Journal of Agricultural Chemistry and Environment, 2026, 15(1), 12-25
https://www.scirp.org/journal/jacen
ISSN Online: 2325-744X
ISSN Print: 2325-7458

Assessment of the Physico-Chemical Quality of Irrigation Water Used in the Niaye of Patte d'Oie (Dakar)

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How to cite this paper: Bakhoum, M., Diop, T., Wade, M., Ndiolene, A., Diop, M., Diallo, M.A. and Diop, C.A.K. (2026) Assessment of the Physico-Chemical Quality of Irrigation Water Used in the Niaye of Patte d'Oie (Dakar). *Journal of Agricultural Chemistry and Environment*, **15**, 12-25.
https://doi.org/10.4236/jacen.2026.151002

Received: November 14, 2025
Accepted: January 4, 2026
Published: January 7, 2026

Abstract

Urban market gardening plays an essential role in meeting the food needs of Dakar's rapidly growing population. This high population density generates significant wastewater discharges in the study area, thereby increasing the risk of contamination of surface and groundwater. This study aims to assess the physico-chemical quality of irrigation water used at the market gardening site of the Niaye of Patte d'Oie (Dakar), in order to evaluate its suitability for irrigation and its potential effects on soils and crops. Three water samples were collected from different points across the site. The collected samples were analyzed for several physico-chemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+} and NH_4^+), and major anions (HCO_3^-, PO_4^{3-}, SO_4^{2-}, Cl^-, NO_3^- and F^-). The obtained values were compared with FAO guideline values for irrigation water. Irrigation water quality indices (SAR, RSC, SSP, KI, and PI) were calculated to evaluate the overall water quality. The results show that most major ions exhibit concentrations within the recommended limits, except for K^+, Na^+, NO_3^-, NH_4^+, and PO_4^{3-}, whose levels locally exceed the guidelines. Most samples show moderate salinity, with TDS values below 2000 mg/L, indicating that the water generally meets irrigation standards. The low to moderate SAR values indicate a limited sodicity risk, while the dominance of Na^+ and Cl^- suggests the influence of salt dissolution. The maximum SAR value (below 10) and RSC value (below 1.25) confirm good water quality for irrigation. Hydrochemical analysis reveals two types of facies: a sodium-potassium bicarbonate-chloride facies and a sodium-potassium sulfate facies. According to the Riverside classification diagram, the irrigation water from the Niaye of Patte d'Oie ranges from medium to poor quality, requiring cautious use. Overall, the water quality in the Niaye of Patte d'Oie is acceptable for irrigation, but regular monitoring remains necessary to prevent salt accumulation in soils and to preserve the sustainability of market gardening production.

Keywords

Niaye, Irrigation Water, Water Quality Indices, Sodicity, Geochemistry

1. Introduction

The high population density in Senegal's capital city, Dakar, which accounts for nearly one-quarter of the national population [1], generates substantial discharges of wastewater [2] and solid waste [3] in areas particularly vulnerable to pollution. These wastewaters are mainly stored and treated in the Technopole area, located near Patte d'Oie, a zone characterized by intensive market gardening activity and the presence of a shallow groundwater table that nearly reaches the surface [4]. This situation may potentially affect the quality of groundwater used for irrigation. Water quality is one of the main environmental factors influencing ecosystems, agricultural productivity, and the socio-economic development of a country [5] [6]. Irrigation water, derived from various sources such as rivers, springs, or wells, may contain chemical substances that can reduce soil fertility and crop yields [7]. Modern irrigated agriculture faces new challenges, notably soil salinization and alkalinization. The salinity risk can be assessed through electrical conductivity (EC), while soil alkalinization, caused by ionic exchanges involving sodium, calcium, and magnesium between irrigation water and soil clays, is evaluated using the Sodium Adsorption Ratio (SAR). Improper irrigation practices can be detrimental to soil health. When soils are too dry, water infiltration becomes inefficient; conversely, excessive water application can lead to stagnation or runoff. As stagnant water evaporates, it leaves behind dissolved salts, progressively salinizing the soil until it becomes infertile and abandoned. Among the major degradation factors are excessive salt concentrations in water and soil, which alter their quality and reduce agricultural productivity [8]. High concentrations of certain chemical parameters, such as carbonates, bicarbonates, magnesium, calcium, sulfates, and water hardness, can compromise irrigation water quality [9]. Cations such as sodium, calcium, and magnesium particularly influence the suitability of groundwater for irrigation. At low concentrations, some of these ions are beneficial to crops; however, at high concentrations, they deteriorate water and soil quality, induce toxic effects on plants, and complicate agricultural management [10]. In the Niaye of Patte d'Oie, where the groundwater table is shallow, groundwater serves as the primary source of irrigation for market gardening. Therefore, this study aims to assess the quality of irrigation water in this area to support urban agricultural production in Dakar and contribute to national economic development.

