

# Market Gardening on the Togolese Coast: Characterization of the Water Resources Used

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**How to cite this paper:** Afatsao, K.B., Johnson, B.N., Etse, K.D., Sodjinou, K.E., Radji, R. and Quashie, A.M. L. (2025) Market Gardening on the Togolese Coast: Characterization of the Water Resources Used. *Journal of Water Resource and Protection*, 17, 811-841.  
<https://doi.org/10.4236/jwarp.2025.1712045>

**Received:** October 25, 2025

**Accepted:** December 9, 2025

**Published:** December 12, 2025

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## Abstract

This study evaluates the physicochemical quality of groundwater used for irrigating vegetable crops along the Togolese coast. Thirty samples collected from five locations were analyzed using standard analytical methods and classification diagrams (Richards and Wilcox) to characterize the water. The results show that, although the water generally has low salinity and is suitable for irrigation, it contains high concentrations of potassium and nitrates. The Ablogamé site, in particular, exhibits the highest levels of anthropogenic influence.

## Keywords

Coastline, Market Gardening, Irrigation Water, Physico-Chemical Composition

## 1. Introduction

Market gardening is a pillar of food security in urban Africa, providing fresh produce rich in vitamins and minerals [1]. Its success depends closely on the availability of quality irrigation water, as each crop has specific water needs, which vary according to climatic conditions [2]. In coastal areas, access to fresh water is often limited and subject to climatic and geographical constraints. Several West African countries, such as Benin and Senegal, are already facing salt stress that affects their horticultural production [3] [4]. In Togo, the coastal zone is a strategic space for market gardening: it supplies the urban markets of Lomé, supplies the sub-region and sometimes opens up export prospects [5]. However, this coastal position ex-

poses water resources and soils to strong environmental pressures. The proximity of the sea and the low altitude of the coastline favour saline intrusion, a phenomenon aggravated by the permeability of sandy soils, coastal erosion and the rise in sea level, estimated at around 12 cm in 2025 and projected to exceed 80 cm by 2100 according to IPCC climate scenarios. The accumulation of dissolved salts ( $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ) in groundwater compromises soil fertility and directly threatens sensitive crops such as tomatoes, peppers and African eggplants [6]-[9]. The impacts on agricultural yields are well documented: salinity reduces plant water absorption, causes ionic imbalances and limits root development. Yield losses of up to 46% were observed for tomatoes irrigated with highly saline water ( $\text{EC} = 8.6$  dS/m) compared to moderately saline water (3.0 dS/m), accompanied by a decrease in aerial growth and fruit size [10] [11]. In addition to these pressures, the coastline is eroding by up to 10 to 15 m per year in some areas, reducing the available agricultural space [12]. The Togolese Institute for Agricultural Research (ITRA) already estimates that a third of the soils in the maritime region have worrying salinity levels, forcing producers to adapt their practices or abandon certain plots. In response to these challenges, initiatives such as the IFAD-supported RESADE project are promoting adapted agricultural techniques and the introduction of salt-tolerant varieties to strengthen farmers' resilience [13]. At the same time, electrical conductivity measurements carried out on irrigation water on the Togolese coast reveal a high spatio-temporal variability, without however making it possible to identify the exact nature of the salts involved [14], hence the need for more in-depth chemical analyses [15]. Thus, salinization appears to be a major issue for the sustainability of Togolese coastal market gardening, with direct socio-economic repercussions on food security and agricultural incomes [16] [17].

The objective of this study is to characterize the physicochemical quality of irrigation water in the Togolese coastal zone using three complementary approaches: an overall assessment based on key indicators such as salinity, pH, dissolved solids and major ions, an analysis using Richards and Wilcox diagrams, and a characterization by production area by districts. The challenge is twofold: to assess the compatibility of this water with market gardening needs and to propose strategies for sustainable management, in order to preserve both agricultural productivity and the quality of water resources.

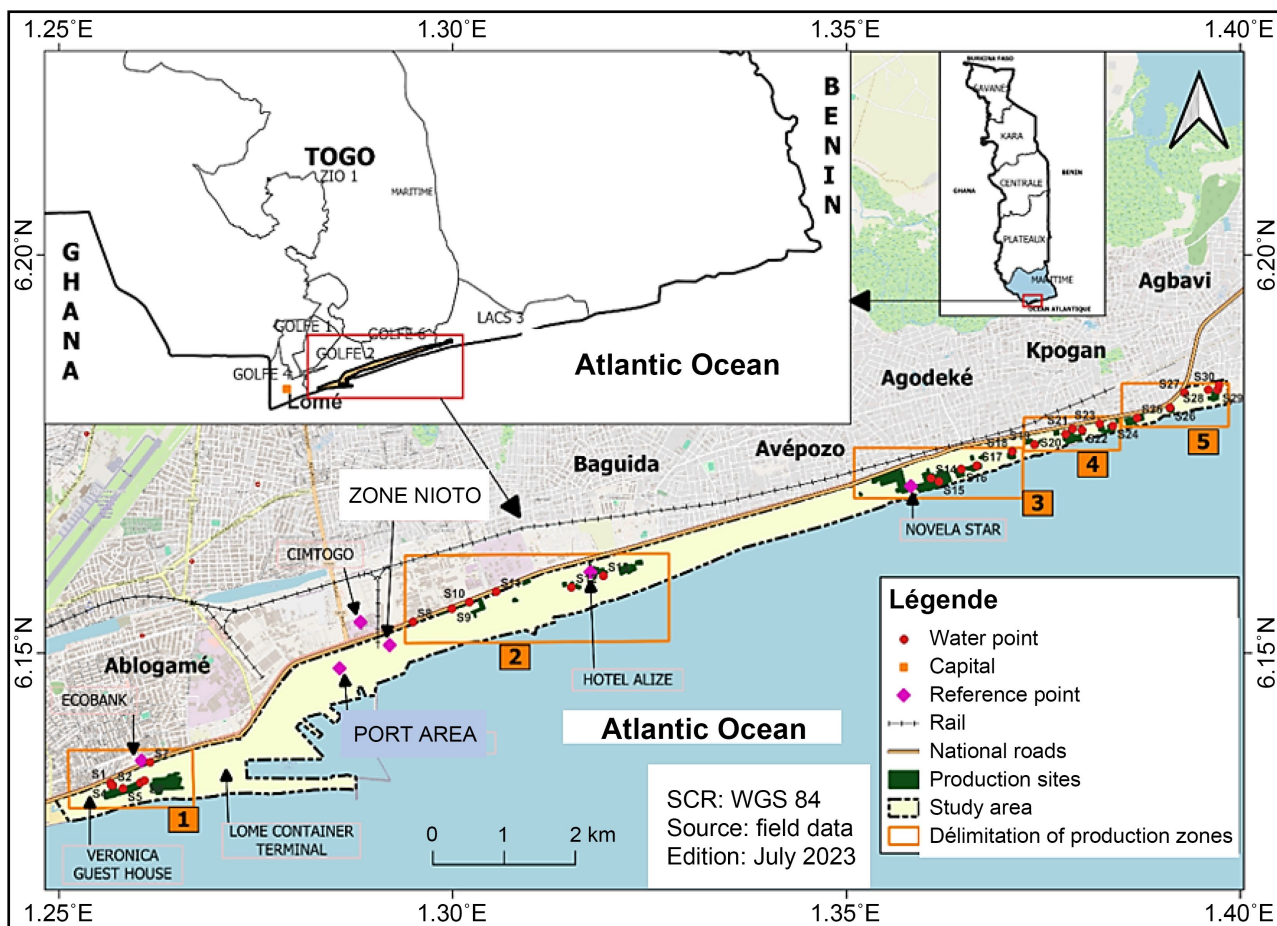
## 2. Materials and Methods

### 2.1. Study Area

The area covered by our study includes several peripheral districts of the capital, Lomé specifically Ablogamé, Baguida, Kpogan, Agodékè, and Agbavi where market gardening production zones with an area greater than or equal to 0.4 hectares were identified (**Figure 1**). The 20-kilometre barrier beach that constitutes the study area is located between 307071.24 meters East 678296.51 meters North and 322668.22 meters East 683768.61 meters North, and is part of ecological zone V in Togo [18]. The coastline is generally characterized by a low, sandy shore

marked by coastal erosion to the east of the main jetty of the Port of Lomé, with significant sediment displacement [19] [20]. More specifically, a set of 30 boreholes formed the basis of the study. The selection of boreholes was made to include all identified market gardening production sites in the study area. Indeed, a total of 55 boreholes were identified in the study area. Electrical conductivity (EC) measurements were taken for each borehole, and the values obtained served as the basis for selecting sampling points. From these data, 30 boreholes were chosen to constitute a representative sample, according to the following criteria:

- The variability of electrical conductivity, in order to cover the entire salinity gradient observed in the area;
- A balanced geographical distribution of the selected boreholes, in order to avoid an excessive concentration of points in the same hydrogeological unit;
- The actual use of the boreholes by market gardeners, ensuring the relevance of the analyses to local irrigation practices.



