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IRON BEHAVIOUR AND SOIL PROPERTIES IN HYDROMORPHIC SOILS OF BENI MOUSSA, TADLA PLAIN, MOROCCO

Abstract: This study aims to determine the behaviour of iron and its relation to the physicochemical properties in the hydromorphic soils of the Tadla plain (Morocco). An extensive analysis using Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) from a statistical perspective was employed to ensure a comprehensive examination. The results reveal that the organic matter (OM) shows very high values, likely due to the collected samples near the sewerage network. Magnetic susceptibility (MS) measurements indicate that all the samples have positive and low values, indicating an abundance of paramagnetic minerals (such as ilmenite, siderite, and clay minerals). The iron concentration [ppm] increases from the top to the bottom of the Rivers, suggesting migration in a reduced form. Pearson's correlation coefficients indicate that OM is positively correlated with cation exchange capacity (CEC) (r = 0.83) and electrical conductivity (EC) (r = 0.85) but negatively correlated with MS (r = –0.57) and iron oxide (r = 0.42). Calcium carbonate content ($CaCO_3$) is positively correlated with sand (r = 0.49), but negatively with MS (r = –0.7). Iron (Fe) is positively correlated with frequency-dependent (FD) (r = 0.7), but negatively with sand (r = –0.608). Clay is strongly negatively correlated with silt (r = –0.88) and oxalate extractable iron oxides (Fe_o) (r = –0.55), respectively. These findings suggest that the physicochemical features of Beni Moussa hydromorphic soils are strongly linked and that iron in the soil is required for the stability of specific soil components.

Keywords: iron behaviour, hydromorphic soil, statistical perspective, Tadla plain

Introduction

Iron is an essential plant micronutrient in various physiological processes such as photosynthesis and respiration. In hydromorphic soils, characterised by waterlogging and anaerobic conditions, the form and availability of iron can be influenced by factors such as soil organic matter, microbial activity, and dissolved gases [1]. Iron in hydromorphic soils can exist in different forms, including ferric (Fe^{3+}) and ferrous (Fe^{2+}) ions, which can affect the soil's fertility and the availability of iron to plants [2].

The behaviour of iron in soils is an essential indicator for understanding various chemical processes in the soil, as well as the relationship between iron and other soil parameters. Iron is crucial in soil chemistry, including nutrient cycling, redox reactions, and microbial activity [1, 3]. Comprehending the behaviour of iron in soils is essential to understanding the health and fertility of the soil and its effects on the plants and

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microorganisms that live there [4, 5]. In the Beni Moussa perimeter, hydromorphic soils are found along poorly drained Rivers, such as the Day, Arich, and Ouerna Rivers. These soils are characterised by a greyish to blackish colour, with a deep yellowish passage of limestone silt and a medium prismatic structure [6]. In this context, Shokr et al. [7] investigated heavy metal contamination with a focus on XRF and remote sensing for digital soil mapping. Also, El Hamzaoui et al. [6] studied soil pollution and identified the sources of contamination in the irrigated area of the Tadla plain. Furthermore, Şener et al. [8] studied soils irrigated by wastewater using GIS and AHP to determine their quality. These research studies, taken together, fill information gaps on hydromorphic soils by offering insights into their physical and chemical properties, pollution levels, and potential ecological concerns in the Beni Moussa region. They are typically found in low-lying areas where waterlogging and anaerobic conditions occur, and the iron in these soils can exist in different forms, including ferric (Fe^{3+}) and ferrous (Fe^{2+}) ions, which can affect the soil's fertility and the availability of iron to plants [9]. These soils are important to study for understanding the behaviour of iron in soil and how it affects this region's agricultural and environmental conditions. In this regard, several studies using multivariate statistical methods such as Pearson's correlation, HCA, and PCA have been conducted to assess soil characteristics and metal contamination [10, 11].

The capacity for heavy metal accumulation also plays an important role in the retention, mobilisation, and migration of heavy metals in the soil [12]. However, the content of heavy metals can be affected by the interactions of soil physicochemical characteristics such as soil pH, particle size and OM [12]. El Hamzaoui et al. [13] emphasised the significance of OM in the soil, specifically highlighting its carbonaceous form. 99.18 % of the Beni Moussa perimeter is appropriate for intensive, sustainable agriculture, according to the geographical distribution, which ranges from 1.98 % to 8.90 % [13]. These findings, however, should be discussed since our investigation emphasises soils that have been altered by wastewater drainage networks along the Ariche, Ouerna, and Day rivers, changing the typical concentrations of OM [14].

Other studies have been done specifically on the soil quality of the Tadla plain. These studies typically use statistical techniques such as PCA and cluster analysis to examine the relationships between different soil properties and to classify the soils into other groups based on their characteristics [15].

Recently, a study by Oumenskou et al. [16] used multivariate statistical techniques such as Pearson's correlation, PCA, and HCA to evaluate the physicochemical properties of agricultural soils from the Beni-Amir irrigated perimeter, Tadla plain, Morocco. The application of these techniques aimed to examine the interrelationships among diverse soil properties and to categorise the soils into groups based on their characteristics. The study provides insight into the soil conditions in the Beni-Amir irrigated perimeter at the Tadla plain and can be helpful for agricultural and environmental management in the region. Studies using multivariate statistical techniques are valuable in understanding complex soil data and identifying patterns that may not be apparent through traditional methods [16]. In the same context, El Hamzaoui et al. [13] used multivariate statistical and geostatistical techniques to understand the spatial variability of agricultural soil quality in the irrigated perimeter of Beni Moussa and to develop sustainable soil management and environmental decisions. The results revealed positive and significant correlations between pH, organic carbon, and carbonates. The soil characteristics in the study area vary depending on intrinsic and soil management factors.

The Tadla plain, known for its unique hydromorphic soils, remains an unexplored territory in terms of the behaviour of iron. Despite the region's ecological importance and potential impact on agriculture and the environment, studies have yet to explore the complex interactions of iron in these waterlogged soils. The scarcity of research in this area raises intriguing questions about how iron behaves under such hydric conditions. A comprehensive study on the behaviour of iron in the hydromorphic soils of the Tadla plain could shed light on fundamental processes governing soil chemistry and plant nutrition. Additionally, the findings have significant implications for the region's sustainable agriculture and land management practices, offering potential solutions for optimising crop yields and mitigating environmental challenges. To unlock the secrets of the Tadla plain enigmatic soils, researchers and experts in soil science, geochemistry, and agronomy must collaborate to design innovative research methodologies. By analysing soil samples, conducting experiments, and monitoring key environmental parameters, they can unearth vital insights into the behaviour of iron in these unique soil conditions.

