SALINIZATION AND SODIFICATION OF THE LAKE CHAD POLDERS : IMPACT ON AGRICULTURE AND LOCAL MANAGEMENT PRACTICES

ABSTRACT

This study focuses on assessing salinization and sodification in the soil profiles polders in the Lake Province. The salinization and sodification of polder soils result from key factors such as endorheism, the capillary rise of brackish groundwater, and wind and water erosion. Additionally, inappropriate agricultural practices, including archaic irrigation methods combined with deep plowing techniques, affect the soil structure of developed and semi-developed polders. These salinized and sodic soils are characterized by the predominance of pale yellow (2.5Y 9.5/2) and white (2.5Y 9.5/1) colors. Physicochemical analysis of these soils reveals a basic pH (pH > 8), relatively high electrical conductivity (EC > 2.5 dS/m), a heavy clayey texture (HCT), and a compact massive structure. The values of these parameters, exceeding tolerable thresholds, clearly indicate soil degradation, leading to a decline in agricultural production.

Keywords: salinization, agricultural practices, polders, saline, impact.

INTRODUCTION

The characterization of salinization and sodification of land represents a major global challenge (Afes, 2021; Boualla et al., 2012; FAO, 2021; Grunberger, 2015; Legros, 2009; Mhiri et al., 1998). According to a report from the Food and Agriculture Organization of the United Nations (FAO, 2021), approximately 833 million hectares, or 8.7% of the total land surface, were affected by these phenomena in 2021. Furthermore, they directly impact 20% of the global population (Afes, 2008, 2021). Saline and sodic soils are characterized by high electrical conductivity and a significant proportion of exchangeable sodium. These soils contain an excessive amount of soluble salts, which hinder plant growth. In agronomy, a salt is defined as a substance with water solubility sufficient to impair plant development (Afes, 2021; Baize, 2016). The presence of soluble salts in soil reduces plants' ability to absorb water, thereby compromising their hydration and nutrition (Lallemand-Barrès, 1980).

In Chad, saline and sodic soils are widespread in the semi-arid regions of the northwest and the arid regions of the north. These areas, characterized by Sahelian and Saharan climates, experience average annual temperatures of around 30°C and annual rainfall below 400 mm (Alladjaba et al., 2023; Bekayo, 1998; Legros, 2009; Mahamat-Saleh et al., 2015). Bekayo (1998) highlighted high salt concentrations in Mara and Zafaye within irrigated rice perimeters in N'Djamena and its surroundings, where capillary rise and surface crust formation are prevalent. In the Bahr el Ghazal region, Pias and Guichard (1952) also reported the presence of saline soils. Further north, between Faya-Largeau and Gaïn, Legros (2009) identified that the Borkou depression is covered with soils exhibiting a whitish crust, commonly known as "banco." These soils, with high salt and sodium content (10 to 30 meq/kg), are characterized by low permeability.

In the Lake Province, saline and sodic soils are frequently observed in the dried polders of Koulouchoua 1 and 2, as well as in the developed polders of Berim Sud, Guini, and Mamdi. This study aims to assess the state of soil degradation in polders affected by these processes, characterize their macromorphological and physicochemical properties, and evaluate their impact on the development of agricultural crops.

MATERIALS AND METHODS

Study Area Description

The study site is located in the Lake Province (13°34'0.25" - 13°24'0.5" N and 14°37' - 14°47' E), northwest of N'Djamena, the capital of Chad (Inseed, 2012; Malet, 2015). The climate is semi-arid Sahelian, with two distinct seasons: a long dry season from October to May and a short rainy season from June to September (Sodeteg, 1992). Monthly cumulative rainfall between 2018 and 2022 ranged from 366.25 mm in August to 76.5 mm in October (Sodelac, 2022). The annual average temperature varies between 12.9°C and 42.2°C (Pias & Guichard, 1952). These climatic conditions significantly influence agricultural activities.

Data Collection

This study focused on four polders in the Lake Province: Berim Sud (partially abandoned), Koulouchoua 1 and 2 (completely abandoned), and Gambia (semi-developed and fully submerged). Samples were collected using an Edelman auger. A shovel and a pickaxe were used to open soil profiles. Once prepared, these soil samples underwent macromorphological characterization and physicochemical analyses at the Soil, Water, and Plant Analysis Laboratory (LASEP) of the Chadian Institute for Agronomic Research and Development (ITRAD).

Data Analysis Methods

The pH and electrical conductivity (EC) were measured using a portable pH meter and conductivity meter, respectively. The AFES textural diagram was used to interpret particle size distribution data. Adobe Illustrator, Microsoft Excel, and QGIS were employed to create diagrams, design maps (Figure 1), and process data. Soil colors were determined using the Munsell color chart, while the "sausage test" was used to assess the soil texture of the Koulouchoua 1, Koulouchoua 2, and Gambia polders. However, the soil textures of the Berim polder were determined in the laboratory using the densimetric method for three fractions (clay, silt, and sand). The Koulouchoua 3 polder exhibits similar morphological and physicochemical characteristics to the Koulouchoua 1 polder. Table 1 below provides the clay content proportions in the sampled soils, derived from a manual assessment using the sausage test.

Table 1: Manual Assessment of Soil Clay Content (Viaux, 2023)

Ability to form a sausage (5 to 10 mm diameter) with a moist soil sample	Clay Content
Unable to form a sausage	<12%
The sausage breaks easily	12 à 18%
Unable to roll the sausage into a ring	18 à 25%
Able to form a ring with the sausage	>25%

