



Article

Soil Quality Evaluation and Limiting Factor Analysis of *Trichosanthes kirilowii* Maxim. Planting Areas Based on the Minimum Data Set: A Case Study of Hubei Province, China

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Abstract

Soil quality constitutes a fundamental foundation for maintaining soil productivity, ecological function and crop health. However, existing research on soil quality assessment and its limiting factors in *Trichosanthes kirilowii* Maxim. planting areas remains insufficient. To construct a soil quality assessment system suitable for *T. kirilowii* Maxim. planting areas and identify key limiting factors, this study took 46 sampling sites from three typical *T. kirilowii* production areas in northwestern Hubei, the Jiangnan Plain and southeastern Hubei Province as research objects. Thirteen physicochemical soil indicators were measured. Principal component analysis (PCA) combined with the Norm value was used to derive the minimum data set (MDS). Three scoring functions were compared to evaluate their applicability for soil quality assessment. The obstacle degree model was applied to identify the main limiting factors of soil quality, and partial least squares structural equation modeling (PLS-SEM) was used to explore the potential relationships associated with soil quality variation. The results show that an MDS composed of soil organic matter (SOM), alkali-hydrolyzable nitrogen (AN), bulk density (BD), electrical conductivity (EC) and total phosphorus (TP) can effectively characterize soil quality. Compared with linear standardization and membership function standardization, the non-linear function (SNL) standardization method performs the best ($E_f = 0.78$, $E_R = 0.05$), and a soil quality index (SQI) calculated based on the MDS and total data set (TDS) shows a significant positive correlation ($R^2 = 0.851$, $p < 0.001$). The average SQI of *T. kirilowii* planting areas in Hubei Province is 0.49, which is a medium level, and shows obvious spatial differences among different regions, in the order of northwestern Hubei (0.59) > southeastern Hubei (0.49) > Jiangnan Plain (0.39). Obstacle degree analysis shows that organic matter and alkali-hydrolyzable nitrogen are the main limiting factors affecting soil quality, but there are obvious differences among regions. PLS-SEM analysis indicated that soil fertility-related factors were positively associated with SQI (path coefficient = 0.720, $p < 0.001$), whereas the soil's physical and salinity-related factors showed negative associations with SQI (path coefficient = -0.259 , $p < 0.05$). Altitude showed indirect associations with SQI through its relationships with soil properties, with a total effect of 0.480, and the model explained 85.7% of the variation in SQI. This study confirms that the constructed MDS performs comparably to the TDS in the present dataset for soil quality assessment in *T. kirilowii* planting areas in Hubei Province. Insufficient organic matter and alkali-hydrolyzable nitrogen were identified as the main factors limiting soil quality, suggesting that improving organic matter accumulation and nitrogen availability should be prioritized in soil management in *T. kirilowii* planting areas. This study can provide a theoretical basis for soil quality assessment, precise fertilization and sustainable soil development in *T. kirilowii* planting areas.



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Keywords: *Trichosanthes kirilowii* Maxim.; minimum data set; soil quality index; limiting factors

1. Introduction

Soil quality refers to the capacity of soil to sustain biological productivity, maintain environmental quality, and support ecosystem functions. In agricultural systems, soil quality is closely associated with crop productivity and quality [1,2]. With increasing agricultural intensification and simultaneous awareness of sustainability concepts in agriculture, soil quality has become a key indicator for assessing soil function, ecosystem stability, and land use sustainability [3,4]. Good soil quality not only ensures consistently high yields but also helps maintain nutrient cycling, increase ecosystem resilience, and improve agricultural resource use efficiency [5,6]. Soil quality, soil fertility, and soil health are closely related but represent different concepts. Soil fertility mainly refers to the capacity of soil to provide the nutrients required for plant growth, whereas soil health represents a broader concept integrating physical, chemical, and biological soil functions. In this study, soil fertility indicators were regarded as functional components of soil quality rather than interchangeable concepts. Therefore, evaluating soil quality and identifying the key factors affecting its development have become important focuses of research in soil science, ecology, and related fields [7,8].

To improve soil quality assessment, extensive research has been conducted on constructing evaluation indicator systems, optimizing assessment models, and analyzing driving mechanisms. Traditional soil quality assessments typically use a total data set (TDS), integrating physical, chemical, and biological soil indicators to comprehensively reflect soil functional status. However, owing to the large number of evaluation indicators, such approaches often suffer from information redundancy, high assessment costs, and complex interpretation of results [9]. Therefore, minimum data sets (MDS) have been adopted for soil quality evaluation by many researchers, significantly reducing monitoring costs while maintaining assessment accuracy [10]. In recent years, the MDS method has been widely applied in soil quality evaluations across ecosystems including croplands, orchards, forests, and grasslands [11–15].

Although soil quality has been assessed for medicinal plants in several studies [16–18], soil quality has not been evaluated for *Trichosanthes kirilowii* Maxim., a perennial climbing vine in the Cucurbitaceae that is a traditional medicinal plant in China, with its roots, fruit rinds, fruits, and seeds all used medicinally [19]. Current research primarily focuses on the pharmacological mechanisms of *T. kirilowii* [20–22]. Previous studies have shown that nitrogen, phosphorus, and potassium fertilizer application significantly affects *T. kirilowii* yield [23], and nitrate nitrogen, total phosphorus, and available phosphorus are important factors influencing soil microbial communities in *T. kirilowii* cultivation soils [24]. However, systematic evaluations of soil quality in *T. kirilowii* cultivation areas remain scarce.

Merely evaluating soil quality levels provides limited guidance for production management. In recent years, the obstacle degree model has gained widespread attention for its ability to quantitatively identify key factors restricting improvements in soil quality [25,26]. Partial least squares structural equation modeling (PLS-SEM) can further explore hypothesized relationships among soil physicochemical properties and their direct and indirect associations with soil quality [27], providing an effective tool for exploring potential pathways associated with soil quality development. Thus, we integrated MDS evaluation, obstacle factor analysis, and PLS-SEM in an “assessment–diagnosis–factor identification” approach for a systematic understanding of soil quality characteristics in *T. kirilowii* cultivation areas.

Our approach was based on sampling 46 cultivated plots (sampling sites) in *T. kirilowii*-growing regions of Hubei Province, China. We measured 13 soil physicochemical properties to construct both the MDS and TDS and compared the reliability of soil quality assessment results under different standardization methods. We hypothesized that (1) soil quality varies among different *T. kirilowii* planting regions due to differences in soil properties and environmental conditions; (2) a subset of key soil indicators can effectively represent overall soil quality through MDS construction; and (3) soil fertility-related factors and physical properties jointly contribute to spatial variations in soil quality. Subsequently, we used the obstacle degree model to identify critical factors limiting soil quality improvement in the planting areas and a PLS-SEM to explore potential relationships associated with soil quality formation. The overall aim of the study is to provide theoretical support for establishing a soil quality evaluation system, precision fertilization, and soil health management in *T. kirilowii* cultivation zones.