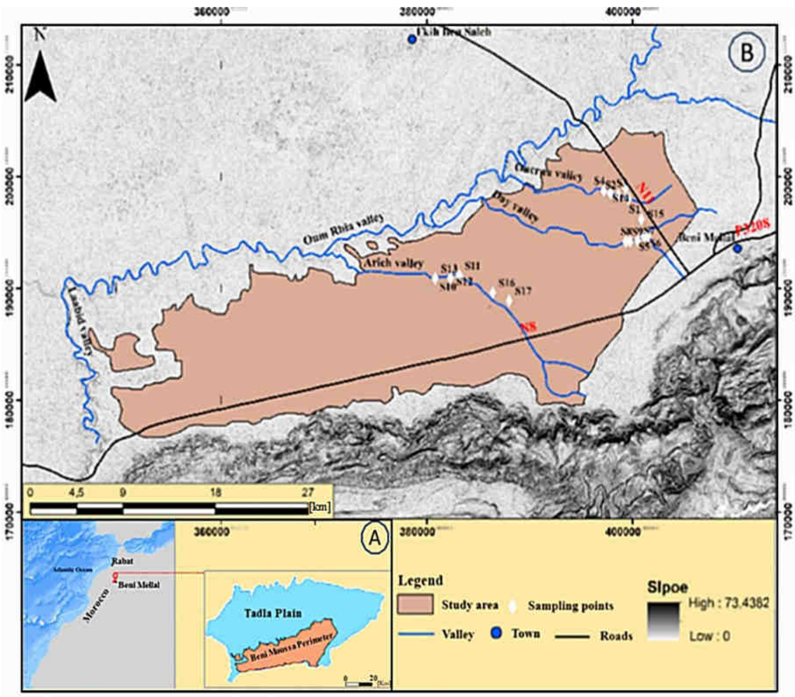

Fig. 1. A - Location of the study area. B - Location of the study area and sampling stations

The study's objective is to understand the behaviour of iron in hydromorphic soils of the Beni Moussa perimeter and examine the relationship between the iron content and other physicochemical properties of the soil. Multivariate statistical techniques such as PCA and HCA are used to analyse the data and identify patterns and relationships between the different soil properties. The outcome of this study provided insights into the soil conditions of the Beni Moussa perimeter, which can be useful for agricultural and environmental management in the region.

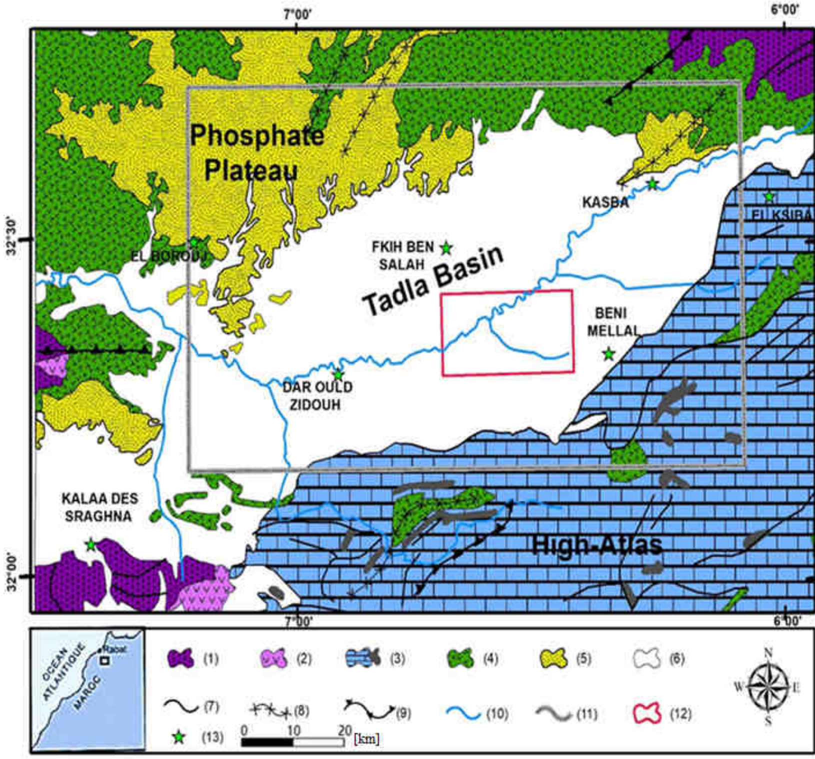

Fig. 2. Geological map of the Tadla Basin: 1 - Paleozoic (shales and quartzites); 2 - Triassic (red clays and basalt); 3 - Jurassic (a, limestones and dolomites, b, diorite and gabbro); 4 - Cretaceous (red detrital facies); 5 - Tertiary (limestones, marls, and phosphatic sands); 6 - Quaternary (alluvium); 7 - Fault; 8 - Synclinal axis; 9 - Anticlinal axis; 10 - River; 11 - Tadla Basin; 12 - Study area; 13 - Town [20]

Materials and methods

Study area

The Tadla plain is located in the Beni Mellal-Khenifra Region (Fig. 1). It's bisected by the Oum Er-Rbia River, dividing it into two large, independent irrigation perimeters: The Beni Moussa perimeter, which covers 69,500 hectares in the eastern part, and the Beni Amir perimeter, which covers 33,000 hectares in the western part. This study focuses specifically on the Beni Moussa perimeter.

The Tadla area has a semi-arid Mediterranean climate, with high temperatures, a five-month rainy season, and little precipitation during the mild winters. The average annual rainfall is between 150 mm and 450 mm, and the temperature varies seasonally, peaking at 28.7 °C in July and falling to 10.6 °C in January [17]. Based on the Koeppen-Geiger climate classification map, which was created using interpolated Digital Geological Model (DGM) ground observation data from 1981 to 2010, the Tadla plain is located in the Bsh zone, which is noted for having a warm, semi-arid climate [18]. These climatic conditions impacted the soil properties, water availability, and irrigation regimes, which are required to optimise crop yields and soil fertility.

The geological formations are mainly composed of numerous series from the Palaeozoic to the Quaternary age and contained the red silts and lacustrine limestone formations, which are distributed in centres and north of the Beni Moussa perimeter (Fig. 2) [19].