Source: Google Maps supplemented by field data, 2025.

**Figure 1.** Location of the study area.

This approach made it possible to obtain a set of samples representative of both the hydrochemical diversity and the actual exploitation of groundwater resources

in the study area. At each production site per district, six boreholes were analyzed, with three replicates per borehole. Sampling was conducted at the end of the region's long dry season to avoid the influence of superficial infiltration and/or surface runoff resulting from heavy rainfall.

## 2.2. Physical Data of the Water Tables Used by Market Gardeners

The measurements concerned the depth of the water table, the distance of the boreholes from the ocean, the temperature, the pH, the total dissolved solids load (TDS) and the electrical conductivity (EC).

- **Depth of the water table**

The depth of the water table was estimated from data collected from drilling installation companies.

- **Distance from boreholes to the sea**

The geographical coordinates of each borehole made it possible to calculate the exact distance of these boreholes from the ocean.

- **Temperature**

The temperature was measured using a WTW type multimeter with temperature function, in accordance with the NF T90-008 standard.

- **pH**

The pH was measured using a pH meter of the WTW pH 330i type, in accordance with the NF T90-008 standard.

- **Total Dissolved Solids (TDS) load**

The dissolved solids were determined with the WTW inoLab conductivity meter, according to the NF T90-111 standard.

- **Electrical Conductivity (EC)**

Conductivity is the measure of the ability of water to conduct an electric current. It is related to the concentration and nature of the dissolved substances [21]. It was evaluated using the WTW inoLab conductivity meter, according to the NF T90-031 standard.

## 2.3. Ion Load of Water Tables Used by Market Gardeners

The measurements concerned calcium ions ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), sodium ( $\text{Na}^+$ ), potassium ( $\text{K}^+$ ), ammonium ( $\text{NH}_4^+$ ), nitrates ( $\text{NO}_3^-$ ), nitrites ( $\text{NO}_2^-$ ), bicarbonates ( $\text{HCO}_3^-$ ), carbonates ( $\text{CO}_3^{2-}$ ), chloride ions ( $\text{Cl}^-$ ) and sulphates ( $\text{SO}_4^{2-}$ ).

The physical and chemical analysis methods for the [22] and [23] standards were used.

- **Identification of calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ) ions**

The EDTA complexometry method was used, in accordance with NF T 90-016 standards, using a volumetric device.

- **Analysis of sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ) ions**

The  $\text{Na}^+$  and  $\text{K}^+$  ions were quantified by atomic absorption spectrometry, according to NF T 90-20 standards, using a Perkin Elmer model 2380 spectrometer.

- **Analysis of ammonium ions ( $\text{NH}_4^+$ )**

For  $\text{NH}_4^+$  ions (cation), the absorption spectrometry method was used according to the NF T 90-015 standard.

- **Nitrate ion ( $\text{NO}_3^-$ ) analysis**

The absorption spectrometry method was used according to the NF T 90-012 standard, using the Digitron Elvi 675 spectrometer.

- **Nitrite ion ( $\text{NO}_2^-$ ) analysis**

The absorption spectrometry method was used according to the NF T 90-013 standard, using the Digitron Elvi 675 spectrometer.

- **Analysis of bicarbonate ( $\text{HCO}_3^-$ ) and carbonate ( $\text{CO}_3^{2-}$ ) ions**

Bicarbonate ( $\text{HCO}_3^-$ ) and carbonate ( $\text{CO}_3^{2-}$ ) ions were determined by acidimetry, in accordance with the NF T 90-036 standard, using a volumetric method.

- **Chloride Ion Analysis ( $\text{Cl}^-$ )**

Chloride ions ( $\text{Cl}^-$ ) were measured using the argentometric method, in accordance with the NF T 90-014 standard.

- **Sulfate Ion Analysis ( $\text{SO}_4^{2-}$ )**

Sulfate ions ( $\text{SO}_4^{2-}$ ) were analyzed by nephelometry, in accordance with the NF T 90-009 standard, using the Digitron Elvi 675 spectrometer.

## 2.4. Evaluation of the Quality of the Water Tables Used by Market Gardeners

Source water quality was assessed using Richards [24] and Wilcox diagrams [25].

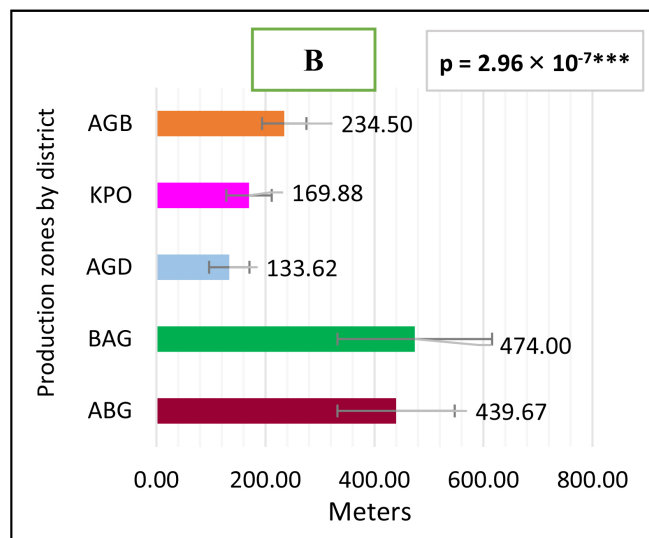
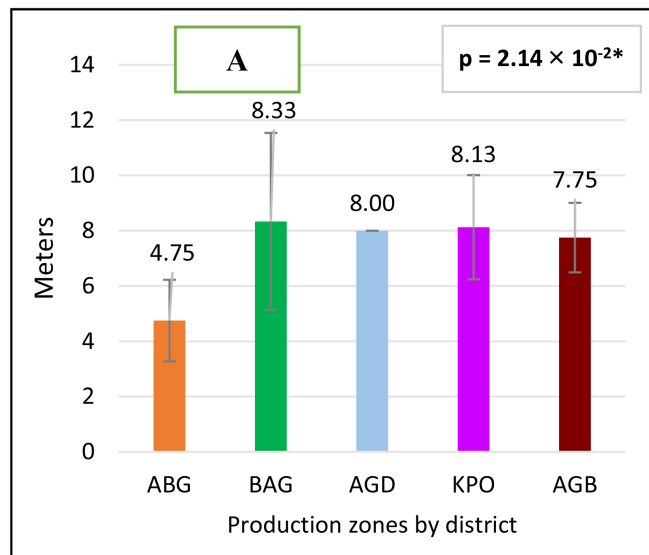
MINITAB and R Studio, version 4.4.1 were used to analyze the data and to perform analyses of variance (ANOVA) for the comparison of the means. The level of significance is 5% ( $p < 0.05$ ). The geographical coordinates were positioned on the map of Togo through the QGIS (quantum GIS) software.

## 3. Results

### 3.1. Physical Data of the Water Tables Used by Market Gardeners

#### 3.1.1. Location and Depth of the Water Tables Used

Analysis of the results reveals that the water tables used by market gardeners are generally shallow. However, there is variability in the depth at which the water table outcrops. Two distinct groups clearly emerge based on groundwater depth, with a significant contrast ( $p = 2.14 \times 10^{-2}$ ) between Ablogamé, where the water table is shallow (4.75 m), and the other districts notably Kpogan, Agbavi, and Baguida where it is significantly deeper (up to 8.33 m). Agodéké occupies an intermediate position, sharing characteristics of both groups, with an average depth of 8 m (**Figure 2(A)**). Regarding the distance from the sea, a highly significant difference ( $p = 2.96 \times 10^{-7}$ ) between two groups is also observed. The boreholes closest to the coast, located between 133.62 m and 234.50 m from the shoreline, are found in the Agodéké, Kpogan, and Agbavi areas, located on the outskirts of Lomé. Conversely, the sites in Ablogamé and Baguida, with average distances greater than 430 m, are located closer to the urban center (**Figure 2(B)**).