2. Materials and Methods

2.1. Overview of the Study Area

The three study areas are in northwestern Hubei, the Jiangnan Plain, and southeastern Hubei Province, China (Figure 1). Northwestern Hubei is in the northwestern part of Hubei Province (31°14′–33°17′ N, 109°29′–113°6′ E), covering Shiyan City, Xiangyang City, and Shennongjia Forestry District. Elevation in this region is high in the west and low in the east, ranging from 29 m to 3099 m. It has an annual average temperature of ~16.7 °C and annual precipitation of ~900 mm. The soil parent material is dominated by weathered materials from metamorphic rocks and sedimentary rocks, and the main soil types are yellow-brown earth and calcareous soil [28,29]. The Jiangnan Plain is in the central–southern part of Hubei Province (29°26′–31°37′ N, 111°14′–114°36′ E), covering Jingzhou City, Tianmen City, Xiantao City, Qianjiang City, and other administrative regions. The terrain of this area is flat, and it has an annual average temperature of 16.3 °C and annual precipitation of ~1200 mm. The soil parent material is mainly alluvial deposits and lacustrine deposits, and the dominant soil types are paddy and fluvo-aquic soils [29–31]. Southeastern Hubei is in the southeastern part of Hubei Province (29°30′–30°50′ N, 114°30′–116°10′ E), covering Xianning City, Ezhou City, Huangshi City, and other regions. Elevation in this area is high in the south and low in the north, and it has an annual average temperature of ~17 °C and annual precipitation ranging from 1200 mm to 1500 mm. The soil parent material is dominated by weathered materials from magmatic and sedimentary rocks, and the main soil types are yellow-brown earth and red soil [29,32]. The geographical locations, sampling point distributions, and landscapes of the study areas are shown in Figure 1. Detailed information on the 46 sampling sites, including sampling locations, elevation, and regional distribution, is provided in Supplementary Table S1.

2.2. Collection and Determination of Soil Samples

The widely planted *Trichosanthes kirilowii* Maxim. cultivar Wanlou 9 in Hubei Province was selected for this study, and the selected cultivated plots had an average planting age of 3 years. From late July to early August 2025, soil samples were collected from the three *T. kirilowii* planting areas in Hubei Province. A total of 46 cultivated plots were selected as independent sampling sites, including 18 plots in northwestern Hubei, 18 plots in the Jiangnan Plain, and 10 plots in southeastern Hubei. Within each plot, the five-point sampling method was adopted, with the sampling area representing the whole cultivated plot. A soil auger (Ø 5 cm) was used to collect 0–20 cm topsoil samples. The five subsamples from each plot were thoroughly mixed and then reduced by the quartering method, and approximately 1 kg of composite soil sample was packed into

self-sealing bags and transported to the laboratory for subsequent measurement. The soil samples were air-dried at room temperature, gently ground, passed through 2 mm and 0.149 mm sieves according to the requirements of different analyses, and stored in sealed bags until determination. A total of 46 mixed soil samples were collected from the three regions. Concurrently, undisturbed soil samples were collected with cutting rings at corresponding sampling points to determine soil bulk density (BD). All other soil indicators were determined following methods described in relevant literature [33–35]. Briefly, pH and electrical conductivity (EC) were measured via the electrode method; total nitrogen (TN) by a semi-micro Kjeldahl method; total phosphorus (TP) via sodium hydroxide fusion–molybdenum antimony anti-colorimetry; total potassium (TK) by sodium hydroxide fusion–flame photometry; alkali hydrolyzable nitrogen (AN) via an alkali hydrolysis diffusion method; available phosphorus (AP) by sodium bicarbonate–molybdenum antimony anti-colorimetry; available potassium (AK) via ammonium acetate extraction–flame photometry; slowly available potassium (SAK) by hot nitric acid extraction–flame photometry; soil organic matter (SOM) via a potassium dichromate external heating method; cation exchange capacity (CEC) by ammonium acetate exchange–distillation nitrogen titration; and total exchangeable base (TEB) via ammonium acetate exchange–neutralization titration.

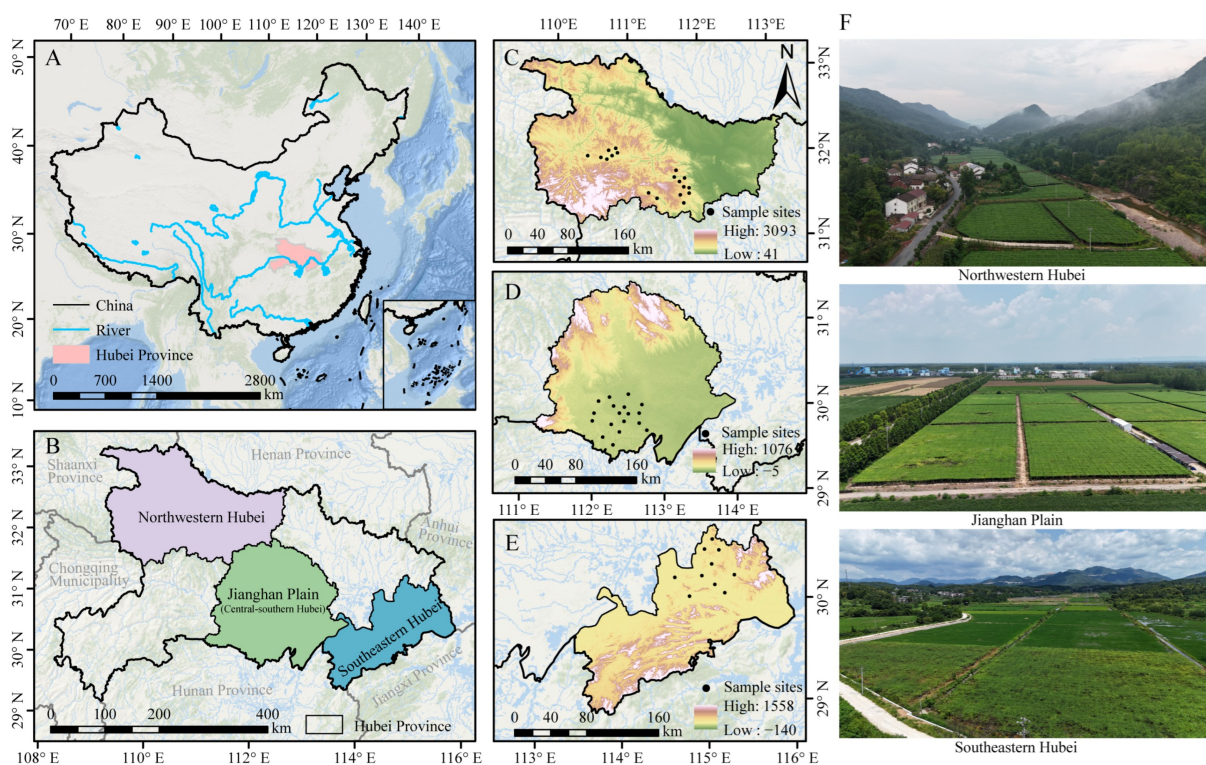


Figure 1. Geographical locations, sample site distributions, and landscape photographs of *Trichosanthes kirilowii* Maxim. planting regions in Hubei Province, China. (A): Location of Hubei Province in China; (B): Locations of northwestern Hubei, Jiangnan Plain (central–southern Hubei), and southeastern Hubei within Hubei Province. (C–E): Elevation maps and spatial distributions of sampling sites in northwestern Hubei, Jiangnan Plain, and southeastern Hubei, respectively. The black circles indicate the locations of the 46 soil sampling sites, including 18 sites in northwestern Hubei, 18 sites in the Jiangnan Plain, and 10 sites in southeastern Hubei. (F): Typical landscapes of *Trichosanthes kirilowii* Maxim. cultivation areas in northwestern Hubei, Jiangnan Plain, and southeastern Hubei.