Soil sampling and analysis

In the present study, 17 soil samples (0, 20) cm were collected in February 2020 for laboratory analysis. These samples were collected from 13 locations within hydromorphic soil zones, with only four locations in Cambisols, all within the Beni Moussa perimeter. This limited distribution is attributed to the prevalence of hydromorphic soils along poorly drained rivers (Day, Ouerna, and Arich), which explains the restriction in the number of collected samples. The main objective was to assess the properties of these two distinct soil types to analyse the influence of hydromorphism on these soils. The soil parameters analysed include pH, OM, $CaCO_3$, EC, CEC, Extractable iron, soil colour, mass magnetic susceptibility, grain size, and heavy metal analysis. These properties were measured following standard technical guidelines.

Statistical analysis

The data obtained underwent multivariate statistical analysis techniques, focused on facilitating a consistent assessment of several variables using Pearson's correlation, PCA, and linear statistical analysis (Fig. 3).

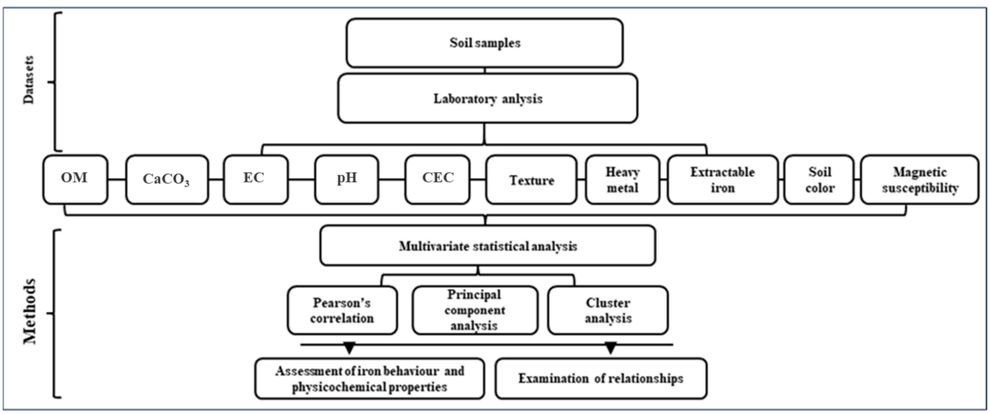

Fig. 3. Flowchart of the methodology used in this study

Pearson's correlation is generally used to assess the relationship between two variables. It is a simple measure to show how well one variable predicts the other. A correlation coefficient (r) of +1 indicates that the two variables are perfectly positively related, while $r = -1$ indicates a negative linear correlation. However, no relation between the two variables exists if $r = 0$. Thus, a positive correlation coefficient between two variables suggests that they share a common source, while a negative correlation coefficient indicates a different source [21, 22]. The PCA is a pattern recognition method that aims to interpret the variance within a large set of variables by transforming them into a smaller set of independent variables [23]. It provides information on the most significant parameters used to describe the data sets and summarises the statistical correlation among soil constituents [24, 25]. Cluster analysis (CA) is a statistical analysis whose primary purpose is to group objects based on their characteristics [26, 27]. It is often represented as a dendrogram and displays intuitive similarity links between any sample and the entire data sets [27-29].

Results and discussion

Physico-chemical properties

The findings derived from the collected data on the physicochemical properties of the soil, including soil pH measured in both H_2O and KCl solutions, *EC*, CEC, total organic matter (TOM), $CaCO_3$, soil texture (represented as percentages of sand, silt, and clay), mass magnetic susceptibility, extractable iron, soil colour, and heavy metal concentrations, are elaborated upon in the following sections.

The presence and distribution of OM in the soil samples collected from the study area are influenced by the hydromorphic conditions of the region. Most of the samples collected from hydromorphic sites exhibit higher organic matter, exceeding 10.00 %. The sample with the highest OM content, at 33.00 %, was collected from location No. 1, which may be attributed to the proximity of the sampling site to the sewerage network. Conversely, Cambisols, soils formed from recent alluvial deposits, exhibit lower OM content, with values of less than 10.00 %. This disparity in OM content between the two soil types may have significant implications for plant and crop suitability and the soil capacity to retain nutrients and moisture [30]. According to Likhanova et al. [31], soil OM distribution is greatly influenced by hydromorphic circumstances. Because plant material is preserved as peat in hydromorphic soils, organic carbon buildup in these conditions increases significantly under surplus moisture (0.38, 0.58) t/ha/year ([t] = tonne = 10^6 g = Mg) and decreases during moisture deficiencies (0.07, 0.11) t/ha/year [31].

The CEC refers to the ability of a soil to retain and exchange positively charged ions, such as sodium, magnesium, potassium, and calcium. It is a crucial parameter that aids in assessing the soil's fertility and productivity [32]. The observed CEC values in the study area varied from 27.60 cmol/kg to 91.00 cmol/kg, with an average value of 49.88 cmol/kg, which may be attributed to the high levels of OM in the soil. The CEC is directly proportional to the clay content, OM content, and soil pH [33]. The high CEC values in the study area suggest that the soil can retain and exchange cations, promoting plant growth and soil fertility. Nonetheless, this parameter should be assessed alongside other soil parameters and the plant species cultivated in the soil. Oorts et al. [34] found a strong relationship between CEC and soil organic matter (SOM). According to their findings, SOM makes up between 75 % and 85 % of the CEC of soils, which is a significant contribution. These findings highlight the critical function that SOM plays in soil ion exchange and retention mechanisms. The significant amount of CEC ascribed to SOM highlights its critical impact on the physicochemical characteristics of the soil [34].

The pH_{H2O} of the soil samples collected ranged from 6.90 to 8.10, with an average of 7.04, indicating that the soil is neutral to alkaline. The pH_{KCl} values of all the samples were satisfactory, with values greater than 5.30, indicating no risk of soil toxicity. The difference between the pH_{H2O} and pH_{KCl} values was between 0.50 and 1.00, indicating average exchangeable acidity and the presence of a strong acidity reserve. The variation observed can be ascribed to the soil's buffering capacity (due to the presence of swelling clays such as smectite and vermiculite), cultivation methods, and climatic factors influencing the exchange between soil components. According to Charpentier et al. [35], vermiculite is the primary clay mineral in alkaline soil conditions and is frequently linked with iron-rich trioctahedral smectite (of the saponite type). Likewise, our findings confirm the identification of iron-rich chlorites associated with Fe-rich trioctahedral smectite (saponite type) in neutral to alkaline conditions [36].

EC is a parameter used to measure the ability of soil to conduct electricity and is considered an indicator of soil salinity [37]. Soil salinity can adversely affect plant growth and agricultural productivity, especially in irrigated areas. The results of the study area indicate low *EC* values, not exceeding 1.00 mS, which implies that the soil is not highly saline. However, it is worth noting that sample No. 1 shows a relatively high *EC* value, which may indicate that it is from an area where irrigation practices are not adequately managed, or there is a high presence of dissolved minerals [37].

