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SOIL QUALITY INDICES EXPLANATION THROUGH MULTIVARIATE ANALYSIS

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Abstract

Environmental and anthropogenic factors, especially agricultural practices, generate a series of changes on the soil physico-chemical and biological indices. The periodic determination of quality indices is important to know the level of soil fertility, and the application of appropriate measures for crop yield. The present study analyzed the agrochemical indices of soil quality, and used multiparameter analysis (PCA) to obtain the loading of the indices on the main components, the mode of action, and the intensity of each soil index. PC1 comprised soil pH (r = -0.923), B (r = -0.883), Fe (r = 0.782), CaO (r = -0.777), NH_4 (r = 0.752), K_2O (r = 0.545), and Mn (r = 0.286). PC2 included Zn (r = 0.873), P_2O_5 (r = 0.786), Cu (r = 0.756), and S (r = 0.316). PC3 included Nmin (r = 0.960), and NO_3 (r = 0.950). PC4 included MgO (r = 0.888), and Na_2O (r = 0.881). In relation to the soil reaction, the 38 soil trials were classified into three categories, acid reaction (11 trials), neutral reaction (7 trials), and basic (alkaline) reaction (20 trials). Based on the PCA, the three groups were positioned differently, with an independent position in the case of the acid reaction, and with an overlap in the case of the neutral and basic reaction, as transition zones.

Key words**:** *component characteristics, components loading, factors action, PCA, soil fertility*

INTRODUCTION

There is a well-known tendency to decrease the area of agricultural and arable land per capita worldwide, with certain variations from one country to another [3, 8, 19]. Knowing and ensuring the quality of soils is of crucial importance for food safety and security, necessary for a growing human population [9, 12, 20, 21].

The way land is used, and agricultural practices, influence in the medium and long term soil quality indices and land productivity. The understanding of the action of these practices and the appropriate interventions, contribute to a sustainable management of soil resources and ensuring the sustainable functioning of agroecosystems [2, 7, 11, 16, 22].

Physico-chemical and biological indices are used in current studies for the analysis and characterization of soil types and sub-types [1, 17, 18]. Certain inadequate agricultural practices have led to the degradation of soil quality, under different aspects of physico-chemical and biological indices, and their identification is important for recovery measures and the sustainable use of agricultural land [5, 22].

The identification of representative soil quality indicators is important for the quick and efficient evaluation and diagnosis of soil quality, the level of soil degradation, and the forms in which this phenomenon manifests itself, when quantifying ecosystem services, and to establishing sustainable agricultural practices [22].

Changes and variations induced by agricultural practices in soil quality are important for crop yield, and associated with the high diversity of cultivated soils it is relatively difficult to use an adequate index for soil quality [16]. The authors of the study used different methods to estimate a soil quality index (SQI), based on samples from different locations (72 samples, three locations), in conditions of organic soils, and mineral soils. The authors recorded different values for SQI, in relation to the calculation methods used.

Representative indices of soil quality were analyzed over time, in relation to different agricultural practices [2]. The authors of the study recorded the differentiated variation of the considered indices, in relation to the applied agricultural practices.

In conventional farming systems, the soil has an important role in plant production, and soil health and productivity capacity is periodically evaluated, based on a comprehensive set of soil quality indices [2, 4, 15]. Soil quality indices are determined by classic laboratory methods, which are more accurate, but more expensive in terms of time, consumables, and human resources [4]. New methods, based on imaging analysis, have been tested and used with a high reliability rate for the quantification of soil quality indices [4].

The assessment of soil quality based on individual indices, or simple indices, may present certain limitations [14]. The authors considered that an integrated index is more relevant to express the soil quality of agricultural lands, especially in relation to anthropogenic influences. The authors have compared two agricultural areas, based on physical-chemical, biological and contaminant indices, as basic indices. According to the PCA, it was possible to identify and select the relevant indicators for soil quality. In relation to anthropic pressure, the soil quality index showed higher values in conditions of lower anthropic pressure.

The way of agricultural land is used generates an impact over time on the quality and functionality of the soil indices [7]. The "life cycle" is considered an important indicator of how land is used. The authors of the study analyzed the impact of land use methods on some representative soil properties. The identification of important indicators was considered, as well as options for indicators combining (aggregating), in order to express the quality of the land, under the conditions of a representative number of ways of land using (57 types of use, according to the authors).

