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Determination of Minimum Data Set for Soil Health Assessment of Farmlands under Wheat–Maize Crop System in Yanting County, Sichuan, China

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Abstract: The assessment of soil health through a robust index system having a sufficient number of indicators is an important step toward sustainable crop production. The present study aimed at establishing a minimum data set (MDS) from soil functional and nutritional attributes using a dual index system to evaluate the soil health of farmlands under wheat (*Triticum aestivum*)–maize (*Zea mays*) crop rotation in Yanting County, Sichuan, China. Farms from 10 villages in the study area were selected, out of which three sites were considered healthy/ideal sites and used as a reference for the remaining seven targeted sites, and soil samples were collected at depth of 20 cm from these farms. The MDS indicators were selected by using principal component analysis (PCA) followed by Pearson's correlation on 25 attributes. Based on significant values, eight attributes were retained in the final MDS, including the sucrase level, pH, wilting coefficient, water holding capacity, organic matter, NK ratio, total potassium, and available phosphorus. Based on the results, most of the farmland soils in Yanting County were in a healthy condition, accounting for 61.71% of the surveyed samples, followed by sub-healthy, degraded, and weak soils, accounting for 19.64%, 9.71%, and 8.93%, respectively. The values of most of the indicators at the targeted sites were significantly lower than those at ideal sites. Thus, specific steps should be taken by adding soil organic matter, combined with other fertilizers, to enhance the microbial biomass, enzymatic activities, and other biological activities in the soil.

Keywords: minimum data set; soil health; soil health index; Yanting County; PCA

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1. Introduction

The world population is expected to increase to 9.8 billion by 2050 [1], which is an alarming situation for those associated with crop production because of the reliance on the same amount of land or even a reduced amount due to its utilization for non-agricultural purposes over time. This has exerted tremendous pressure on land and other natural resources because more and more efforts have been dedicated to enhancing food production, causing the over-utilization and degradation of soil and other natural resources [2]. Therefore, it is high time that strategies should be devised to attain food security without deteriorating the soil health, so that the sustainable management of natural resources can be ensured.

Given the urgency of the matter, the United Nations has set a total of 17 sustainable development goals, out of which 13 goals are related to soil and food production, directly or indirectly [3]. The sustainable management of soil resources is crucial not only for their role as a medium for plant growth but also for the provision of essential ecosystem services (ES) like water purification, carbon sequestration, habitat provision, and nutrient cycling [4]. The smooth functioning of all these processes depends upon the soil health (SH), which can be defined as the ability of soil to support various ecosystem services while producing high-yield and high-quality products with the best soil functions and ensuring sufficient and coordinated soil nutrition that fulfils crop needs [5]. In addition, SH is the combination of certain attributes that represent the soil and is used to evaluate its status; if one or more of these attributes becomes unhealthy, the soil may be considered unhealthy. According to Bi et al. [6], based on the time scale, SH is the "dynamic" and "potential" status in a short period.

Moreover, SH is a term commonly referring to agricultural soils, and it is important to perform a timely assessment of SH because of its immense impact on both the environment and human health [2]. It can be assessed using fundamental components of soil, like soil chemical, physical, and biological indicators. In addition, some scientists also suggest evaluating SH based on soil ecosystem services along with the fundamental components [7,8]. As soil is a heterogeneous and diverse medium, a holistic approach based on a comprehensive set of indicators is required to assess the inter-relationships among these components and the SH status. However, it is difficult to evaluate SH with a large number of indicators; thus, researchers commonly adopt a standard minimum data set (MDS), which is more relevant to soil functions and ecosystem services integrated with soil nutritional properties [3,7,8], through standard scoring and weighting approaches, using advanced or innovative statistical techniques [9], to reduce the analysis and time cost of SH assessment [10]. The MDS is a small subset of soil fundamental components that can be used as an SH assessment tool [11] and can be obtained from a total data set (TDS) using expert opinions, multivariate techniques, and other data reduction techniques like principal component analysis (PCA), discriminant analysis (DA), redundancy analysis (RDA), standard scoring functions (SSF), and analysis of variance (ANOVA) [5,12]. It comprises a sufficient number of attributes that reflect the real SH status and the relationships between soil functions and management goals.

Purple soils formed from purple rocks are widely distributed in China from the southwest to the southeast, covering an area of approximately 219,880 km^2 [13]. In a favorable climate and with the inherent fertile properties of the parent rocks, purple soils cover only 7% of the national arable land and contribute 10% of China's food and livestock feed [14]. Furthermore, out of these 219,880 km^2, a major portion of purple soils is distributed in the Sichuan basin. Yanting County is one of the typical farmland regions dominated by purple soils in the Sichuan basin. The area has 3000 years of cultivation history [15]. Due to continuous cropping, severe erosion, and the excessive use of agrochemicals, the health status of these arable lands is severely affected, causing economic losses and deterioration of the soil's physical, chemical, and biological health.

There is a broad understanding that the health status of cultivable soils directly affects the yield and quality of the crops. However, the current health status of farmlands under wheat (*Triticum aestivum*)–maize (*Zea mays*) crop rotation in Yanting County is still unclear. Therefore, the present study aimed at determining the MDS of SH indicators for selected farmlands under wheat (*Triticum aestivum*)–maize (*Zea mays*) crop rotation for both the evaluation of the SH status and recommendations regarding the sustainable management of these soils.

2. Materials and Methods

2.1. Description of the Study Area

The present study was carried out at selected farmlands in 10 villages of Yanting County (31°16′ N, 105°27′ E), located in the central Sichuan Basin. The total area of the county is 1645 km^2; purple soils are mainly distributed in the area and are classified as Regosols in FAO Taxonomy or Entisols in USDA Taxonomy [16,17]. These farmlands are one of the most fertile regions of the basin because of the favorable climate and the same inherent fertile properties. The climate is subtropical, with an annual mean temperature of 17.2 °C; higher precipitation is observed during summer seasons, with an average rainfall of 836 mm annually [15,18]. Forest and croplands are mainly distributed across the county. The main forest vegetation types are cypress forest and alder–cypress mixed forest, while the main crops are wheat (*Triticum aestivum*)–maize (*Zea mays*) and sweet potato (*Ipomoea batatas)* in drylands and rice (*Oryza sativa*), rape seed (*Brassica napus*), or wheat (*Triticum aestivum*) in paddy fields (Figure 1).