The analysis of carbonates $CaCO_3$ in soil revealed that most samples contain limestone concentrations not exceeding 11.00 %, except for those collected at Oued Arich, which exhibits notably high values of up to 35.00 %. The variation in limestone concentrations observed in these samples may be linked to the geological composition of the parent rock that formed these soils. The observed carbonates $CaCO_3$ values align closely with those documented in a recent investigation conducted across various sites within the Beni Moussa area [6].

The soil texture refers to the distribution proportion of different granular sizes such as sand, silt, and clay. The sand content in the analysed samples ranges from 4.00 % to 33.00 %, with an average value of 17.09 %, while the silt content varies from 23.31 % to 80.83 %, with an average of 61.01 %. The clay content ranges from 3.20 % to 63.68 %, with an average of 21.89 %. These results suggest that most soils have a silty loam to silt clay loam texture and are primarily composed of alluvial and red silt.

Table 1

Physicochemical parameters of hydromorphic soil samples

Samples	OM [%]	CEC [cmol/kg]	pH_{H2O} [-]	pH_{KCl} [-]	*EC* [mS]	$CaCO_3$ [%]	Sand [%]	Silt [%]	Clay [%]
S1	33.00	91.00	7.20	6.50	3.63	7.00	11.00	80.83	8.17
S2	14.00	58.20	6.90	6.10	0.56	6.00	13.00	23.32	63.68
S3	16.40	71.10	6.90	6.40	0.56	11.00	7.00	55.42	37.58
S4	7.70	30.20	6.80	6.20	0.31	5.00	21.00	54.98	24.02
S5	11.80	63.40	6.80	6.30	0.26	7.00	4.00	62.00	34.00
S6	11.10	50.30	6.80	6.20	0.24	7.00	13.00	83.80	3.20
S7	9.00	43.20	6.90	6.10	0.23	6.00	15.00	74.29	10.71
S8	10.90	54.40	6.90	6.10	0.19	5.00	13.00	80.87	6.13
S9	15.90	44.10	7.20	6.30	0.66	29.00	28.00	40.14	31.86
S10	12.80	42.10	7.20	6.70	0.56	35.00	23.00	56.30	20.70
S11	14.60	44.70	7.00	6.50	2.31	23.00	33.00	63.20	3.80
S12	14.90	64.70	7.00	6.20	0.29	34.00	17.00	56.50	26.50
S13	10.30	50.10	7.80	7.30	0.31	6.00	25.50	60.55	13.95
S14	7.10	44.50	8.10	7.60	0.28	9.00	16.00	69.02	14.98
S15	7.50	29.00	6.70	5.90	0.20	8.00	21.00	61.06	17.94
S16	6.60	27.60	6.70	5.90	0.26	6.00	15.00	49.03	35.97
S17	9.90	39.40	6.90	6.00	0.40	7.00	15.00	65.98	19.02

Assessment of the behaviour of iron in hydromorphic soil

✓ Extractable iron by citrate-dithionite and ammonium oxalate

The outcomes of iron extraction using citrate-dithionite and ammonium oxalate methods indicate that the levels of Fe that are extractable with citrate-dithionite are low and range from 0.33 ppm to 4.24 ppm, while those extractable with ammonium oxalate vary from 0.25 ppm to 3.93 ppm (Table 2). The low values obtained with these methods suggest that the iron in the samples is present in a form that is not easily extractable using these techniques. This could be due to the iron being present in a mineral form that is insoluble in the reagents or bound to other components in the sample, which impedes its extraction.

The discrepancy between the two iron extractions provides an estimate of the soil ferruginous mineral concentration (such as hematite and goethite). Additionally, the correlation between the two types of iron extractions can indicate the level of iron crystallisation and soil formation, as the crystallisation of iron oxides is a critical aspect of soil genesis [38]. The analysis results for these parameters are presented in Table 2 and demonstrate the following:

- Except for samples 4 and 10, where Fe_o values are higher than dithionite extractable iron (Fe_d) values, the results of iron extraction by citrate-dithionite (Fe_d values) are representative of the majority of the samples, where Fe_d values are more significant than Fe_o values. This suggests that certain soils may have a low concentration or absence of ferruginous minerals, responsible for the difference in iron extraction between the two methods.
- Most samples exhibit very low levels of crystalline iron; in some instances, it is absent. This can be attributed to the fact that the Fe_o concentrations are higher than the Fe_d concentrations in samples 4 and 10.

Table 2

Levels of free iron extracted with dithionite and oxalate from the different samples

Samples	**Fe_d [ppm]**	**Fe_o [ppm]**	**Fe_o/Fe_d [-]**	**Crystallised iron ($Fe_d - Fe_o$) [ppm]**
S1	4.16	3.93	0.95	0.23
S2	1.25	0.48	0.38	0.77
S3	4.36	0.68	0.16	3.68
S4	0.33	2.58	7.77	0.00
S5	0.43	0.25	0.59	0.18
S6	4.14	3.50	0.85	0.64
S7	3.85	3.57	0.93	0.28
S8	4.28	3.68	0.86	0.60
S9	3.46	3.42	0.99	0.03
S10	3.15	3.06	0.97	0.09
S11	0.42	2.67	6.36	0.00
S12	1.03	0.50	0.48	0.53
S13	0.82	0.75	0.91	0.07
S14	2.53	0.41	0.16	2.12
S15	1.12	0.44	0.39	0.68
S16	2.16	1.23	0.57	0.94
S17	3.62	2.09	0.58	1.54

The high ratios of Fe_o/Fe_d in soils correspond with maximum Fe_o concentrations, indicating a low degree of iron crystallisation. This could be attributed to the low content of ferruginous minerals or unfavourable crystallisation conditions. Typically, OM is responsible for high Fe_o/Fe_d ratios observed in surface soils [38]. Buyukkılıc et al. [39] showed a strong correlation between the amount of OM in the soil and the abundance and availability of iron in various forms. The study revealed that OM has a significant role in determining the variation of iron levels in soil, underscoring the need to comprehend and take into account the OM composition when evaluating iron accessibility in soil-plant relationships [39].

A study conducted by Blume and Schwertmann in 1969 aimed to examine the functions of different soluble paedogenic oxides in various soil types, encompassing aluminium, iron, and manganese. This investigation utilised ammonium oxalate and dithionite citrate solutions. They observed that the presence of dithionite- and oxalate-soluble iron was indicative of significant paedogenic processes and could serve as an indicator of crystallinity in soil samples. Therefore, these solutions have been used as a substitute for detecting the degree of crystallinity in soil samples [38].