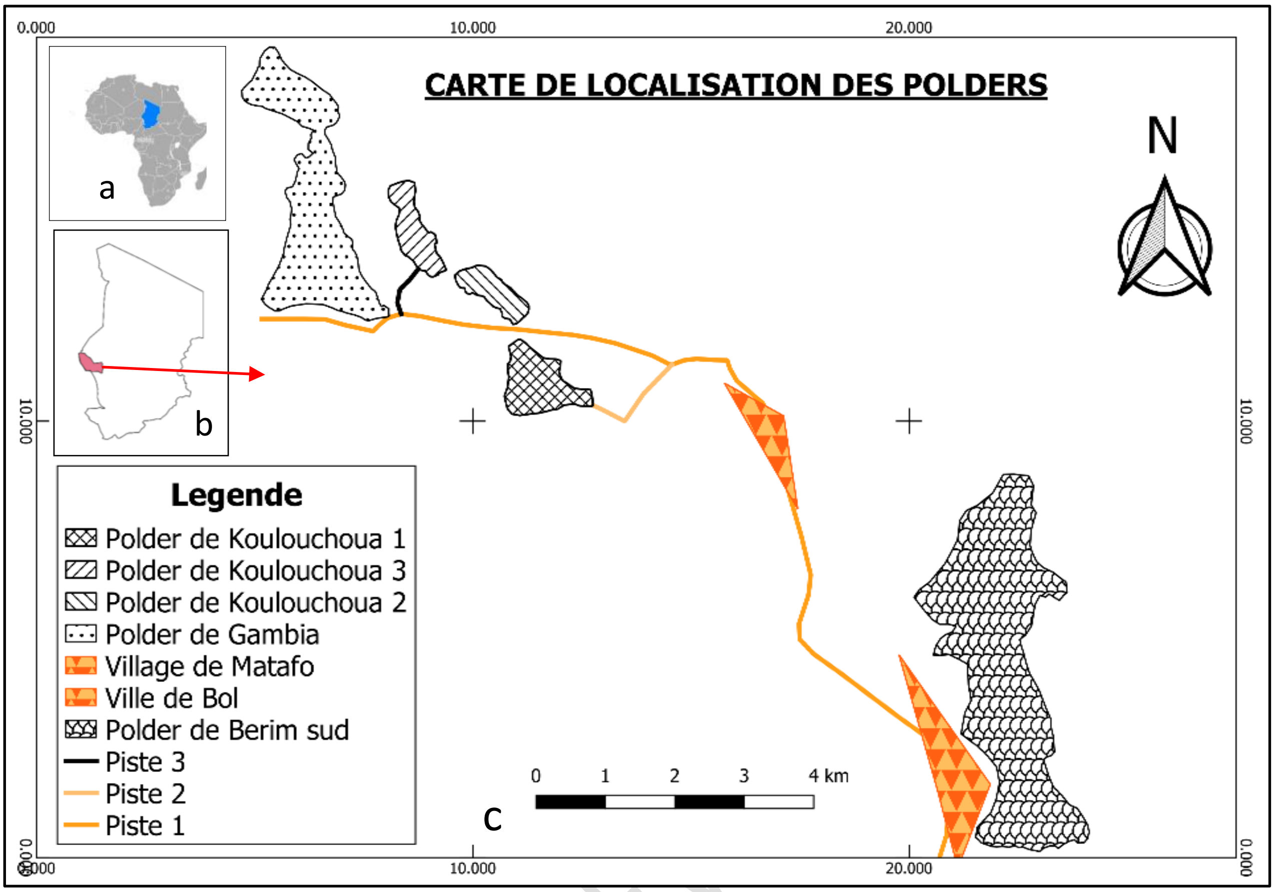


Figure 1: Study Area Localization, (a) map of Africa, (b) map of Chad with the Lake Province highlighted in pink, and (c) close-up of the various polders.

RESULTS

Macromorphological and Physicochemical Characterization of Soils from the Polders of Berim Sud, Gambia, and Koulouchoua 1 and 2

Koulouchoua 1 Polder

This is a completely abandoned polder. Data on pH and electrical conductivity (EC) from the soil profile across five horizons indicate a decrease in salinity with depth ($0.12 \leq$ EC (dS/m) ≤ 8.01). Conversely, the pH, although extremely basic, remains constant throughout the profile ($9.4 \leq$ pH ≤ 10.2). These values characterize soils that are highly alkalinized and moderately to extremely saline (Table 2). Such conditions are unfavorable for the development of agricultural crops (Figure 2).

Figure 2: Abandoned Polder of Koulouchoua 1 North of the City of Bol

The morphological characterization of the soils from Koulouchoua 1 reveals a dominance of pale yellow color throughout the profile depth. This coloration is generally associated with very low organic matter and nitrogen content. The first three horizons exhibit massive and very compact structures, typical of heavy clay-textured soils. In contrast, horizon 4, also pale yellow, is distinguished by a platy structure, indicating the presence of water at depth. The deeper horizon 5 is characterized by a granular structure, reflecting very low consistency. According to Viaux (2023), soil structure influences its aeration, water movement, living organisms, and the ability of plant roots to explore and penetrate deeply into the soil. However, the morphological examination of the soils from the Koulouchoua 1 polders indicates a compact surface structure, which is very characteristic of degraded soil and unfavorable for good agricultural production.

00–25 cm
Horizon 1 with very pale yellow color (2.5Y 9.5/2) in both dry and wet states. The texture is clayey with a very compact, massive, and non-friable structure. The transition with the underlying horizon is sharp.

25–50 cm
Horizon 2 with very pale yellow color (2.5Y 9.5/2) in both dry and wet states. The texture is clayey with a very compact, massive, and non-friable structure. The transition with the underlying horizon is gradual.

50–90 cm
Horizon 3 with very pale yellow color (2.5Y 9.5/2) in both dry and wet states. The texture is clayey with a very compact, massive, and slightly friable structure. The transition with the underlying horizon is sharp.

90–120 cm
Horizon 4 with pale yellow color (2.5Y 8.5/2) in both dry and wet states. The texture is clayey with a platy structure composed of thin horizontal layers, very compact and non-friable. The transition with the underlying horizon is sharp.

120–140 cm
Horizon 5 with pale yellow-orange color (10YR 9.5/2) in both dry and wet states. The texture is clayey with a sandy granular structure, non-compact, non-coherent, and very friable. Presence of the water table at depth.

Figure 3: Morphological characteristics of the soil profile of the abandoned Koulouchoua 1 polder composed of five horizons from the surface to depth.

pH plays a decisive role in soil fertility. A pH above 9 (Table 2) is not only unfavorable to the biological activity of microorganisms but also compromises the structural stability of agricultural soils. The high pH values (>9) in the Koulouchoua 1 polder are likely related to the polder's endorheic nature and the geology of the groundwater. Our results similarly indicate a basic pH corresponding to soils affected by salinity or sodicity. Table 2 shows that horizons 4 and 5 (H4 and H5) are non-salinized (EC ≤ 2.5 dS/m), while the surface horizons (H1, H2, H3) are salinized (EC > 2.5 dS/m).

Table 2: pH and Electrical Conductivity of the Soil Profile of the Koulouchoua 1 Polder.

