

Integrated Agrochemical Characterization of an Agricultural Land through Composite Indices and Statistical Analysis

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Abstract. The study summarizes the agrochemical characterization of an agricultural land module, composed of five plots (A1–A5) from the area of Ciacova locality, Timiș County, Western Plain of Romania. The agricultural module studied had an area of 137.05 ha, in the arable category. The study was based on 28 soil samples and 16 agrochemical indicators of soil reaction (pH, hydrolytic acidity – HA, sum of base cations – SBC, base saturation degree – V, aluminium – Al), organic matter (humus – H), and supply of macro- and microelements (NI, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn). Descriptive statistics, area-weighted means, standardized indicators, Nutrient Balance Index (NBI), Soil Quality Index (SQI), Pearson's correlations, multivariate analysis, hierarchical cluster analysis, and effect sizes (η^2) for plot differentiation were calculated. The overall average pH was 6.33, in the slightly acidic–neutral range, and the surface-weighted averages confirmed a predominantly slightly acidic reaction. The weighted average SQI was 0.48 and the weighted average NBI was 0.62, indicating an intermediate agrochemical quality, with relatively better nutritional balance than the overall quality score. PCA separated plot A1 from the others of the plots, and cluster analysis confirmed the same differentiation. The key indicators resulting from the combination of the PCA contribution and the relationship with SQI were H, NI, Mg, S, Cu, Mn and HA, which suggested that the land cannot be adequately characterized by a single index, but by a group of indices covering organic matter, soil reaction and cation/nutrient balance.

Keywords: agricultural land, cluster analysis, key indicators, macroelements, microelements, multivariate analysis, NBI, soil quality indices, SQI

INTRODUCTION

Soil quality is functionally defined by the soil's ability to support biological production, maintain environmental quality, and contribute to the health of plants, animals, and humans (Doran and Parkin, 1994; Doran and Jones, 1996; Karlen et al., 1997; Doran, 2002). In agriculture, this definition is useful because it converts a large set of physical, chemical and biological measurements into an applied assessment of agricultural land functioning, relevant for fertility management (amendment, fertilization) and long-term monitoring (Andrews and Carroll, 2001; Andrews et al., 2002; Karlen et al., 2003).

Chemical indicators are frequently used in soil monitoring programs because they are management-sensitive, can be measured in a standardized manner, and describe essential agronomic processes: nutrient availability, soil reaction, buffering capacity, base saturation, and aluminum toxicity risk (Smith and Doran, 1996; Havlin et al., 2014; Brady and Weil, 2017). In particular, soil pH controls phosphorus solubility, micronutrient mobility, microbial activity and the chemical form of aluminum, thus being a central indicator in the interpretation of fertility (McLean, 1982; McBride, 1994; Sposito, 2008).

Organic matter and humus influence cation exchange capacity, soil particle aggregation, water retention and nitrogen cycling; therefore, H and NI indicators are important for assessing the sustainability of agricultural lands (Nelson and Sommers, 1996; Lal, 2004; Bünemann et al., 2018). In parallel, phosphorus and potassium are main macroelements that determine crop productivity and response to fertilization, and calcium, magnesium and sulfur complete the assessment of nutrient balance through their role in plant nutrition, structure and metabolism (White and Brown, 2010; Marschner, 2012; Havlin et al., 2014).

Microelements (e.g. Fe, Mn, Cu, Zn, B, Mo) are required in small amounts, but can become limiting or excessive depending on pH, texture, organic matter and redox conditions; their interpretation together with soil reaction is essential for responsible agronomic recommendations (Lindsay and Norvell, 1978; Alloway, 2008; Kabata-Pendias, 2011). From this perspective, a complete agrochemical profile should not be reduced to a single raw value, but should be analyzed as a system of correlated indicators (Cambardella et al., 1994; Bünemann et al., 2018).

Multivariate methods allow for dimensionality reduction and identification of a minimum set of indicators, especially when variables are correlated with each other. PCA has been used in numerous soil quality studies for the selection of representative indicators and the calculation of weighted indices (Hotelling, 1933; Kaiser, 1960; Jolliffe, 2002; Andrews et al., 2002). At the same time, hierarchical cluster analysis provides a

classification of plots into similar agrochemical groups, being useful for zoning differentiated management (Ward, 1963; Everitt et al., 2011).

In the case of agricultural lands in western Romania, integrated agrochemical interpretation is relevant because soils may present spatial variations in reaction, humus and nutrient supply, and correction recommendations must be adapted to both the reaction class and the balance between nutrients (Ciobanu, 2007; Agapie et al., 2025). Soil fertility is reflected in the status of agricultural crops, and optimization of fertilization systems is necessary (Boldea and Sala, 2010; Sala et al., 2020). Starting from these considerations, the objective of the work is the statistical and multivariate characterization of the five plots, the calculation of NBI and SQI, the identification of the indicator or group of key indicators and the formulation of recommendations for soil reaction correction and agrochemical management.

MATERIAL AND METHODS

The agricultural land, arable category, considered in the study was located in the area of Ciacova, Timis County, Romania, Figure 1. The study was conducted during 2021, with the objective of evaluating soil quality based on agrochemical indices and through integrated methods of mathematical and statistical analysis.