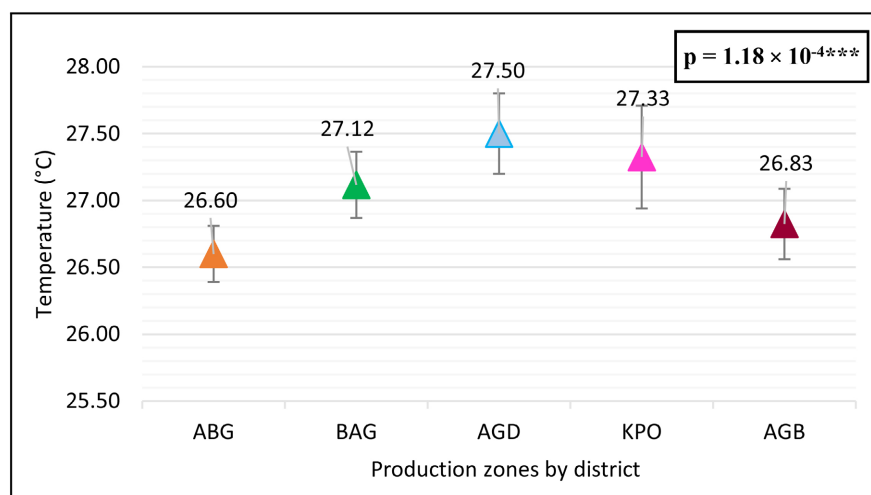
ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; AGB = Agbavi; Tukey test: the values followed by the same letter in a column are not significantly different at the 5% threshold. Significance Codes: 0 “\*\*\*” 0.001 “\*\*” 0.01 “\*” 0.05 “.” 0.1 “ ” 1.

**Figure 2.** Depth (A) and distances from the sea (B) of the water tables used by market gardeners.

The cross-analysis of these two parameters highlights a notable heterogeneity in the distribution of groundwater depth and distance from the sea across the districts studied. Boreholes located near the sea particularly in Agodéké, Kpogan, and Agbavi provide access to the deepest water tables. Conversely, in sites located farther from the coast, a marked contrast is observed: in Ablogamé, the water table is closest to the surface, while in Baguida, it reaches its maximum depth. These results reveal significant spatial variability in the characteristics of the groundwater exploited at the surveyed market gardening sites.

### 3.1.2. Water Temperature

Groundwater temperature ranges from 26.60°C to 27.50°C, with a statistically very significant difference ( $p = 1.18 \times 10^{-4}$ ). Two main groups emerge: the first is represented by Ablogamé, with an average temperature of 26.60°C, very close to that measured in Agbavi. The second group includes sites with higher temperatures, between 27.12°C and 27.50°C, about 1°C higher. The temperature recorded at Agbavi (26.83°C) occupies an intermediate position, allowing it to be associated with both groups (Figure 3).



ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; AGB = Agbavi; Tukey test: the values followed by the same letter in a column are not significantly different at the 5% threshold. Significance Codes: 0 “\*\*\*” 0.001 “\*\*” 0.01 “\*” 0.05 “.” 0.1 “ ” 1.

**Figure 3.** Comparison of the average temperatures of the water tables used by market gardeners.

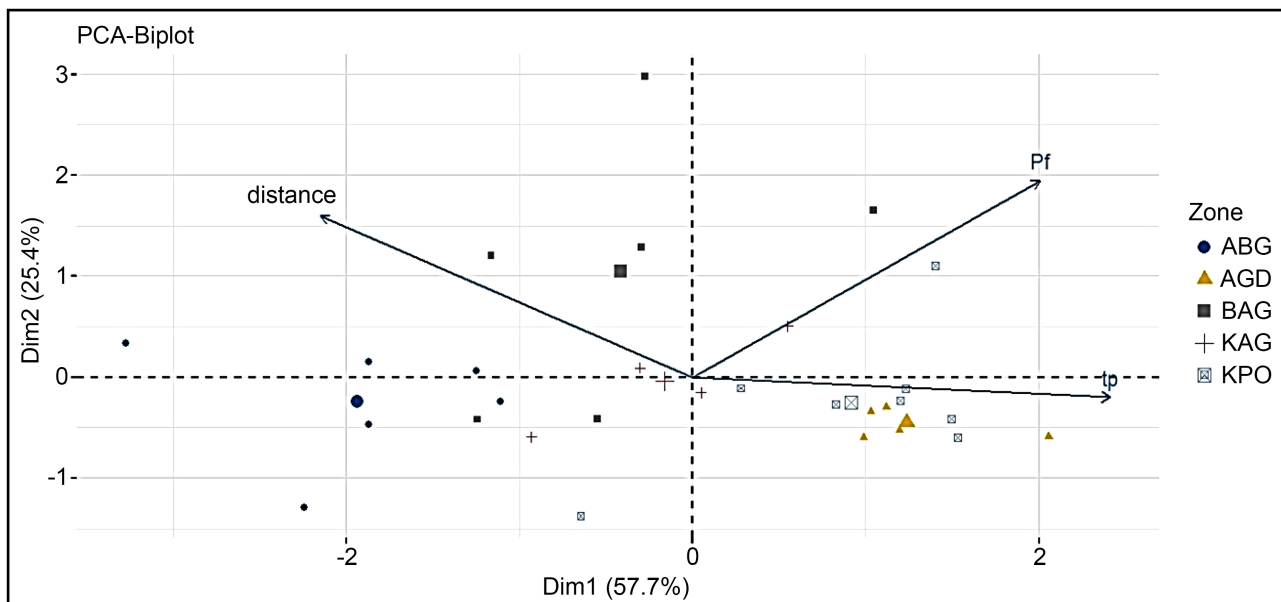
By cross-referencing the characteristics of the water tables and the temperatures measured, the results highlight hydrogeological configurations that are strongly influenced by geographical position. Peripheral areas close to the coast (Agodéké, Kpogan, Agbavi) generally have deeper water tables and higher water temperatures, with the exception of Agbavi, where the temperature remains relatively low.

Conversely, in more central urban areas (Ablogamé, Baguida), either a very shallow water table (Ablogamé) or a greater distance from the sea (Baguida) is observed, both accompanied by lower water temperatures. The case of Agbavi is unique: although located in a coastal area on the outskirts of the city, its water temperature is similar to that of the central urban districts.

Principal Component Analysis (PCA) highlights two main axes that together explain 83.1% of the data variability. The first axis (57.7%) is strongly correlated with water table depth and temperature, while the second axis (25.4%) is mainly associated with distance from the sea (Figure 4). The variables “depth” and “temperature” evolve in the same direction and are opposed to “distance”, indicating that boreholes located closer to the sea tend to have deeper water tables and higher

temperatures, while those farther from the sea are characterized by shallower water tables and lower temperatures.