Horizons	**H1**	**H2**	**H3**	**H4**	**H5**
Depth (Cm)	0-25	25-50	50-90	90-120	120-140
pH	9.71	10.03	9.44	9.64	10.2
Ec (dS/m)	3.45	8.01	4.8	0.904	0.12
Structure	Massive	Massive	Massive	Foliated	Particulate
Texture	Clayey	Clayey	Clayey	Clayey	Sandy

Koulouchoua 2 Polder

Located about one (1) kilometer from Koulouchoua 1, this polder exhibits similar characteristics (Figure 4). However, minor surface features are observed, including white crusts and desiccation cracks (Figure 4). During soil sampling with an auger, difficulty was noted in penetrating the tool into the deeper horizons. This indicates pronounced soil compaction due to poor aeration. Such a structure is unfavorable for the penetration of plant roots.

Figure 4: Abandoned Koulouchoua 2 Polder with Desiccation Cracks

The high pH values (>9) and electrical conductivity (EC > 4 mS/cm) indicate that these soils are strongly basic (alkaline) and saline, compared to the salinity scale where the critical threshold is set at 2.5 mS/cm (Servant, 1975). When the electrical conductivity exceeds EC > 9 mS/cm, the sum of anions in the soil sample ranges from 50 to 105 meq/liter (Table 3). The elevated pH and electrical conductivity values confirm the unsuitability of these soils for agricultural use.

Table 3 : pH and Electrical Conductivity of the Soil Profile of the Abandoned Koulouchoua 2 Polder

Horizons	***H1***	***H2***	***H3***
Depth (cm)	0-30	30-70	70-90
pH	9.97	9.95	9.82
EC (dS/m)	9.77	9.00	4.47
Structure	Massive	Massive	Massive

Texture	Clayey	Clayey	Clayey

The morphological characterization of the horizons in the soil profile of Koulouchoua 2 reveals a dominance of white color throughout the depth (Figure 5). This coloration reflects a very low organic matter content, as evidenced by the complete absence of vegetation in this polder (Figure 5). Soil structure represents the natural and stable arrangement of soil particles. It plays a crucial role in plant growth processes, meaning an “ideal” structure offers many advantages, including natural drainage, water and nutrient retention, aeration, and good penetration and distribution of the root system. However, in the Koulouchoua 2 polder, the soil structure is massive, which is unfavorable to water infiltration. This promotes the formation of white crusts on the surface, a sign of severe degradation of the soil’s physical and chemical properties.

0-30 cm	Horizon 1 is white (2.5Y 9.5/1) when dry and white (2.5Y 9/1) when wet. The texture is clayey, with a massive, loose structure that is slightly compact and very friable. The transition is gradual.
30-70 cm	Horizon2 is very pale yellow (2.5Y 9/2) when dry and white (10YR 9.5/1) when wet. The texture is clayey, with a massive structure that is slightly compact and very friable. The transition is sharp.
70-90 cm	Horizon3 is white (2.5Y 9.5/1) when wet and white (10YR 9/1) when dry. The texture is clayey, with a massive, loose structure that is very friable.

Figure 5: Morphological characteristics of the soil profile in Koulouchoua 2, consisting of three horizons from the top to the bottom of the profile.

Gambia Polder

Covering an area of 531 hectares, the Gambia polder has been cultivated for many years. Locally referred to as a "semi-modern polder" due to its irrigation system involving prolonged submersion of parcels with water, this irrigation technique facilitates the leaching of surface salts to deeper horizons (Table 4). Soil tillage is carried out when the polder dries. Analysis of soil samples revealed a predominant sandy (particulate) structure throughout the profile depth. The soils are slightly compact and very friable, exhibiting a black color (5Y 2.5/2) when wet, which transitions to pale yellow (2.5Y 8/2) when dry. The black coloration in the wet state indicates the presence of organic matter in these sandy-textured soils.

Figure 6: Gambia Polder under cultivation

The particulate structure observed across the three horizons indicates low cohesion between soil particles. Such soil structure can promote good water infiltration and leaching of salts to deeper horizons. However, it can hinder water retention. A low potential for water and nutrient retention in the soil increases the risk of leaching, particularly for nitrates, which can deplete surface horizons of nitrates.

0-30 cm
Horizon1 Black (5Y 2.5/2) when wet and dry. Its texture is sandy, and its structure is particulate, slightly compact, and slightly friable when dry. The transition to the underlying horizon is gradual.

30-50 cm
Horizon2 Black (5Y 2.5/2) when wet but pale yellow (2.5Y 8/2) when dry. Its texture is sandy, and its structure is particulate, slightly compact, and very friable when dry. The transition to the underlying horizon is gradual.

50-90 cm
Horizon3 Black (5Y 2.5/2) when wet but pale yellow (2.5Y 8/2) when dry. Its texture is sandy, and its structure is particulate, slightly compact, and very friable when dry. The transition to the underlying horizon is gradual.

Figure 7: Morphological characteristics of the soil profile in the Gambia Polder

The pH of 9.4 across all three horizons indicates particularly high alkalinity in the deeper horizon (Table 4). The increase in pH with depth is attributed to leaching caused by the total submersion irrigation technique or the brackish quality of groundwater. These values indicate low availability of essential nutrients such as iron, zinc, manganese, and phosphorus, as these elements become less soluble in alkaline conditions.

Electrical conductivity (EC) values are low, indicating low to moderate salinity (Table 4). At this stage, this parameter reflects soils that are still suitable for most crops, as higher salinity levels could induce osmotic stress in plants. However, the slight increase in EC with depth (from H1 to H3) suggests potential gradual salt accumulation. If this trend continues over the long term, it could lead to slow soil salinization.

Table 4: pH and Electrical Conductivity of the soil profile in the cultivated Gambia Polder

Horizons	***H1***	***H2***	***H3***
Depth (cm)	0-30	30-50	50-90
pH	8.44	8.68	9.4
EC (dS/m)	0.33	0.37	0.39
Structure	Particulate	Particulate	Particulate
Texture	Sandy	Sandy	Sandy

Polder of South Berim

In an abandoned plot within the South Berim Polder, white spots on the surface indicate the formation of crusts resulting from the capillary rise of groundwater to the surface (Figure 8). Olive coloration and massive structure dominate the soil profile of this abandoned plot (Figure 9).