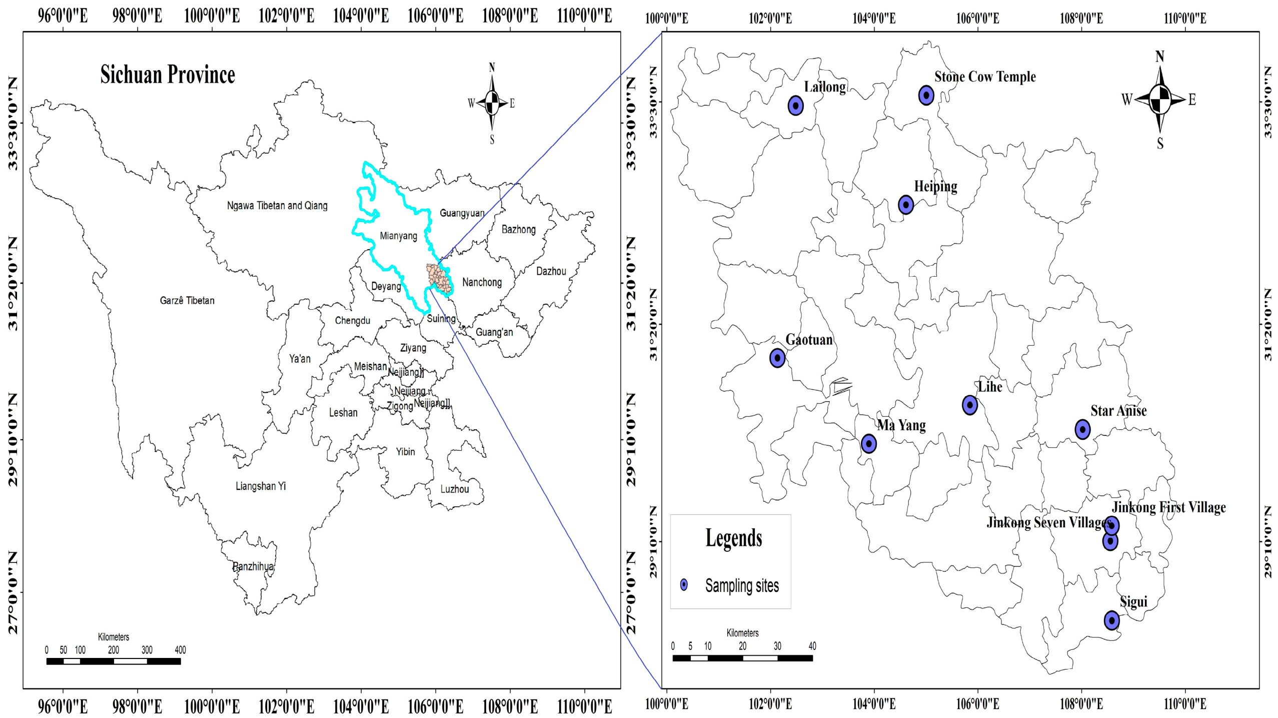

Figure 1. Map of the sampling sites (Yanting County).

2.2. Sampling Sites

The sampling sites (Figure 1) were located in 10 villages of Yanting County (Table 1). Among the selected sites, the first three (E1, E2, E3) were identified as ideal or high-performing soils, while the rest of the sites (C1–C7) were considered targeted or low-yielding soils. The ideal sites were selected based on the feedback of farmers about the performance (yield, quality, and disease incidence) of their previous crop. These sites are mainly under a wheat (*Triticum aestivum*)–maize (*Zea mays*) cropping system.

Table 1. General characteristics of the study area.

Sample ID	Area	Latitude	Longitude	Elevation (m)
E1	Yanting Gaotuan	31°09′42.13″ N	105°24′22.20″ E	387
E2	Yanting Sigui	31°13′52.28″ N	105°18′43.96″ E	363
E3	Yanting Ma Yang	31°01′07.92″ N	105°39′21.68″ E	368
C1	Yanting Lihe	31°11′34.67″ N	105°30′35.84″ E	407
C2	Yanting Star Anise	31°10′24.21″ N	105°37′33.30″ E	423
C3	Yanting Jinkong Seven Village	31°04′59.05″ N	105°39′15.94″ E	432
C4	Yanting Jinkong First Village	31°21′18.07″ N	105°26′39.58″ E	547
C5	Yanting Heiping	31°26′07.77″ N	105°19′51.66″ E	610
C6	Yanting Lailong	31°05′43.31″ N	105°39′20.69″ E	451
C7	Yanting Stone Cow Temple	31°26′37.38″ N	105°27′54.96″ E	671

2.3. Soil Health Assessment Method

The SH status of any area can be assessed using a SH index (SHI), which reflects the current SH status and identifies the most significant and sensitive soil attributes and their interactive relationships [19–22]. In this study, a novel SHI with a "dual index system method", developed by Hussain et al. [5], was used to evaluate the SH status. This index uses a relative method of SH evaluation, which requires healthy/ideal and targeted sampling sites having the same cropping and management history. The ideal sites are referred to as "E" and the targeted sites as "C". The E values are used as a reference for the C values, and the health status is obtained by using the ratio (R) of C to E (average) for the respective index systems and their degree of deviation from "1" (R-1) (Equation (1a,b)). For any evaluated soil, the farther the number of attributes and their ratios deviate from 1, the unhealthier the soil is. Based on this principle, out of the ten sampling sites, three sites (E1, E2, and E3) were considered ideal sites, and the average health status of these sites was used to evaluate soil health. The remaining seven sites (C1–C7) were considered targeted sites based on the yield, quality, and disease incidence of previous crops. The SH indicators were divided into a soil functional index (i), a nutritional index (j), and further subcategories. The indicators of each index were measured to evaluate the E and C values.