Soil quality indices were used, under experimental conditions, for the analysis of management options in the assessment of soil health at the regional scale [15]. Based on soil samples from variable depths (0-30 cm) and a representative number of working points, the authors used different types of analyzes and methods (e.g. PCA, soil function, percentile method), and information based on soil functionality (SF), to establish and select a minimum set of data, with a certain number of parameters to result in weights of key indicators.

Factors and processes that determine soil degradation (e.g. erosion) have led to low agricultural yields [6]. The authors of the study evaluated the level of soil sustainability based on a representative number of indicators, in different land use conditions. Based on some soil quality indexing methods, and the recorded results, the authors identified that the method that considered PCA for the soil quality index, showed high sensitivity and generated more robust results.

Uthappa et al. (2024) [22] studied various land use systems (agroforestry, horticultural, agricultural systems, natural forests, and tree plantations) and analyzed how they influenced the soil quality index. Principal component analysis was used, associated with different linear and non-linear scoring methods. The authors found that the quality index (weighted value) based on non-linear models ensured an efficient assessment of soil quality.

This study used multiparameter analysis (PCA) to explain the positioning of some indices that define soil fertility, in relation to the main components, mode and intensity of action of the considered indices.

MATERIALS AND METHODS

The study took place in the conditions of specific agricultural lands, in the area of ATU Sacalaz, Beregsau Mare Locality, Timis County, Romania (Map 1).

In relation to the purpose of the study, 38 soil trials were considered, from arable land category, sampling depth 0-30 cm. For the characterization of soil, specific soil quality indices were determined, namely the soil reaction (soil pH), the content of macroelements, and the content of microelements. The soil samples were analyzed within Vantage SRL, by accredited laboratory methods. In relation to the purpose of the study, the soil quality index data were analyzed by appropriate mathematical and statistical methods.

(a) (b) (c)

Map 1. Study area; (a) Romania; (b) Timis County, ATU Sacalaz; (c) Area of study
Source: original figure, generated based on (a) [23]; (b) [24]; (c) [25]

The correlation analysis was applied to evaluate the interdependence between the quality indices considered in the study. Multiparameter analysis (PCA) was used to determine the principal components and the loading of quality indices (as factors) on each component. Appropriate mathematical and statistical tools were used [10, 13].

RESULTS AND DISCUSSIONS

Based on the soil samples and laboratory analyses, the values of the soil quality indices were obtained, presented in Table 1. The soil reaction, and the content of macro- and microelements in the soil, the upper soil horizon (0 – 30 cm depth), were considered.

Table 1. Descriptive statistics for soil quality indices, ATU Sacalaz, Beregsau Mare, Timis County

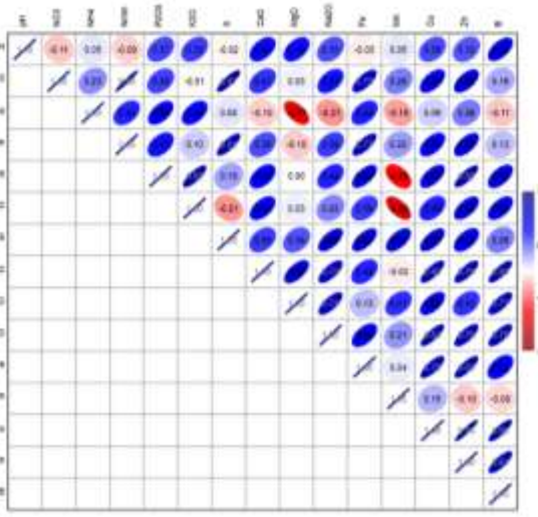
Statistical parameter	Soil quality indices														
	pH	NO_3	NH_4	Nmin	P_2O_5	K_2O	S	CaO	MgO	Na_2O	Fe	Mn	Cu	Zn	B
Valid	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38
Missing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mode	7.13	5.26	1.61	7.22	19.21	176.03	14.79	4273.20	604.83	23.59	12.04	5.13	1.96	0.33	0.19
Median	7.33	12.43	1.86	14.38	71.74	334.95	14.05	5970.21	1390.8	49.20	33.80	5.13	1.99	0.47	0.55
Mean	7.21	13.81	2.18	15.99	106.13	324.95	14.01	7017.53	1535.5	57.37	48.38	5.89	1.92	0.57	0.65
Std. Error	0.11	0.94	0.14	0.92	20.18	10.93	0.54	355.94	83.23	4.28	5.78	0.37	0.15	0.05	0.07
Std. Deviation	0.69	5.80	0.87	5.66	124.38	67.36	3.30	2194.18	513.04	26.39	35.62	2.25	0.90	0.31	0.43
Minimum	5.93	5.26	1.21	7.22	19.21	176.03	9.45	4273.20	604.83	23.59	12.04	2.59	0.71	0.29	0.12
Maximum	8.10	26.82	4.17	29.01	712.01	442.02	21.10	11288.2	2595.6	132.16	146.89	11.43	4.84	1.63	1.59
25th percentile	6.70	9.41	1.49	12.10	47.20	298.05	11.33	5032.45	1184.9	40.65	19.91	4.38	1.19	0.37	0.25
50th percentile	7.33	12.43	1.86	14.38	71.74	334.95	14.05	5970.21	1390.8	49.20	33.80	5.13	1.99	0.47	0.55
75th percentile	7.81	17.62	2.60	19.50	123.48	371.78	17.10	9086.92	1777.1	64.53	71.24	7.24	2.25	0.64	1.02