Figure 8: Salt precipitation and formation of white crusts in an abandoned plot of the South Berim Polder

The soil profile reveals heavy clay textures, sticky when wet, dominating the entire column, with clay content increasing at greater depths (H3). This type of soil, difficult to work mechanically, often ensures low permeability and poor drainage but provides high water retention. The polyhedral structure at the surface is, however, favorable for good aeration and water infiltration (Figure 9). In contrast, the deeper horizons (H2 and H3) exhibit massive structures with low porosity and a heightened risk of compaction.

0-25 cm :
Horizon1 Pale olive (5Y 6/3) when dry and olive (5Y 4/4) when wet. The texture is heavy clay with a polyhedral, compact structure, slightly friable. Roots are present, but no nodules are observed.

25-50 cm
Horizon2 Olive (5Y 5/4) when dry and olive (5Y 4/4) when wet. The texture is heavy clay with a massive, compact structure, slightly friable. Very fine roots and nodules are present, but calcareous nodules are absent.

50-90 cm :
Horizon3 Olive (5Y 4/3) both dry and wet. The texture is heavy clay with a massive, compact structure, slightly friable. Very fine roots are present, but no nodules are observed.

Figure 9: Morphological characteristics of the soil profile of the abandoned plot in the South Berim Polder composed of three horizons from top to bottom.

The pH is alkaline, with a decreasing trend at greater depths. Alkalinity can limit the availability of essential nutrients (iron, zinc, manganese, phosphorus). In Horizon H1, the pH value of 8.9 poses a significant risk of deficiencies in these elements (Table 5), although H2 and H3 are only mildly alkaline. The electrical conductivity (EC > 2.5 dS/m) values indicate feeble saline soils throughout the profile, suggesting that this type of soil is generally unfavorable for most crops.

Table 5: Physico-chemical characterization of the soil profile of the abandoned plot in the South Berim Polder

Horizon	*H1*	*H2*	*H3*
Depth (cm)	0–25	25–50	50–70
Clay (%)	54	55	65
Silt (%)	14	18	10.1
Sand (%)	32	26	24.9
Texture	Heavy Clay	Heavy Clay	Heavy Clay
Structure	Polyhedral	Massive	Massive

pH	8.9	8.2	8.0
EC (dS/m)	5	4,5	4

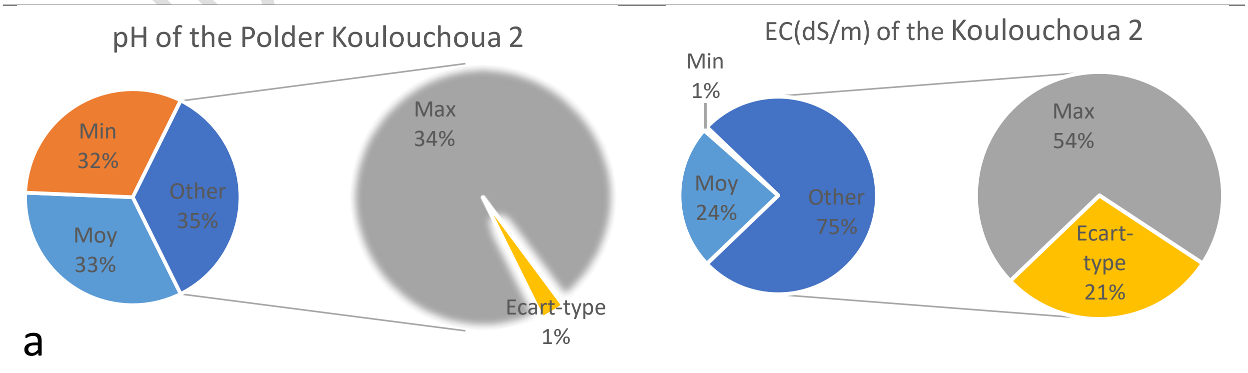
Statistical Analysis of Soil pH and Electrical Conductivity in the South Berim, Gambia, Koulouchoua 1, and Koulouchoua 2 Polders

The statistical analysis of soil data across the four polders reveals that pH levels range from basic to highly basic in all studied sites (Table 6). However, the Koulouchoua 1 and Koulouchoua 2 polders stand out with significantly higher electrical conductivity values compared to the Gambia and South Berim polders. According to agronomic standards established by the US Salinity Laboratory, electrical conductivity (EC) levels exceeding 8 dS/m lead to significant yield reductions for most crops due to the negative effects of salinity on plant growth.

Table 6: Statistical Results for pH and Electrical Conductivity Across the Four Polders

Polder Type	*Parameter*	*Minimum*	*Maximum*	*Mean*	*Standard Deviation*
Koulouchoua 1	pH	9.4	10.2	9.8	0.3
	EC (dS/m)	0.1	8.0	3.5	3.2
Koulouchoua 2	pH	9.8	10.0	9.9	0.1
	EC (dS/m)	4.5	9.9	9.9	2.7
Gambia	pH	8.4	9.4	8.8	0.4
	EC (dS/m)	0.3	0.4	0.4	0.05
South Berim	pH	8.0	8.4	8.9	4
	EC (dS/m)	4	5	4,5	2,26

Figure 10 below considers the maximum, average, minimum values, as well as the standard deviations of pH and electrical conductivity for the Koulouchoua 2 Polder, which is highly salinized, and the South Berim Polder, which is feebly salinized. The standard deviation of pH for the South Berim and Koulouchoua 2 polders, as illustrated in Figure 10, is 1%, indicating that pH values are high in both polders. However, the standard deviations of electrical conductivity are significantly higher in the Koulouchoua 2 Polder, highlighting more pronounced variation. The soils of the Koulouchoua 2 Polder are highly salinized, whereas those of the South Berim Polder exhibit feeble salinity, with electrical conductivity values above the salinity threshold set at EC >2.5 dS/m.



