sensitive to temperature response.

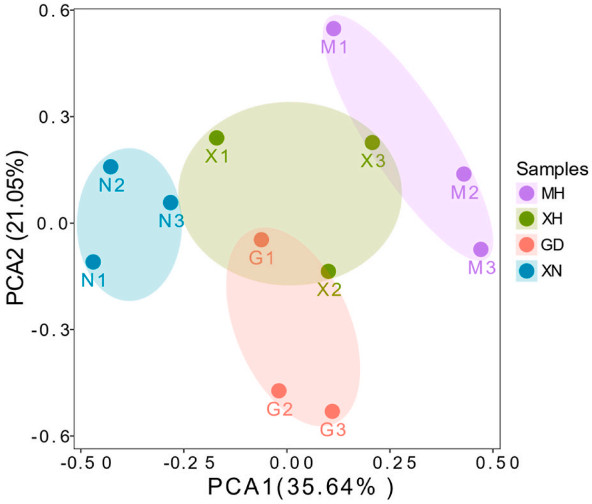

Fig. 8. PCA of fruit quality in each region. Each color represents one region, with three repetitions per region.

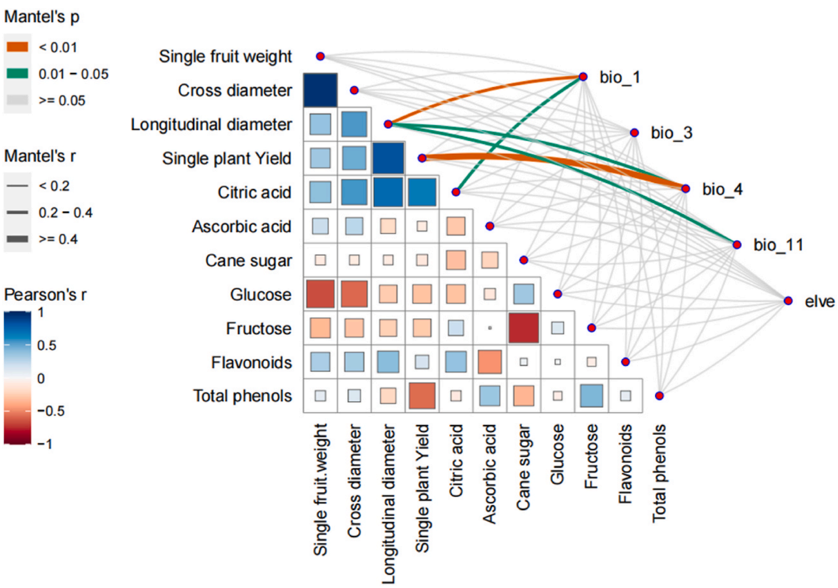

Fig. 9. Correlation between Pepino fruit quality and environmental variables assessed using the Mantel test.

In China, Pepino is mainly distributed in plateau areas such as Gansu, Qinghai, and Yunnan, with distinct plateau climates; hence, Pepino displays an evident plateau climate adaptability. Production data has shown that Yunnan located at a high altitude on the Yunnan–Guizhou plateau, with small annual and large daily temperature differences, abundant precipitation, distinct dryness, and humidity, is the main open-cultivation area for Pepino. Yunnan climate has similarities with the Qaidam Basin climate in Qinghai Province. Therefore, the Qaidam Basin, except for the agricultural area east of Qinghai Province, is also presumed to be an excellent suitable cultivation area. However, few cultivation studies in the eastern agricultural areas of Qinghai have confirmed its suitability for Pepino growth. The Qaidam Basin is the main development area of the plateau oasis, sensitive to climate change, with long sunshine hours, strong solar radiation, and large diurnal temperature differences. The climate of the two regions is relatively mild, and the agricultural area in eastern Qinghai has long sunshine, abundant precipitation, and a good natural environment for plant growth. In the future, we aim at study the feasibility of Pepino cultivation in the Qaidam Basin, where we will primarily address irrigation due to the arid conditions.