✓ Soil colour

The MUNSELL code is a commonly used method for characterising and communicating the colour of soil samples. This code is composed of three attributes: hue, value, and chroma, which can be employed to define the colour of a soil sample precisely in terms of its predominant wavelength, brightness or darkness, and intensity or saturation.

In this study, soil colour was determined using the MUNSELL code in different states (Table 3):

- In the desiccated state, the soil colour is evaluated after dehydration and pulverisation into a fine powder.
- In the hydrated state, the soil colour is evaluated following its mixture with water and subsequent air-drying.
- After extracting iron, the soil colour is evaluated after treating it with a solution containing dithionite and oxalate. This procedure facilitates the identification of colour changes in the soil arising from iron removal.

Table 3

Soil colour

Soil	**Sample types**	**Dry soil colour**	**Wet soil colour**	**Soil colour post-dithionite iron extraction**	**Soil colour post-oxalate iron extraction**
Hydromorphic soils of Ouerna River	S1	GLEY2;6/5PB	GLEY2;5/5PB	GLEY2;6/10B	GLEY2;6/5PB
	S2	GLEY2;6/5GB	GLEY2;6/10B	GLEY2;6/10B	GLEY2;6/5GB
	S3	GLEY2;6/5PB	GLEY2;5/10B	GLEY2;5/10B	GLEY2;6/5PB
	S4	GLEY2;7/10G	GLEY2;6/5PB	GLEY2;6/5PB	GLEY2;7/10G
Hydromorphic soils of Day River	S5	5YR6/3	5YR5/3	5YR5/1	5YR6/3
	S6	5YR6/3	5YR4/3	GLEY1;7/5G_/2	5YR6/3
	S7	7.5YR6/2	7.5YR5/3	GLEY2;7/5PB	7.5YR6/2
	S8	5YR6/4	5YR4/3	GLEY2;7/5PB	5YR6/4
	S9	2.5YR6/2	2.5YR4/3	GLEY1;5/10Y	2.5YR6/2
Hydromorphic soils of Arich River	S10	GLEY1;8/10Y	GLEY1;7/5G_/2	GLEY1;8/5GY	GLEY1;8/10Y
	S11	GLEY1;7/10Y	GLEY1;5/5GY	GLEY1;6/10Y	GLEY1;7/10Y
	S12	GLEY1;7/10Y	GLEY1;6/5G_/2	GLEY1;6/5G_/1	GLEY1;7/10Y
	S13	GLEY2;7/5PB	GLEY2;5/10GB	GLEY2;6/5GB	GLEY2;7/5PB
Cambisols	S14	2.5YR6/2	2.5YR4/4	2.5YR6/1	2.5YR6/2
	S15	10R6/2	10R4/2	GLEY1;6/5G_/2	10R6/2
	S16	10R7/3	10R6/3	7.5YR6/2	10R7/3
	S17	5R7/4	5R5/6	5R7/2	5R7/4

It should be emphasised that multiple factors, including the presence of organic matter, weathering, and mineralogy, can impact the colour of a soil sample. Therefore, it is crucial to interpret the MUNSELL colour code alongside other relevant soil data to understand the soil sample properties comprehensively.

The investigation of soil colour after iron extraction is a significant parameter for determining the type of iron accountable for the observed colouration (Fig. 4). The study results indicate that most soil samples have changed colouration due to iron oxidation in hydromorphic soils in the Day River, resulting in a loss of their original colour. Following iron extraction, these soils reverted to their initial gray colouring. Conversely, a considerable decrease in colour saturation (Chroma) was observed for soils originally red after iron extraction with dithionite. In contrast, other hydromorphic soils in the Ouerna River and Arich River demonstrated a distribution skewed towards higher saturation values. Analysis of the soil samples revealed that red and brown colouring is attributed to crystallised iron oxide, specifically hematite and goethite. This is corroborated by previous research, such as the findings of Lamouroux et al. [40], who identified that hematite is mainly responsible for the red colour of soils and that its largest crystallites are dissolved by hydrochloric acid and sodium dithionite.

Fig. 4. Variation in the colour of the soil after the extraction of dithionite iron

✓ Magnetic susceptibility

Magnetic susceptibility refers to the extent to which a material influences a given magnetic field, and this influence depends on the type and quantity of magnetic compounds present in the analysed sample, such as soil. The most prevalent iron forms found in soils include hematite, goethite, lepidocrocite, magnetite, and maghemite. The emergence of these forms is influenced by the prevailing climate and geological conditions [41]. As the iron content increases from the bedrock to the surface, there is a concomitant rise in the MS of soil particles [42].

The grain size of the ferromagnetic phase is an important factor affecting the soil frequency-dependent (FD). This susceptibility is sensitive to sub-micron-sized grains, particularly those that fall within the super-paramagnetic (SP) and single domain (SD) limits (0.01-0.03) [43-45]. The magnetic methods indicate the level of ferromagnetic minerals and their granulometric fraction, which allows differentiation between metallic dust and pedological particles [46].

The soil samples were analysed using mass magnetic susceptibility measurements in low- and high-frequency modes (χlf and χhf), and the magnetic susceptibility frequency dependence (χfd) reported in Table 4. The results indicate that all the samples have low positive values, indicating the presence of paramagnetic minerals such as ilmenite, siderite, and clay minerals. Moreover, 11 samples have excluded values of χfd between 10 % and 14 %, which suggests that most soils have a high percentage (greater than 75 %) of super-paramagnetic (SP) magnetic grains of pedological origin, indicating that these sediments have undergone significant pedogenesis. In contrast, the remaining samples show a mixture of SP grains (diameter < 0.005 mm) and coarse grains (MD and PD) with moderate concentrations. These findings are consistent with those reported by El Hamzaoui et al. [6], who found that the FD value of Beni Moussa soils ranges from 5.64 % to 19.68 %, with an average of 12.14 %. FD > 5 % indicates the presence of a large quantity of ultrafine ferromagnetic material, which might be related to the presence of a paedogenic SP magnetite.