2.3. Soil Quality Assessment

2.3.1. Construction of the Minimum Data Set

Principal components with eigenvalues ≥ 1 were selected via principal component analysis (PCA), and soil indicators with absolute loading values ≥ 0.5 on the same principal

component were classified into the same group. When a soil indicator was loaded on two principal components simultaneously with both absolute loading values ≥ 0.5 , a correlation analysis was performed, and the indicator was assigned to the group with lower correlations with other indicators [36]. The Norm value of each indicator was calculated, and indicators whose Norm values were within the top 10% range of the maximum Norm value in each group were screened out. For a group containing multiple indicators, when the absolute value of the correlation coefficient between indicators $|r| \geq 0.5$, the indicator with the highest Norm value was preferentially retained to enter the MDS; conversely, when $|r| < 0.5$, all indicators in the group were included in the set [37].

Norm values were calculated as follows:

$$N_{ik} = \sqrt{\sum_{i=1}^k (u_{ik}^2 e_k)} \quad (1)$$

where N_{ik} denotes the Norm value of the i indicator on the first k principal components with eigenvalues ≥ 1 ; u_{ik}^2 denotes the loading value of the i indicator on the k principal component; and e_k is the eigenvalue of the k principal component.

2.3.2. Indicator Standardization

To identify the most appropriate indicator standardization method for soil quality evaluation of *T. kirilowii* planting areas in Hubei Province, we compared the methods: membership function (MF), standard linear function (S_L), and standard nonlinear function (S_{NL}), with standardization eliminating dimensional differences among indicators. Among the methods, the membership function uses ascending, descending, and parabolic function types for standardization processing, which are based on the action direction of indicators on soil quality and their influence on the growth of *T. kirilowii*. The specific formulas and parameters of each function are presented in Table 1 [38,39].

For the S_L method, the following two equations were used

$$S_L = (x - x_1) / (x_4 - x_1) \quad (2)$$

$$S_L = 1 - (x - x_1) / (x_4 - x_1) \quad (3)$$

where S_L denotes the linear function value of each evaluation index, x represents the measured value of each index, and x_1 and x_4 are the minimum and maximum values of the measured values of all indices, respectively. For “the-larger-the-better” type indices, Equation (2) was used; for “the-smaller-the-better” type indices, Equation (3) was used. For “optimal-at-intermediate-value” type indices, when the measured value was lower than the optimal range, Equation (2) was used, and when the measured value exceeded the optimal range, Equation (3) was used [37,40].

For the S_{NL} method, the following equation was used:

$$S_{NL} = \frac{a}{1 + (x/x_0)^b} \quad (4)$$

where S_{NL} denotes the nonlinear function value of each evaluation index, x denotes the measured value of each index, x_0 denotes the average value of each corresponding index, a represents the maximum score achieved by the scoring function, which is equal to 1, and b is the slope of the equation. For the “the-higher-the-better” type indices, the value of b was -2.5 , while for the “the-lower-the-better” type indices, the value of b was 2.5 . For the “optimal-moderate” type indices, when the measured value was lower than the optimal range, the value of b was -2.5 ; otherwise, the value of b was 2.5 [41].

Table 1. Membership functions for soil quality assessment.

Evaluation Indicator	Function Type	Calculation Formula	Membership Function Parameters			
			x_1	x_2	x_3	x_4
TN	Ascending type	$X'(x) = \begin{cases} 0.1 & x \leq x_1 \\ 0.9(x - x_1)/(x_4 - x_1) + 0.1 & x_1 < x < x_4 \\ 1 & x \geq x_4 \end{cases}$	0.34			3.39
TP			0.20			1.30
TK			10.40			28.9
SOM			8.59			54.20
AN			17.10			100.49
AP			0.77			102.26
AK			41.00			403.40
SAK			298.00			954.00
CEC			5.33			35.50
TEB			3.36			31.05
BD	Descending type	$X'(x) = \begin{cases} 0.1 & x \geq x_4 \\ 0.9(x - x_4)/(x_1 - x_4) + 0.1 & x_1 < x < x_4 \\ 1 & x \leq x_1 \end{cases}$	1.05			1.55
EC			0.02			0.24
pH	Parabolic type	$X'(x) = \begin{cases} 0.1 & x \leq x_1, x \geq x_4 \\ 0.9(x - x_1)/(x_2 - x_1) + 0.1 & x_1 < x < x_2 \\ 1 & x_2 \leq x \leq x_3 \\ 1 - 0.9(x - x_3)/(x_4 - x_3) & x_3 < x < x_4 \end{cases}$	5.06	5.50	6.50	8.36

Note: $X'(x)$ denotes the membership function value of each evaluation index, and x represents the measured value of each index; x_1 and x_4 are the minimum and maximum measured values of all indicators, respectively. When the measured minimum and maximum values exceed the three-standard deviation range, they are replaced by the corresponding three-standard deviation values; x_2 and x_3 are the optimal lower bound and optimal upper bound, respectively, of the parabolic membership function. Abbreviations: TN, total nitrogen; TP, total phosphorus; TK, total potassium; SOM, soil organic matter; AN, alkaline hydrolysable nitrogen; AP, available phosphorus; AK, available potassium; SAK, slowly available potassium; CEC, cation exchange capacity; TEB, total exchangeable bases; BD, bulk density; EC, electrical conductivity; pH, soil pH.

In this study, the “the-higher-the-better” type indices were TN, TP, TK, SOM, AN, AP, AK, SAK, CEC, and TEB; the “the-lower-the-better” type indices were BD and EC; and the “optimal-moderate” type index was pH, and its optimal range was set as 5.5–6.5.

2.3.3. Calculation of Soil Quality Index

The standardized values of each soil quality indicator were obtained based on the MF, S_L , and S_{NF} methods. Then, the weight of all soil quality indicators was calculated by PCA, and the soil quality index (SQI) was calculated by the weighted summation method [42]. The formula was the following:

$$SQI = \sum_{i=1}^n W_i N_i \quad (5)$$

where N_i denotes the membership degree of the i soil indicator; W_i denotes the weight of the i soil indicator; and n is the total number of indicators for soil quality assessment in the data set.