$$\frac{\text{Current value of function index}(\text{Ci})}{\text{Expected value of function index}(\text{Ei})} = R\text{i} \tag{1a}$$

$$\frac{\text{Current value of nutrition index}(\text{Cj})}{\text{Expected value of nutrition index}(\text{Ej})} = R\text{j} \tag{1b}$$

2.4. Soil Sample Collection

Soil samples were collected from each site that had the same previous cropping history and inherent properties. For the accurate diagnosis of nutritional characteristics and the functional SH, soil samples were collected from the plough layer at a depth of 0–20 cm, as this depth is the most common sampling depth for soil testing [23,24]. At each sampling location, three transects of 100 m were laid out from the center of the field in different directions, having equal distances (angle ~120°). Each transect was considered as one replicate to cover the wide spatial variability of soil properties. Furthermore, to minimize the effects of fertilization in cropland soils, sampling was performed in April 2021, close to the wheat harvest time. The organic layer was removed before sampling from the soils that contained an organic layer. Three types of soil sampling were performed, viz., composite, microbial, and ring knife sampling. The composite and microbial samples were obtained using an auger, while ring knife samples were obtained with a ring cutter (100 cm^3). These samples were kept in sterile bags and immediately taken to the laboratory for further analysis. In addition, microbial samples were stored at 4 °C.

2.5. Soil Analysis

For the soil analysis, a total of 25 soil indicators were considered, out of which 17 indicators represent the soil functional index and 8 represent the soil nutritional index. For the soil functional index, the bulk density (BD) was obtained using the standard method described by Blake and Hartge [25]. The soil water holding capacity (WHC) and wilting coefficient (WC) were determined using a pressure plate extractor (Soilmoisture Equipment corp santa Barbara, California, USA, model 0775L60). The soil organic carbon (SOC) was quantified by the Mebius method [26]. The soil organic matter (SOM) was calculated using the Van Bemmelen factor (1.724) [27]. The cation exchange capacity (CEC) was measured by the sodium acetate method [28]. The soil carbon–nitrogen ratio (CN ratio) was determined by dividing the value of total SOC by the soil total nitrogen (TN). The soil pH was determined through the potentiometric method using a pH meter with a soil-to-water ratio of 1:2.5 [29]. The selective enzymes were measured using standard methods. The sucrase, urease, polyphenol oxidase (PO), glucosidase, protease, and cellulase lev-els were measured using the 3,5-dinitro salicylic acid colorimetry [30], indophenol blue colorimetry [31,32], iodometric titration [33], nitrophenol colorimetry [34], ninhydrin colorimetry [35], and anthrone colorimetry [36] methods, respectively. The soil micro-bial biomass carbon (MC), microbial biomass nitrogen (MN), and microbial biomass phosphorus (MP) were determined using the high-throughput sequencing method [37].

For the soil nutritional index, the total and available amounts of soil macronutrients were determined by conventional analysis methods. The soil total nitrogen (TN) was measured via the Kjeldahl method [38], while the available nitrogen (AN) was determined by the alkali hydrolysis method [39]. The total phosphorus (TP) was analyzed using the sodium hydroxide alkali fusion–molybdenum antimony colorimetric method [39], and the available phosphorus (AP) was determined using 0.5 mol/L $NaHCO_3$ extractions followed by the molybdenum–antimony colorimetric resistance method [40]. The total potassium (TK) was determined using the sodium hydroxide alkali fusion–flame photometry method [41], and the available potassium (AK) was measured by the photometry method [42]. The soil nitrogen-to-phosphorus ratio (NP ratio) and nitrogen-to-potassium ratio (NK ratio) were calculated by dividing the soil TN by TP and TK, respectively.

2.6. Determination of the Minimum Data Set

SH assessment with a higher number of indicators can increase the analysis cost and be time-consuming. Therefore, to determine the MDS, PCA and Pearson's correlation analysis were employed. Based on the dual index system, i.e., the soil functional index and nutritional index, two PCAs were applied separately to extract the principal components (PCs), and under each PC, only the highly weighted factor loadings (i.e., >0.50) were considered and retained for correlation analysis. The data set was standardized using the Z-scores method before applying PCA.

Correlation analysis was employed to obtain the correlated and uncorrelated attributes. After the analysis, the highly weighted and uncorrelated factors (i.e., >0.60) from the correlation analysis and the attributes with the highest factor loading were retained for the final MDS [43]. In the dual index system, both the functional and nutritional indices were classified into sub-levels; therefore, at least one attribute from each sub-level was retained in the final MDS.

2.7. Statistical Analysis

Health assessments were performed based on the ratios of the dual index system and their degree of deviation from 1 (Equation (1a,b)). Analyses to obtain descriptive statistics, Pearson's correlations, and other statistics were performed in MS Excel 2016 [44] and R Studio software (version (2022.12.0+353)) [45]. Packages including psych, Corrplot, and RColorBrewer were used for the Pearson's correlations analysis. PCA was carried out to find the MDS using SPSS 16.0 [46]. The health status of the sampling sites was assessed based on the total number of healthy indicators for that site. The classification of health status is given in Table 2.

Table 2. Soil health grading levels and evaluation method of health status (Adopted from Hussain et al., Sustainability; published by MDPI, 2022 [5]).

Deviation of Ratios (Ri, Rj) from "1" and Their Health Grading		Classification of Soil General Health Status	
Ratios (Ri, Rj)	**Level**	**Number of Indicators (q = m + n) [1]**	**Health Level**
$0 \leq \lvert RiorRj - 1\rvert < 0.2$	0	≥80% of indicators meet level "0"	Healthy
$0.2 \leq \lvert RiorRj - 1\rvert < 0.4$	1	≥20% of indicators meet level "1"	Sub-healthy
$0.4 \leq \lvert RiorRj - 1\rvert < 0.6$	2	≥20% of indicators meet level "2"	Weak
$0.6 \leq \lvert RiorRj - 1\rvert$	3	≥20% of indicators meet level "3"	Degraded

[1] m is the total number of functional indicators and n is the total number of nutritional indicators.