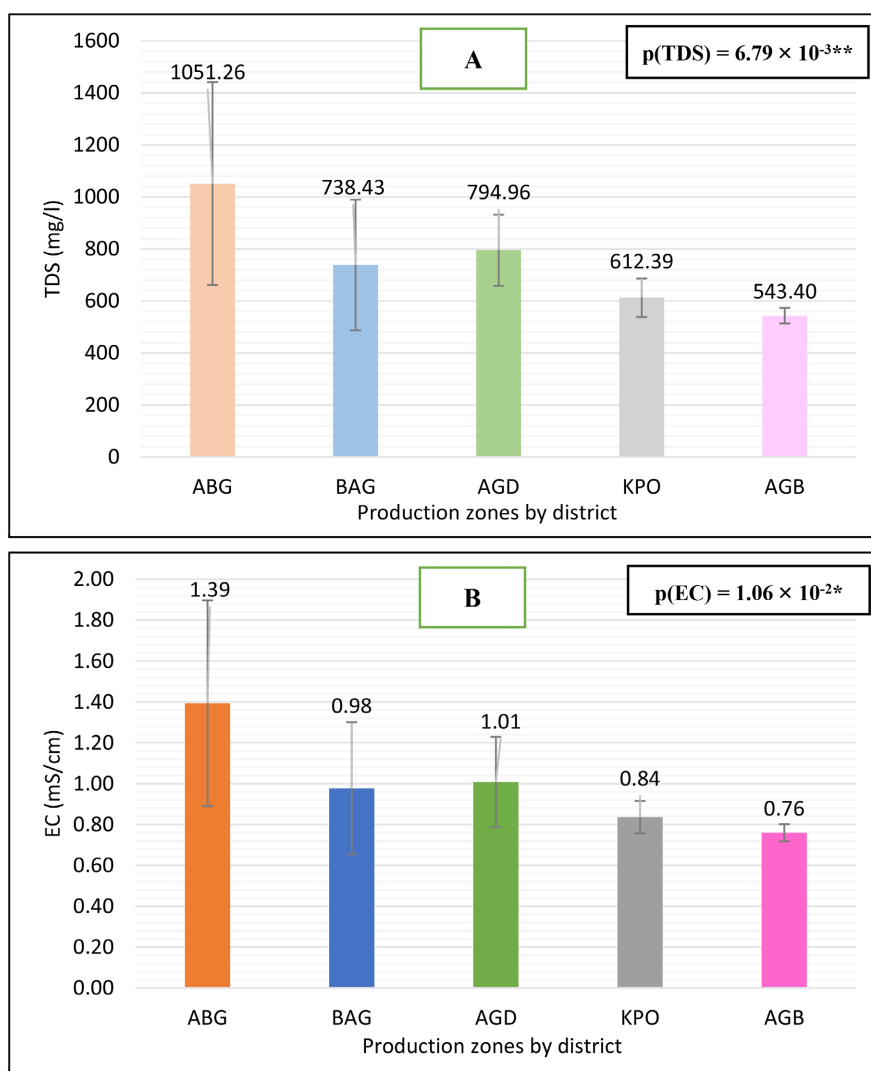
The spatial distribution of the zones confirms this trend: the Agodéké and Kpogan zones are grouped on the positive side of axis 1, reflecting their proximity to the sea and their association with high depth and temperature values. In contrast, the Ablogamé zone projects onto the negative side of axis 1 and is more associated with greater distance from the sea. The Baguida and Agbavi zones occupy intermediate positions, reflecting greater internal variability or less well-defined characteristics.



**Figure 4.** Principal Component Analysis (PCA) of the water tables used: relationship between temperature, depth and distance from the sea.

### 3.1.3. Total Dissolved Solids (TDS) Concentration and Electrical Conductivity (EC)

The analysis of total dissolved solids shows a distribution with a very significant variation ( $p = 6.79 \times 10^{-3}$ ) in the production areas by district. The lowest concentrations in total dissolved solids are observed at Agbavi (612 mg/L) and Kpogan (543.40 mg/L), while the maximum value is recorded at Ablogamé (1051.26 mg/L). Baguida and Agodéké are characterized by intermediate levels, similar to the two groups identified (Figure 5(A)). Electrical conductivity, used as an indirect indicator of salinity, closely correlated with TDS, shows significant variations between sites ( $p = 1.06 \times 10^{-2}$ ). The corresponding figures of the EC and the TDS overlap almost perfectly, illustrating the strong coherence between these two parameters (Figure 5(A) and Figure 5(B)). The lowest values are recorded in Agbavi (0.84 mS/cm) and Kpogan (0.76 mS/cm), located among the areas furthest from Lomé. Conversely, the maximum value is recorded at Ablogamé (1.39 mS/cm), which is almost double the minimum value. The sites of Baguida and Agodéké have intermediate values, statistically similar at the two extremes (Figure 5(B)).



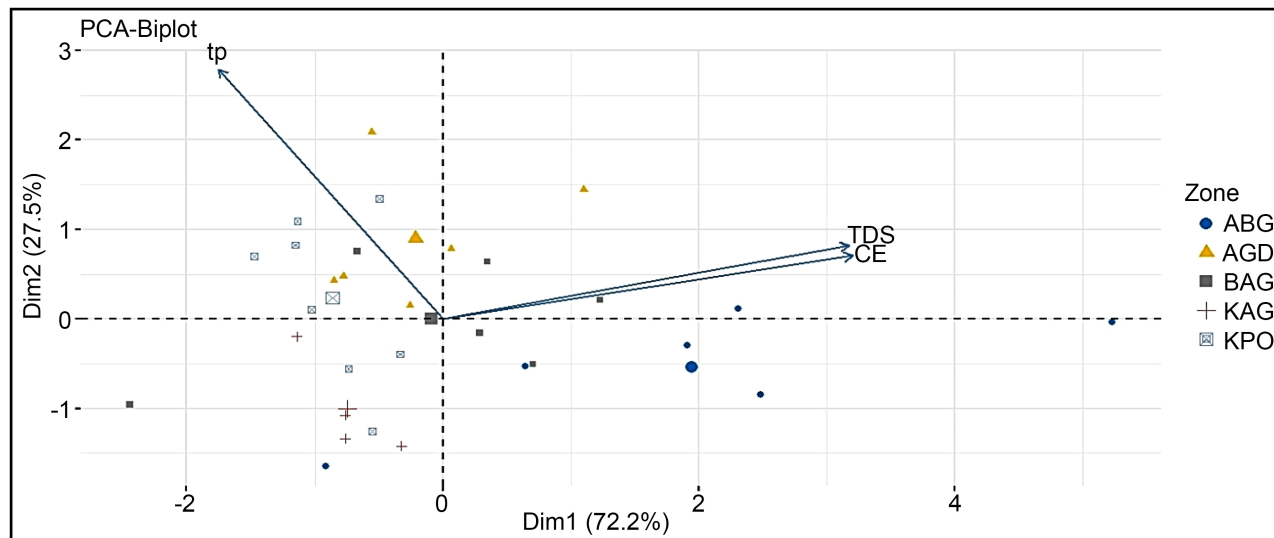
ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; AGB = Agbavi; Tukey test: the values followed by the same letter in a column are not significantly different at the 5% threshold. Significance Codes: 0 “\*\*\*” 0.001 “\*\*” 0.01 “\*” 0.05 “.” 0.1 “ ” 1.

**Figure 5.** Comparison of the average values of total dissolved solids (TDS) and electrical conductivity (EC) of the water tables used by market gardeners.

The further away from the capital, the lower the total dissolved solids charge and consequently the electrical conductivity as well.

The principal component analysis (PCA) performed on temperature, total dissolved solids and electrical conductivity reveals two main axes explaining 99.7% of the total variance, *i.e.* 72.2% for axis 1 and 27.5% for axis 2 (**Figure 6**). The first axis is strongly associated with water mineralization, represented by TDS and EC, two variables that are highly positively correlated. The second axis is mainly driven by temperature, as opposed to TDS and EC, reflecting a negative relationship between these parameters. The projection of individuals indicates that the production area, especially Ablogame, is characterized by high levels of TDS and EC, while the Agodeke and Kpogan areas are rather associated with higher tem-

peratures. The Baguida and Agbavi zones have intermediate profiles, reflecting moderate mineralization and temperature.



**Figure 6.** Principal Component Analysis (PCA) of the water tables used: relationship between temperature, Dissolved Solids Load (TDS) and Electrical Conductivity (EC).