2.3.4. Validation of Nash Efficiency Coefficient and Relative Deviation Coefficient

The Nash efficiency coefficient (E_f) and relative deviation coefficient (E_R) were used to evaluate the accuracy of the MDS [43] which were calculated using the following equations:

$$E_f = 1 - \sum_{m=1}^M (R_m - R_c)^2 / \sum_{m=1}^M (R_m - R_a)^2 \quad (6)$$

$$E_R = \left| \sum_{m=1}^M R_m - \sum_{m=1}^M R_c \right| / \sum_{m=1}^M R_m \quad (7)$$

where R_m and R_a denote the SQI calculated based on the TDS and the average value of the SQI, respectively; R_c is the SQI calculated based on the MDS. The closer the E_f value to 1, the closer the SQI calculated based on MDS is to the reference value, which indicates relatively high accuracy. The closer the E_f value to 1, the closer the E_R value is to 0, indicating that the deviation of the SQI is small and the result calculated based on MDS has high accuracy.

2.4. Identification of Soil Obstacle Factors

The obstacle degree model was used to diagnose the obstacle factors affecting soil quality in different *T. kirilowii* planting areas in Hubei Province [44], according to the following equations:

$$M_{ij} = P_{ij}W_i / \sum_{j=1}^n P_{ij}W_i \quad (8)$$

$$P_{ij} = 1 - S_{ij} \quad (9)$$

$$M_j = \sum_{i=1}^n M_{ij} / n \quad (10)$$

where M_{ij} denotes the obstacle degree of the j indicator at the i sampling site; P_{ij} represents the gap between a given soil indicator and its ideal state, where the membership degree equals 1; W_i indicates the weight of the i indicator; S_{ij} is the standardized value of the i indicator at the j sampling site; and M_j is the average obstacle degree of the j indicator.

2.5. Construction of Partial Least Squares Structural Equation Model

To reveal the functional relations among altitude, soil properties, and soil quality, a PLS-SEM was developed to analyze the direct and indirect effects of each latent variable on the SQI. The model latent variables were altitude, soil property factors, and SQI, where topographic factors were represented by altitude and soil property factors were constructed from indicators screened via the MDS. The model was constructed using the plspm package (version 0.6) in R software (version 4.5.0; R Foundation for Statistical Computing, Vienna, Austria). Model performance was evaluated using the coefficient of determination (R^2), path coefficients, direct effects, indirect effects, total effects, and the goodness-of-fit (GOF) index. The statistical significance of path coefficients was assessed by bootstrapping with 5000 resamples, and the corresponding p -values were used to evaluate the significance of path relationships. Considering the relatively limited sample size ($n = 46$), the results were interpreted with caution, and the potential uncertainty associated with spatial variability was considered during model evaluation and result interpretation. Because the present study was based on cross-sectional observational data and management variables such as fertilization and irrigation were not quantitatively recorded, the PLS-SEM results were interpreted as exploratory associations rather than causal evidence.

2.6. Statistical Analyses

Data sorting was performed using Microsoft Excel 2019 (Microsoft Corp., Redmond, WA, USA), and graphs were plotted with Origin 2024b (OriginLab Corporation, Northampton, MA, USA). Analysis of variance was conducted via SPSS 27.0 (IBM Corp., Armonk, NY, USA) to test whether there were significant differences in soil quality and SQI among different *T. kirilowii* planting regions in Hubei Province, followed by post hoc significance testing among means with Tamhane's T2 method. The planting region was considered the independent factor, while individual soil physicochemical properties and SQI were treated as dependent variables. Statistical significance was determined at $p < 0.05$.

3. Results and Analysis

3.1. Soil Fertility Status of *Trichosanthes kirilowii* Planting Regions in Hubei Province

As shown in Table 2, soil quality indicators exhibited significant spatial variations among the three *T. kirilowii* planting regions in Hubei Province. Overall, northwestern Hubei showed a relatively higher soil nutrient status, with significantly greater TN, SOM, CEC, and TEB contents than the Jiangnan Plain and southeastern Hubei, indicating stronger nutrient storage and exchange capacity. In contrast, soils in the Jiangnan Plain exhibited significantly higher pH, EC, and BD values, suggesting relatively alkaline conditions, higher salinity, and greater soil compaction compared with the other regions. Southeastern Hubei generally showed lower nutrient levels, particularly for TN and available nutrient-related indicators. Some indicators, including TP, TK, and AP, showed no significant differences among regions, indicating relatively stable spatial distribution patterns. These results demonstrate that soil quality differences among *T. kirilowii* planting regions were mainly associated with variations in soil nutrient availability, structural properties, and salinity conditions.

Table 2. Differences in soil quality indicators among different planting regions of *Trichosanthes kirilowii* in Hubei Province, China.

Indicators	Northwestern Hubei	Jiangnan Plain	Southeastern Hubei
pH	7.34 ± 0.91 b	8.09 ± 0.22 a	5.50 ± 0.34 c
EC (mS cm ⁻¹)	0.08 ± 0.03 b	0.13 ± 0.04 a	0.07 ± 0.07 b
BD (g cm ⁻³)	1.26 ± 0.10 b	1.39 ± 0.09 a	1.24 ± 0.08 b
TN (g kg ⁻¹)	1.96 ± 0.68 a	1.13 ± 0.30 b	0.89 ± 0.32 b
TP (g kg ⁻¹)	0.64 ± 0.27 a	0.77 ± 0.18 a	0.68 ± 0.25 a
TK (g kg ⁻¹)	20.21 ± 4.35 a	20.83 ± 4.01 a	21.04 ± 4.19 a
SOM (g kg ⁻¹)	32.40 ± 9.67 a	16.83 ± 4.14 b	21.30 ± 8.91 b
AN (mg kg ⁻¹)	59.64 ± 18.25 a	33.72 ± 8.77 b	35.04 ± 14.13 b
AP (mg kg ⁻¹)	28.70 ± 21.20 a	22.51 ± 16.48 a	50.21 ± 36.05 a
AK (mg kg ⁻¹)	182.86 ± 109.21 a	117.37 ± 65.95 ab	82.62 ± 29.97 b
SAK (mg kg ⁻¹)	752.75 ± 161.48 a	490.22 ± 112.94 b	706.90 ± 199.13 a
CEC [cmol(+) kg ⁻¹]	23.23 ± 6.07 a	13.65 ± 3.98 b	9.60 ± 4.44 b
TEB [cmol(+) kg ⁻¹]	17.47 ± 5.57 a	10.99 ± 2.82 b	8.03 ± 5.87 b

Note: Values are the mean ± standard deviation. Different lowercase letters following the values in each row indicate significant differences in soil quality indicators among different regions ($p < 0.05$). Abbreviations: pH, soil pH; EC, electrical conductivity; BD, bulk density; TN, total nitrogen; TP, total phosphorus; TK, total potassium; SOM, soil organic matter; AN, alkaline hydrolysable nitrogen; AP, available phosphorus; AK, available potassium; SAK, slowly available potassium; CEC, cation exchange capacity; TEB, total exchangeable bases.