Source: original data.

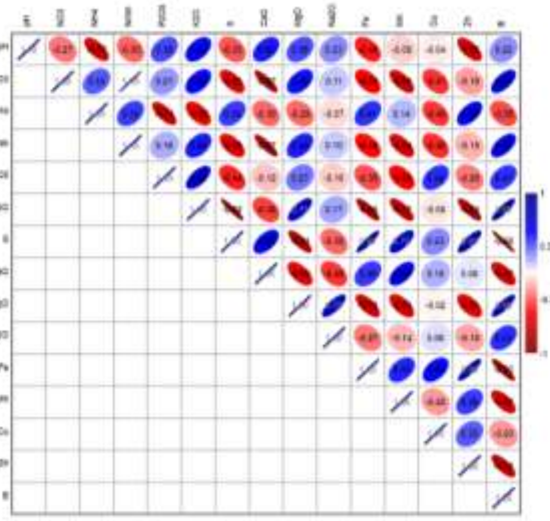
From the total of 38 soil trials, 11 trials were recorded in the acid pH range (pH = 5.93 – 6.73), seven trials in the neutral pH range (pH = 6.82 – 7.20), and 20 samples in the basic (alkaline) pH range (pH = 7.30 – 8.10).

The mineral elements recorded variable values, descriptive statistical parameters indicating the limits of variation in the case of each soil quality index, considered in the analysis (Table 1).

The degree of agricultural land variability was assessed based on the coefficient of variation, calculated for each soil quality index. Very high variability was registered in the case of phosphorus (CV = 117.1964), followed by iron (CV = 74.6397), boron (CV = 66.8402), zinc (CV = 54.3009), copper (CV = 46.7108), sodium (45.9891). Low value of variability presented the reaction of the soil (CV = 9.5136). In the case of the other indices, intermediate values were recorded, CV = 20.7287 for K_2O, 23.5748 for S, CV = 31.2671 for CaO, CV = 33.4121 for MgO, CV = 35.4255 for Nmin, CV = 38.1529 for Mn, CV = 39.9965 for NH_4, and CV = 42.0332 for NO_3, respectively. The correlation analysis was done on the data series within the three pH domains recorded, with the representation of the correlation coefficient values in Figure 1 (a), (b), (c).



(a)



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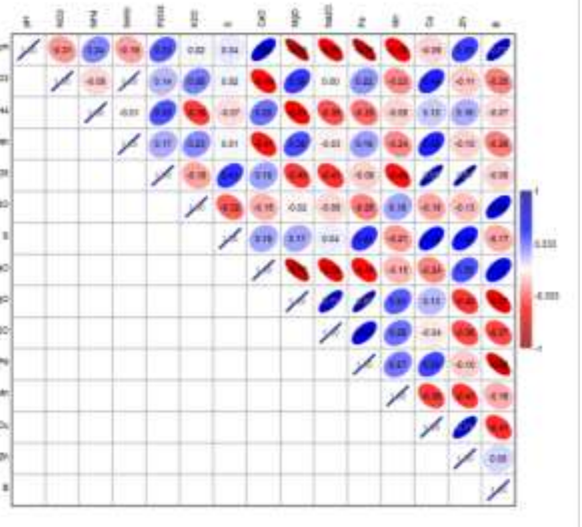

(c)

Fig. 1. Correlation diagrams between soil quality indices; (a) acid pH conditions, (b) neutral pH conditions, (c) basic (alkaline) pH conditions
Source: Original diagrams, resulted from data analysis.