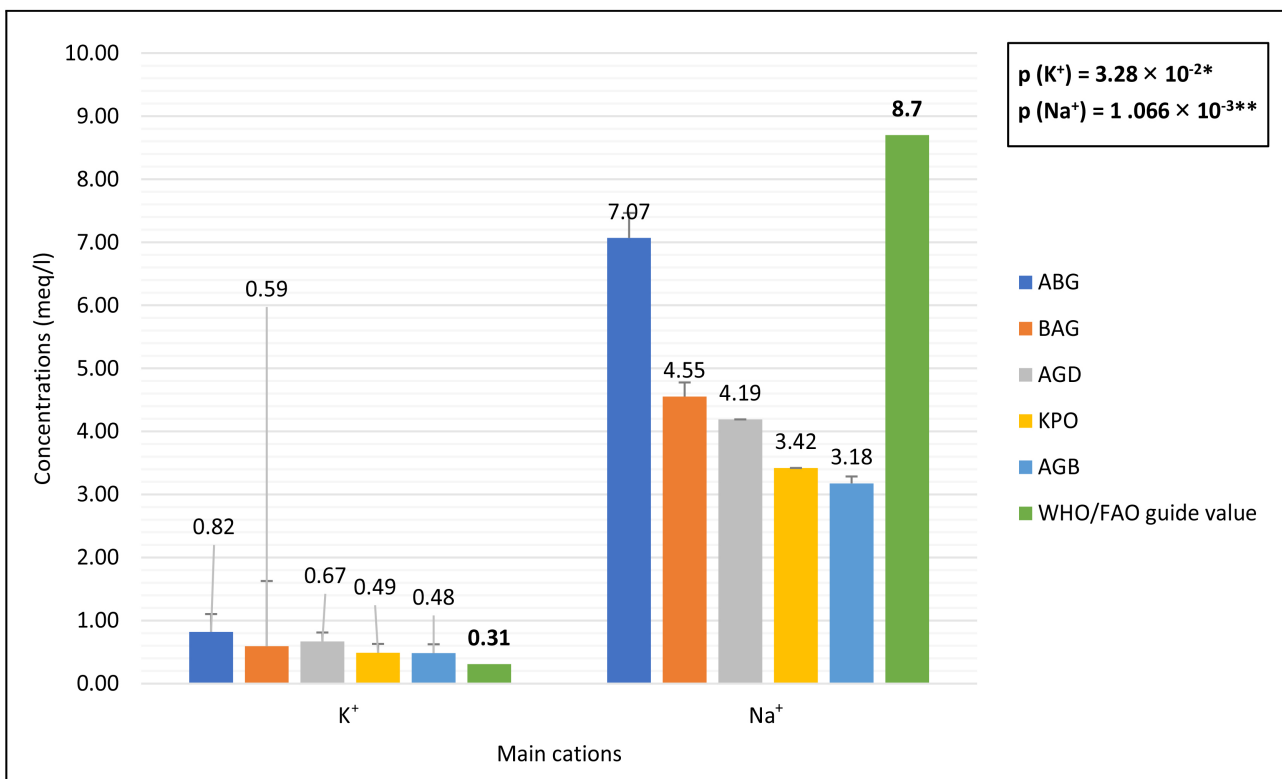
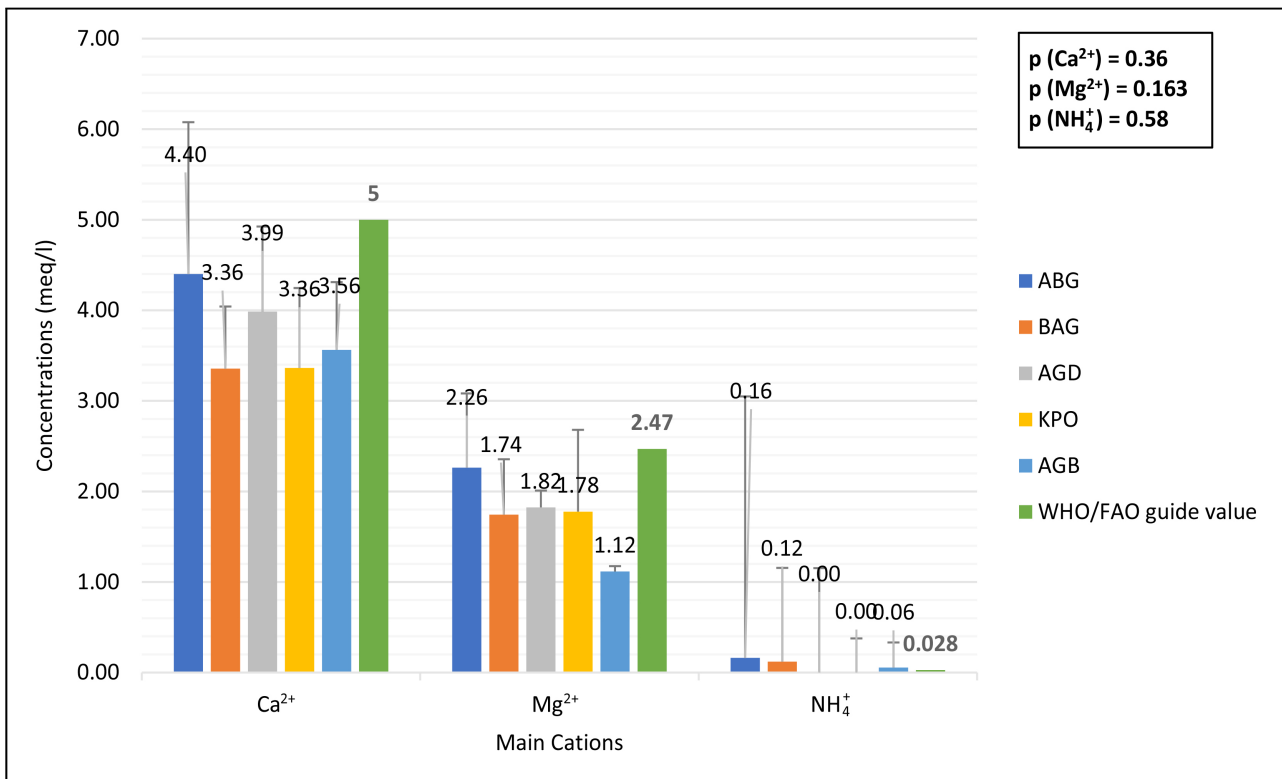
## 3.2. Ion Loading of Water Tables Used by Producers

### 3.2.1. Main Cation Concentrations

The cationic analysis showed a stability of the calcium, magnesium and ammonium elements, with no significant difference between the five areas studied. Calcium concentrations, ranging from  $3.28 \pm 0.98$  to  $4.40 \pm 1.68$  meq/l, are similar across sites ( $p = 0.36$ ) and in line with the WHO/FAO guidance value ( $<5$  meq/l) (Figure 5). This is also the case for magnesium concentrations, which vary in a fine and non-significant way ( $p = 0.163$ ) from  $1.53 \pm 0.28$  to  $2.26 \pm 0.82$  meq/l, while also respecting the guide value of 2.47 meq/l. With respect to ammonium concentrations, there were no significant differences between production areas by quarters ( $p = 0.588$ ) (Figure 7).

Significant variations are observed for sodium ( $p = 1.06 \times 10^{-3}$ ) and potassium ( $p = 3.28 \times 10^{-2}$ ) within production areas by districts. As far as sodium is concerned, all measurements remain below the limit of 8.7 meq/l set by the WHO/FAO and the production area of Ablogamé with a maximum value of  $7.07 \pm 2.88$  meq/l is the first group that clearly distinguishes itself from the other four production areas in the districts of Baguida. Agodéké, Kpogan and Agbavi, whose concentrations vary between 5.58 and 2.85 meq/l.

For potassium, in comparison with the WHO/FAO guideline, all measurements are found to be above this threshold of 0.31 meq/l. The highest value is also recorded in Ablogamé ( $0.82 \pm 0.28$  meq/l). The lowest concentrations, significantly, are found in Kpogan ( $0.49 \pm 0.15$  meq/l) and Agbavi ( $0.48 \pm 0.12$  meq/l). Those of Baguida and Agodéké have intermediate levels, close to those of both Ablogamé and Kpogan-Agbavi (Figure 7).



ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; KAG = Agbavi; Tukey test: the values followed by the same letter in a column are not significantly different at the 5% threshold. Significance Codes: 0 “\*\*\*” 0.001 “\*\*” 0.01 “\*” 0.05 “.” 0.1 “ ” 1.

**Figure 7.** Concentration of main cations in the water tables used by market gardeners.

Analysis of the main cation concentrations in the Togolese coastal production areas surveyed reveals homogeneity in calcium, magnesium, and ammonium levels, reflecting the basic chemical stability of the exploited water tables. In contrast, sodium and potassium concentrations vary significantly across the zones, with particularly high sodium levels observed in Ablogamé, the district closest to Lomé.