3. Results

3.1. Soil Functional and Nutritional Properties in the Study Area

The average values for all soil functional and nutritional indicators were significant at the ideal sites (Table 3).

Table 3. Soil functional and nutritional properties of ideal sites.

Indicators [1]	E1	E2	E3	Mean (X)	Max	Min	CV%
BD (gcm^{-3})	1.31	1.41	1.33	1.35	1.41	1.31	7.61
WHC (%)	22.54	25.47	22.01	23.34	25.47	22.01	9.85
WC (%)	17.29	20.57	15.33	17.73	20.57	15.33	18.69
CEC ($mmolkg^{-1}$)	184.04	269.58	209.61	221.08	269.58	184.04	16.56
OM (%)	1.69	1.79	2.27	1.92	2.27	1.69	35.31
CN ratio	11.14	11.93	11.06	11.38	11.93	11.06	11.95
ST (cm)	100.00	100.00	100.00	100.00	100.00	100.00	2.21
pH	8.10	8.10	8.00	8.07	8.10	8.10	15.88
MC ($mgkg^{-1}$)	281.71	212.98	231.64	242.11	281.71	212.98	16.54
MN ($mgkg^{-1}$)	46.23	34.39	40.79	40.47	46.23	34.39	24.56
MP ($mgkg^{-1}$)	10.68	8.03	12.77	10.49	12.77	8.03	21.07
SU (mg Glucose·g^{-1}soil·d^{-1})	73.38	58.33	66.10	65.94	73.38	58.33	15.24
UR (mg NH_4^+-N g^{-1}24 h^{-1})	16.57	14.67	17.13	16.12	17.13	14.67	34.31
Pol. O (mg galhut.g^{-1} soil)	0.20	0.16	0.25	0.20	0.25	0.16	15.59
GL (PNP mg.kg^{-1}.h^{-1})	3.75	3.11	4.02	3.63	4.02	3.11	18.90
PR (mg NH_2-N·g^{-1}soil·d^{-1})	0.28	0.23	0.28	0.26	0.28	0.23	31.70
CE (mg.g^{-1}72 h^{-1})	0.62	0.54	0.69	0.61	0.69	0.54	36.79
TN (%)	0.09	0.09	0.12	0.10	0.12	0.09	29.28
TP (%)	0.12	0.07	0.06	0.08	0.12	0.06	10.61
TK (%)	3.27	4.07	3.07	3.47	4.07	3.07	19.69
AN ($mgkg^{-1}$)	96.30	106.10	98.30	100.23	106.1	96.3	82.80
AP ($mgkg^{-1}$)	33.10	11.90	9.90	18.30	33.10	9.90	66.83
AK ($mgkg^{-1}$)	270.00	117.00	102.00	163.00	270.00	102.00	33.66
NP ratio	0.72	1.18	2.11	1.33	2.11	0.72	40.94
NK ratio	0.03	0.02	0.04	0.03	0.04	0.02	7.61

[1] BD: bulk density, WHC; water holding capacity, WC: wilting coefficient, CEC: cation capacity, SOM: soil organic matter, CN: carbon-to-nitrogen ratio, ST: soil thickness, MC: microbial biomass carbon, MN: microbial biomass nitrogen, MP: microbial biomass phosphorus, SU: sucrase, UR: urease, Pol. O: polyphenol oxidase, GL: glucosidase, PR: protease, CE: cellulase, TN: total nitrogen, TP: total phosphorus, TK: total potassium, AN: available nitrogen, AP: available phosphorus, AK: available potassium, NP ratio: nitrogen-to-phosphorus ratio, NK ratio: nitrogen-to-potassium ratio.

However, the values of the indicators for the targeted sites varied across the study area (Table 4). The sites C1 and C2 showed the highest values for WHC (23.22%), ST (100 cm), AP (12.20 $mgkg^{-1}$), and AK (280 $mgkg^{-1}$), while the highest values for BD (1.66 gcm^{-3}), WC (19.54%), pH (8.50), and TK (4.20%) were observed at C3. Furthermore, site C4 recorded the highest values for CEC (281.72%) and the CN ratio (11.21). Likewise, the highest values for O.M (2.65%), MC (250.98 $mgkg^{-1}$), MN (37.69 $mgkg^{-1}$), MP (11.17 $mgkg^{-1}$), SU (72.02 mg Glucose·g^{-1}soil·d^{-1}), Pol. O (0.30 mg galhut.g^{-1} soil), CE (0.83 mg.g^{-1} 72 h^{-1}), TN (0.16%), the NP ratio (1.87), and the NK ratio (0.05) were found at site C5. TP was the only recorded indicator that was highest at site C6, while the indicators UR (17.55 mg NH_4^+-N g^{-1}24 h^{-1}), GL (3.83 PNP $mgkg^{-1}$.h^{-1}), PR (0.29 mg NH_2-N·g^{-1}soil·d^{-1}), and AN (116 $mgkg^{-1}$) were highest at site C7 (Table 4). In conclusion, significantly higher values of indicators were obtained at site C5, followed by C3 and C7, over sites C1, C2, C4, and C6. However, the values of most of the indicators at the targeted sites were significantly lower than those at the ideal sites.

Table 4. Soil functional properties of targeted sites.