3.2. Construction of the Minimum Data Set for Soil Quality in *Trichosanthes kirilowii* Planting Regions of Hubei Province

In the PCA, four principal components with eigenvalues ≥ 1 were extracted in total, with 74.40% of the cumulative variance explained (Table 3). For the first principal component, the highest Norm value was for AN, and the Norm values of SOM, TN, and CEC were all within the 10% range of the highest Norm value.

In the correlation analysis, the correlation coefficients between AN and SOM, TN, and CEC were all greater than 0.5 (Figure 2). Therefore, only AN, which has the highest Norm value, was included in the minimum data set. In the second principal component, BD had the maximum Norm value, while the Norm values of all other indicators were not within the 10% threshold range of the maximum value; thus, only BD was retained. Following the

same principle, EC was retained in the third principal component, and TP was retained in the fourth principal component.

Table 3. Results of principal component analysis and Norm values of soil quality indicators.

Indicators	Principal Component				Grouping	Norm Value
	1	2	3	4		
pH	0.173	0.65	0.501	0.099	2	1.207
EC (mS cm ⁻¹)	0.061	0.005	0.915	0.099	3	1.270
BD (g cm ⁻³)	−0.45	0.662	0.276	−0.015	2	1.383
TN (g kg ⁻¹)	0.866	−0.059	−0.117	0.194	1	1.849
TP (g kg ⁻¹)	0.098	0.202	0.218	0.742	4	0.979
TK (g kg ⁻¹)	−0.009	−0.035	−0.174	0.706	4	0.857
SOM (g kg ⁻¹)	0.839	−0.432	−0.054	0.084	1	1.875
AN (mg kg ⁻¹)	0.9	−0.259	−0.019	0.133	1	1.939
AP (mg kg ⁻¹)	−0.096	−0.826	0.148	−0.103	2	1.203
AK (mg kg ⁻¹)	0.748	0.158	−0.069	0.215	1	1.615
SAK (mg kg ⁻¹)	0.254	−0.076	−0.767	0.157	3	1.202
CEC [cmol(+) kg ⁻¹]	0.819	0.271	−0.058	−0.241	1	1.792
TEB [cmol(+) kg ⁻¹]	0.796	0.187	0.11	−0.289	1	1.738
Eigenvalue	4.446	1.981	1.891	1.354	—	—
Variance contribution rate (%)	34.199	15.239	14.548	10.416	—	—
Cumulative contribution rate (%)	34.199	49.438	63.986	74.402	—	—

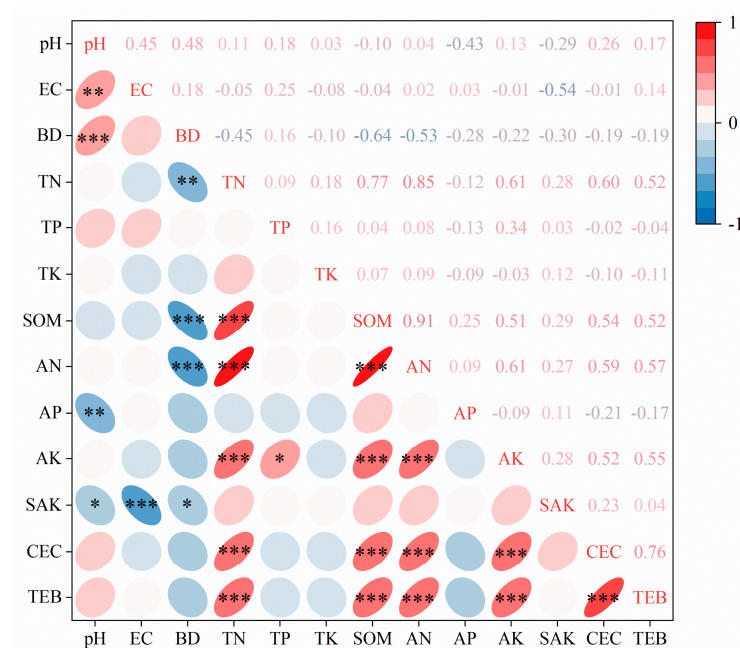


Figure 2. Pearson correlation matrix of soil quality indicators (Pearson's correlation coefficient, r , ranging from -1 to 1). The shape and size of the ellipses indicate the direction and strength of the correlations, respectively. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Abbreviations: pH, soil pH; EC, electrical conductivity; BD, bulk density; TN, total nitrogen; TP, total phosphorus; TK, total potassium; SOM, soil organic matter; AN, alkaline hydrolysable nitrogen; AP, available phosphorus; AK, available potassium; SAK, slowly available potassium; CEC, cation exchange capacity; TEB, total exchangeable bases.

However, statistical screening alone may overlook the differences among indicators in characterizing soil functions. Although SOM is highly significantly positively correlated with AN ($r = 0.909$, $p < 0.01$), the soil function information carried by the two individually

is irreplaceable. As a result, many soil quality assessment studies retain both SOM and AN in the MDS based on functional differences and practical application requirements. Therefore, we followed precedent and included SOM in the MDS. Ultimately, the MDS constructed consisted of five indicators: AN, SOM, BD, EC, and TP.

3.3. Validation of the Minimum Data Set and Calculation of Soil Quality Index

Principal component analysis was used to extract the common factor variances and weights of each soil quality indicator in the TDS and MDS (Table 4). The SQI was calculated according to Equation (5), and the accuracy of the MDS was verified using Equations (6) and (7).

Table 4. Common factor variances and weights of the total data set (TDS) and minimum data set (MDS) for soil quality evaluation in *Trichosanthes kirilowii* cultivation areas of Hubei Province.

Indicators	TDS		MDS	
	Communality	Weight	Communality	Weight
pH	0.714	0.074	—	—
EC	0.851	0.088	0.59	0.16
BD	0.717	0.074	0.695	0.19
TN	0.804	0.083	—	—
TP	0.649	0.067	0.631	0.17
TK	0.529	0.055	—	—
SOM	0.899	0.093	0.931	0.25
AN	0.895	0.093	0.881	0.24
AP	0.724	0.075	—	—
AK	0.636	0.066	—	—
SAK	0.684	0.071	—	—
CEC	0.805	0.083	—	—
TEB	0.764	0.079	—	—

Note: pH, soil pH; EC, electrical conductivity; BD, bulk density; TN, total nitrogen; TP, total phosphorus; TK, total potassium; SOM, soil organic matter; AN, alkaline hydrolysable nitrogen; AP, available phosphorus; AK, available potassium; SAK, slowly available potassium; CEC, cation exchange capacity; TEB, total exchangeable bases.

For the three different indicator standardization methods, all E_f values were greater than 0.7 and all E_R values were less than 0.1, indicating that the MDS constructed in this study showed good agreement with the TDS in the present dataset for soil quality assessment. Among the three methods, the S_{NL} method achieved the optimal performance, with the highest E_f value (0.78) and the lowest E_R value (0.05).