The findings are expected to guide agricultural and environmental policies toward sustainable water resource management, promoting a productive and resilient urban agriculture system.

2. Materials and Methods

2.1. Description of the Study Area

The study area, known as the Greater Niaye of Dakar, covers a surface area of approximately 1.298 hectares [11]. It straddles the departments of Dakar, Pikine, and Guediawaye, encompassing ten (10) municipalities: Pikine Ouest, Pikine Nord, Pikine Est, Sam Notaire, Medina Gounass, Dalifort, Golf Sud, Patte d'Oie, Grand-Yoff, and Hann Bel-Air. The study area includes three main sites, the Grande Niaye of Pikine (Technopole site), the Niaye of Patte d'Oie, and the Niaye of Hann Maristes. Groundwater samples were collected from shallow wells located in the Niaye of Patte d'Oie. The Niaye of Patte d'Oie, an agricultural zone located in the Dakar Department, covers an area of approximately 100 hectares [12], representing about one-third of the total surface area of the municipality. Due to its proximity to the city center, it has been designated as a non-building zone (zone non aedificandi), primarily reserved for agricultural purposes or landscape development [13]. Groundwater samples were collected within the Patte d'Oie study area from two production boreholes and one well, all situated in the Niaye of Patte d'Oie. The chain of custody was strictly maintained throughout the sampling and analytical process, including sample coding, double data entry, quality control, and secure digital archiving. Analytical results were expressed in mg/L following standard procedures and compared to FAO guideline thresholds to assess the water stress level of the site.

2.2. Analytical Methods

The parameters pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using a portable multiparameter meter (Thermo Scientific model). Water samples were collected in 1.5 L plastic bottles and transported to the Inorganic and Analytical Chemistry Laboratory (LACHIMIA) for analysis. The analyzed chemical parameters included: Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, PO_4^{3-}, and F^-.

- ✓ Sulfate (SO_4^{2-}), nitrate (NO_3^-), phosphate (PO_4^{3-}), and fluoride (F^-) ions were determined using a HACH DR39000 spectrophotometer.
- ✓ Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were measured by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).
- ✓ Sodium (Na^+), potassium (K^+), and ammonium (NH_4^+) were analyzed using a LAQUA ion meter.
- ✓ Bicarbonate (HCO_3^-) and chloride (Cl^-) ions were determined by titrimetric methods [14].

2.2.1. Ionic Balance

The ionic balance (IB) was calculated using the following equation, with a tolerance limit of ±5%, to verify the analytical consistency of ionic concentrations expressed in meq/L [15] [16]:

$$IB = \frac{\left(\sum \text{Cations} - \sum \text{Anions}\right)}{\left(\sum \text{Cations} + \sum \text{Anions}\right)} \times 100$$

Analytical procedures were validated through a rigorous quality control process, including regular instrument calibration and verification of measurement accuracy for each analyzed sample.

2.2.2. Data Processing

The hydrochemical classification of water samples was performed using the Piper, Wilcox, and Riverside diagrams, generated with the DIAGAMMES 6.5 software. The water quality indices used to assess the suitability of groundwater for irrigation included the Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Kelly's Index (KI), Potential Salinity (PS), and Residual Sodium Carbonate (RSC).