Indicators [1]	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**Mean (X)**	**Max**	**Min**
BD (gcm^{-3})	1.50	1.47	1.66	1.43	1.61	1.46	1.65	1.54	1.66	1.43
WHC (%)	23.22	21.01	22.57	18.18	20.64	18.95	20.65	20.75	23.22	18.18
WC (%)	19.09	15.86	19.54	10.44	16.21	13.45	15.94	15.79	19.54	10.44
CEC ($mmolkg^{-1}$)	192.45	191.66	205.50	281.72	197.79	209.56	199.49	211.17	281.72	191.66
OM (%)	1.36	1.68	0.52	1.14	2.65	2.04	1.55	1.56	2.65	0.52
CN ratio	9.99	9.19	7.73	11.21	9.73	10.30	9.77	9.70	11.21	7.73
ST (cm)	100.00	90.00	50.00	60.00	90.00	95.00	50.00	77.14	100.00	50.00
pH	8.40	8.20	8.50	8.40	8.00	8.10	8.10	8.24	8.50	8.00
MC ($mgkg^{-1}$)	207.49	216.76	151.48	190.48	250.97	224.21	238.25	211.38	250.97	151.48
MN ($mgkg^{-1}$)	30.96	33.98	26.81	29.45	37.69	36.62	33.34	32.69	37.69	26.81
MP ($mgkg^{-1}$)	7.50	9.63	5.25	6.94	11.17	8.45	9.63	8.37	11.17	5.25
SU (mg Glucose·g^{-1}soil·d^{-1})	52.02	58.82	32.21	44.83	72.02	63.48	67.94	55.90	72.02	32.21
UR (mg NH_4^+-N g^{-1}24 h^{-1})	13.59	14.98	10.18	12.17	16.26	15.41	17.55	14.31	17.55	10.18
Pol. O (mg galhut.g^{-1} soil)	0.13	0.18	0.06	0.18	0.30	0.22	0.24	0.19	0.30	0.06
GL (PNP mg.kg^{-1}.h^{-1})	2.90	3.20	2.46	2.76	3.64	3.33	3.83	3.16	3.83	2.46
PR (mg NH_2-N·g^{-1}soil·d^{-1})	0.21	0.23	0.14	0.21	0.27	0.25	0.29	0.23	0.29	0.14
CE (mg.g^{-1}72 h^{-1})	0.45	0.57	0.17	0.38	0.83	0.61	0.72	0.53	0.83	0.17
TN (%)	0.08	0.11	0.04	0.06	0.16	0.11	0.09	0.09	0.16	0.04
TP (%)	0.06	0.08	0.05	0.06	0.08	0.08	0.07	0.07	0.08	0.05
TK (%)	3.93	3.68	4.20	3.24	3.32	3.63	3.53	3.65	4.20	3.24
AN ($mgkg^{-1}$)	84.50	98.30	66.80	57.00	114.00	86.50	116.00	89.01	116.00	57.00
AP ($mgkg^{-1}$)	7.50	12.20	4.80	4.60	10.50	9.80	7.30	8.10	12.20	4.60
AK ($mgkg^{-1}$)	240.00	280.00	108.00	62.00	134.00	122.00	86.00	147.43	280.00	62.00
NP ratio	1.34	1.26	0.75	1.07	1.87	1.42	1.33	1.29	1.87	0.75

[1] The abbreviations for the indicators are defined in the legend of Table 3.

3.2. Selection of the Minimum Data Set

The first PCA was applied to the soil functional index. This index mainly included water and gas regulation, nutrition regulation, and comprehensive regulation functions. The results showed only three PCs with eigenvalues of >1, explaining 59.81%, 14.28%, and 13.0% variance, respectively, with a cumulative variance of 87.1% (Table 5 and Figure 2). In PC 1, there were nine highly weighted attributes, i.e., SU (0.982), UR (0.957), PR (0.954), GL (0.945), CE (0.942), MC (0.936), MP (0.930), pH (−0.903), Pol. O (0.886), MN (0.881), and SOM (0.878). Among the highly weighted attributes, SU recorded the highest factor loading (0.982), and it was positively correlated with the other attributes except for pH, with which it had a strong negative correlation (r −0.903 **). Therefore, SU and pH were retained for the MDS, representing the soil compressive regulation function. However, for the nutrition regulation function, the variable with the highest factor loading among all three PCs was SOM; thus, this indicator was also retained in the final MDS from PC1.

Table 5. Results of principal component analysis (PCA) of the functional index system.

Eigenvector [1]	**Principal Components (PCs)**		
	1	**2**	**3**
SU	0.982		
UR	0.957		
PR	0.954		
GL	0.945		
CE	0.942		
MC	0.936		
MP	0.930		
pH	−0.903		
Pol. O	0.886		

Table 5. *Cont.*

Eigenvector [1]	Principal Components (PCs)		
	1	**2**	**3**
MN	0.881		
SOM	0.878		
WC		0.850	
CEC		−0.696	
WHC		0.670	0.682
BD		0.594	−0.652
ST	0.554		0.628
CN ratio	0.503		0.627
Eigenvalue	10.169	2.428	2.210
Variance (%)	59.819	14.285	13.002
Cumulative variance (%)	59.819	74.104	87.106

[1] The abbreviations for the indicators are defined in the legend of Table 3.

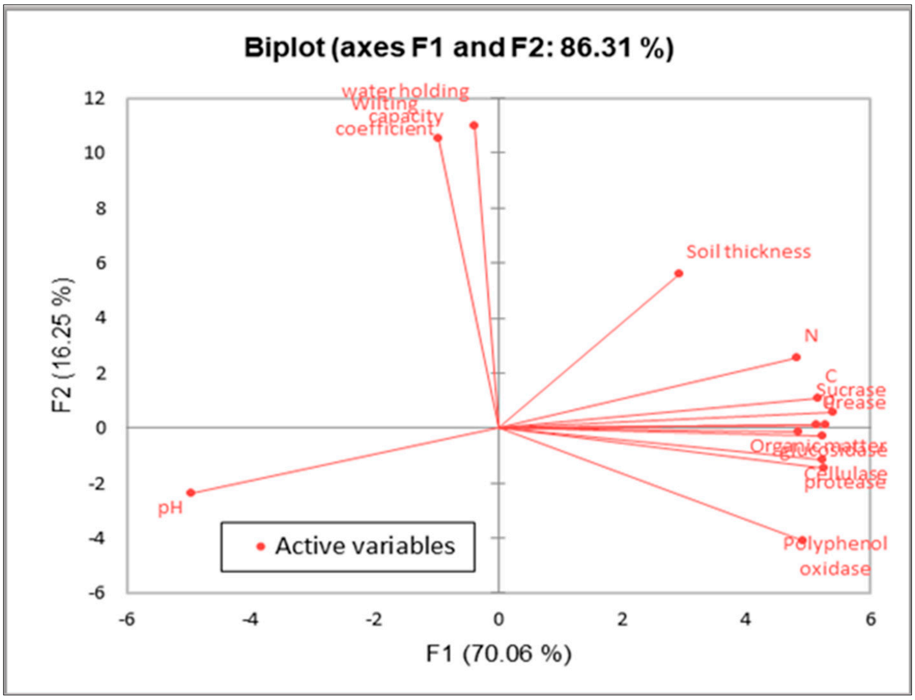

Figure 2. Biplot of soil functional index attributes.