There was a significant positive linear relation between the SQIs calculated based on the TDS and MDS for the three different indicator standardization methods (Figure 3). The regression equation for evaluation via the membership function was $y = 1.051x + 0.002$ ($R^2 = 0.834$, $p < 0.001$); via the linear function $y = 1.051x + 0.008$ ($R^2 = 0.835$, $p < 0.001$); and via the nonlinear function $y = 0.996x + 0.026$ ($R^2 = 0.851$, $p < 0.001$). The results indicated that the nonlinear function standardization method was the most suitable for this study and further confirmed that the constructed MDS showed good agreement with the TDS in the present dataset for soil quality assessment in *T. kirilowii* planting areas of Hubei Province.

When using membership functions for indicator standardization, the SQIs based on TDS and MDS were 0.47 (range: 0.28–0.77) and 0.49 (range: 0.29–0.92) (Figure 4A), respectively, with coefficients of variation of 24.84% and 27.05%, respectively. Under linear functions, the values were 0.41 (range: 0.20–0.75) and 0.43 (range: 0.20–0.91), respectively, with coefficients of variation of 31.58% and 34.00%, respectively. With nonlinear functions, they were 0.46 (range: 0.27–0.73) and 0.49 (range: 0.30–0.76), respectively, with coefficients

of variation of 23.82% and 24.46%, respectively. The mean SQI values obtained from all three standardization methods were less than 0.5 (Figure 4A).

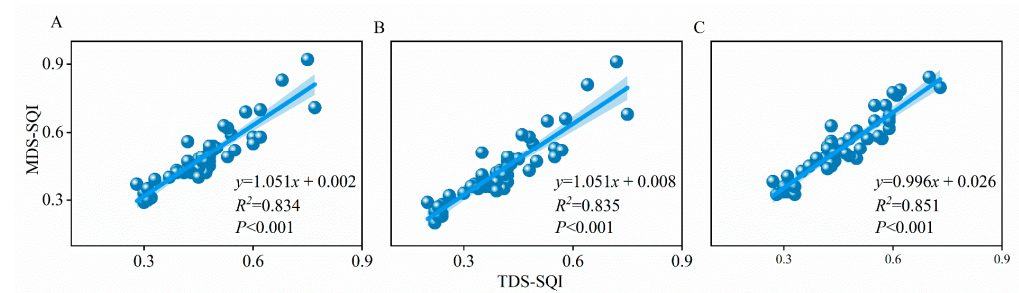


Figure 3. Linear regressions of the relation between soil quality indices (SQI) based on the total data set (TDS) and the minimum data set (MDS) under different standardization methods. (A): Membership function. (B): Linear function. (C): Nonlinear function. R^2 , coefficient of determination.

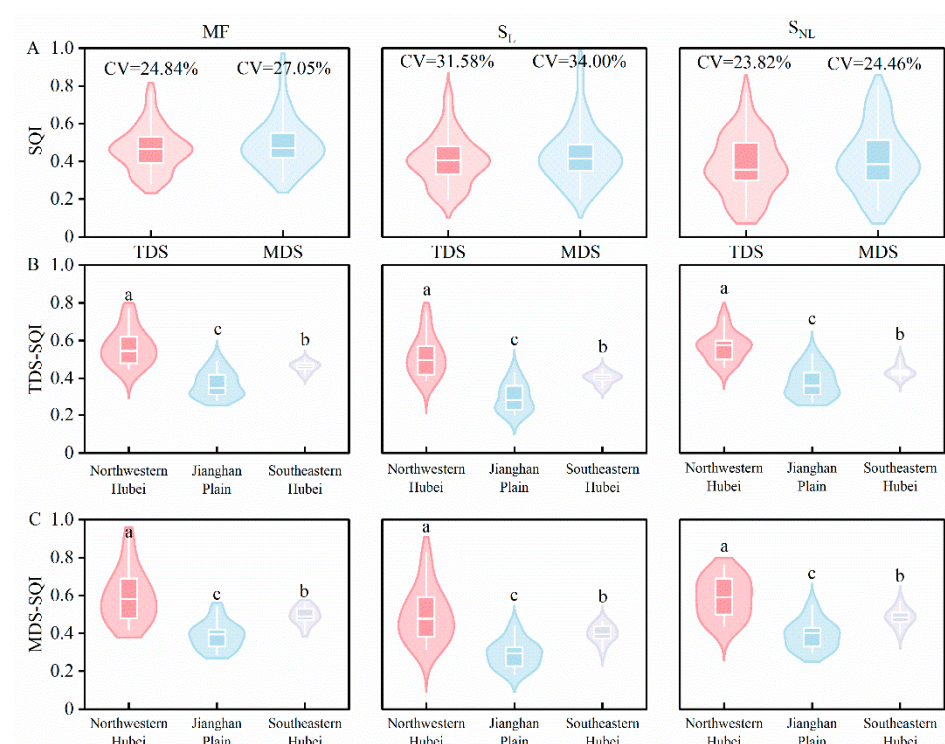


Figure 4. Soil quality indices (SQI) of *Trichosanthes kirilowii* cultivation areas in Hubei Province based on the standardization membership (MF), linear (S_L), and nonlinear (S_{NL}) functions for the total data set (TDS) and minimum data set (MDS). (A) SQI calculated using the TDS and MDS under the three standardization methods. (B) SQI calculated using the TDS for different *T. kirilowii* cultivation regions under MF, S_L , and S_{NL} , from left to right. (C) SQI calculated using the MDS for different *T. kirilowii* cultivation regions under MF, S_L , and S_{NL} , from left to right. The lower boundary of boxes in the boxplot represents the 25th percentile of the data set, the upper boundary represents the 75th percentile, and the horizontal line inside the box indicates the median. The area outside the boxplot represents the data density distribution. Different lowercase letters above the boxes indicate significant differences ($p < 0.05$) in the SQI among different *T. kirilowii* cultivation regions.

Regional comparison results (Figure 4B,C) showed that for membership functions, the mean SQI values based on TDS in northwestern Hubei, Jiangnan Plain, and southeastern Hubei were 0.57, 0.37, and 0.46, respectively, while those based on MDS were 0.59, 0.39, and 0.49, respectively. For linear functions, the corresponding means based on TDS were 0.52, 0.30, and 0.40, respectively, and those based on MDS were 0.55, 0.32, and 0.44, respectively. Under nonlinear functions, the means based on TDS were 0.57, 0.38, and 0.44, respectively,

and those based on MDS were 0.59, 0.39, and 0.49, respectively. Overall, regardless of the standardization method or data set used, the mean SQI values in northwestern and southeastern Hubei were higher than those in the Jiangnan Plain.

3.4. Soil Constraints in *Trichosanthes kirilowii* Cultivation Areas of Hubei Province

The analysis of soil constraint factors revealed that the main limiting factors for *T. kirilowii* cultivation soils varied across the different regions (Figure 5). The soil constraint degrees in *T. kirilowii* cultivation areas of Hubei Province ranged from 0.111 to 0.273. The primary constraints on improving soil quality were SOM (0.278), AN (0.273), TP (0.168), BD (0.170), and EC (0.111). In both northwestern and Jiangnan Plain regions, SOM was the main constraint factor, with constraint degrees of 0.239 and 0.297, respectively. By contrast, in southeastern Hubei, AN was the dominant constraint, reaching a constraint degree of 0.328.