### 3.2.2. Main Anion Concentrations in Water Tables Used by Market Gardeners

The analysis of anions, present in the groundwater exploited for vegetable production reveals that all concentrations comply with the WHO/FAO guideline values, except for nitrates. Two major trends can be observed: a heterogeneity of concentrations, with highly significant variations and a grouping into distinct categories for bicarbonates ( $p = 9.78 \times 10^{-6*}$ ), chlorides ( $p = 2.9 \times 10^{-3**}$ ), and nitrates ( $p = 2.9 \times 10^{-3**}$ ); and a homogeneity of concentrations between zones for sulphates ( $p = 0.383$ ) and nitrites ( $p = 0.197$ )\*\*. Regarding bicarbonate ion concentrations, the differences are highly significant. The highest concentrations are recorded in Ablogamé ( $6.34 \pm 1.49$  meq/L), forming a first group, while the other water tables Baguida ( $2.93 \pm 0.60$  meq/L), Agodéké ( $3.58 \pm 0.78$  meq/L), Kpogan ( $3.56 \pm 0.87$  meq/L), and Agbavi ( $3.58 \pm 0.60$  meq/L)—form a second group (**Figure 8**).

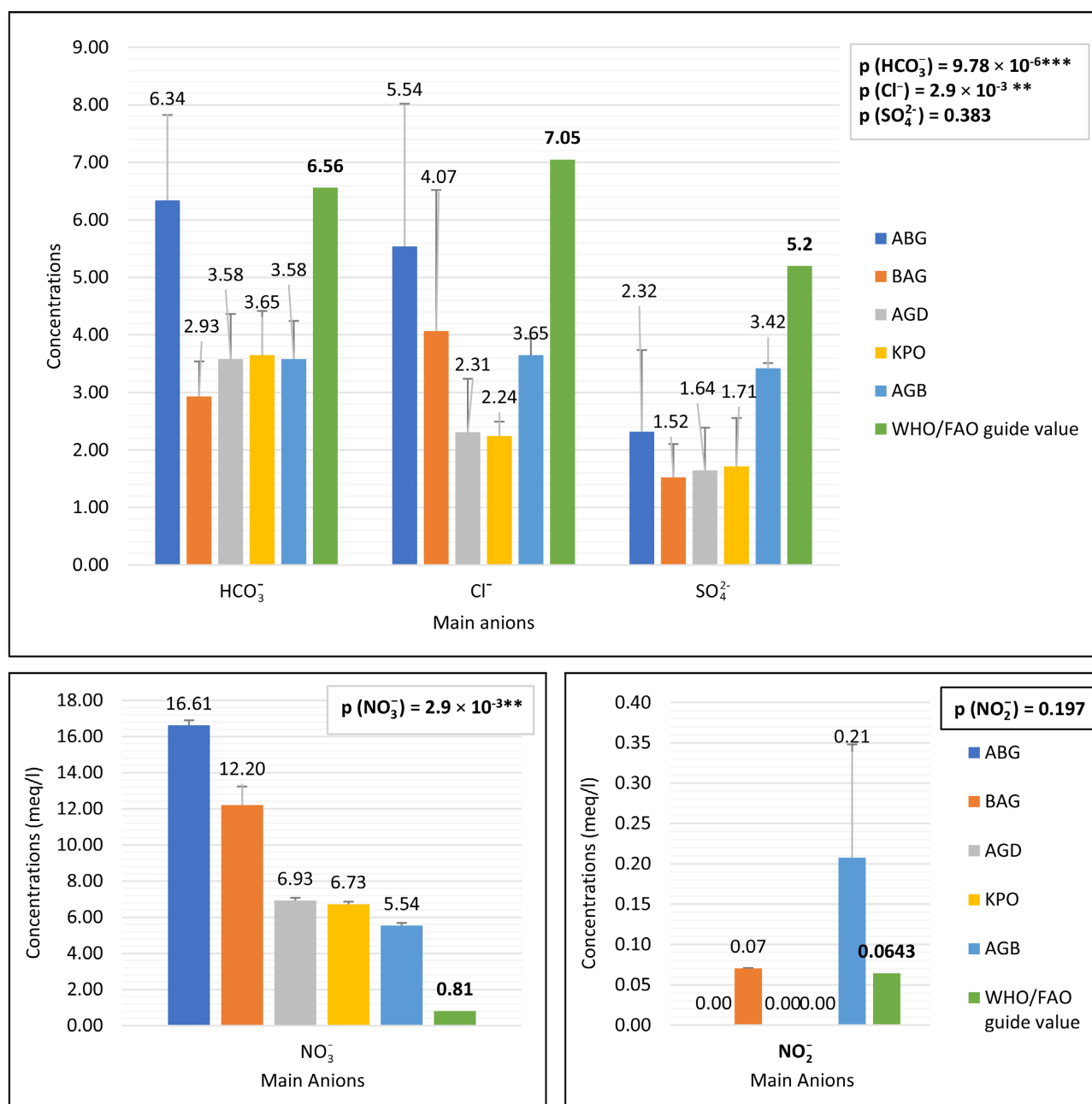
As for chloride ions, although all measured concentrations remain below the recommended limit of 7.05 meq/L, two distinct groups are also identified: Ablogamé, with the highest concentrations ( $5.54 \pm 2.48$  meq/L), and Agodéké ( $2.31 \pm 0.93$  meq/L) and Kpogan ( $2.24 \pm 0.26$  meq/L), where concentrations are significantly lower. The concentrations in Agbavi ( $3.65 \pm 0.60$  meq/L) and Baguida ( $4.07 \pm 2.45$  meq/L) fall in between and are statistically comparable to both groups (**Figure 8**).

Sulphate concentrations remain within the guideline limit of 5.2 meq/L, ranging from  $1.22 \pm 0.31$  to  $2.32 \pm 1.42$  meq/L, indicating minor and non-significant fluctuations (**Figure 8**).

Nitrate levels show very marked contrasts, exceeding the WHO/FAO guideline value of 0.81 meq/L by 7 to 20.5 times. The highest concentrations are recorded in Ablogamé ( $16.61 \pm 7.45$  meq/L), while the lowest are found in Agbavi, Agodéké, and Kpogan (ranging from  $5.54 \pm 0.87$  to  $6.93 \pm 2.78$  meq/L). Nitrate concentrations in Baguida are statistically comparable to both Ablogamé and the other zones (**Figure 8**).

Finally, nitrites are virtually absent from the groundwater used by market gardeners. All measured concentrations are below the WHO/FAO guideline value of 0.064 meq/L (**Figure 8**).

In summary, among the anions analysed, only bicarbonates, chlorides and nitrates show significant variations between production areas by districts. However, while bicarbonates and chlorides remain in line with the WHO/FAO guideline values, nitrates are distinguished by concentrations well above the standards, reflecting a potential risk to the quality of water intended for vegetable irrigation.



ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; AGB = Agbavi; Tukey test: the values followed by the same letter in a column are not significantly different at the 5% threshold. Significance Codes: 0 “\*\*\*\*” 0.001 “\*\*\*” 0.01 “\*\*” 0.05 “\*” 0.1 “.” 1.

**Figure 8.** Concentration of main anions in the water tables used by market gardeners.

The water tables used in the market gardening areas on the Togolese coast comply with WHO/FAO quality standards (Table 1). However, two exceptions stand out: potassium, whose concentrations exceed the norm by a factor of 2 to 3, and nitrates, which exceed the reference value by a factor of 7 to 20.5 in all the areas studied. In addition, the Ablogamé area is distinguished by particularly high concentrations of sodium, potassium, bicarbonates, chlorides and nitrates, sometimes reaching double the values measured elsewhere, although they remain within the

recommended ranges. Finally, the variations observed for the major ions agree with those of the electrical conductivity (EC) and, consequently, of the total dissolved solids (TDS).