Figure 1. Ciacova ATU, Timis County, Romania (google maps)

Data analyzed

The database included five agricultural plots (A1–A5), the area of each plot (Area, ha), the number of soil samples and agrochemical indicators. The land area considered in the study was 137.05 ha. 28 soil samples were taken, with an average area of about 5 ha for each sample (A1 = 7 samples, A2 = 7 samples, A3 = 3 samples, A4 = 5 samples and A5 = 6 samples). Each soil sample consisted of 25 sub-samples. The analysis of the agrochemical indices was done in the SC Cartare Agrochimica SRL Laboratory, using accredited laboratory methods. 16 agrochemical indicators were considered determined: pH (soil pH, H₂O), HA (hydrolytic acidity, me/100 g soil), SBC (sum of base cations, me/100 g soil), V (base saturation degree, %), Al (aluminium, mg/kg), H (humus, %), NI (nitrogen index, %), P (phosphorus, mg/kg), K (potassium, mg/kg), Ca (calcium, mg/kg), Mg (magnesium, mg/kg), S (sulfur, mg/kg), Fe (iron, mg/kg), Mn (manganese, mg/kg), Cu (copper, mg/kg) and Zn (zinc, mg/kg).

According to the database, the indicators pH, HA, SBC, V and Al described the soil reaction; indicators H and NI described the supply of organic matter and nitrogen; indicators NI, P and K described the main macroelements; indicators Ca, Mg and S described the secondary macroelements; indicators Fe, Mn, Cu and Zn described the trace elements.

Descriptive statistics and weighted averages

The data series were processed for descriptive statistical analysis, based on specific statistical parameters. The coefficient of variation was calculated according to Equation (1).

$$CV = (sd/\bar{x}) \times 100 \quad (1)$$

where: CV – the coefficient of variation; sd – the standard deviation; $\bar{x}$ – arithmetic mean.

The area-weighted average was calculated at the indicator level, according to Equation (2)

$$\bar{x}_w = \sum (A_j \times \bar{x}_j) / \sum A_j \quad (2)$$

where: $\bar{x}_w$ – weighted average; A_j – area of j plot; $\bar{x}_j$ – the mean of the indicator in plot j.

The use of area weighting is justified when plots are of different sizes and a representative value for the whole plot is sought.

Standardization of NBI and SQI indicators

Indicators have different units and ranges. Indicators were standardized by z-score transformation to eliminate the effect of different measurement units (Johnson and Wichern, 2018; Hair et al., 2019), according to Equation (3).

$$Z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j} \quad (3)$$

where: Z_{ij} – the standardized value (z-score) of indicator j for sample i; x_{ij} – the measured value of indicator j in sample i; $\bar{x}_j$ – arithmetic mean of indicator j calculated for all analyzed samples; s_j – standard deviation of indicator j; i – agrochemical sample index; j – the index of the agrochemical indicator.

Standardization transforms all variables to the same statistical scale, with mean equal to 0 and standard deviation equal to 1. Thus, indicators expressed in different units (e.g. mg kg⁻¹, cmol(+) kg⁻¹, %, pH, etc.) can be directly compared and used in multivariate analyzes such as PCA and cluster analysis.

Linear score for favorable indicators

For composite indices, variables were transformed to the 0–1 scale. For indicators of the "higher is more favorable" type, the linear score was used, according to Equation (4).

$$S_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (4)$$

where: S_i – the standardized score of indicator i; x_i – the observed value; $x_{\max}$ – the maximum value of the indicator i; $x_{\min}$ – the minimum value of the indicator i.

The score is between 0 and 1; 0 – the least favorable value; 1 – the most favorable value.

The score for the restrictive indicators (HA and Al)

For the indicators of the "lower is more favorable" type (HA and Al), the score according to Equation (5) was used.

$$S_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} \quad (5)$$

where: S_i – the score of the indicator i; x_i – the observed value of the indicator i; $x_{\max}$ – the maximum value of the indicator i; $x_{\min}$ – the minimum value of the indicator i.

For hydrolytic acidity (HA) and mobile aluminum (Al), lower values indicate a more favorable agrochemical status, which is why the scale is inverted.

Optimal function for pH

For pH, an optimum type function was used, with a maximum around 6.5, compatible with the general interpretation for agricultural mineral soils, according to Equation (6).

$$S_{pH} = 1 - \frac{|pH - 6.5|}{d_{\max}} \quad (6)$$

where: S_{pH} – the score associated with the soil reaction; pH – the measured value of the soil reaction; 6.5 – the optimal value considered for most agricultural crops; $d_{\max}$ – the maximum observed deviation from the optimal value.

The maximum score (1) is obtained for pH ≈ 6.5, and more acidic or alkaline values receive progressively lower scores.

Nutrient Balance Index (NBI)

The Nutrient Balance Index (NBI) was calculated from the standardized 0–1 scores of N, P, K, Ca, Mg, S, Fe, Mn, Cu, and Zn, Equation (7), as an inverse function of the relative variability among nutrients.

$$NBI = \frac{1}{1 + CV_{\text{nutrient}}} \quad (7)$$

where: NBI – Nutrient Balance Index; CV_{nutrient} – coefficient of variation of the nutrient score considered (N, P, K, Ca, Mg, S, Fe, Mn, Cu and Zn) for the same sample.