2.2.3. Irrigation Water Quality Indices (IWQI)

The calculation of Irrigation Water Quality Indices (IWQI) was performed using the equations presented in **Table 1**. Since agricultural practices, soil types, and water quality all influence the most appropriate irrigation techniques [17] [18], several indices were applied in this study to evaluate the suitability of water for agricultural use, particularly the irrigation-specific indices: SAR, KI, RSC, PS, and SSP. These parameters help to highlight the risk of soil salinization and the potential adverse effects of irrigation on soil and plant health. The data derived from the IWQI calculations were statistically analyzed to determine the overall suitability of the water for agricultural purposes.

Table 1. Equations used for the calculation of irrigation water quality indices.

Irrigation water quality index	Equations	References
Sodium adsorption ratio (SAR)	$\frac{Na^{+}}{\sqrt{\frac{1}{2}\left(Ca^{2+} + Mg^{2+}\right)}}$	[19]
Kelly's index (KI)	$\frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$	[20]-[22]
Residual sodium carbonate (RSC)	$\left(HCO_3^{-} + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right)$	[23]
Potential salinity (PS)	$Cl^{-} + \frac{SO_4^{2-}}{2}$	[24]
Soluble sodium percentage (SSP)	$\frac{\left(Na^{+}\right) + \left(K^{+}\right)}{\left(Ca^{2+}\right) + \left(Mg^{2+}\right) + \left(Na^{+}\right) + \left(K^{+}\right)} \times 100$	[25]

Note: All indices were calculated in meq/L.

3. Results and Discussion

3.1. Physico-Chemical Parameters of Groundwater

The classification of groundwater was based on physico-chemical parameters relevant for assessing their suitability for irrigation in the Niaye of Patte d'Oie. These parameters include pH, electrical conductivity (EC), total dissolved solids (TDS), as well as major cations (K^+, Na^+, Mg^{2+}, Ca^{2+}, and NH_4^+) and anions (Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, PO_4^{3-}, and F^-). These elements directly influence soil quality and crop productivity. **Table 2** presents the measured physico-chemical parameters from the three groundwater samples collected.

Table 2. Physico-chemical parameters of groundwater.

Parameters	Ech. 1	Ech. 2	Ech. 3	FAO [26]
pH	6.10	7.45	8.46	6.5 - 8.5
EC (µS/cm)	1797	2340	1660	0 - 3000
TDS (mg/L)	434.1	554.3	427.8	0 - 2000
MEST (mg/L)	100	41	55	-
Na^+ (mg/L)	206	318	218	0 - 290
K^+ (mg/L)	43.8	113	63.9	0 - 2
Mg^{2+} (mg/L)	54.6	53.9	32.3	0 - 60
Ca^{2+} (mg/L)	95	155	95	0 - 400
NH_4^+ (mg/L)	3.61	13.7	19	0 - 2
NO_3^- (mg/L)	229.31	101.37	3.54	0 - 10
SO_4^{2-} (mg/L)	243	297	146	-
HCO_3^- (mg/L)	381.25	594.75	603.9	0 - 610
PO_4^{3-} (mg/L)	0.38	19.30	14.54	0 - 2
Cl^- (mg/L)	301.75	379.85	255.60	0 - 1000
F^- (mg/L)	0.02	1.15	0.77	-
Balance ionique (%)	4.08	1.12	4.3	-

To assess the quality of groundwater, the measured parameter values were compared with the guideline values of the Food and Agriculture Organization of the United Nations (FAO) [26] for irrigation water (**Table 2**). The analysis results show that the pH values of the groundwater ranged from 6.10 to 8.46, falling within the intervals defined by the FAO. Electrical conductivity (EC) values varied between 1660 and 2340 µS/cm, indicating the presence of several mineralization processes. These results are consistent with the findings of [27], which report slightly mineralized groundwater. The maximum total dissolved solids (TDS) content reached 472.06 mg/L, which remains within FAO regulatory limits. The concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in all samples comply with FAO irrigation standards. However, potassium (K^+) concentrations exceeded the