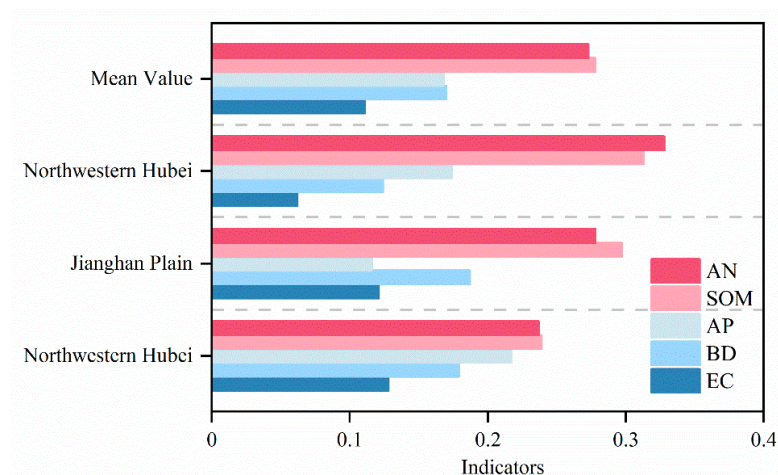


Figure 5. Soil constraint degree for different soil indicators in the three *Trichosanthes kirilowii* cultivation areas of Hubei Province.

3.5. Partial Least Squares Structural Equation Model

A partial least squares path model (PLS-PM) was used to explore the potential relationships among environmental factors and soil quality index (SQI), with good model performance ($R^2 = 0.857$ for SQI, GOF = 0.523; Figure 6). Elevation showed a negative but non-significant association with soil physical properties and salinity (path coefficient = -0.251) but a significant positive association with soil fertility (SOM, TP, AN) (0.371), while its direct association with SQI was weak and non-significant (0.071). Soil physical properties and salinity were significantly negatively associated with both soil fertility (-0.463) and SQI (-0.259), whereas soil fertility showed a strong positive association with SQI (0.720) (Figure 6A). Effect decomposition indicated that soil fertility had the strongest positive contribution to SQI (total effect = 0.720); elevation showed an overall positive association with SQI (total effect = 0.487), mainly through indirect pathways; and soil physical properties and salinity exhibited a negative overall association with SQI, with a total effect of -0.592 (Figure 6B).

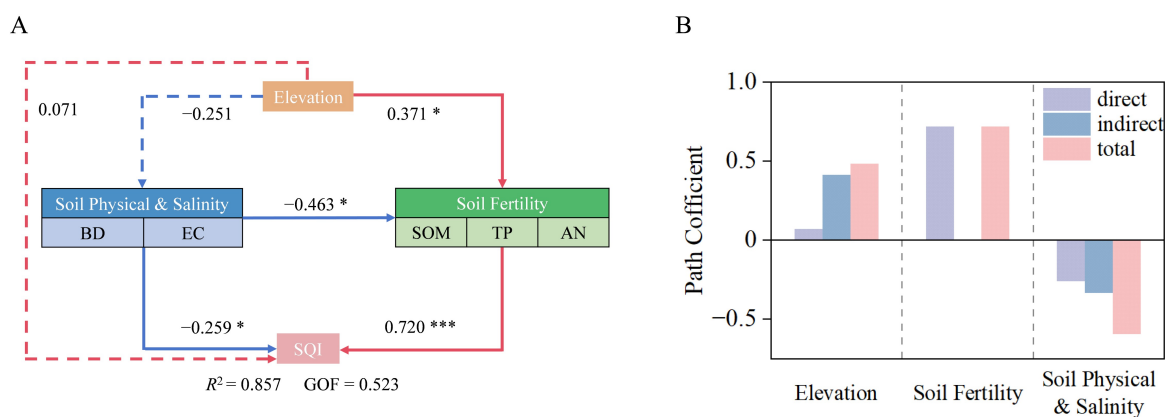


Figure 6. (A): Path diagram and (B): path effect diagram of partial least squares structural equation model. Red and blue arrows indicate positive and negative relationships, respectively; and the numbers on the arrows represent standardized path coefficients. Solid and dashed lines indicate significant and non-significant paths, respectively, based on bootstrap results from 5000 resamples and 95% confidence intervals. Asterisks indicate significance levels based on bootstrap-derived p -values (* $p < 0.05$, *** $p < 0.001$).

4. Discussion

4.1. Spatial Variation in Soil Properties and Applicability of the Minimum Data Set in *Trichosanthes kirilowii* Planting Regions of Hubei Province

Soil quality conditions across different *T. kirilowii* planting regions in Hubei Province, China, were found to have significant differences among the three planting areas. North-western Hubei exhibited relatively higher soil nutrient availability and fertility status, with significantly higher contents of TN, SOM, CEC, and TEB than the Jiangnan Plain and southeastern Hubei. In contrast, the Jiangnan Plain showed higher soil pH, EC, and BD, indicating potential limitations associated with soil alkalization, salinity accumulation, and soil compaction. Such regional differences may be attributed to the combined effects of parent material, topographic conditions, and long-term tillage management practices. Previous studies have demonstrated that parent material plays an important role in regulating soil nutrient accumulation and fertility development. For instance, Wang et al. [45] compared soil properties in citrus orchards developed from five different parent materials and found via principal component comprehensive scoring that the comprehensive soil fertility followed the order plate shale > sandstone > Quaternary red clay > fluvial and lacustrine sediments > limestone, while Hu et al. [46] found that calcium-rich parent material can promote the storage of C, N, and P in soil.

Four principal components were extracted via PCA, which cumulatively explained 74.40% of the total soil information. Then, the five indicators AN, SOM, BD, EC, and TP were screened to form the MDS, with a screening rate of 61.54%. The five indicators respectively reflect the key soil functions of nutrient supply, nutrient storage, physical structure, and salinity environment and thus can comprehensively characterize the soil quality of *T. kirilowii* planting areas. Previous studies have evaluated soil quality in Hubei Province, targeting medicinal plants or Cucurbitaceae crops. For example, Liu et al. [47] evaluated soil fertility quality in paddy–upland rotation areas of Hubei Province and identified the MDS indicators of SOM, AN, AP, AK, available boron, available molybdenum, and available zinc. In the evaluation of soil health of melon fields in Turpan City, Xinjiang, China, Hu et al. [41] identified the soil indicators BD, EC, AP, organic C, and exchangeable calcium. According to Sun et al. [48], the indicators SOM, total calcium, total gallium, total boron, and total magnesium can be used to evaluate the soil quality for *Astragalus*

membranous cultivation. Therefore, previous studies included SOM, AN, BD, and EC as indicators in the MDS, which is consistent with the results of this study.