NBI quantifies the supply balance of nutrients; values close to 1 indicate balanced distribution of nutrients; values close to 0 indicate pronounced nutritional imbalances.

Soil Quality Index (SQI)

Soil Quality Index (SQI) was calculated as the mean of five category indices: soil reaction (CI_1), organic matter (CI_2), main macrolelements (CI_3), secondary macrolelements (CI_4), and microelements (CI_5), according to Equation (8). This approach followed the logic of additive and weighted indices used in soil quality assessment (Andrews et al., 2002; Andrews et al., 2004; Karlen et al., 2001; Karlen et al., 2003; Bünemann et al., 2018).

$$SQI = \frac{CI_1 + CI_2 + CI_3 + CI_4 + CI_5}{5} \quad (8)$$

where: SQI – Soil Quality Index; CI_1 – soil reaction category subindex; CI_2 – organic matter category subindex; CI_3 – main macrolelements category subindex; CI_4 – secondary macrolelements category subindex; CI_5 – microelements category subindex.

The meaning of SQI is interpreted according to the grid: $SQI < 0.40 \rightarrow$ low quality; $SQI = 0.40 - 0.60 \rightarrow$ moderate quality; $SQI = 0.60 - 0.80 \rightarrow$ good quality; $SQI > 0.80 \rightarrow$ very good quality.

Correlations, PCA, clustering

The relationships between the indicators were evaluated by correlation analysis, Pearson's r (Pearson, 1896). Multivariate analysis (EFA - Exploratory Factor Analysis) was applied to all indicators, the complete series of data. Multivariate analysis (PCA – Principal Component Analysis) was used to reduce dimensionality and identify dominant agrochemical gradients (Jolliffe, 2002; Jolliffe and Cadima, 2016). Cluster analysis was applied to standardized plot means, using Euclidean distance and Ward's method (Ward, 1963; Everitt et al., 2011).

Effect size η^2 (Eta squared)

The differentiation of plots for each indicator was assessed by unifactorial ANOVA, and the size of the effect was expressed by η^2 , Equation (9), which represents the proportion of the total variation explained by the analyzed factor (Cohen, 1988; Richardson, 2011).

$$\eta^2 = \frac{SS_{\text{between}}}{SS_{\text{total}}} \quad (9)$$

where: η^2 – the squared Eta coefficient; SS_{between} – sum of squares explained by the analyzed factor (plot); SS_{total} – the total sum of the squares.

Eta squared (η^2) expresses the proportion of the total variation of an indicator that can be explained by the belonging of the samples to a certain plot; $\eta^2 = 0.10 \rightarrow$ 10% of the variation of the indicator is explained by the plot; $\eta^2 = 0.50 \rightarrow$ 50% of the variation is explained by the plot; $\eta^2 = 0.80 \rightarrow$ differences between plots explain 80% of the observed variation. The interpretation of η^2 was used as a measure of the proportion of the total variation explained by the sample belonging to the plot, according to the values in Table 1.

Table 1. Interpretation thresholds Eta squared (η^2)

η^2	Effect magnitude
<0.01	Negligible
0.01 – 0.06	Small
0.06 – 0.14	Moderate
>0.14	Large

In the context of the present study, regarding the agrochemical characterization of the land, η^2 is very useful because it allows the identification of the indicators that best differentiate the five plots. Indicators with high η^2 can be considered candidates for the group of key indicators of agrochemical soil characterization. This is even more valuable than choosing a single key indicator.

PAST software v.4.14 (Hammer et al., 2001) and JASP software v.0.16.2 (2022) were used for data processing and the generation of graphical representations.

RESULTS AND DISCUSSIONS

Descriptive statistical analysis

The pH values ranged from 5.81 to 6.75, with an overall mean of 6.33, and CV of 5.1%, indicating little variability in the reaction. Indicators with higher relative variability were Mg (CV = 34.1%), Al (CV = 29.1%), Mn (CV = 27.2%), HA (CV = 26.4%) and SBC (CV = 26.2%). This structure shows that the agrochemical differentiation of the soil is mainly generated by secondary cations, potential acidity and reaction-sensitive micronutrients, Table 2.