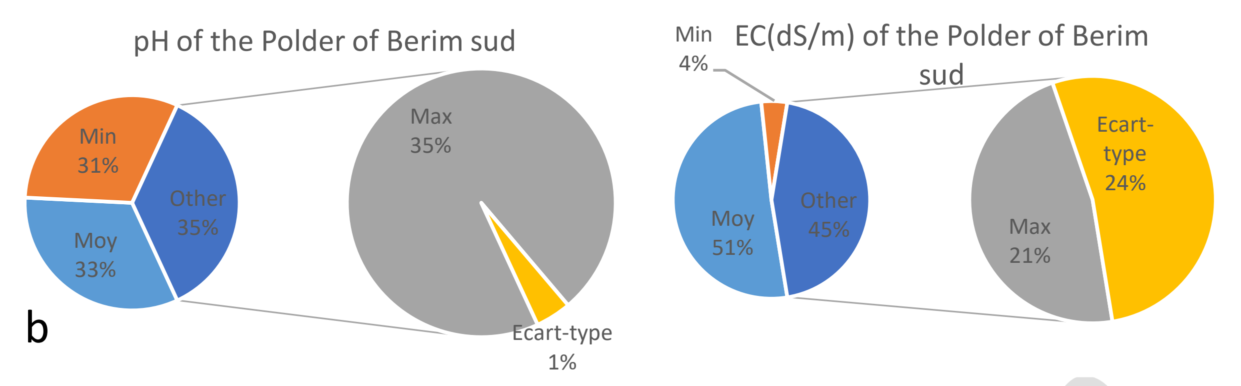


Figure 10 : Maximum Value and Standard Deviation of pH and Electrical Conductivity in the Koulouchoua 2 (a) and South Berim (b) Polders

Factors Leading to the Formation of Saline and Sodic Soils in the Polders of the Lake Province

Morphological observations and results from physico-chemical analyses reveal that the soils in the polders are affected by both primary and secondary salinization.

Primary Salinization: Resulting from natural processes, primary salinization is influenced by geological, hydrological, and climatic factors. The loss of water through evaporation and/or infiltration (endorheism), along with the lack of external drainage in the South Berim and Koulouchoua 1 and 2 polders, fosters surface salt accumulation. Furthermore, aridity and high evaporation rates during prolonged dry seasons lead to surface salt deposition, such as the formation of white crusts (Figure 2). Relatively brackish groundwater can also transport salts to the upper soil horizons within the top 30 cm through capillary action. Wind and water erosion are additional contributors. During the dry season (October to May), wind deposits evaporitic sediments directly into the polders. Similarly, raindrops falling on bare fallow soil disintegrate soil aggregates, suspending particles in water and facilitating their movement during surface runoff.

Secondary Salinization : Secondary salinization arises primarily from human activities, including improper agricultural practices like uncontrolled irrigation and the use of saline water from drainage systems (NaCl), particularly in the South Berim polder. Inadequate drainage systems further aggravate salt buildup in the root zone (Cheverry, 1966, 1974).

This phenomenon, noted in the agricultural polders of South Berim and Guini, is likely associated with inefficient drainage systems incapable of removing percolation water, leading to capillary salt rise toward the upper soil horizons (Figure 11b).

Figure 11: Two Plots Affected by Salinization : (a) Completely Abandoned Plot in Koulouchoua 2 and (b) Abandoned Rice Field During the Agricultural Campaign in the South Berim Polder

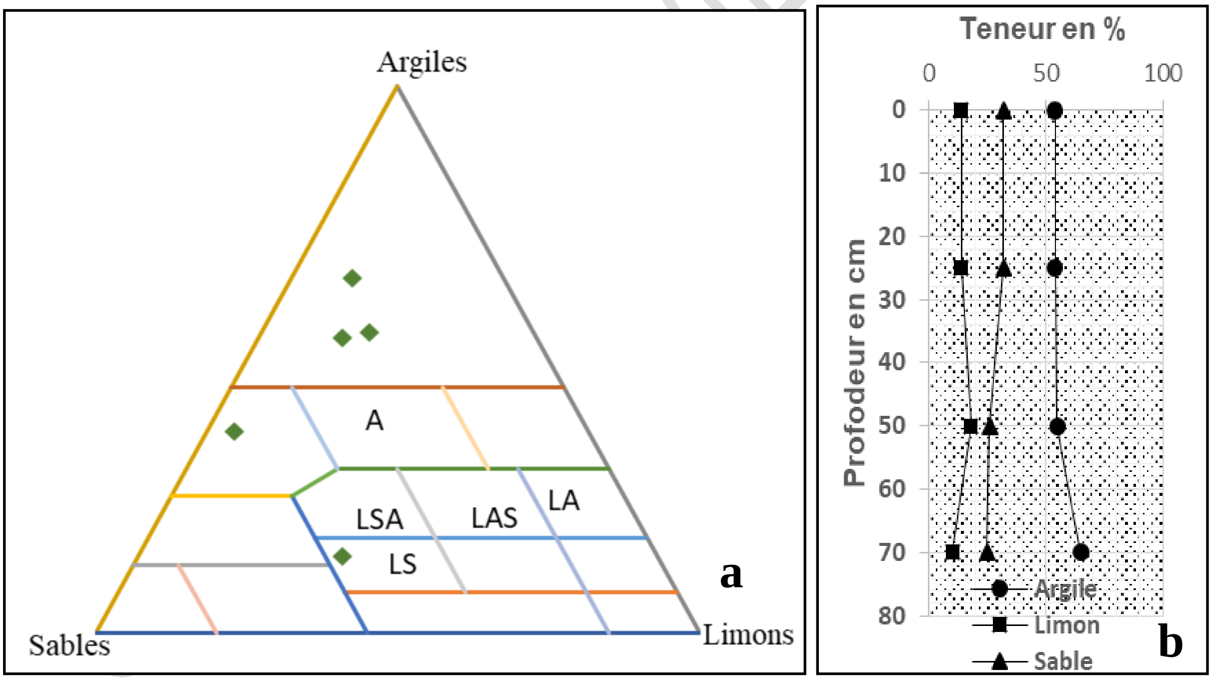


Figure 12 : Variation in Particle Size Texture (a) in Afes' Triangular Diagram and (b) in the Soil Profile of Plot 1 in South Berim polder (C(A) = Clay; SCS (LSA)= Clay, Sand, Silt; SCS (LAS) = Silt, Clay, Sand; SC = Silt, Clay; SS = Silt, Sand)

Local Methods for Managing Saline and Sodic Soils:

In the context of cultivating saline and sodic soils, several methods are locally applied in the Lake Province. These approaches aim to improve soil structure, reduce salinity and sodicity, and optimize agricultural productivity (Alladjaba et al., 2023; Cheverry, 1974; Dabin, 1970).