Predominantly positive correlations were recorded in the acidic pH range, predominantly negative correlations in the neutral pH range, and more balanced correlations (positive, negative) in the basic (alkaline) pH range. In all three pH domains addressed, there were varying levels of intensity of correlations. In some cases, the type and intensity level of the correlation was maintained (e.g. NO_3 with Nmin, r = 0.976 in the acid domain, r = 0.998 in the neutral domain, r = 0.997 in the basic (alkaline) domain), or there were small differences between the intensity level (e.g. P_2O_5 with Zn, r = 0.820 in the acid domain; r = 0.908 in the basic (alkaline) domain).

In most cases, however, the level of correlation between quality indices has changed, in relation to the domain of soil reaction, and the content of mineral elements in the soil, Figure 1 (c).

Considering the large number of indices used in soil quality assessment, the distribution of these indices was analyzed in relation to the main components, according to PCA.

The loading of the quality indices (as factors determining soil quality) in the main components was found, with different values of the correlation coefficient, depending on the importance of each factor in the respective component (Table 2, Figure 2).

Table 2. Component loadings, soil quality indices

Soil quality indices	PC1	PC2	PC3	PC4	Uniqueness
pH	-0.923				0.089
B	-0.883				0.140
Fe	0.782				0.110
CaO	-0.777				0.140
NH_4	0.752				0.283
Zn		0.873			0.194
P_2O_5		0.786			0.210
Cu		0.756			0.064
Nmin			0.960		0.066
NO_3			0.950		0.067
MgO				0.888	0.108
Na_2O				0.881	0.186
K_2O					0.545
S					0.316
Mn					0.286

Source: Original data.

Within PC1, the first position was occupied by soil reaction (pH), with r = -0.923, followed by B (r = -0.883), Fe (r = 0.782), CaO (r = -0.777), NH_4 (r = 0.752), K_2O (r = 0.545), and Mn (r = 0.286), according to Table 2, and Figure 2.

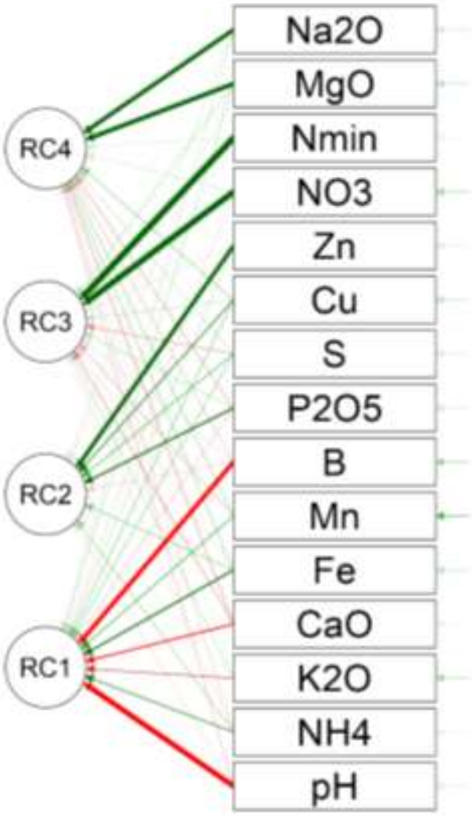

Fig. 2. The graphic representation of the main components and the factors loading (soil indices) on the component
Source: Original figure.

Zinc (Zn) was positioned in PC2, with r = 0.873, followed by P_2O_5 (r = 0.786), Cu (r = 0.756), and S (r = 0.316), according to table 2, and figure 3.

In PC3, with very high values of the correlation coefficient, Nmin with r = 0.960, and NO_3, with r = 0.950, was positioned. In PC4, MgO was positioned with r = 0.888, followed by Na_2O with r = 0.881.

The characteristics of the components, in relation to the analysis mode, are presented in Table 3.

In order to obtain a general distribution of the soil trial (T1 to T38) in relation to the values of the soil quality indices, the PCA multiparameter analysis was applied. According to PCA, the diagram in Figure 3 was generated, where PC1 explained 40.738% of variance, and PC2 explained 17.822% of variance.

The formation of three clusters of points (soil trials) was found, but also the independent distribution of some trials.