Table 2. Descriptive statistical analysis results of the agrochemical indicators

	pH	HA	SBC	V	Al	H	NI	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
N	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28
Min	5.81	0.86	17.76	73.36	1.40	2.27	2.06	20.57	140.00	526.16	152.96	0.83	98.10	26.02	4.65	1.06
Max	6.75	4.99	42.36	98.62	3.85	3.52	3.44	39.66	240.00	1023.15	541.84	1.22	154.18	57.67	8.04	1.44
Mean	6.33	3.42	28.09	89.81	2.42	2.81	2.52	30.85	193.57	777.85	349.18	1.03	127.17	40.41	5.91	1.28
Std. error	0.06	0.17	1.39	1.11	0.13	0.06	0.07	1.14	5.64	24.58	22.50	0.02	2.87	2.08	0.16	0.02
Stand. dev	0.32	0.90	7.35	5.89	0.70	0.32	0.36	6.05	29.84	130.07	119.04	0.11	15.19	11.01	0.87	0.11
Median	6.39	3.73	25.77	90.46	2.26	2.80	2.51	31.09	200.00	765.94	371.43	1.02	127.94	42.16	5.92	1.32
25 prentil	5.98	2.95	23.09	87.43	1.92	2.58	2.19	24.54	165.00	667.46	253.03	0.97	114.62	27.23	5.07	1.19
75 prentil	6.60	3.90	33.70	93.33	3.01	3.01	2.70	36.25	220.00	890.20	428.94	1.13	139.53	50.63	6.55	1.35
Skewness	-0.26	-1.05	0.30	-0.90	0.61	0.25	0.53	-0.31	-0.12	0.04	-0.16	0.12	-0.14	-0.06	0.47	-0.55
Kurtosis	-1.50	1.60	-1.02	1.07	-0.38	-0.21	0.10	-1.07	-1.01	-0.64	-0.91	-0.63	-0.96	-1.49	-0.37	-0.81
Geom. mean	6.32	3.25	27.17	89.62	2.32	2.79	2.50	30.24	191.29	767.14	326.88	1.03	126.28	38.89	5.85	1.27
Coeff. var	5.07	26.44	26.16	6.56	29.11	11.33	14.09	19.59	15.42	16.72	34.09	10.34	11.95	27.25	14.76	8.83

Area weighted averages

The area-weighted mean for pH was 6.32, very close to the arithmetic mean, indicating that the distribution of soil reaction is relatively balanced across areas. For P and K, the weighted means were 30.68 and 192.51, respectively, and for Ca and Mg they were 776.71 and 348.59, respectively, Table 3. The large weight of plots A1, A2 and A5 stabilizes the overall mean but does not eliminate the multivariate contrast between A1 and the other plots.

Table 3. Area-weighted means for the whole agricultural land

Index	pH	HA	SBC	V	Al	H	NI	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
Area-weighted mean	6.32	3.42	28.27	89.92	2.41	2.81	2.53	30.68	192.51	776.71	348.59	1.03	127.48	40.50	5.91	1.28

NBI and NQI indices

The average area-weighted NBI was 0.621 and the average area-weighted SQI was 0.473. At plot level, the highest SQI was calculated for A2 (0.526), followed by A3 (0.517) and A1 (0.503), Table 4. A4 had the lowest SQI (0.365), mainly due to the low score for organic matter. NBI was relatively higher in A3 and A5, suggesting that nutrient balance is better than overall quality score in some plots.

Table 4. Plot-level NBI and NQI indices

Plot	NBI	SQI
A1	0.591	0.503
A2	0.640	0.526
A3	0.661	0.517
A4	0.584	0.365
A5	0.647	0.450

Characterization by index categories

Category analysis shows that A1 plot has the best profile for soil reaction and microelements, but lower scores for secondary macroelements. A2 and A3 plots have better scores for secondary and main macroelements, and A4 is distinguished by a low organic matter score, Table 5. A5 plot has an intermediate position, with relatively favorable reaction and acceptable nutritional balance, but without dominating all categories.

Table 5. Category-level standardized scores by plot

Plot	Soil reaction	Organic matter	Primary macronutrients	Secondary macronutrients	Micronutrients
A1	0.630	0.560	0.360	0.245	0.720
A2	0.488	0.477	0.669	0.611	0.383
A3	0.429	0.422	0.743	0.528	0.461
A4	0.440	0.057	0.296	0.690	0.341
A5	0.568	0.323	0.376	0.551	0.434

Soil reaction classes and correction recommendations

The pH classification indicated that plot A1 is in the neutral class, plots A2, A3 and A4 are slightly acidic, and plot A5 is moderately acidic, Table 6. For plot A1, no general calcareous amendment is recommended, only monitoring. For plots A2–A4, moderate and localized corrections are recommended only if the culture system has higher pH requirements, or if Al and HA increase over time. For A5, where the average pH is below 6.0, it is recommended as a priority to monitor hydrolytic acidity (HA) and mobile aluminum (Al) and, after confirmation by mapping/analysis, apply calcareous amendments in doses calculated according to soil texture, pH target and crop requirements. In general, amendment should be avoided as a uniform intervention throughout the plot, as pH does not indicate severe acidity in all plots.

Table 6. Soil reaction classes by plot

Plot	Mean pH	Reaction class
A1	6.61	slightly acidic
A2	6.41	slightly acidic
A3	6.20	slightly acidic
A4	6.28	slightly acidic
A5	6.01	moderate acidic

Correlations between indicators

The strongest relationships were H–NI ($r = 0.887$), Mg–Cu ($r = -0.760$), Al–S ($r = 0.698$), Al–Mn ($r = -0.679$) and P–Fe ($r = -0.632$), Figure 2. The H–NI relationship confirms the consistency between organic matter (humus, H) and the nitrogen index (NI), while the correlations between Mg, Cu, Mn, Al, and S suggest a combined control of reaction, cations, and micronutrient availability.

The negative P-Fe correlation is consistent with fixation/precipitation interactions and pH control of phosphorus and iron availability.