FAO guideline value of 2 mg/L. Pollution indicator parameters, such as nitrogen and phosphate compounds (NO_3^-, NH_4^+, and PO_4^{3-}), showed values exceeding FAO guideline limits. These chemical parameters originate from the weathering of clay formations or from the dissolution of chemical fertilizers (NPK) applied by farmers. Nitrates present in the water can come from various natural and anthropogenic sources. In urban areas, such as the study zone, high nitrate levels are often linked to domestic and urban wastewater, local contamination of groundwater, latrine influence, and animal waste. Chlorides (Cl^-) and sulfates (SO_4^{2-}) were the dominant anions in groundwater, with average concentrations of 312.40 mg/L and 228 mg/L, respectively, generally compatible with irrigation standards. When present in irrigation water, these elements contribute to increasing the concentration of soluble salts. Excessive chloride concentrations can cause tip burn on the leaves of certain crops and may even lead to plant death. Concentrations ranging from 250 to 400 ppm, as observed in our study, are considered undesirable for the irrigation of salt-sensitive plants. Fortunately, chloride salts are highly soluble and can therefore be leached from well-drained soils. Bicarbonates (HCO_3^-) showed concentrations acceptable for irrigation, with a maximum value of 603.9 mg/L [26].

3.2. Correlation Matrix and Factor Analysis

The correlation matrix between the different analyzed parameters (16 elements) shows that some variables (considered in pairs) are strongly correlated, with highly significant coefficients exceeding 0.95. This is particularly the case for the following element pairs: pH- HCO_3^- (r = 0.91); pH- NH_4^+ (r = 0.99); EC-Na^+ (r = 0.95); EC-Ca^{2+} (r = 0.98); EC- Cl^- (r = 0.98); Na^+-Ca^{2+} (r = 0.99); Na^+- Cl^- (r = 0.92); Mg^{2+}- SO_4^{2-} (r = 0.92); and PO_4^{3-} - Cl^- (r = 0.99). These highly significant correlations may provide insight into the possible origin of these elements (natural or anthropogenic), particularly those contributing to the mineralization of groundwater (Cl^-, HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, and K^+). In the factorial plane (axes 1-2), axis F1 contains the largest amount of information, accounting for 70.5% of the total variance (**Figure 1**). This axis is defined by the chemical elements responsible for the mineralization of the water. The grouping of these variables along axis F1 indicates that this factor explains the predominant mechanisms governing the mineralization processes in the aquifer. The correlation observed among the variables defining factor F1 reflects a common origin for most of these ions. It is worth noting that pH, NH_4^+, Ca^{2+}, Na^+, K^+, F^-, PO_4^{3-}, and HCO_3^- contribute to the mineralization pole and are mainly opposed to NO_3^-. This suggests that axis 1 highlights the key roles played in water chemistry by both the rock matrix (through element dissolution) and anthropogenic activities, particularly agriculture. Axis 2, which explains 29.5% of the total variance, is characterized by a group of water samples dominated by Mg^{2+}, SO_4^{2-}, Cl^-, and NO_3^- ions. This opposition reveals the influence of anthropogenic contamination.

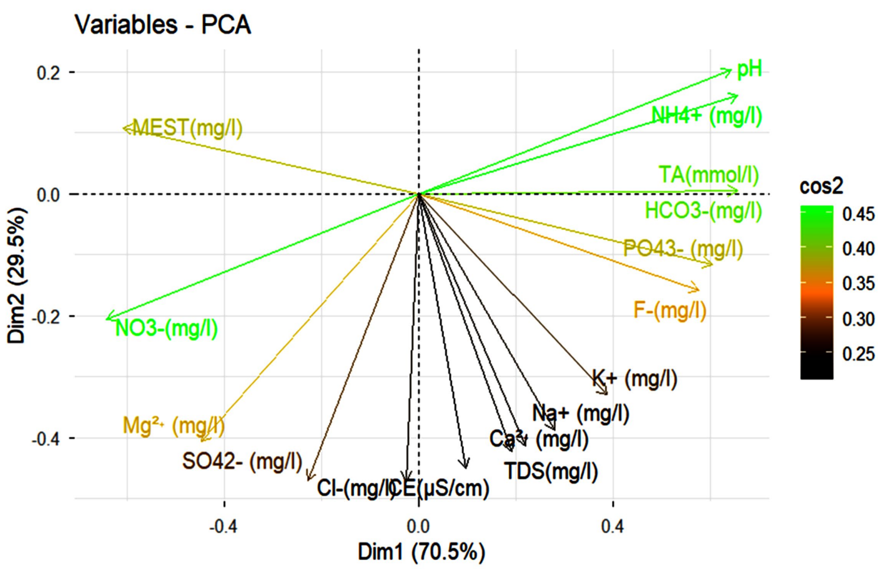

Figure 1. Principal component analysis (PCA) of the measured physicochemical parameters.