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Table 3. Component Characteristics

Components	Unrotated solution			Rotated solution		
	Eigenvalue	Proportion var.	Cumulative	SumSq. Loadings	Proportion var.	Cumulative
Component 1	6.111	0.407	0.407	4.815	0.321	0.321
Component 2	2.673	0.178	0.586	2.712	0.181	0.502
Component 3	2.192	0.146	0.732	2.371	0.158	0.660
Component 4	1.221	0.081	0.813	2.298	0.153	0.813

Source: Original data.

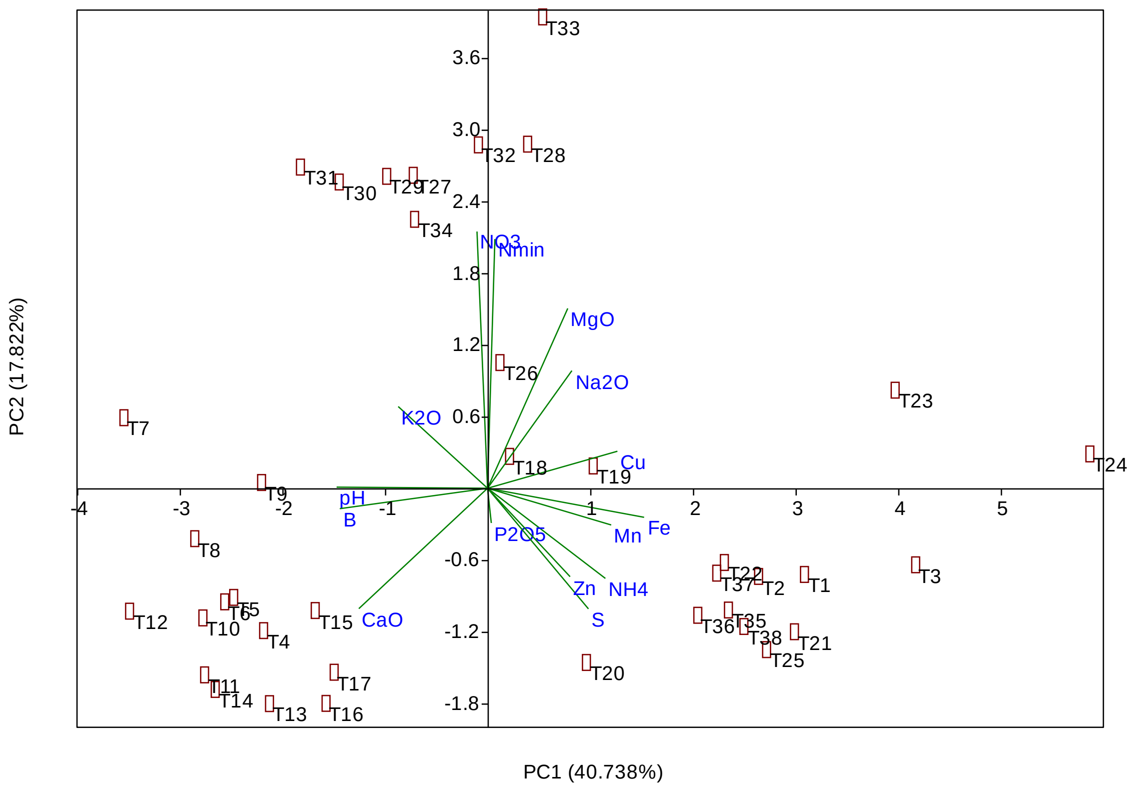

Fig. 3. PCA diagram, based on general soil indices analysis
Source: original diagram, resulting from the data analysis.

Considering the three fields of soil reaction in which the soil trials were included, the PCA multiparameter analysis was applied to obtain the distribution of the indices in relation to the three classification groups.

The diagram in Figure 4 resulted, with the three marked groups that included the soil trials, respectively the acid domain (red color), the neutral domain (green color), the basic (alkaline) domain (blue color). PC1 explained 74.848% of variance, and PC2 explained 25.152% of variance.

According to the PCA, the group of soil trials, indicating acidic soil domain (11 trials), was positioned distinctly (Figure 4).

The other two groups in relation to the soil reaction (neutral soil domain - 7 trials, alkaline soil domain - 20 trials) presented the highest proportion of soil trials as independent (green filled region, blue filled region), but they have a common area, like a transition area (Figure 4). It is an area of interferences, in the conditions of the overall analysis of the soil indices, in the study conditions.