Multivariate analysis

The multivariate analysis EFA (Exploratory Factor Analysis) was applied to describe and understand the positioning of the agrochemical indices of the soil in relation to the main components. Bartlett's test and Chi-squared test indicated a high level of statistical confidence in the applied EFA analysis ($p < 0.001$).

The loading values of the factors are presented in Table 7, and the characteristics of the factors are presented in Table 8. The graphic representation resulting from the EFA analysis is presented in Figure 3, which shows the factor loading in the principal components and the mode of action of the factors (positive action - green color; or negative action - red color).

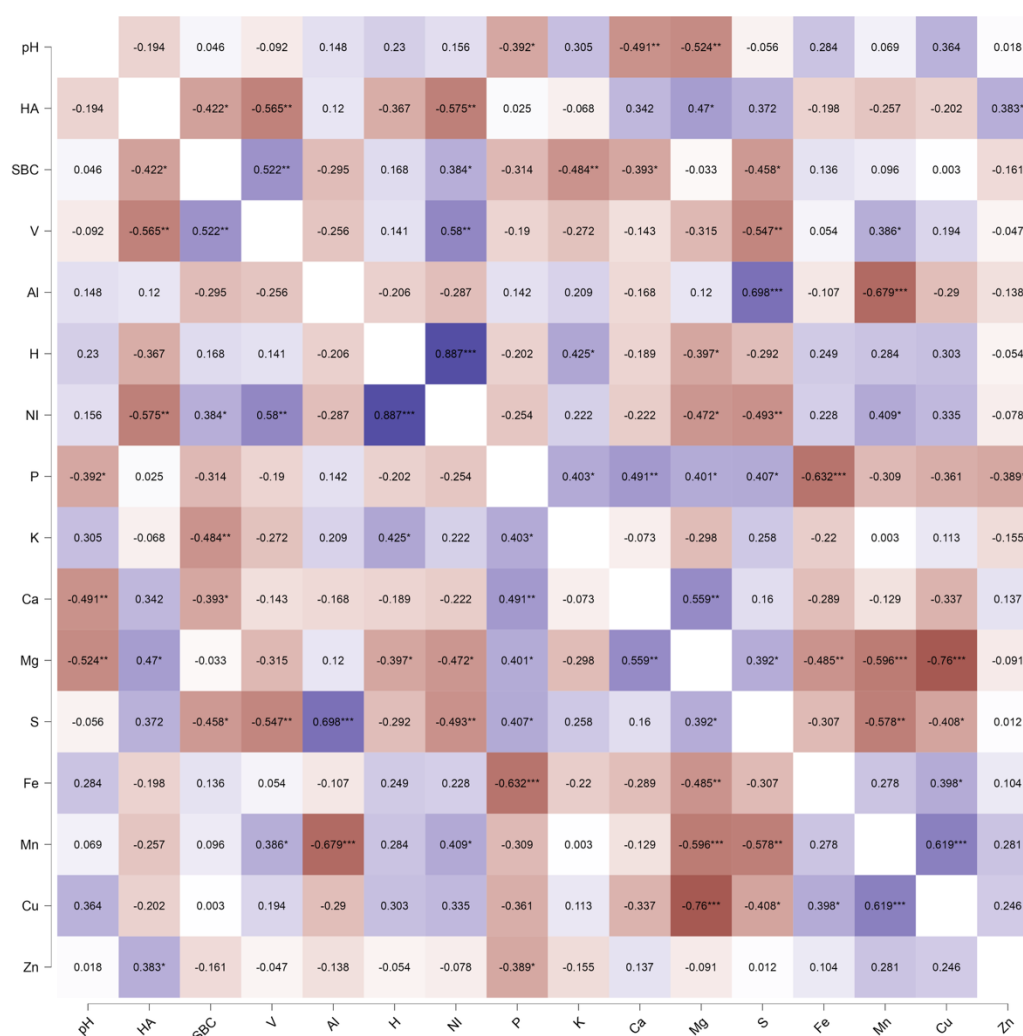


Figure 2. Pearson Correlation Matrix of Agrochemical Indicators

Table 7. Factor loading values

Indices	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Uniqueness
Mg	-0.818					0.003
Ca	-0.712					0.383
P	-0.669					-0.014
pH	0.661					0.528
Mn		0.878				0.162
Al		-0.755				0.326

S	-0.677			0.305
K		0.847		0.136
SBC		-0.662		0.311
H			0.955	0.003
NI			0.813	0.054
HA				0.731
V				0.430
Fe				0.600
Cu				0.345
Zn				0.618

Note: varimax rotation method

Table 8. Factor characteristics

Factors	Unrotated solution			Rotated solution		
	SumSq. Loadings	Proportion var.	Cumulative	SumSq. Loadings	Proportion var.	Cumulative
Factor 1	5.029	0.314	0.314	2.929	0.183	0.183
Factor 2	2.183	0.136	0.451	2.851	0.178	0.361
Factor 3	1.880	0.118	0.568	2.047	0.128	0.489
Factor 4	1.531	0.096	0.664	1.950	0.122	0.611
Factor 5	0.908	0.057	0.721	1.743	0.109	0.720