In PC 2, WC (0.850), CEC (−0.696), WHC (0.670), and BD (0.594) were the highly weighted attributes. Among the highly weighted attributes, WC recorded the highest factor loading (0.850) and was positively correlated with WHC and BD, with a weak negative correlation with CEC; thus, WC was retained for the MDS from PC2. In PC 3, WHC (0.682), BD (−0.652), ST (0.628), and the CN ratio (0.627) were the highly weighted attributes. WHC recorded the highest factor loading (0.682) and was positively correlated with ST and the CN ratio, with a weak negative correlation with BD. Thus, WHC was retained for the MDS from PC3 (Table 5 and Figure 3).

The second PCA was applied to the soil nutritional index. The results showed only two PCs with eigenvalues of >1, explaining 47.25% and 31.42% variance, respectively, with a cumulative variance of 78.67% (Table 6 and Figure 4). In PC1, there were five highly weighted attributes: the NK ratio (0.952), TN (0.938), AN (0.762), TK (−0.639), TP (0.570), and the NP ratio (0.652). Among the highly weighted attributes, the NK ratio recorded the highest factor loading (0.952) and was positively correlated with all other highly weighted attributes except for TK, with which it was negatively correlated (−0.706 *). Therefore, both the NK ratio and TK were considered for the MDS from PC1.

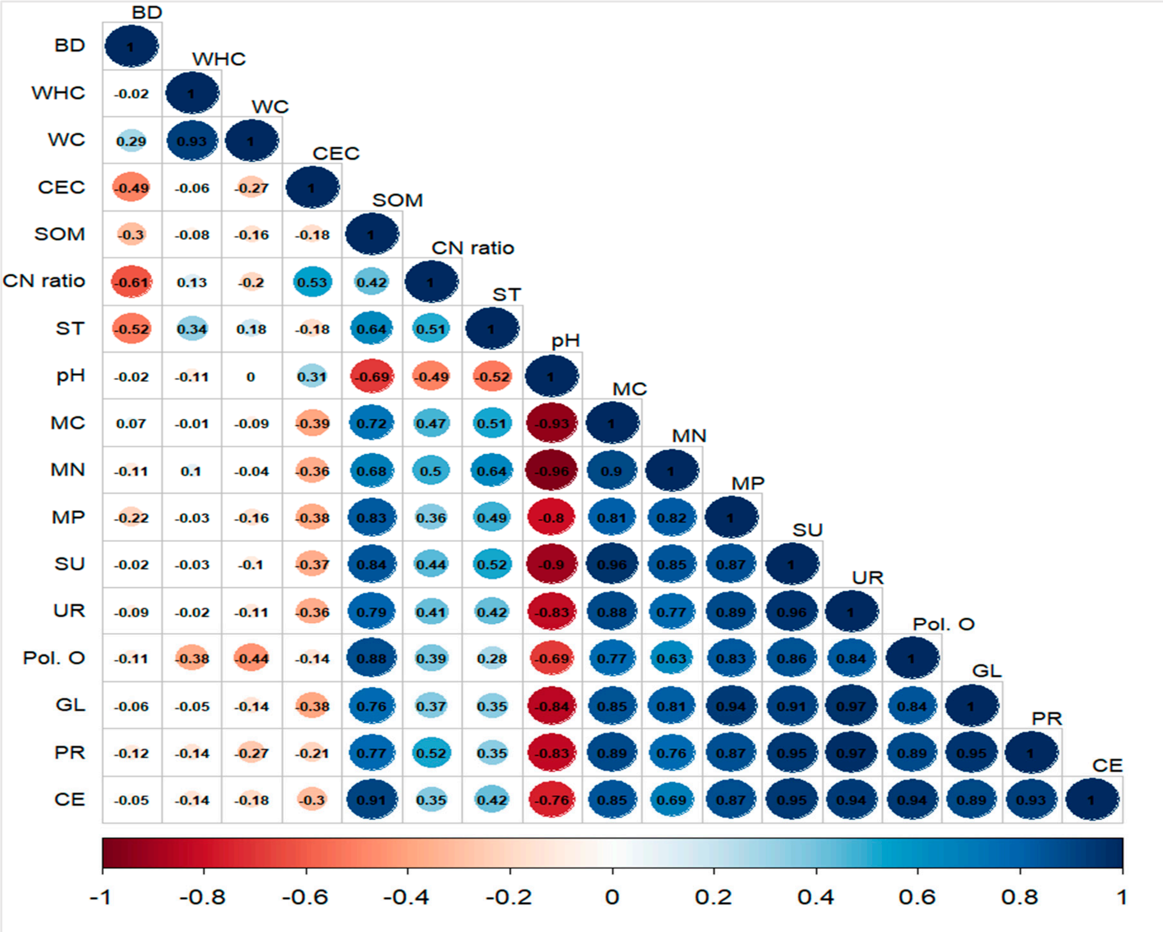

Figure 3. Correlation matrix among the indicators of the functional index (the abbreviations for the indicators are defined in the legend of Table 3).

Table 6. Results of principal component analysis (PCA) of the nutrition index system.

Eigenvector [1]	Principal Components (PCs) 1	2
NK ratio	0.952	
TN	0.938	
AN	0.762	
TK	−0.639	
AP		0.835
TP	0.570	0.780
AK		0.754
NP ratio	0.652	−0.706
Eigenvalue	3.78	2.51
Variance (%)	47.25	31.42
Cumulative variance (%)	47.25	78.67

[1] The abbreviations for the indicators are defined in the legend of Table 3.