The saline soils of the polders are reclaimed using agricultural and hydraulic techniques designed to control water and enhance soil quality. The main practices include:

Plowing: This mechanical technique is the most commonly practiced in the Lake Province. It aims to break surface crusts and improve soil aeration. Plowing facilitates water infiltration and root movement, which helps reduce salt concentrations on the soil surface (Figure 12a).

Water management through the construction of dikes: Earthen dikes are built to control water retention and flow. This management prevents the stagnation of saline water on the surface of cultivated soils (Figure 12a).

Fallowing: Allowing land to rest enables natural fertility restoration and the leaching of salts by precipitation.

Drain installation: Surface drainage systems are installed to facilitate the evacuation of salt-laden water. These drains collect saline water and direct it to storage areas or outlets, particularly Lake Chad (Figure 12c).

Pumping stations: Saline water accumulated in drains is removed using pumping stations (Figure 12d). This active drainage technique reduces salinity in cultivated plots by extracting dissolved salts and discharging them into controlled disposal areas, notably Lake Chad.

To address soil salinization in these regions, it is recommended to adopt controlled irrigation that considers plant water requirements, cover the topsoil layers with coarse materials from the Lake polders to reduce evaporation and the formation of surface salt crusts (Baize, 2011), plant deep-rooted trees to curb saline water rise, and improve cultivation methods by adding nitrogen, organic matter, and compost to abandoned plots.

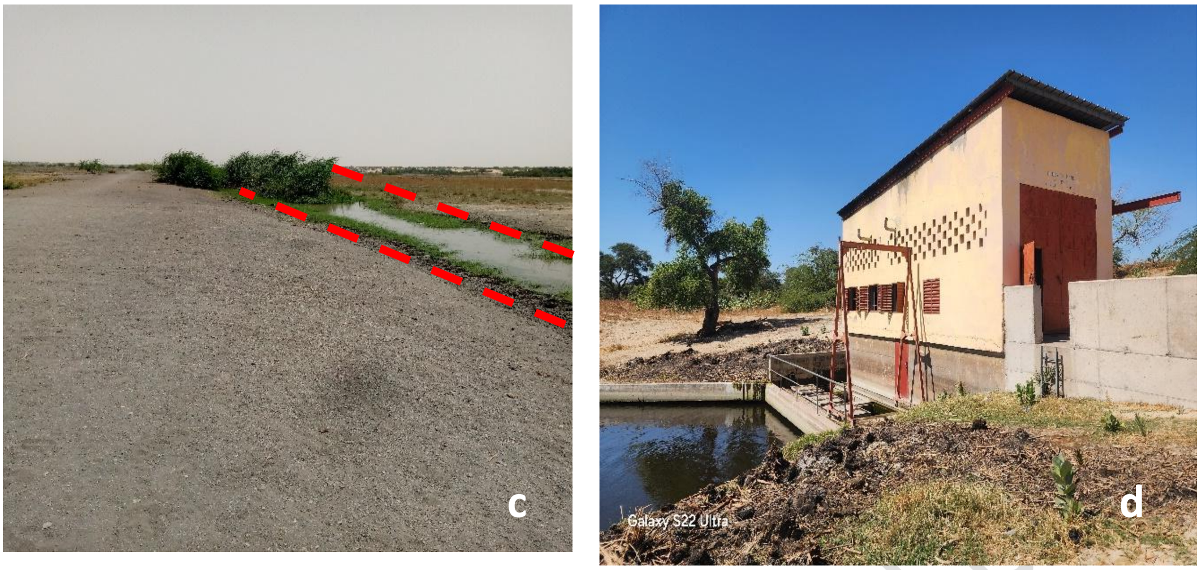


Figure 12 : Various Methods of Soil Salinity Management in Reclaimed Polders (a) Leveling with small dikes before irrigation in this wheat plot, (b) salt precipitation on the surface, (c) use of a clogged drain causing surface salt precipitation, and (d) utilization of a pumping station.

DISCUSSION

Soil salinization and sodification are major challenges in arid and semi-arid regions globally. Saline and sodic soils are found in areas near the sea, in polders, coastal marshes, estuaries, and continental environments (Baize, 2011). According to Hand (2018), the areas affected by salinity and sodicity, expressed in millions of hectares, are distributed across five continents: Africa (80.5 Mha), Europe (50.8 Mha), North America (15.7 Mha), South America (129.2 Mha), Australia (357.3 Mha), Mexico and Central America (2 Mha), North Asia (20 Mha), Central Asia (211.7 Mha), and South Asia (87.6 Mha).

In Africa, saline and sodic soils are primarily located in the Sahel and North Africa, notably in Cameroon (Hand, 2018), Tunisia (Annabi, 2011; Escadafal, 1989; Job, 1992; Montoroi, 1993; Saida, 2013), Morocco (Kundzewicz, 2016; Lahlou et al., 2005; Mathieu & Ruellan, 1987; Ruellan, 1971), Senegal (Boivin & Brunet, 1990; Boualla et al., 2012; Med et al., 2024), Mali (Dicko, 2005; Valenza, 1996), Niger (Zairi, 2008), and Chad. Mhiri et al. (1998) demonstrated that agricultural soil salinization stems from the scarcity of good-quality water resources and the increasing use of brackish water for irrigation. However, soil salinity is often better evaluated based on plant behavior, as the sensitivity of plant species to salinity can vary significantly (Hand, 2018). In the Lake region, abandoned rice fields during the agricultural season reveal that rice is a plant species sensitive to salinization (Figure 10b). These plants struggle to extract the necessary water due to changes in the osmotic potential of soil water (Baize, 2016). The lightly salinized and abandoned plots in the South Berim polder exhibit physico-chemical characteristics similar to those of slightly saline soils described by Dabin (1970). These lightly saline soils are clayey (clay content >30%) and have a basic pH (pH >8). At Faya-Largeau, Dabin (1970) noted that sandy amendments, the use of Tili (rich in sodium, potassium, and magnesium), and animal manure improve soil porosity and structure, thereby enhancing water infiltration and plant rooting. These practices differ significantly from those observed in the Lake Province, which involve drains, pumping stations, plowing, and limited use of urea fertilizers. Minda et al. (2015), in examining the influence of soil physico-chemical characteristics on flora and woody vegetation across three stations (Lake, Kanem, and Barh el Gazal) along Chad's Great Green Wall, highlighted soils ranging from slightly to highly salinized, with high pH levels between 7.8 and 9.3. These descriptions align with the results obtained for agricultural polder soils in the Lake Province.