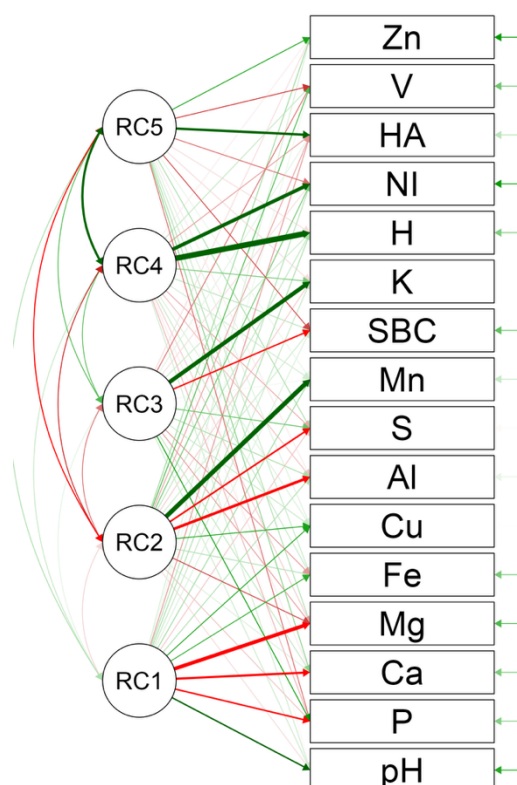


Figure 3. Path diagram with graphic representation of the loading and action mode of the factors

PCA and identification of key indicators

The first two principal components explained 75.70% of the variation in plot means, Table 9, Figure 4. PC1 mainly separated the gradient associated with organic matter (H), NI, Mg and trace elements, and PC2

contributed to the secondary differentiation of cationic profile and soil reaction. Indicators with the best combined ranks, considering PCA loadings and correlation with SQI, were: H, Mg, NI, S, Cu, Mn, HA, Table 10. The recorded results supported the idea that the agricultural land does not have a single key agrochemical indicator, but a key group: H–NI for organic matter and nitrogen, Mg–S for secondary macroelements, and Cu–Mn–HA for the soil reaction component / microelements.

Table 9. PCA explained variance

Component	Explained variance (%)	Cumulative variance (%)
PC1	52.90	52.90
PC2	22.77	75.67
PC3	18.10	93.77
PC4	6.23	100.00
PC5	0.00	100.00

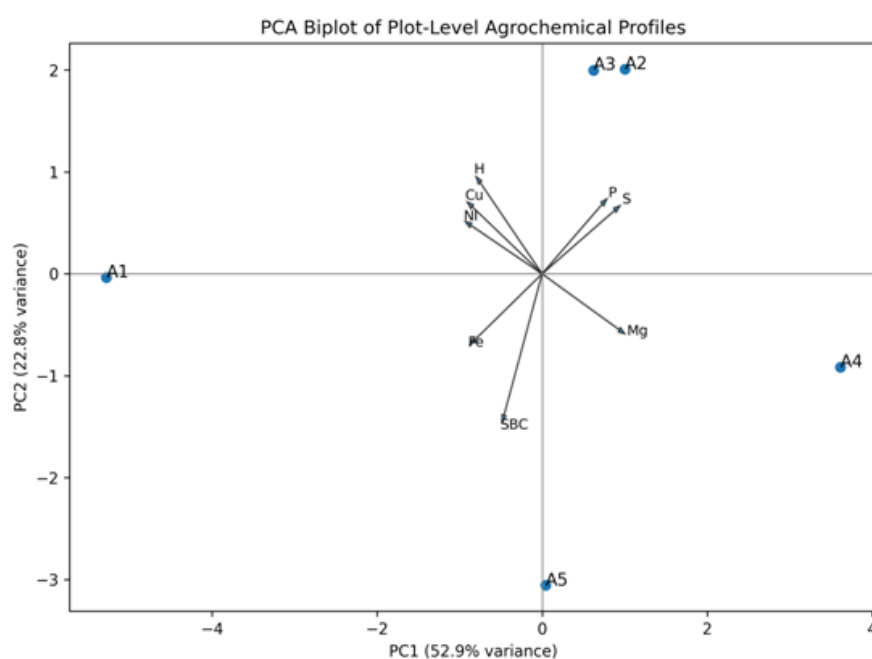


Figure 4. PCA biplot of plot-level agrochemical profiles

Table 10. Candidate key agrochemical indicators ranked by PCA and SQI relationship

Index	PCA_loading_score	abs_r_with_SQI	rank_mean
H	0.201	0.868	2.50
Mg	0.207	0.360	3.50
NI	0.189	0.879	3.50
S	0.203	0.291	6.00
Cu	0.199	0.337	6.50
Mn	0.174	0.440	7.00
HA	0.166	0.466	7.00
V	0.179	0.358	8.00
Fe	0.193	0.134	8.50
SBC	0.187	0.179	9.00

Cluster analysis and parcel differentiation

Hierarchical cluster analysis separated plot A1 into a distinct group, while plots A2, A3, A4 and A5 formed a second group, Table 11, Figure 5.