**Table 1.** Comparison of measured parameters to WHO/FAO standards.

Parameter	Results	WHO/FAO guidance values	Evaluation/Interpretation
Temperature (°C)	26.6 - 27.48 S	<30°C (no hard limit, recommended <25 - 30)	Normal for irrigation
pH	7.18 - 7.50 NS	6.5 - 8.5	Within the norms, slightly basic
Calcium (meq/L)	3.36 - 4.40 NS	<20 meq/L (according to FAO - for irrigation)	Crop-safe concentrations
Magnesium (meq/L)	1.12 - 2.26 NS	<5 meq/L (FAO)	Crop-safe concentrations
Sodium (meq/L)	3.18 - 7.07 S	<3: good; 3 - 9: moderate; >9: to watch (FAO)	Crop-safe concentrations
Potassium (meq/L)	0.48 - 0.82 S	No fixed WHO/FAO limit (<2 meq/L acceptable)	Crop-safe concentrations
Ammonium (meq/L)	0.06 - 0.16 NS	<0.5 meq/L (≈0.9 mg/L NH <sub>4</sub> <sup>+</sup> - WHO/FAO)	Crop-safe concentrations
Bicarbonates (meq/L)	2.93 - 6.34 S	<8.5 meq/L (FAO - tolerable up to 10)	Crop-safe concentrations
Chlorides (meq/L)	1.85 - 5.54 S	<7.05 meq/L; tolerable up to 10 (CAM)	Crop-safe concentrations
Sulfates (meq/L)	1.52 - 3.42 NS	<5.2 meq/L (FAO)	Crop-safe concentrations
Nitrates (meq/L)	1.34 - 16.61 S	<10 mg/L NO <sub>3</sub> <sup>-</sup> for drinking water; <0.81 meq/L for irrigation (FAO)	Concentrations above the standard; major overtaking at Ablogame
Nitrites (meq/L)	Low, with no significant change in NS	<0.0643 meq/L NO <sub>2</sub> <sup>-</sup> for irrigation	Crop-safe concentrations
TDS (mg/L)	543.40 - 1051.26 S	≤500: good; 500 - 1000: acceptable; >1000: Limit	Good to Acceptable
Conductivity (mS/cm)	0.76 - 1.39 S	<0.7: bonne; 0.7 - 3 mS/cm: acceptable	Good (freshwater)

NS = non-significant differences for the parameter between production areas; S = significant differences for the parameter between production areas.

### 3.2.3. pH

Generally speaking, the pH is in the range of neutral to slightly alkaline for all production areas. The pH values of the water tables in the different coastal production areas of Togo vary between 7.18 and 7.50. However, there was no significant difference between the pH of the production areas by districts ( $p = 0.08$ ).

### 3.3. Characterization of Water Tables by District

**Table 2** highlights the comparison between the measured parameters and the standards established by the WHO/FAO. In general, the comparison of the measured parameters to these standards shows that:

- The parameters temperature, pH, calcium ions ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ), ammonium ( $\text{NH}_4^+$ ), sulphates ( $\text{SO}_4^{2-}$ ), nitrites ( $\text{NO}_2^-$ ) comply with the standards and show no difference in the water tables studied;
- As regards sodium ( $\text{Na}^+$ ), potassium ( $\text{K}^+$ ), bicarbonate ( $\text{HCO}_3^-$ ), chloride ( $\text{Cl}^-$ ) ions, compliance with standards with significant differences between water tables;
- Considering nitrates ( $\text{NO}_3^-$ ), it can be seen that for all water tables, the concentrations above the standard are very contrasted and also show significant differences between them.

**Table 2.** Characterization of the water tables by district according to the parameters evaluated.

Parameters	Ablogame	Baguida	Agodeke	Kpogan	Agbavi
<b>Physical</b>					
Depth S	5.08 ± 1.49a	8.00 ± 3.58b	7.67 ± 0.82ab	8.00 ± 0.00b	8.00 ± 2.45b
Distance to the sea S	399.50 ± 42.95a	530.33 ± 126.63a	161.8 ± 76.67b	178.83 ± 44.47b	204.00 ± 57.30b
Temperature (°C) S	26.6 ± 0.21a	27.12 ± 0.25ab	27.48 ± 0.27b	27.48 ± 0.28b	26.83 ± 0.23a
pH NS	7.41 ± 0.50a	7.18 ± 0.21a	7.46 ± 0.31a	7.49 ± 0.20a	7.50 ± 0.32a
TDS (mg/L) S	931.0 ± 286.0a	738.4 ± 251.1ab	795.0 ± 136.7ab	611.0 ± 80.2b	567.7 ± 56.6b
Conductivity (mS/cm) S	1.39 ± 5.03a	0.98 ± 3.23ab	1.01 ± 2.21ab	0.76 ± 0.60b	0.84 ± 0.87 b
<b>Cations</b>					
Calcium (meq/L) NS	4.4 ± 1.68a	3.35 ± 0.68a	3.98 ± 0.94a	3.58 ± 0.66a	3.28 ± 0.98a
Magnesium (meq/L) NS	2.26 ± 0.82a	1.74 ± 0.61a	1.82 ± 0.18a	1.53 ± 0.28a	1.59 ± 1.14a
Sodium (meq/L) S	7.07 ± 2.89a	4.55 ± 1.03b	4.19 ± 1.15b	3.44 ± 0.43b	3.24 ± 0.27b
Potassium (meq/L) S	0.82 ± 0.28a	0.59 ± 0.22ab	0.67 ± 0.14ab	0.52 ± 0.15b	0.45 ± 0.12b
Ammonium (meq/L) NS	0.16 ± 0.4a	0.12 ± 0.27a	0.00 ± 0.00a	0.00 ± 0.00a	0.04 ± 0.09a
<b>Anions</b>					
Bicarbonates (meq/L) S	6.34 ± 1.49a	2.93 ± 0.60b	3.58 ± 0.78b	3.56 ± 0.87b	3.58 ± 0.6b
Chlorides (meq/L) S	5.54 ± 2.48a	4.07 ± 2.45ab	2.31 ± 0.926b	2.27 ± 0.26b	3.58 ± 0.6ab
Sulphates (meq/L) NS	2.32 ± 1.42a	1.52 ± 0.58a	1.64 ± 0.74a	1.76 ± 0.98a	1.95 ± 0.31a
Nitrates (meq/L) S	16.61 ± 7.45a	12.20 ± 7.36ab	6.93 ± 2.78b	6.80 ± 0.79 p	1.34 ± 0.23bc
Nitrites (meq/L) NS	0.00 ± 0.00a	0.07 ± 0.10a	0.00 ± 0.00a	0.00 ± 0.00a	0.14 ± 0.34a

NS = non-significant differences for the parameter between production areas; S = significant differences for the parameter between production areas.

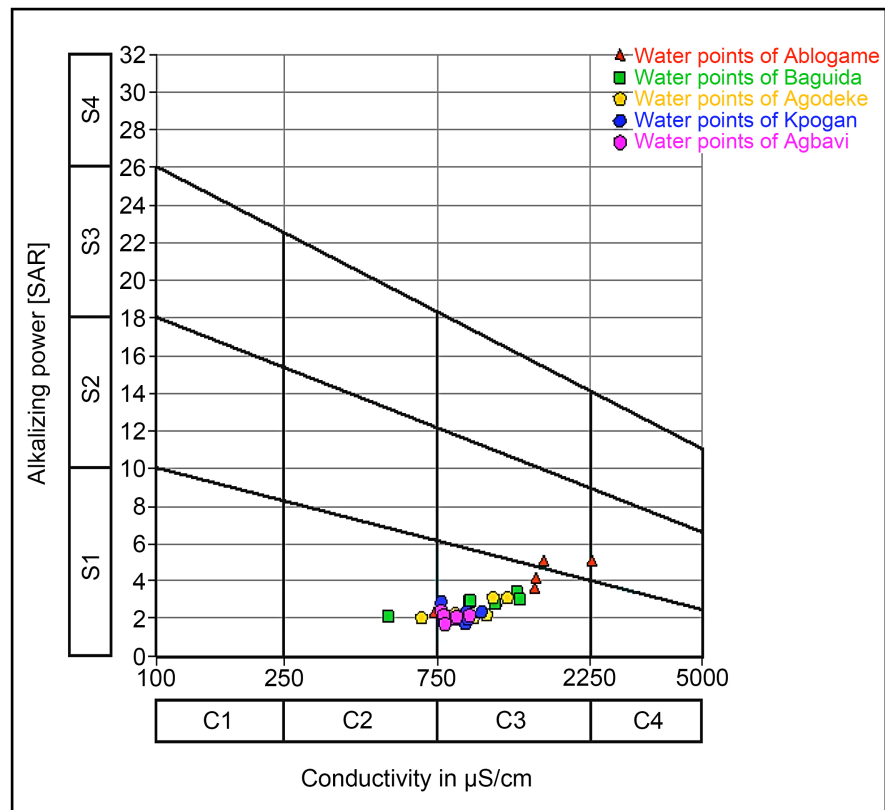
All these elements make it possible to achieve, for all production areas by district, water tables whose water quality varies from good to acceptable as regards the total dissolved load. Electrical conductivity, on the other hand, makes it possible to qualify all freshwater water tables, good for cultivation, despite nitrates. They also make it possible to characterize the water tables of the production areas by district.