3.3. Sodium Adsorption Ratio (SAR)

The results obtained from this study showed a significant variation in the general hydrochemistry among the different samples. A summary of the general hydrochemical characteristics of the irrigation waters is presented in Table 3.

Table 3. Water quality indices and agricultural classification [28].

Parameters	1	2	3	Mean	Range [28]	Water category
SAR	1.39	1.50	1.59	1.49	<10	Good
SSP	52.14	57.84	60.00	56.66	<60	Fair
RSC	−8.62	−2.44	2.49	−2.85	<0	Fair
KI	0.96	1.13	1.27	1.12	>1	Unsuitable
PS	10.74	13.18	8.94	10.95	>5	Harmful to unsatisfactory

In irrigation water, the SAR parameter reflects the soil matrix's ability to release Ca^{2+} and Mg^{2+} ions and adsorb Na^{+} ions at exchange sites, which can disperse soil particles and reduce its infiltration capacity [29] [30]. Highly saline water can sometimes improve soil structure by accelerating infiltration; however, it imposes increased water stress on plants, which must expend more energy to extract water from the soil. SAR is a key indicator of water quality for agricultural use [17]. A high SAR, indicating a high sodium content, corresponds to poor water quality for irrigation [31] [32]. In this study, the maximum SAR value for all samples was below 10, indicating excellent water quality for irrigation.

3.4. Study of Soil Salinization Using the Riverside Diagram

The Riverside diagram (Figure 2) is used to assess the risk of soil salinization. It considers electrical conductivity and the sodium adsorption ratio (SAR), also referred to as the "alkalizing power."