Although there was a highly significant positive correlation between SOM and AN ($r = 0.909$), both indicators were included in the MDS in this study. The justification for including both is that SOM is an important source of N mineralization but also directly affects the formation of soil aggregates, water and fertilizer retention capacity, and microbial activity [49], and thus, its ecological functions are substantially different from those of AN. Therefore, from the perspective of soil functional integrity, retaining both SOM and AN as indicators best characterizes the soil quality of *T. kirilowii* planting areas. To further evaluate the influence of SOM retention on MDS performance, a sensitivity analysis was conducted by comparing the SQI calculated using the final MDS including SOM with that calculated using a reduced MDS without SOM. The results showed that the SQI based on the MDS including SOM exhibited a stronger relationship with the TDS-derived SQI ($R^2 = 0.851$) than the reduced MDS without SOM ($R^2 = 0.722$) (Figure S1), indicating that retaining SOM improved the representativeness of the MDS. Moreover, SOM is widely used in MDS studies, included in 67.7% [50].

The E_f and E_R values of 0.78 and 0.05, respectively, indicate that the best standardization method was the nonlinear function. In addition, the linear relation between SQIs based on the TDS and MDS was highly significantly positive for S_{NL} ($R^2 = 0.851$, $p < 0.001$), indicating that the MDS showed good agreement with the TDS for soil quality evaluation of *T. kirilowii* planting areas in Hubei Province. The best performance of the nonlinear function standardization method in this study is consistent with the findings of previous studies [51,52].

4.2. Current Status of Soil Quality and Analysis of Obstacle Factors in *Trichosanthes kirilowii* Planting Regions of Hubei Province

Based on calculations using the MDS and nonlinear function, the average SQI of *T. kirilowii* planting regions in Hubei Province was 0.49, with values ranging from 0.30 to 0.76. The SQI ranking across subregions was Northwest Hubei (0.59) > Southeast Hubei (0.49) > Jiangnan Plain (0.39). According to the equal interval method, soil quality was divided into five grades [53]. Overall, the level of soil quality in *T. kirilowii* planting regions in Hubei Province was moderate. However, there were significant regional differences, and the highest soil quality was in Northwest Hubei while the lowest was in the Jiangnan Plain. The lowest soil quality in the Jiangnan Plain may be related to reduced nutrient availability caused by high soil pH and the increased soil compactness caused by high bulk density.

According to the obstacle degree analysis, SOM (0.278) and AN (0.273) were the two main factors limiting soil quality improvement in *T. kirilowii* planting regions of Hubei Province. Their obstacle degrees were very close, indicating that low SOM accumulation and weak N supply capacity are the main problems facing current *T. kirilowii* planting regions. There were significant differences in obstacle factors among regions: the primary obstacle was SOM in both Northwest Hubei (0.239) and the Jiangnan Plain (0.297), while AN (0.328) was the main limiting factor in Southeast Hubei, indicating that strategies to improve soil quality should be targeted for different regions. The primary soil obstacle factors across the whole province are SOM (0.278) and AN (0.273), with obvious regional heterogeneity. Northwest Hubei and the Jiangnan Plain both have SOM as the primary obstacle (0.239 and 0.297, respectively), while Southeast Hubei is mainly constrained by AN (0.328). Further analysis revealed that the average soil pH in Southeast Hubei was a relatively low 5.50, indicating soils were acidic to strongly acidic. Low soil pH can directly inhibit soil microbial activity and microbially mediated N mineralization. It can also reduce the conversion efficiency of organic N to mineral N by affecting the activities of key enzymes such as urease and protease [54], explaining why low AN supply was the

main limiting factor in the southeastern region. In contrast, soil in the Jiangnan Plain was alkaline with pH 8.09. Under high pH conditions, the reduced availability of trace elements such as iron and zinc and potential calcium–magnesium antagonism greatly restrict the accumulation and turnover of organic matter [55,56].

The PLS-SEM indicated that both soil physical properties and fertility characteristics were significantly associated with the SQI, although the contribution of fertility factors was greater than that of physical and salinity factors. These model results indicate that nutrient supply capacity showed the strongest association with soil quality in *T. kirilowii* planting regions of Hubei Province, while soil structure was indirectly associated with the formation of soil quality by affecting nutrient retention and conversion processes. This conclusion is consistent with those of most studies, that is, SOM and N cycling are key processes associated with variation in soil quality [57,58].

This study is the first to construct an MDS for soil quality evaluation that is suitable for *T. kirilowii* planting regions in Hubei Province. We used an innovative approach that combined the obstacle degree model with a PLS-SEM to systematically reveal the spatial differentiation pattern of soil quality and the integrated path of “evaluation–diagnosis–factor identification”, providing a new framework for soil health management of medicinal plants. However, the study still has certain limitations: (1) sampling was only conducted once in the summer of 2025, making it difficult to capture the seasonal dynamics and interannual evolution of soil quality; (2) the number of samples is relatively small ($n = 46$) and management measures such as fertilization and irrigation by farmers were not quantified, so the extrapolation of conclusions is limited by the region and sample size; in addition, the PLS-SEM path coefficients may be sensitive to the sampling structure and indicator selection, and therefore should be interpreted as exploratory relationships rather than robust causal effects and (3) the evaluation indicators were physical and chemical soil properties, and soil biological indicators such as microbial biomass and enzyme activity as well as other parameters such as pollutant levels were not included. Future research should expand the spatiotemporal scale, integrate multidimensional indicators, and conduct specific nutrient requirement experiments for *T. kirilowii* to further improve the evaluation system.

5. Conclusions

The MDS, consisting of AN, SOM, BD, EC, and TP, effectively reflects the soil quality status of *T. kirilowii* planting areas in Hubei Province and can therefore serve as a good agreement for the TDS in regional soil quality assessment. The overall soil quality of *T. kirilowii* planting areas in Hubei Province was moderate, but there was a clear spatial pattern, with the highest soil quality in northwestern Hubei, followed by that in southeastern Hubei, and the lowest in the Jiangnan Plain. Low SOM and AN levels were identified as the primary factors limiting improvement in soil quality, although the dominant obstacle factors differed markedly among regions. Soil fertility was the strongest positive association with improving soil quality, whereas soil physical properties and salinity negatively affected soil quality. In addition, altitude showed an indirect association with soil quality-regulating properties. Therefore, region-specific management practices, particularly organic matter amendment and precision nutrient management, may be considered potential approaches for improving soil quality in *T. kirilowii* planting areas.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12081035/s1>, Table S1. Geographical information of soil sampling sites in *Trichosanthes kirilowii* Maxim. planting regions of Hubei Province, China. Figure S1. Sensitivity analysis of retaining soil organic matter (SOM) in the minimum data set (MDS) based on linear regression with total data set (TDS)-derived soil quality index (SQI). A: Relationship between SQI calculated using the final MDS including SOM and TDS-derived SQI; B: Relationship

between SQI calculated using the reduced MDS without SOM and TDS-derived SQI. All SQI values were calculated using the nonlinear function (SNL) standardization method.

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Conflicts of Interest: The authors declare no conflicts of interest.

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