Table 11. Cluster membership and index values by plot

Plot	Cluster	Mean SQI	Mean NBI
A1	2	0.503	0.591
A2	1	0.526	0.640
A3	1	0.517	0.661
A4	1	0.365	0.584
A5	1	0.450	0.647

The differentiation of A1 was explained by the more favorable profile of the soil reaction and the high microelement score, while the other plots were closer by the level of P, K, Ca and Mg and by the slightly more pronounced acidity profile. From a practical point of view, the result recommends differentiated management of plots; plot A1 can be followed as a reference zone for soil reaction and microelement content, and plots A4 and A5 require attention for organic matter, respectively moderately acidic soil reaction.

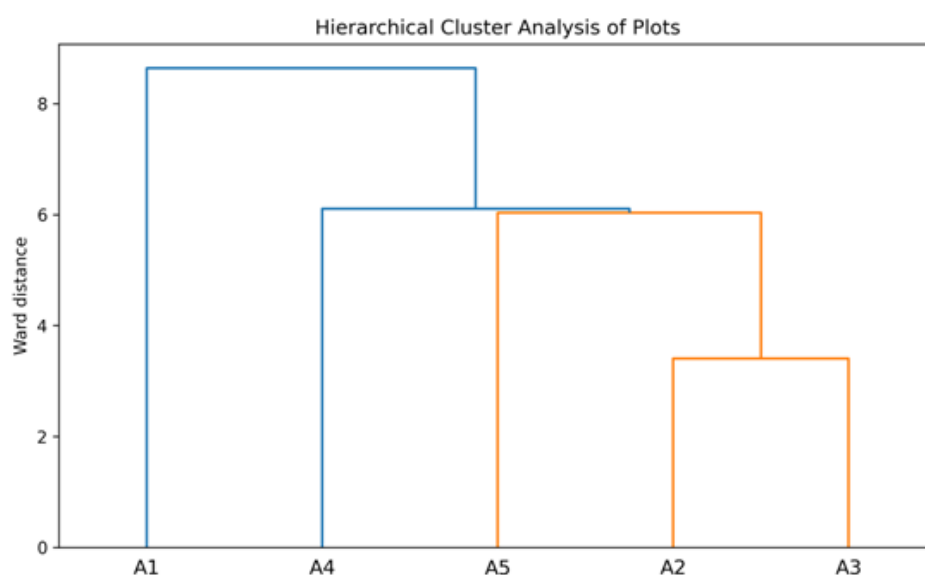


Figure 5. Hierarchical Cluster analysis of plots

The cluster analysis also evaluated the degree of similarity of the agrochemical plots on which the soil samples were taken (28 soil samples). The values of the ten agrochemical indicators, candidates for key indicators (H, Mg, NI, S, Cu, Mn, HA, V, Fe, SBC) were used in the analysis. The dendrogram in Figure 6 resulted, in conditions of statistical safety (Coph.corr. = 0.766). Two distinct clusters resulted, a cluster C1 which included 11 subplots, and cluster C2 which included 17 subplots.

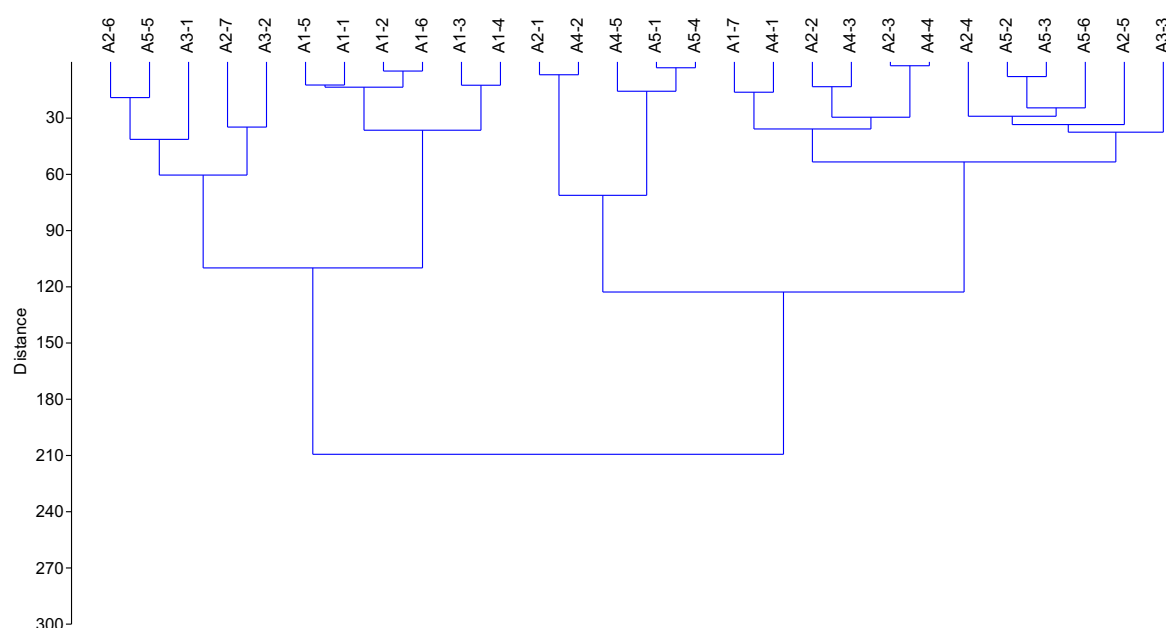


Figure 6. Cluster dendrogram with grouping of agrochemical subplots based on similarity

The highest level of similarity was recorded between subplots A2-3 and A4-4 ($SDI = 2.02$), followed by subplots A5-1 and A5-4 ($SDI = 3.11$), and subplots A1-2 and A1-6 ($SDI = 4.85$), respectively..