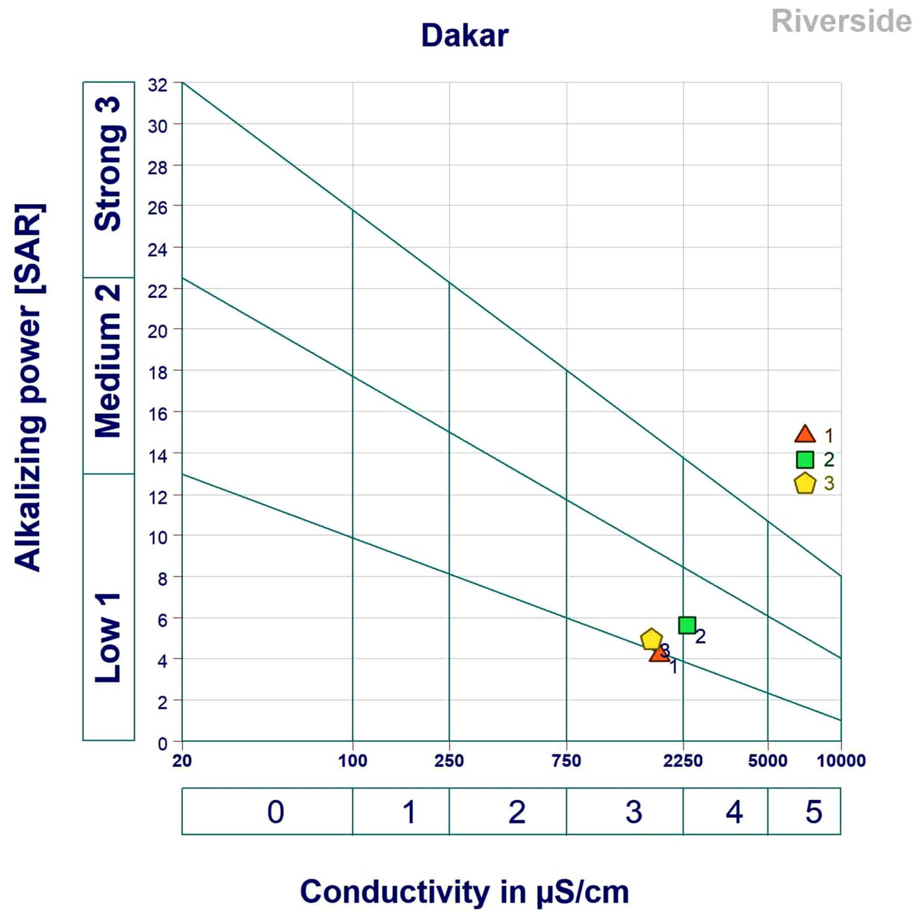

Figure 2. Riverside diagram of the analyzed waters.

According to the classification derived from the Riverside diagram [33]:

- Samples 1 and 3 fall into the C3-S1 class, meaning low SAR and moderate to high salinity (Table 4).
- Sample 2 falls into the C4-S1 class, corresponding to very high salinity with a low SAR.

Table 4. Classes from the riverside diagram [33].

SAR	Class CE µS/cm)				
	C1 0 - 250	C2 250 - 750	C3 750 - 2250	C4 2250 - 5000	C5 5000 - 10,000
*S*1 (0 - 10)	C1S1	C2S1	C3S1	C4S1	C5S1
*S*2 (10 - 18)	C1S2	C2S2	C3S2	C4S2	C5S2
*S*3 (18 - 26)	C1S3	C2S3	C3S3	C4S3	C5S3
*S*4 (>26)	C1S4	C2S4	C3S4	C4S4	C5S4

These results indicate that the irrigation waters are of medium to poor quality and should be used with caution. Proper drainage, along with leaching doses and/or gypsum application [34], is recommended to prevent soil sodification. In conclusion, all three samples are characterized by a high risk of salinization but low alkalinity, suggesting that these waters can be used for irrigation without risk of soil alkalinization.

3.5. Kelly's Index (KI)

The Kelly's Index (KI) is used to assess the suitability of groundwater for agricultural irrigation. A Kelly's Index greater than 1 indicates a high sodium concentration in the irrigation water [35], making it unsuitable for irrigation. Conversely, a value below 1 reflects a relative deficiency of sodium ions, and the water is considered suitable for irrigation [36]. In the study area, Kelly's Index values ranged from 0.96, 1.13, to 1.27, as shown in **Table 3**. These results indicate that the water contains a moderately high sodium content, which can reduce water infiltration into the soil [37].

3.6. Sodium Percentage Relative to Electrical Conductivity

The Wilcox diagram is a graphical tool used in hydrochemistry to classify water quality, primarily for irrigation purposes. It classifies water based on electrical conductivity (EC) on the horizontal axis and sodium percentage on the vertical axis.