Table 4

Magnetic susceptibility of hydromorphic soil

Samples	**χlf [SI]**	**χhf [SI]**	**χfd [%]**
S1	$2.86 \cdot 10^{-7}$	$2.56 \cdot 10^{-7}$	9.58
S2	$6.41 \cdot 10^{-7}$	$5.69 \cdot 10^{-7}$	11.30
S3	$5.24 \cdot 10^{-7}$	$4.69 \cdot 10^{-7}$	10.30
S4	$1.96 \cdot 10^{-6}$	$1.75 \cdot 10^{-6}$	11.10
S5	$1.69 \cdot 10^{-6}$	$1.51 \cdot 10^{-6}$	10.90
S6	$5.91 \cdot 10^{-7}$	$5.36 \cdot 10^{-7}$	9.44
S7	$1.93 \cdot 10^{-6}$	$1.71 \cdot 10^{-6}$	11.30
S8	$1.50 \cdot 10^{-6}$	$1.33 \cdot 10^{-6}$	11.40
S9	$5.09 \cdot 10^{-8}$	$4.34 \cdot 10^{-8}$	14.90
S10	$3.43 \cdot 10^{-8}$	$3.50 \cdot 10^{-8}$	4.10
S11	$5.95 \cdot 10^{-8}$	$5.93 \cdot 10^{-8}$	5.66
S12	$6.55 \cdot 10^{-8}$	$6.92 \cdot 10^{-8}$	2.87
S13	$1.75 \cdot 10^{-6}$	$1.56 \cdot 10^{-6}$	11.00
S14	$2.00 \cdot 10^{-6}$	$1.76 \cdot 10^{-6}$	11.90
S15	$1.06 \cdot 10^{-6}$	$9.53 \cdot 10^{-7}$	10.30
S16	$1.28 \cdot 10^{-6}$	$1.14 \cdot 10^{-6}$	11.30
S17	$6.39 \cdot 10^{-7}$	$5.78 \cdot 10^{-7}$	9.94

✓ Heavy metals

X-ray fluorescence analysis can be used to determine the concentration of major elements (ME) and trace metallic elements (TME) in soil samples in parts per million [ppm]. The findings are presented in Table 5. The iron concentration [ppm] values obtained from this examination indicate that the soils of hydromorphic nature in Arich River demonstrate low levels, which increase progressively from the top to the bottom of the River, as depicted in Figure 5. The iron’s migration in a reduced state by water, from the top to the bottom of the River, could account for this phenomenon. The same trend is noted for Ouerna River, except for sample No. 2. The other examined samples present high values ranging from 11,107.50 ppm to 40,708.44 ppm.

Table 5

Major element concentrations

Samples	Fe [ppm]	Ca [ppm]	K [ppm]	Mn [ppm]	Al [ppm]	Cu [ppm]	Zn [ppm]
S1	11,107.50	29,329.58	1,477.30	269.46	3,932.02	17,635.00	107.69
S2	27,774.18	36,707.70	6,299.03	406.61	13,205.80	30.91	153.83
S3	23,519.20	46,841.20	4,477.84	366.66	7,564.59	31.08	578.82
S4	25,958.83	43,765.77	5,197.06	270.77	14,428.52	23.37	136.09
S5	27,458.54	37,187.41	8,814.92	532.04	17,726.90	45.32	123.81
S6	40,708.44	45,032.11	10,817.70	652.71	20,560.70	53.18	148.19
S7	36,527.54	36,315.39	10,075.20	461.43	17,384.30	47.39	150.80
S8	27,304.12	44,200.36	8,905.12	518.71	16,295.09	38.70	85.86
S9	31,252.03	26,285.17	9,633.94	613.43	17,863.30	37.63	106.29
S10	5,462.73	165,541.70	1,828.98	122.30	4,426.79	21.01	211.05
S11	5,704.63	223,367.80	2,277.29	174.46	5,164.79	-	44.27
S12	8,874.98	150,434.80	2,955.26	125.07	4,839.96	-	35.93
S13	11,244.87	191,532.70	4,399.47	124.92	8,989.29	18.08	54.39
S14	30,729.55	16,899.40	6,285.21	500.65	12,744.65	26.27	84.35
S15	23,531.09	54,749.67	5,329.82	385.69	13,300.97	19.42	67.83
S16	27,813.98	38,251.27	9,831.80	398.77	14,973.24	40.97	96.28
S17	29,821.28	57,199.35	6,695.23	442.57	14,702.95	-	71.45

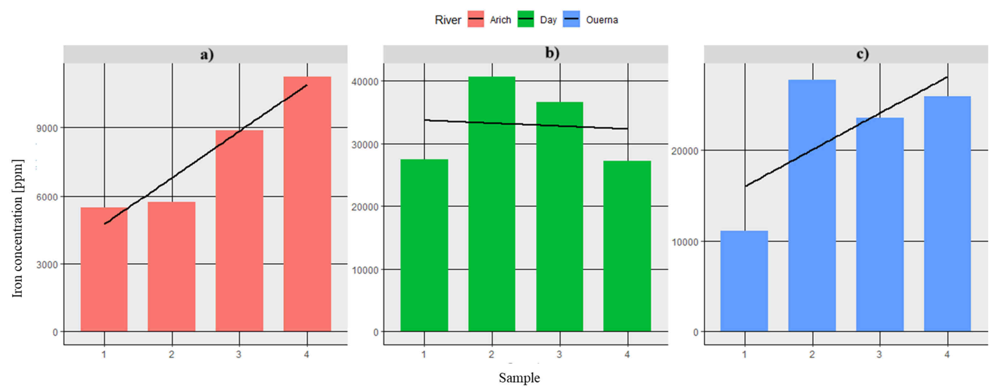

Fig. 5. Representative profile of iron results in the soils of the: a) Arich, b) Day and c) Ouerna Rivers from upstream to downstream

Multivariate statistical techniques

Multivariate statistical methods, including Pearson correlation coefficient, PCA, and HCA, were utilised to extract significant data insights. All mathematical and statistical calculations were performed using the R programming language.

Pearson's correlation coefficient

Pearson correlation coefficient was calculated to determine the interrelationship between some physicochemical soil properties and their relation to the behaviour of iron in the Beni Moussa plain (Fig. 6) [47].