The components presented variable weights, both in the "unrotated solution" analysis version, and in the "rotated solution" version. Thus, in the case of the "unrotated solution" analysis, according to Eigenvalue, Component 1 recorded the value 6.111, Component 2 recorded the value 2.673, Component 3 recorded the value 2.192, and Component 4 recorded the value 1.221, respectively.

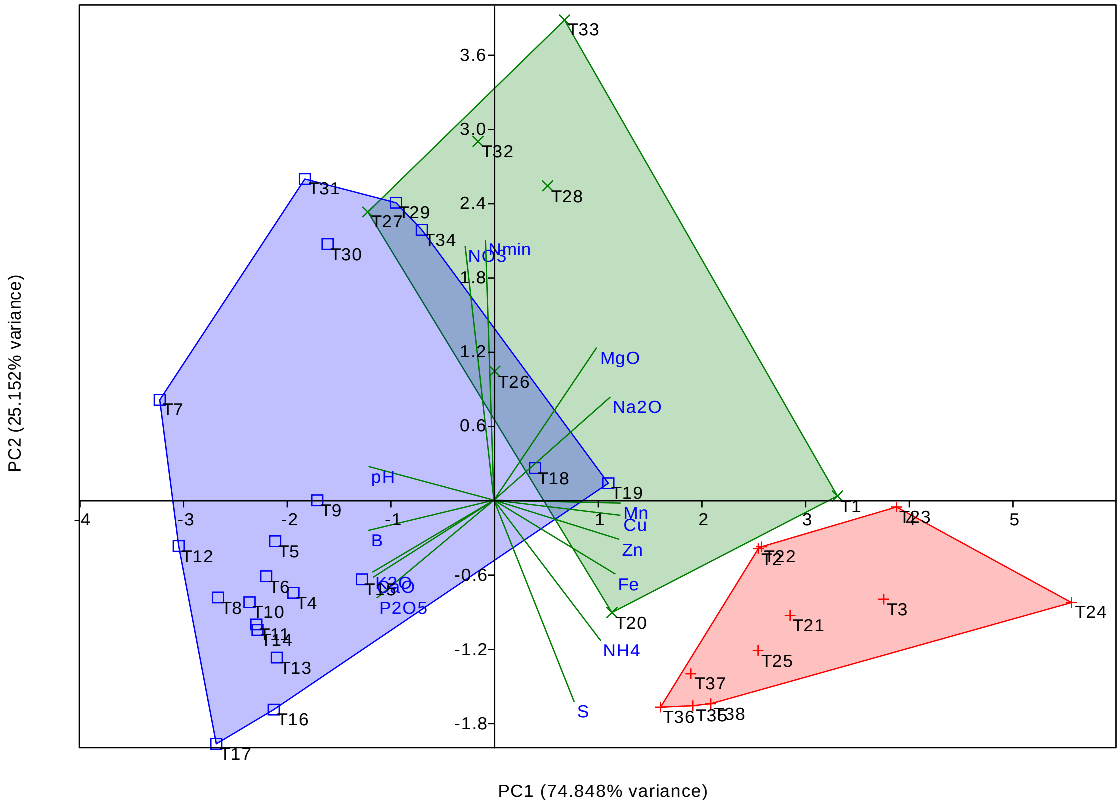

Fig. 4. PCA Correlation Between-group; red color field – acid pH range, green color field – neutral pH range, blue color field – basic (alkaline) pH range
Source: Original figure.

In the "rotated solution" version, and the statistical parameter "SumSq. Loadings", Component 1 recorded the value 4.815, Component 2 recorded the value 2.7112, Component 3 recorded the value 2.371, and Component 4 recorded the value 2.298.

After identifying the classification of indices on the main components, and the levels of correlations between indices by categories of soil reaction, the overall correlation of indices from PC1, especially soil reaction (pH), with indices from the other components (PC2, PC3, and PC4).

At the level of the PC1 component, in the ranking order of the indices, the soil reaction (pH) showed a strong correlation with B ($r = 0.86^{***}$), a strong correlation with Fe ($r = -0.868^{***}$), a strong correlation with CaO ($r = 0.822^{***}$), moderate correlation with NH_4 ($r = -0.714^{***}$), moderate correlation with Mn ($r = -0.695^{***}$), weak correlation with K_2O ($r = 0.461^{**}$) (Figure 5).