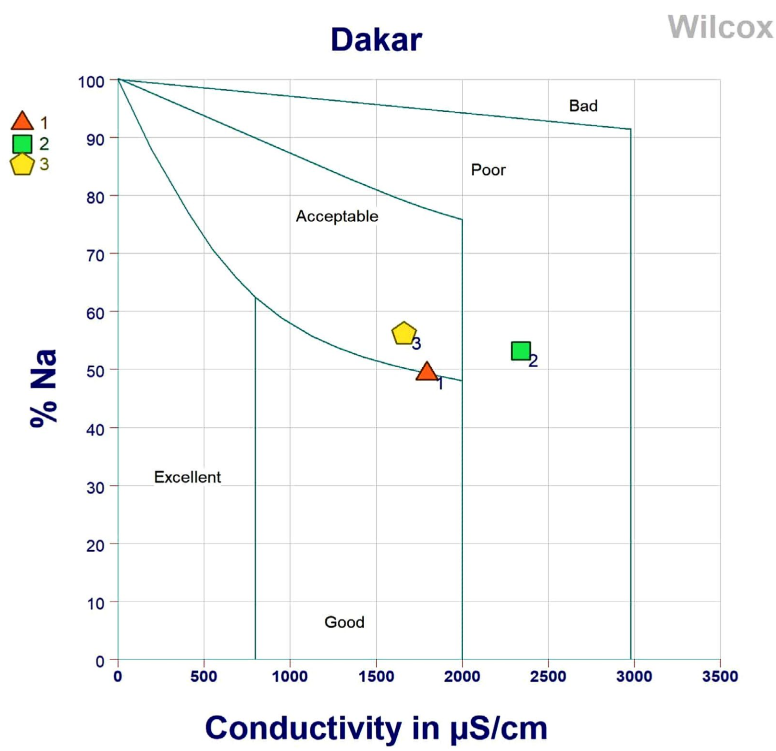

Figure 3. Wilcox diagram of the waters.

In our study, the three samples plotted on the Wilcox diagram (**Figure 3**) are divided into two groups:

- Sample 2 is highly loaded with sodium, corresponding to a very high EC (2340 µS/cm), placing it in the class of poor-quality water unsuitable for irrigation.
- Samples 1 and 3 have EC values ranging from 1660 to 1797 µS/cm, which fall within the acceptable range for irrigation water (can be used if moderate leaching is applied).

3.7. Potential Salinity (PS)

The concentration of chloride ions and half the concentration of sulfates are important parameters for assessing the suitability of groundwater for irrigation through the potential salinity index (PS). PS values are generally classified as:

- Unsuitable when PS > 3
- Suitable when PS < 3 [24]

In this study, PS values ranged from 8.94 to 13.18, with a mean of 10.95 (**Table 3**), indicating that the waters fall into the harmful to unsatisfactory class.

3.8. Residual Sodium Carbonate (RSC)

An excess of carbonate and bicarbonate relative to calcium and magnesium ions is commonly used to assess irrigation water quality. The RSC was calculated to predict the potential precipitation of Ca^{2+} and Mg^{2+} on soil particle surfaces, which removes them from the soil solution. Precipitation of Ca^{2+} and Mg^{2+} as carbonate minerals can increase Na^{+} concentrations and consequently SAR values [23]. High RSC can deteriorate soil physical properties, causing organic matter dissociation and the formation of black patches on the soil surface when dry [38] [39]. Based on RSC values, groundwater is classified into three categories [40]:

- RSC < 1.25: Acceptable irrigation water
- RSC 1.25 - 2.5: Tolerable
- RSC > 2.5: Unacceptable

In this study, all three water samples had RSC values below 1.25 (**Table 3**), indicating that the water is acceptable and of good quality for irrigation.

3.9. Piper Diagram

The Piper diagram highlights the hydrochemical facies of the three water samples.

- Samples 2 and 3 mainly show a bicarbonate-chloride sodium-potassium facies.
- Sample 1 is characterized by a sulfate-sodium-potassium facies.

Overall, the samples show a predominance of chloride, sulfate, calcium, and magnesium ions in Sample 1. Sample 2 exhibits a chloride sodium-potassium facies with a tendency toward sulfate-sodium, while Sample 3 is characterized by a bicarbonate sodium-potassium facies (**Figure 4**).

The majority of the analyzed samples show that salinity (represented by $SO_4^{2-} + Cl^{-}$) is generally higher than alkalinity ($HCO_3^{-} + CO_3^{2-}$), and that alkali ions ($Na^{+} + K^{+}$) predominate over alkaline-earth ions ($Ca^{2+} + Mg^{2+}$). These ionic relationships are the main factors controlling the hydrochemistry of groundwater in the Niaye de Patte d'Oie region.