η^2 and the importance of the plot effect

The η^2 values showed that the differences between plots explained a very large proportion of the variation in P ($\eta^2 = 0.878$), K ($\eta^2 = 0.779$), Mg ($\eta^2 = 0.570$), H ($\eta^2 = 0.549$), Fe ($\eta^2 = 0.486$), pH ($\eta^2 = 0.452$) and NI ($\eta^2 = 0.429$), Table 12. Therefore, zoning into plots is statistically justified, especially for major and minor macroelements and organic matter.

Table 12. ANOVA effect size by indicator (top 12 η^2 values)

Index	Indicator	F	p	Eta_squared
7	P	41.432	0	0.878
8	K	20.292	0	0.779
10	Mg	7.608	0	0.570
5	H	7.005	0.001	0.549
12	Fe	5.426	0.003	0.486
0	pH	4.740	0.006	0.452
6	NI	4.324	0.009	0.429
14	Cu	3.780	0.017	0.397
11	S	3.517	0.022	0.380
2	SBC	2.683	0.057	0.318
9	Ca	2.595	0.063	0.311
13	Mn	2.544	0.067	0.307

The results indicated a predominantly slightly acidic to neutral terrain with moderate variability in some fertility indicators. Soil pH is not severely limiting overall, but plot A5 should be monitored for correction as the average is in the moderately acidic class. Soil reaction is an index that influences the availability of nutrients, and the knowledge of spatial variability is important for ameliorative measures and differentiated management of soil resources (Yan et al., 2019). Different values were communicated that explained the spatial variability of soil reaction, in relation to soil type, land morphology, agricultural systems, technological practices and crop

plants (Guo et al., 2024; Subhash et al., 2025).

Organic matter, represented by H and NI, is central to SQI and PCA. This supports the literature that considers organic matter a major determinant of soil functions, cation exchange capacity and agroecosystem resilience (Ramos et al., 2018; Balík et al., 2025; Kabelka et al., 2025; Lal, 2025).

The main macroelements P and K strongly differentiated the plots, but they are not the only ones that explained the overall quality, because the SQI also integrated the soil reaction, secondary macroelements and microelements. For this reason, the "key group" of indicators is more robust than choosing a single key index. The specialized literature communicated results based on different key indicators in the assessment of soil quality (Evangelou and Giourga, 2024; Abshiba et al., 2025; Theresa et al., 2026).

Under the given conditions, the minimum set proposed for monitoring includes agrochemical indices: pH, HA, H, NI, P, K, Mg, S, Mn, and Cu. The agrochemical indices considered expressed the quality of the soil differently: pH and HA described the reaction and the potential need for correction; H and NI described organic and nitrogen background; P and K were the indices with the highest power to separate the parcels; Mg and S completed the cation/secondary balance; Mn and Cu captured the micronutrient component sensitive to reaction and soil chemical conditions. This set can be used for future monitoring without completely eliminating the periodic analysis of Ca, Fe and Zn.

The practical recommendations are: (i) maintaining the pH in the slightly acid-neutral range, with calcareous amendment only where pH, HA and Al confirm the need; (ii) increasing the input of organic matter in A4 and, secondarily, in A5 through crop residues, green crops and well-managed manure/compost; (iii) differentiated fertilization with P and K based on plot levels and specific crop consumption; (iv) monitoring Mg and S, as they have important contribution in PCA and SQI; (v) avoiding the uniform application of corrections on all plots, as the cluster analysis indicated agrochemical heterogeneity.

CONCLUSIONS

From the analysis of the database that included the data set with 28 agrochemical samples, 16 indicators of soil quality, for an agricultural land module consisting of 5 parcels of arable land, with the total area analyzed is 137.05 ha, they have direct information and indices derived through calculations that facilitated the understanding, explanation and description of soil fertility.

Regarding the soil reaction, the overall average pH was 6.33, and the surface-weighted pH was 6.32, indicating a slightly acid-neutral reaction at the land level.

The weighted average SQI was 0.473 and the weighted average NBI is 0.621. Nutrient balance was moderate, but overall quality was limited by some categories, especially organic matter in plot A4.

The multivariate analysis (EFA) explained the position and mode of action of the factors in relation to the main components. Multivariate analysis (PCA) and cluster analysis separated A1 from the rest of the plots, which supports the need for differentiated agrochemical management.

There was no single agrochemical index strong enough to characterize the land. The recommended key group was "H–NI–Mg–S–Cu–Mn–HA", operationally supplemented with "pH, P and K" for fertilization and amendment recommendations.

Correction of soil reaction is recommended with localized application: plot A1 does not require general correction; plots A2–A4 require monitoring and moderate interventions, and plot A5 is a priority for assessing the need for calcareous amendments.

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