At the level of the PC2 component, the soil reaction (pH) showed correlation with Zn at the level of $r = -0.26$, correlation with P_2O_5 at the level of $r = 0.133$, correlation with Cu at the level of $r = - 0.558^{***}$, correlation with S at level $r = - 0.385^{*}$. At the level of the PC3 component, the soil pH showed a correlation with NO_3 at the $r = 0.107$ level, and with Nmin, $r = 0$. At the PC4 level, the soil pH showed a correlation with MgO at the $r = -0.364^{*}$ level, correlation with Na_2O at the $r = -0.344^{*}$ level. A very strong, positive correlation was recorded between Nmin and NO3, both indices in PC3 ($r = 0.989^{***}$) (Figure 5).

Based on the values of the correlation coefficient recorded between the first index in PC1 and the other indices in PC1, as well as with indices from PC2, PC3, PC4, it was estimated that the level of correlation, therefore also of influence, was variable in the study conditions.

PCA analysis is increasingly used in soil quality assessment, to differentiate the contribution of primary quality indices (physical, chemical, biological) and generate synthetic soil quality indices (e.g. SQI).

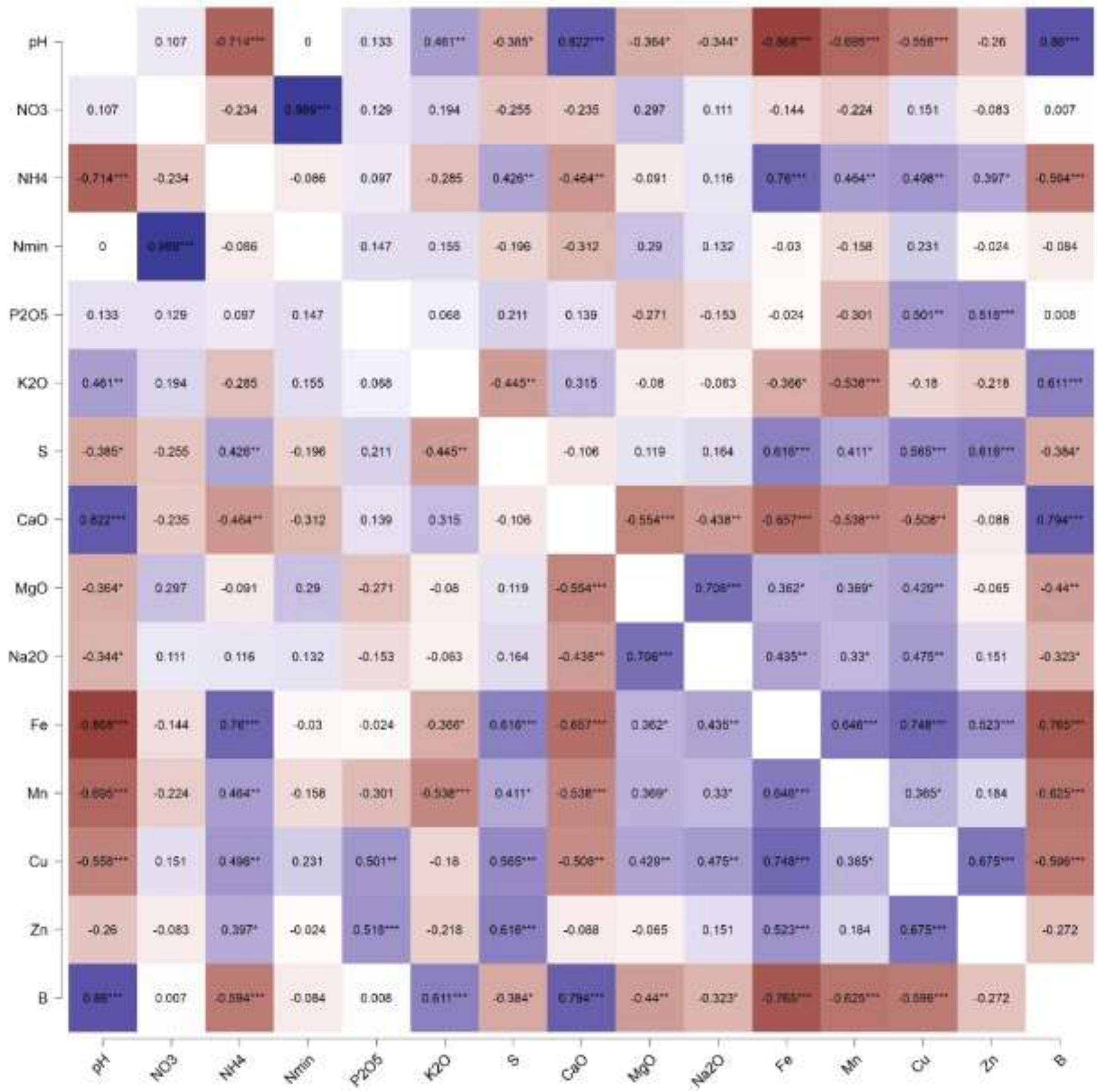

Fig. 5. Correlation heatmap, in the conditions of the overall analysis of the soil quality indices, in the study conditions
Source: Original figure.

Mukherjee and Lal (2014) [16] obtained a soil quality index (SQI-3, according to the authors) that resulted from principal component analysis (PCA) of some soil parameters, obtained from 72 samples. The authors communicated a strong correlation of the SQI-3 index (result through PCA analysis) with crop yield, compared to other indices obtained by other methods.

The variation of some soil quality indices was analyzed in relation to certain agricultural practices, under the conditions of a clay-loamy soil [2]. The authors of the study recorded the decrease in the value of some important indices for soil quality (e.g. soil pH, extractable content of P and K) that influenced soil quality and the yield of wheat and soybean crops. The authors concluded that the indices represented by pH, P and K are representative for the soil, in the study conditions, and require monitoring over time, to evaluate the dynamics of soil quality, fertility and agricultural yields in soybeans and wheat, on the medium and long term.

Lenka et al. (2022) [15] used PCA analysis to define the soil quality index (SQI), in order to find a high correlation with yield in wheat and rice crops. The authors obtained six main components, with 75% of the total variation, of which the first two components (PC1, and

PC2) explained 42.8%.