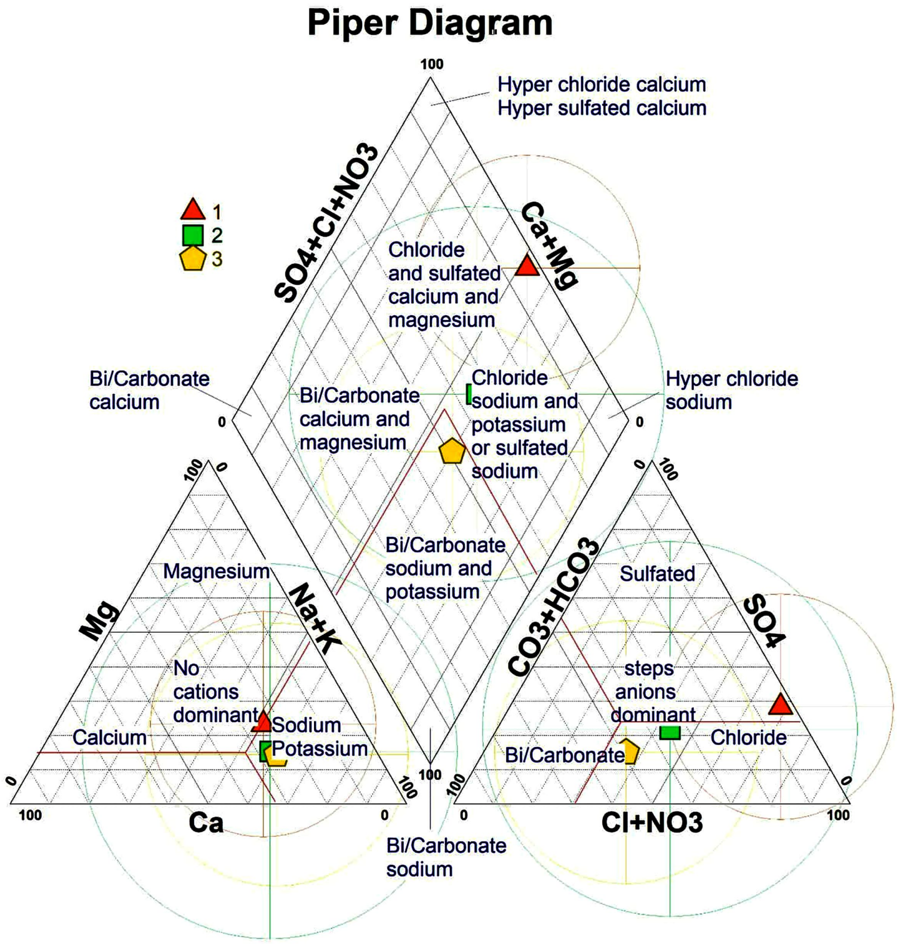

Figure 4. Piper diagram of the waters.

4. Conclusion

The evaluation of the physico-chemical quality of irrigation water used in the Technopole market gardening site (Dakar) enabled an assessment of its suitability for agricultural use. The results of this study on irrigation water from the Technopole wetland indicate that sodium (Na^+) is the dominant cation, with the order: $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > NH_4^+$, while bicarbonate ($HCO_3^-$) is the most abundant anion, following the order: $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-} > F^-$. The samples exhibit sodium-potassium bicarbonate-chloride and sodium-potassium sulfate facies. The presence of multiple hydrochemical facies in the study area reflects the interaction of several mineralization processes. The measured physical parameters (pH, EC, and TDS) fall within ranges acceptable for irrigation, although some localized variations may influence salinity or nutrient content. SAR, RSC, and PSS values indicate that the waters are generally suitable for irrigation, whereas KI classifies them as "unsuitable" and Potential Salinity (PS) classifies them as "harmful to unsatisfactory." According to the Wilcox diagram, the water samples fall into the "permissible to poor" category, suggesting a potential long-term risk of soil salinization or degradation. The Riverside diagram identified C3-S1 class waters, corresponding to moderate to high salinity levels. Overall, these results show that the irrigation waters are of medium to poor quality and should be used with caution. Regular monitoring of water quality is recommended, along with careful irrigation management, to preserve soil sustainability and crop productivity. In conclusion, water from the Niaye de la Patte d'Oie market gardening site can be used for irrigation, provided that its quality is regularly and continuously monitored. To ensure better soil protection and to limit the risk of sodicity, the application of chemical amendments, particularly gypsum ($CaSO_4 \cdot 2H_2O$), is recommended to replace exchangeable sodium with calcium. The use of acidifying amendments, such as elemental sulfur or sulfuric acid, may also be considered when soil conditions require it.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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