Subsequently, suitable cultivation areas for Pepino were projected for the years 2050 and 2070, and climate data were selected as Representative Concentration Pathway (RCP)4.5. RCP4.5 and RCP6.0 indicate medium greenhouse gas emission scenarios, with RCP4.5 having a higher priority than RCP6.0. Both nationwide and within Qinghai Province, an increase in the high potential area for Pepino was observed. However, the high potential area within Qinghai Province increased proportionally compared with nationwide, presumably due to the sensitivity of Pepino to climate change in the Qinghai–Tibet Plateau region, where climate change is more pronounced than nationwide climate. Moreover, the increase in high potential areas implies that the climatic conditions in some areas of Qinghai Province may be suitable for Pepino cultivation.

The eastern region of Qinghai was selected as a pilot, and four regions were selected for cultivation trials based on the predicted results. The cultivation results were tallied, which revealed unavoidable human and geographical factors in the differences in yield between the four regions. Correlation analysis revealed differences between climatic factors and fruit quality in the four regions. Because Qinghai Province is located in the mid-latitude and high-altitude area, the sunshine hours are long, and the short-wave radiation is mainly expressed as solar radiation. Solar radiation becomes more substantial with increasing altitude. These data reveal a strong positive correlation between sunshine hours and short-wave radiation. Long-wave radiation is mainly expressed as ground and atmospheric radiation; the air pressure and temperature decrease with increasing latitude. Therefore, long-wave radiation was positively correlated with ground pressure and average radiant temperature. The difference between the Guide and Xunhua areas is insignificant in terms of high Pepino yield and quality. In this study, single plant yield, citric acid, flavonoids, and total phenols were positively correlated with the average air temperature because higher air temperature favors fruit photosynthesis and thus fruit growth and organic matter accumulation. In contrast, precipitation leads to insufficient solar radiation, reducing sugar accumulation; therefore, precipitation was negatively correlated with sugar substances. Precipitation was positively correlated with single plant yield because ripened Pepino are harvested in September and October when precipitation is low, and adequate precipitation is required to promote fruit water uptake and fruit growth. RDA results were compared with the Pearson correlation analysis results. Average wind speed, average air temperature, and relative humidity considerably influenced fruit quality, consistent with the unique geographical location and climatic conditions of the Qinghai plateau. In the PCA, the quality was directly related to the climate of each region. The difference in climate conditions between GD and XH was minor, leading to an insignificant difference in quality.

Pepino habitat prediction can screen the cultivation range of Pepino in Qinghai province, China, which is of great reference value for expanding the cultivation range, developing the cultivation industry, and resource utilization and conservation of Pepino [47]. Few studies have verified that the plateau region's climatic environment promotes the fruit's morphological development, and the fruit size increases considerably compared to the lower altitude regions, but the yield decreases. This phenomenon is consistent with the results of the present study [53], which revealed that Pepino yield was reduced at higher altitudes, but fruit size increased.

5. Conclusions

In this study, the MaxEnt model was applied to successfully predict the suitable habitat of Pepino based on different environmental factors. Within China, the Pepino high suitability area is mainly distributed in Yunnan. In Qinghai province, suitable areas for Pepino cultivation are mainly distributed in the Qaidam Basin and some areas in eastern Qinghai. Several important environmental variables affecting Pepino distribution were identified through MaxEnt predictions: bio1 (Annual mean temperature), bio3 (Isothermality), bio4 (Temperature Seasonality), bio11 (Mean temperature of the coldest quarter), and Elev (Elevation). We projected the habitat distributions under future climate. The predicted results showed an increase in the area suitable for Pepino in the future scenario. Further, we determined the association between environmental factors and the quality yield. The predicted results of this study can provide a considerable reference value for selecting Pepino cultivation sites, help expand Pepino cultivation, facilitate Pepino conservation and resource utilization, and improve the ecological and economic value of the species.

Author contribution statement

Houzhi Chao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Zhu Sun: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Guolian Du and Dengkui Shao: Analyzed and interpreted the data; Wrote the paper.

Qiwen Zhong: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shipeng Yang: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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