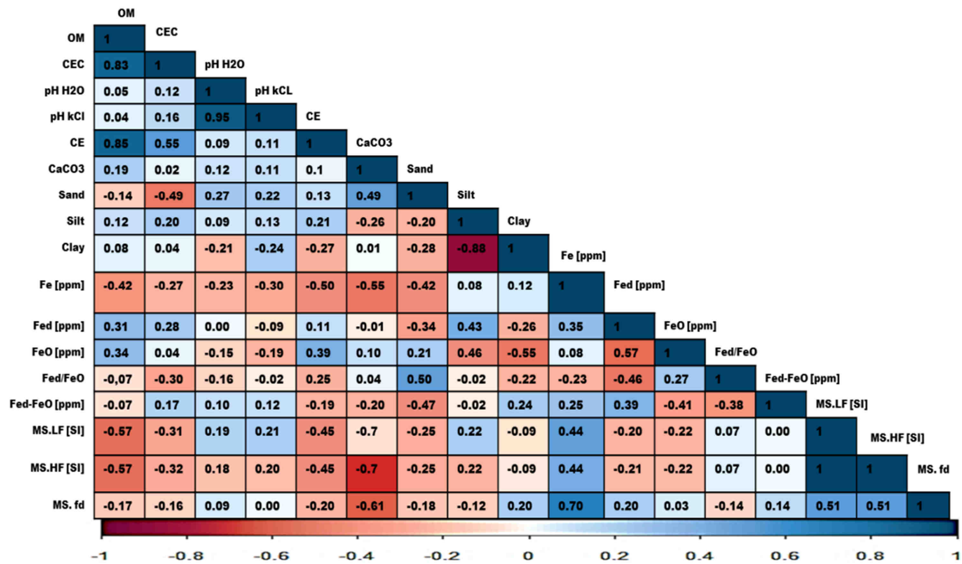

Fig. 6. Pearson correlation matrix of some physicochemical properties of soils in the Beni Moussa area

The Pearson correlation coefficient was utilised to investigate the relationship between various physicochemical soil properties [48]. Figure 6 shows the correlation coefficients of soil properties from the Beni Moussa irrigated perimeter. The results indicate that OM is positively correlated with CEC and cation exchange (CE), with correlation coefficients of 0.83 and 0.85, respectively. Conversely, OM is negatively correlated with Magnetic Susceptibility Low Frequency (MS.LF) and Magnetic Susceptibility High Frequency (MS.HF), with correlation coefficients of –0.57, as well as iron oxide measured by XRF (r = 0.42), indicating that increases in OM are associated with decreases in MS.LF, MS.HF, and iron oxide. A previous study conducted by Hervé Guibert in 2002 found a positive association between CEC and OM, indicating that CEC is closely related to OM and the proportion of clay in the soil. Guibert also introduced the concept of "organic CEC", which refers to the increase in CEC associated with high levels of OM in the soil. In addition, calcium carbonate ($CaCO_3$) is positively correlated with sand (r = 0.49) but negatively correlated with MS.LF, MS.HF, and Fine Sand (FD) (r = −0.7). Iron is positively correlated with FD (r = 0.7) but negatively correlated with sand (r = −0.608), as confirmed by several previous studies [49-51]. Clay is strongly negatively correlated with silt (r = −0.88) and iron oxide (r = −0.55), respectively. These findings can be traced back to the work of Blume and Schwertmann [38] who demonstrated that clay migration in sediments is mainly caused by low soil iron concentration [ppm].

Principal component analysis

The PCA was performed on data sets containing 17 individuals (sampling points) and 17 variables (parameters analysis results). The analysis made it possible to retain several dimensions. PCA reveals that the first two dimensions together account for 45.29 % of the total variability in our data sets. This indicates that a significant portion of the variability in the persons or variables may be explained by the defined plane produced by these dimensions. This proportion, notably, is higher than the 40.7 % reference value, highlighting the statistical importance of the explained variability. As shown in Figure 7, these results emphasise the significance of the recognised dimensions in identifying and clarifying important patterns within the data sets.

✓ Description of the dimension 1

Dimension 1 opposes individuals such as 7, 13, 8, 4, 6, and 14 (to the right of the graph). The data sets highlight several categories stressing apparent geographic segregation in the graph, from people with highly positive coordinates on the axis (e.g., 1, 10, 3, 12, 9, and 2) to those with substantially negative values. Notably, the numbers 7, 8, and 6 comprise a unified group with positive coordinates. High silt and Fe [ppm] readings identify this cluster, demonstrating the strong impact of these factors. In contrast, there is a divergent trend in the data sets for this group, which shows lower values for CE and sand. These results highlight the data sets spatial distribution and unique features, illuminating the connections between important variables.

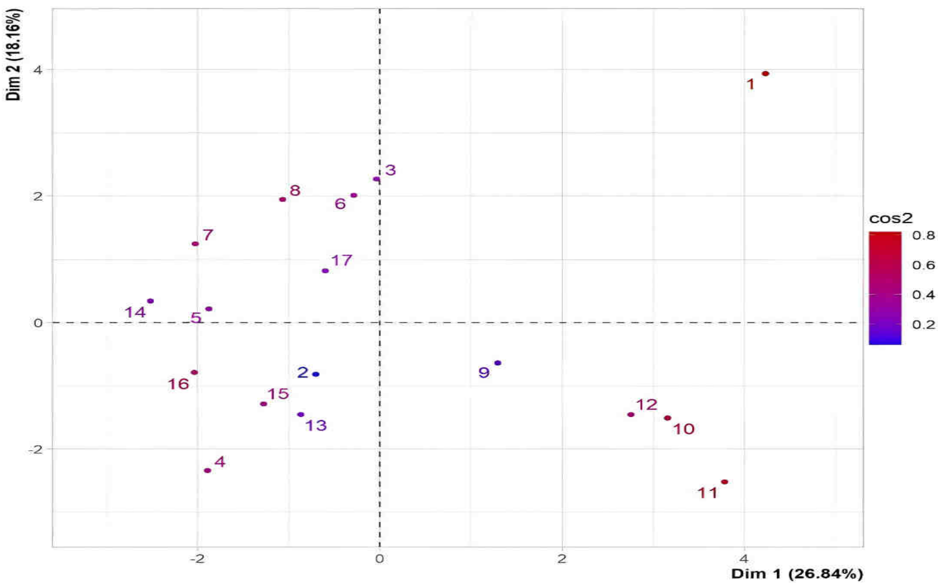

Fig. 7. Individual mapping in PCA visualising their contribution through cos2

The data sets reveal that the cluster of individuals 13, 4, and 14 designated by positive coordinates on the axis displays unique features. This group has higher values for MS.HF and MS.LF indicates a significant impact from these variables. On the other hand, this cluster has lower values for Fe_d and OM, suggesting a divergent trend in the data sets. Individuals 10, 3, 12, 9, and 2, shown by negative coordinates on the axis, form a cluster that displays certain tendencies in the data sets.

Interestingly, this group shows higher values for the clay, $CaCO_3$, OM, and CE variables, indicating a more substantial influence from these components. Conversely, the variables MS.HF, MS.LF, and silt show lower values, suggesting a different trend within this cluster.