Based on the PCA and Pearson's correlation analysis, the eight attributes SU, pH, SOM WC, WHC, the NK ratio, TK, and AP were identified as the final MDS to evaluate the SH status of the study area. In PC2, there were only four highly weighted attributes, i.e., AP (0.835), TP (0.780), AK (0.754), and the NP ratio (−0.706). Among these highly weighted attributes, all variables were positively correlated, except the NP ratio, which showed a weak negative correlation; thus, AP was selected as the MDS indicator from PC 2 (Table 6 and Figure 5).

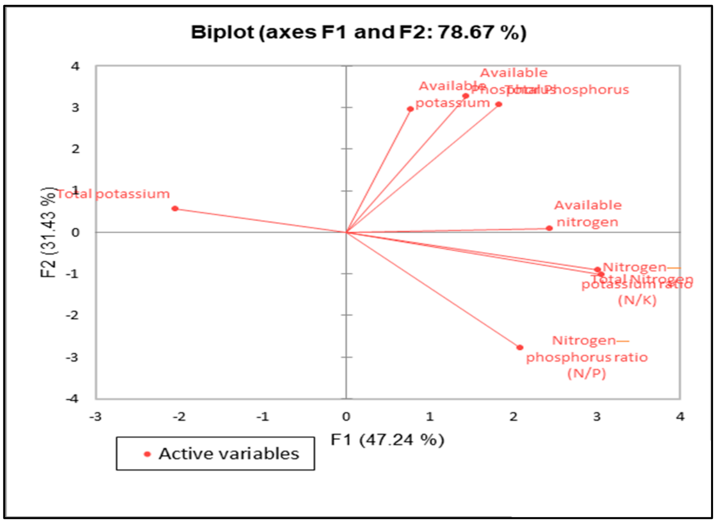

Figure 4. Biplot of soil nutritional index attributes.

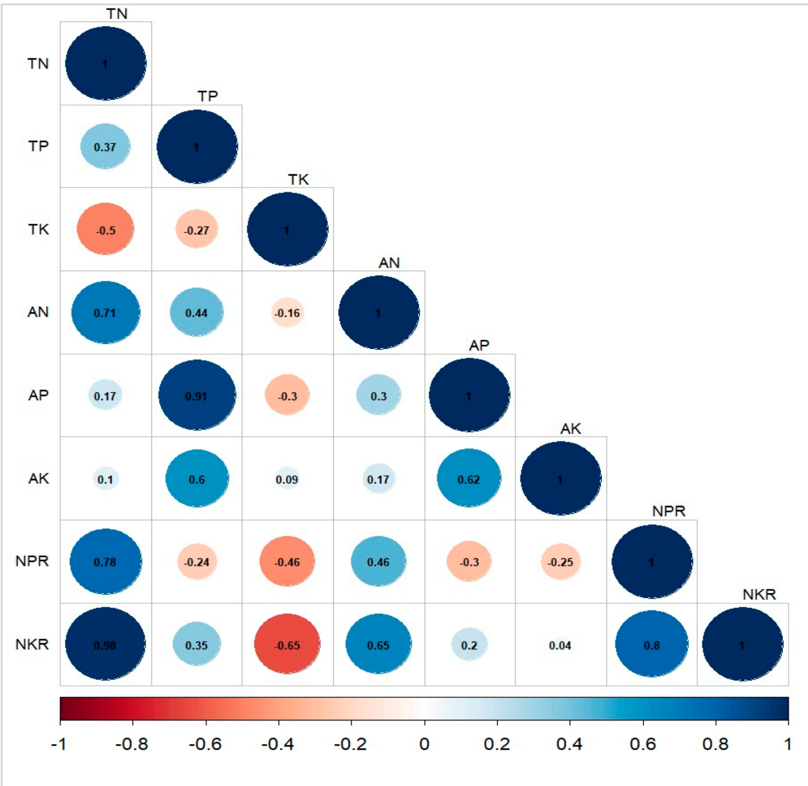

Figure 5. Correlation matrix among the indicators of the soil nutritional index (the abbreviations for the indicators are defined in the legend of Table 3).

3.3. Soil Health Status of Yanting County

The SH was evaluated based on the method described in Table 2. The overall SH status is the sum of the health of all evaluated indicators and the health of the selected sites (Figure 6). Based on the TDS, the results indicated that the soil sampling sites were 61.71% healthy, 20.57% sub-healthy, 10.86% weak, and 76.86% degraded, whereas the results of MDS revealed that the soil sampling sites were 61.71% healthy, 19.64% sub-healthy, 8.93% weak, and 9.71% degraded (Table 7), indicating that most of the sampling sites were under healthy conditions.