Damiba et al. (2024) [6] used two methods for evaluating and indexing soil quality, a method based on LDS to find the A-SQI index (additive soil quality index), and a method based on PCA to find the W-SQI index (weighted index of soil quality). Based on the recorded results, the authors appreciated that the method based on PCA, which led to the W-SQI index, was more sensitive and led to more accurate results.

Uthappa et al. (2024) [22] used the PCA method associated with other methods, linear and non-linear, for precise quantification of the contribution or weight of the basic indices in the calculation of the synthetic index (SQI, according to the authors).

In the conditions of the present study, the multiparameter analysis (PCA) led to different results regarding the distribution and explanation of the soil quality indices. Under the conditions of the general analysis of the indices (independent manifestation of the indices), the first two main components (PC1 and PC2) explained 58.56% of variance (Figure 3).

In terms of grouping the indices in relation to the domain of soil reaction, on the three categories recorded in the study conditions (acidic, neutral, and basic or alkaline reaction, respectively), the main components PC1 and PC2 fully explained the variance between the data groups (PC1 and PC2, 100% of variance).

CONCLUSIONS

According to the results of this study, the importance of the aggregation of primary soil indices emerged, in relation to the factor placed in PC1, with the highest action value (soil pH, r = -0.923). The PCA analysis, based on the grouping of the indices in relation to the soil reaction (acidic, neutral and alkaline pH range), fully explained the variance (100%), based on the main components (PC1 and PC2).

According to the coefficient of variation (CV), the soil quality indices showed different variability, phosphorus was found with a high level (CV = 117.1964), and nitric nitrogen, NO_3, was found with a low value (CV = 42.0332), in the case of nutrients.

A positive or negative correlation was found between the quality indices, with different levels of intensity, under conditions of statistical safety.

In the case of some quality indices, the type and intensity level of the correlation was maintained (e.g. NO_3 with Nmin, r = 0.976 in the acid domain, r = 0.998 in the neutral domain, r = 0.997 in the basic domain), or there were small differences between intensity level (e.g. P_2O_5 with Zn, r = 0.820 in the acid domain; r = 0.908 in the basic domain). In the case of most indices, the type and level of correlation in relation to the scope of the soil sample based on the soil reaction have changed.

The study recommends the analysis of the soil quality indices to find out the dominant index as an action in relation to the main components, the framing of the indices on the main components and the generation of a synthetic, convergent result for the assessment of the quality of the soil and agricultural land.

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