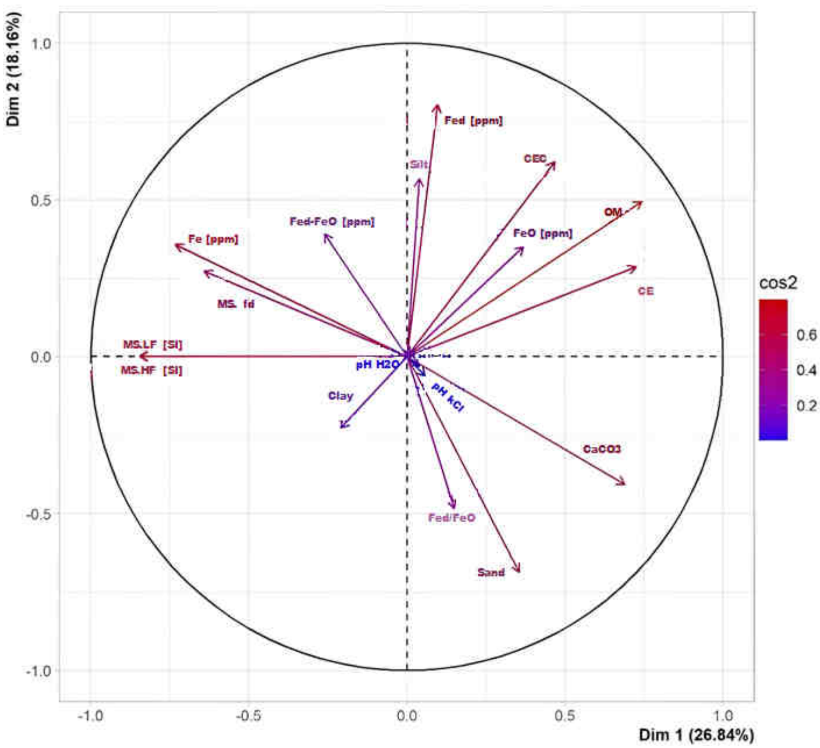

Fig. 8. Factor map of PCA representing the distribution and relationships of variables

✓ Hierarchical cluster analysis

The result of the Q-mode cluster analysis can be displayed in a tree-like structure called a dendrogram. The derived dendrogram is used in this study and is shown in Figure 8. This Q-mode HCA has highlighted three large clusters, 1, 2, and 3 (Fig. 9).

Cluster 1 is mainly characterised by high levels of CE, $CaCO_3$, and OM, which indicate that these are the most significant factors. In contrast, the group in question has lower values for Fe [ppm] and MS.FD, suggesting a much smaller contribution from these factors to Cluster 2 comprising people 2, 8, 9, and 16. This cluster is characterised by elevated values for MS.FD, clay, and Fe [ppm], with these variables having the most influence. Ultimately, individuals 6 and 7 in Cluster 3 are distinguished by elevated levels of the variable Fe [ppm]. With a focus on the different strengths and weaknesses of the important variables in the data sets, this summary highlights the distinctive qualities of every cluster. Cluster 1 comprises individuals: 1, 10, 11, 12 and 13.

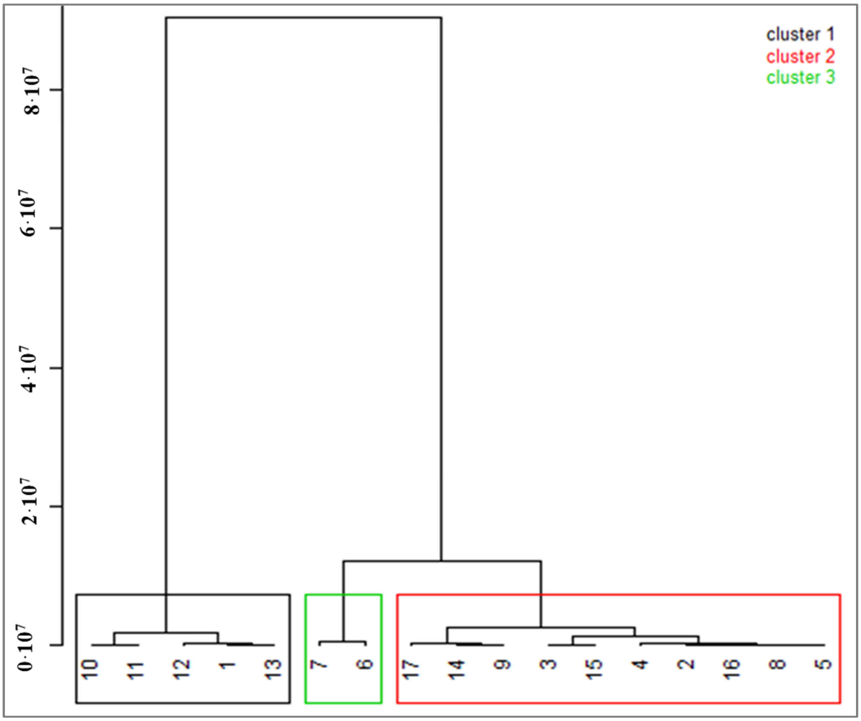

Fig. 9. Ascending hierarchical classification of the individuals

Conclusion

The main objective of this work is to analyse the behaviour of iron and its relationship with the physicochemical properties of hydromorphic soils in the Tadla plain in Morocco. An in-depth approach, involving the use of physicochemical analysis of 17 soil samples taken at a depth of 20 cm, as well as PCA and HCA from a statistical perspective, was employed to ensure a comprehensive assessment. The results showed that:

- The studied soils had a loamy-sandy to loamy-clayey texture, with a neutral to alkaline pH_{H2O}. They were rich in OM and carbonates $CaCO_3$. Additionally, they exhibited high levels of iron, suggesting migration in reduced form. The values of *EC* and MS were positive and low, indicating an abundance of paramagnetic minerals such as ilmenite, siderite, and clay minerals.
- Statistical analysis, in conjunction with PCA, HCA, and Pearson correlation coefficient analysis, revealed significant associations between different physicochemical properties of hydromorphic soils in Beni Moussa, especially between iron, OM, and MS. This suggests a complex interdependence between soil components, highlighting the importance of iron in regulating specific physicochemical characteristics of these hydromorphic soils.

These results have important implications for understanding the dynamics of iron in hydromorphic soils and for improving irrigation practices and land management in the region to promote sustainable agriculture. Therefore, this study contributes to scientific knowledge based on soil properties and provides essential information for soil management and agricultural practices in the Beni Moussa region and in similar contexts elsewhere.

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