In North Africa, Mhiri et al. (1998) proposed a concept of anthropogenic endorheism for exorheic regions. This concept contrasts with soil management in the Lake Province polders, which rely entirely on drainage systems and pumping stations. In the Lake Province, salinization and sodification are primarily attributed to the endorheism of the polders, the brackish quality of groundwater, the shallow water table, and wind and water erosion.

These findings align with Bekayo (1998), who identified soil salinization in rice fields around N'Djamena as caused by capillary rise of the water table, surface crust formation, and poor irrigation. Cheverry (1965) also demonstrated that salinization results from capillary water table rise and groundwater quality. These observations differ from Hand (2018)'s findings in Cameroon, where irrigation is identified as the main cause of salinization in coastal areas.

These disparities highlight the need for context-specific management approaches to effectively combat soil salinization.

CONCLUSION

In Chad, saline soils are predominantly found in the northern and northwestern regions. Despite their prevalence, in-depth research on these soils remains limited. Their cultivation represents a major challenge for agricultural productivity due to multiple physical, chemical, and hydrological constraints on production systems.

To better understand and manage these soils, detailed studies on their mineralogy and geochemistry are essential. Such analyses would allow for precise characterization of their properties, identification of the factors causing salinization, and proposal of tailored solutions to enhance their agronomic potential.

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REFERENCES

1. Afes. (2008). Référentiel pédologique 2008 (Éditions Quæ). Edition Quae. https://www.afes.fr/wp-content/uploads/2017/11/Referentiel_Pedologique_2008.pdf
2. Afes. (2021). Journée mondiale de sol.
3. Alladjaba, A., Likius, A., Abderamane, M., Malick, M. A., & Midir, D. (2024). Méthode simple, efficace et économique pour déterminer le pH et le calcaire actif des sols sous blé des polders agricoles de la province du Lac : Test au vinaigre d'alcool, au bicarbonate de sodium et à l'acide chlorhydrique. 196. https://doi.org/10.35759/JABs.196.3
4. Alladjaba, A., Likius, A., & Mousa, A. (2023). Granulométrie et évaluation de la salinité des sols des parcelles cultivées et non cultivées des polders agricoles sous culture de blé. Cas de Mandi, Berim-sud et Guini dans la commune de Bol en république du Tchad. 42, 85-97.
5. Annabi, M. (2011). Influence des racines sur la stabilité structurale d'un sol du Nord de la Tunisie. Etude et Gestion des Sols, 18(2), 63-73.

6. Anonyme. (2007). Mechanisms of High Salinity Tolerance in Plants. Narendra Tuteja. Methods in Enzymology, Volume 428.
7. Baize, D. (2016). Petit lexique de pédologie (édition Quae).
8. Baize, D. (2018). Guides des analyses en pédologie. 3e édition revue et augmentée (édition Quae). Christel Desmaris.
9. Baize, D., & Afes (Éds.). (1995). Référentiel pédologique (Nouvelle éd). INRA.
10. Bekayo, N. D. (1998). Projet CHD/96/G31/B/IG/99 « Elaboration de la Stratégie Nationale et Plan d'Action pour la Concervation de la Diversité Biologique ».
11. Boivin, P., & Brunet, D. (1990). Bilan de quatre années de suivi de la salure d'une vallée aménagée anti-sel par Conductivimétrie Electromagnétique et Krigeage (p. 13) [Rapport de Campagne]. Pédologue ORSTOM.
12. Boualla, N., Benziane, A., & Derrich, Z. (2012). Origine de la salinisation des sols de la plaine de M'léta (bordure sud du bassin sebkha Oran). Journal of Applied Biosciences, 53, 3787-3796.
13. Cheverry, C. (1965). Caractérisation pédologique des sols des polders de Bol (Lac-Tchad).
14. Cheverry, C. (1966). Étude préliminaire des processus d'hydromorphie -et d'halomorphie dans les sols de polders de la région de bol (rives du lac tchad). Cah . ORSTOM. sér. Pédol., 4(3), 63-96.
15. Cheverry, C. (1972). La genèse de sols salés à alcalis dans les polders des rives nord-est du lac Tchad.
16. Cheverry, C. (1974). Contribution à l'étude pédologique des polders du Lac Tchad dynamique des sels en milieu continental subaride dans des sédiments argileux et organiques [Thèse de Doctorat]. Université Louis Pasteur de Strasbourg.
17. Cirad. (1996). Atlas d'élevage du Bassin du Lac-TChad.
18. Colomb, B. (2017). Guide de la fertilisation raisonnée 2e édition (Edition France Agricole). Productions végétales.
19. Comifer. (2019). Fertilisation P-K-Mg : Les bases du raisonnement. Edition 2019. https://comifer.asso.fr/wp-content/uploads/2015/03/COMIFER_RAPPORT_fertilisation_15102019.pdf
20. CPCS. (1967). Classification des sols.
21. CRAAQ. (2006). Guide de référence en fertilisation, 1re édition 2e mise à jour.
22. Csao-Cilss. (2008). Profil sécurité alimentaire Tchad.
23. Dabin, B. (1969). Etude générale des conditions d'utilisation des sols de la cuvette tchadienne. O.R.S.T.O.M.
24. Dabin, B. (1970). Étude d'une méthode d'extraction de la matière humique du sol. 47-63.
25. Dicko, M. (2005). Analyse du foncionnement d'une parcele de riz irrigué sur sol alcalin. Application à la gestion intégrée de la fertilisation azotée et du calendrier cultural dans le delta intérieur du fleuve Niger (Mali) [These de doctorat]. Ecole Nationale Supérieure de Montpélier.
26. Dieye, M., Dia, D., Barbier, B., Sylla, E. H. M., Sall, M., & Bader, J.-C. (2020). L'Agriculture de décrue en Afrique de l'Ouest et du centre Une certaine résilience face à la variabilité climatique et à la régulation des fleuves. In Risque climatique et agriculture en Afrique de l'Ouest (IRD édition, p. 121-131). Marseille.