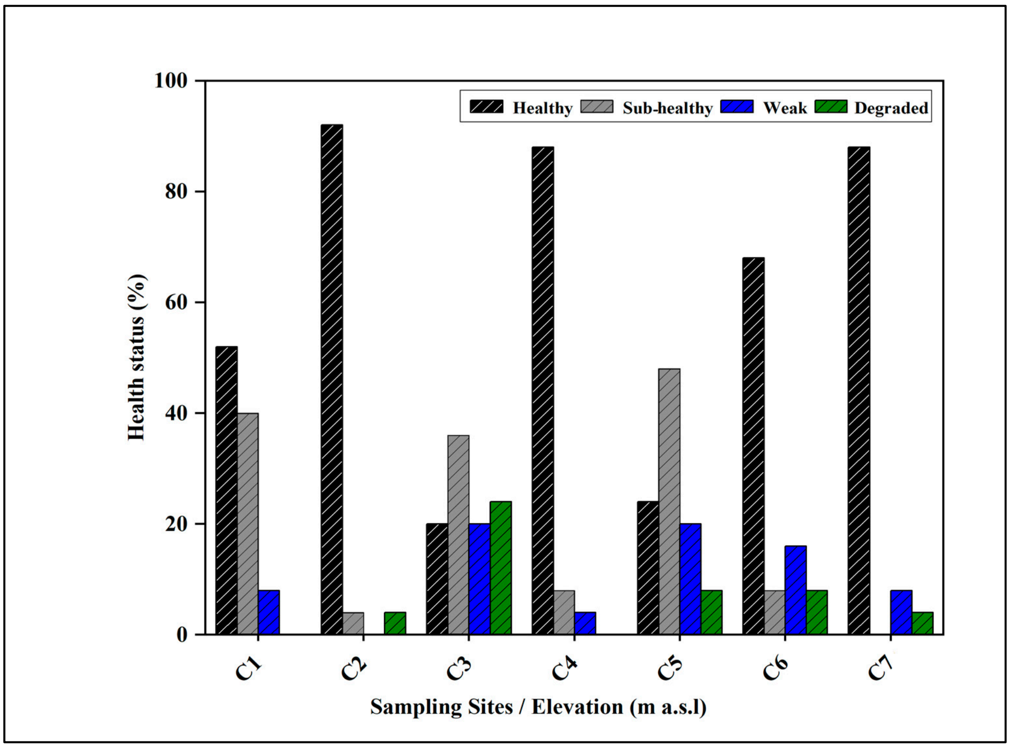

Figure 6. Health status of individual sampling sites.

Table 7. The overall health status of the study area based on the total data set and the minimum data set.

Data Set	Soil Health Status (%)			
	Healthy	**Sub-Healthy**	**Weak**	**Degraded**
Total Data Set	61.71	20.57	10.86	6.86
Minimum Data Set	61.71	19.64	8.93	9.71

4. Discussion

For both ideal and targeted sites, the present study recorded considerable values for all soil functional and nutritional attributes. However, the values for most of the indicators at targeted sites were significantly lower than those at ideal sites, showing the impact of continuous cropping and management strategies [47]. Furthermore, the lower amount of SOM could be the basis of the higher BD and reduced WHC, WC, CEC, and CN ratio, which is consistent with the works of many authors [48–51]. In addition, the higher pH across the study area could be ascribed to the higher amount of $CaCO_3$, which was also reported by Xiao et al. [15]. Important markers of soil microbial biomass and soil enzyme activity include the amounts of nitrogen, phosphorus, and carbon in the soil. These also indirectly reflect the SH status to a certain extent. In the current study, the amounts of microbial biomass and enzymatic activity were also lower at the targeted sites, which is consistent with the findings of Yan et al. [52] and Zhang et al. [53] that soil microbial biomass and enzymatic activity decline with an increasing number of cropping years; the reduction in enzyme activities may be due to the continuous cropping as well as the lower content of SOM. It is also necessary to mention that MC/SOC (%) is a significant attribute of soil health. In this study, in contrast to the individual MC and SOC values, MC/SOC (%) was higher at targeted sites as compared to ideal sites; this variability within the targeted sites suggests that there may be significant differences in soil conditions across these sites. However, to evaluate the overall SH, this should be contextualized with other SH indicators. The crucial elements of SH evaluation are the soil nutritional indicators.

These variables are employed not just to assess agricultural SH but also as markers of forest SH. In a recent study, Yu et al. [54] used these characteristics to assess the SH of alkaline soils under various land uses, while Kingsley et al. [43] used them to determine the MDS for vegetable fields. In the current study, there were variations in the total and available amounts of soil macronutrients. Low soil nitrogen and phosphorus contents were observed among most of the targeted sites, which is consistent with the findings of Zhong et al. [55] and Gao et al. [56] that there is greater variability in soil nitrogen and phosphorus in the purple soil of the Sichuan basin. In contrast, the amount of soil potassium was higher across the study area due to its parent material, which was also reported by Gao et al. [56] and Xiao et al. [15].

The final appearance of sucrase, pH, WC, WHC, the NK ratio, TK, and AP in the final MDS obtained using PCA and Pearson's correlation is consistent with the works of Kingsley et al. [43] and Rahmanipour et al. [57]. All the indicators retained for the final MDS (sucrase, pH, WC, WHC, SOM, the NK ratio, TK, and AP) in the current study are uncorrelated and independent, except for SOM, which was retained to represent the soil nutrition regulation function; consequently, their appearance is considered significant. Among the indicators, WC and WHC represent the soil's water and gas regulation, SU and pH represent soil comprehensive regulation, SOM reflects soil nutrition regulation functions, and the NK ratio, TK, and AP represent the major nutrients required for plant growth.

The SH status obtained using the TDS and MDS was almost equivalent for the healthy, sub-healthy, and weak categories. A small difference was observed for the degraded category due to the nonappearance of some degradation indicators in the MDS, but in both conditions, a major portion of the soil sampling sites was under the healthy category. Moreover, SH mostly depends on biological indicators, and due to the lower availability of organic substances, lower microbial biomass and enzymatic activities were recorded. Therefore, specific steps should be taken by adding soil organic matter in combination with other fertilizers to enhance the microbial biomass, enzymatic activities, and other biological activities in the soil.

5. Conclusions

Eight attributes, including soil functional and nutritional indicators, were selected for a MDS for SH evaluation using PCA followed by Pearson's correlation. Among the functional indicators, WC and WHC represent the soil's water and gas regulation, SU and pH represent soil comprehensive regulation, and SOM reflects soil nutrition regulation functions. Meanwhile, among the soil nutritional indicators, the NK ratio, TK, and AP represent the macronutrients required for plant growth. These selected indicators can be used to monitor changes in soil health over time, which is critical for promoting sustainable agriculture and maintaining soil health.

A majority of the examined farmlands in Yanting County were at a healthy level, accounting for 61.71% of the analyzed samples, followed by 19.64% at a sub-healthy level, while the weak and degraded levels accounted for 8.93% and 9.71%, respectively. Among the sampling sites, significantly higher values were obtained for the indicators at site C5, followed by C3 and C7, over sites C1, C2, C4, and C6. However, the values of most of the indicators at the targeted sites were significantly lower than those at the ideal sites. Thus, specific steps should be taken, including the addition of organic matter combined with other fertilizers, to enhance the microbial biomass, enzymatic activities, and other biological activities in the soil.

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