27. Djili, K., Daoud, Y., Gaouar, A., & Beldjoudi, Z. (2003). La salinisation secondaire des sols au Sahara.
28. Escadafal, R. (1989). Caractérisation de la surface des sols arides par observations de terrain et par télédétection. Applications : Exemple de la région de Tataouine (Tunisie) [Thèse de Doctorat]. Université Pierre et Marie Curie-Paris.
29. Fao (Réalisateur). (2021). Sols touchés par la salinisation [Documentaire]. Youtube.
30. Grunberger, O. (2015). Dynamique salines des sols des mileiux arides et semi-arides. UNiversité de Montpellier
31. Comifer (2017) Guide de la fertilisation raisonnée 2e édition. Edition France Agricole.
32. Hand, M. J. (2018). Effets de la salinité et des fertilisants sur les paramètres physiologiques, biochimiques et agronomiques chez trois variétés de poivron (Capsicum annuum L.) cultivées dans la zone littorale du Cameroun [These de doctorat]. Université de Yaoundé I.
33. Job, J.-O. (1992). Les sols salés de l'oasis d'El Guettar (Sud Tunisien) [Thèse de Doctorat]. Université de Montpellier.
34. Kundzewicz, Z. W. (2016). Salinisation de l'aquifère libre de la Chaouia côtière (Azemmour-Tnine Chtouka), Maroc. Hydrological Sciences Journal, 62(5), 749-759.
35. Kusnir, I. (1995). Géologie, Ressources Minérales Et Ressources En Eau Du Tchad.
36. Lahlou, S., Ouadia, M., Issa, O. M., & Bissonnais, Y. L. (2005). Modification de la porosité du sol sous les techniques culturales de conservation en zone semi-aride Marocaine. Etude et Gestion des Sols, 12(1), 69-76.
37. Lallemand-Barrès, A. (1980). Aménagement des sols salés irrigation avec des eaux salés, étude documentaire.
38. Legros, J.-P. (2009). La salinisation des terres dans le monde. Académie des Sciences et Lettres de Montpellier.
39. Mahamat-Saleh, M., Diallo, M. D., NDiaye, O., Niang, K., Sane, S., Touroumgaye, G., Matty, F., & Guisse, A. (2015). Influence des caractéristiques physico-chimiques des sols sur la flore et la végétation ligneuse de trois stations du tracé de la grande muraille verte du Tchad. Journal of Applied Biosciences, 95, 8937-8949.
40. Maley, J. (1981). Études palynologiques dans le bassinduTchad et paléoclimatologie de l'Afriquenord-tropicale de 30000 ans à l'éppque actuelle.
41. Maley, J. (2000). Les variations des niveaux du lac Tchad au cours du dernier millénaire rôle des conditions climatiques régionales et des apports fluviatiles. Réactions des populations régionales. Comparaison avec le lac Naivasha en Afrique orientale.
42. Mathieu, C., & Ruellan, A. (1987). Evolution morphologique de sols irrigués en région méditerranéenne semi-aride : L'exemple de la Basse-Moulouya (Maroc). Cah. ORSTOM, ser. Pédol., 23(1), 3-25.
43. Med, F., Dick, B. A., Ammar, M. B., Ould Sidi, Y. M., Mohamed, L. S., Yehdhih, M. L., & Fekhaoui, M. (2024). The Effect of Senegal River Irrigation Water Quality on Soil Salinization : A Study of the Main Canal of the M'Pourie Plain in Mauritania. Nature Environment and Pollution Technology, 23(2), 1085-1093. https://doi.org/10.46488/NEPT.2024.v23i02.042

44. Mekila, M., Abakar, G., Gapili, N., Diallo, A., & Guisse, A. (2022). Caractérisation des sols sur le tracé de la grande muraille verte : Cas des provinces de Wadi-Fira-Est et de l'Ennedi-Est du Tchad. Rev. Ivoir. Sci. Technol, 39, 334-350.
45. Mhiri, A., Tarhouni, J., Hachicha, M., & Lebdi, F. (1998). Approche systémique des risques de salinisation par endoréisation anthropique. Etude et Gestion des Sols, 5(4), 257-268.
46. Montoroi, J.-P. (1993). Le contrôle de la salinité à l'aide de capteurs électriques : Application à un périmètre irrigué en Tunisie. Agronomie tropicale, 46(3), 233-240.
47. Nadjiam, D. (2013). Les ressources en sols du Tchad : Les actions prioritaires pour une gestion durable. Partenariat Mondial sur les Sols.
48. Pias, J. (1962). Les sols du Moyen et Bas Logone, du bas Chari, des régions riveraines du Lac-Tchad et du bahr el ghazal.
49. Pias, J., & Guichard, E. (1952). Etude pédologique des rives du Lac Tchad de Djimtilo a Bol et du Sillon du Bahr el Ghazal de Massacory a Moussoro.
50. Qadir, M., & Schubert, S. (2002). Degradation processes and nutrient constraints in sodic soils. Land Degradation & Development, 13(4), 275-294. https://doi.org/10.1002/ldr.504
51. Ruellan, A. (1971). Contribution à la connaissance des sols des régions méditerranéennes : Les sols a profil calcaire différencié des plaines de la basse moulouya (maroc oriental). ORSTOM.
52. Saida, M. (2013). Effets à long terme de la salinité conjuguée aux effets du changement climatique sur une culture du blé dur. 3, 1623-1628.
53. Servant, J. (1975). Contribution à l'étude pédologique des terrains hallomorphes : Exemple des sols salés du sud et du sud ouest de la France [Thèse de Doctorat]. Université des Sciences Techniques du Languedoc.
54. Sodeteg. (1992). Schéma directeur de développement socio-économique de la région du Lac : Tome I -Partie l Milieu Physique.
55. Tearfund. (2009). Évaluation des risques et de l'adaptation au changement climatique et à la dégradation de l'environnement.
56. UICN PACO. (2020). Adaptation aux changements climatiques au Tchad : Leçon apprises du projet UICN-AMCC/UICN PACO.
57. Valenza, A. (1996). Rôle des eaux souterraines et d'irrigation dans les processus de salinisation-alcalinisation des sols en zone sahélienne : Cas du Delta Intérieur du Niger (MALI). Géologie. Montpellier., Université des Sciences du Languedoc.
58. Wicke, al. (2011). Salinisation des sols.
59. Zairi, R. (2008). Etude géochimique et hydrodynamique de la nappe libre du bassin du lac Tchad dans les régions de Diffa (Niger oriental) et du Bornou (nord-est du Nigeria) [These de doctorat]. Université Montpellier II Sciences et Technique du Languedoc.