### 3.4. Quality of Groundwater Used by Producers

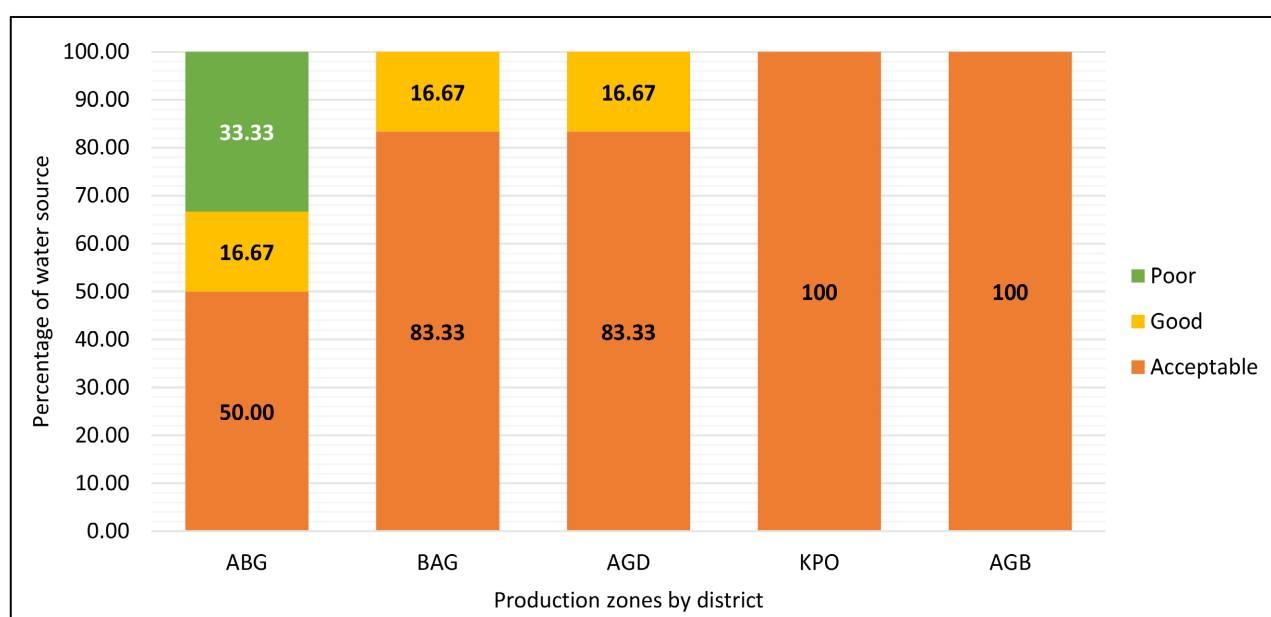
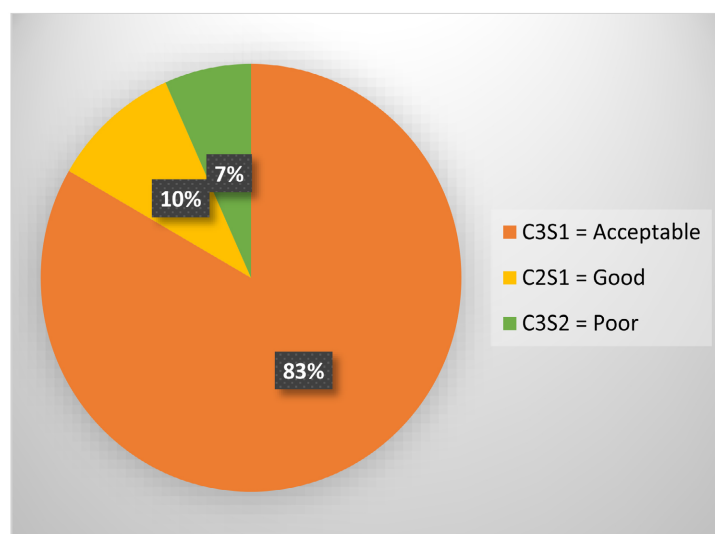
#### 3.4.1. Richards Diagram

The analysis of the quality of the irrigation water through its positioning on the Richards diagram (Figure 9) highlights three distinct classes of quality:

- 10% of the samples belong to class C2S1, corresponding to water of good quality, suitable for the irrigation of crops that are moderately tolerant to salts, and do not require any special control measures.
- 80% of the samples fall under class C3S1, which refers to moderately saline waters, which can be used on any type of soil, but require controlled salinity management and the cultivation of salt-tolerant plants.
- Finally, 7% of the springs are classified as C3S2, indicating water of inferior quality, suitable only for crops that are very tolerant to salts, on well-drained soils, with rigorous salinity monitoring.



**Figure 9.** Richards' diagram concerning the water tables of the production zones of the Togolese coastal strip.



ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; AGB = Agbavi.

**Figure 10.** Classification of the water tables used by market gardeners according to the Richards diagram.

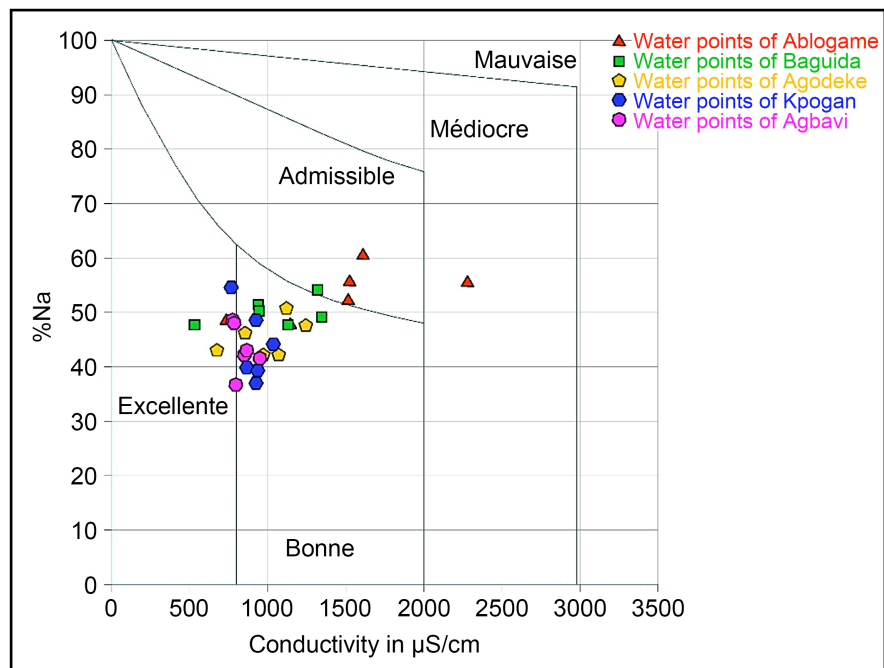
At the scale of each production area, the groundwater facies remains globally homogeneous. In Baguida, Agodéké, Kpogan and Agbavi, the resources are characterized by a mix of “good” (17%) and “acceptable” (50% to 100%) quality waters. More specifically, in Baguida and Agodéké, the water tables are composed of 17% of “good” quality water and 83% of “acceptable” water. In Kpogan and Agbavi, the quality is even more favourable, with 100% of the water classified as “good”. On the other hand, the Ablogamé area is distinguished by greater heterogeneity, with the simultaneous presence of all the quality classes: about 16% of “good” water, 50% of “acceptable” water and 33% of “poor” water (Figure 10).

It appears that more than 90% of groundwater sources exploited for market gardening irrigation along the Togolese coast have negligible salinity, which al-

lows them to be classified as freshwater.

### 3.4.2. Wilcox Diagram

The evaluation of the quality of irrigation water using the Wilcox' diagram (**Figure 11**), based on electrical conductivity and the percentage of sodium ions ( $\text{Na}^+$ ), makes it possible to classify the groundwater of the barrier beach into several categories (**Figure 11**): 83.33% of the samples belong to the “excellent” to “good” classes, indicating a quality suitable for irrigation without major risk. Only 13.33% of water points are classified as “eligible”, requiring a certain caution in agricultural use, while water of poor quality represents a very small proportion (3.33%).

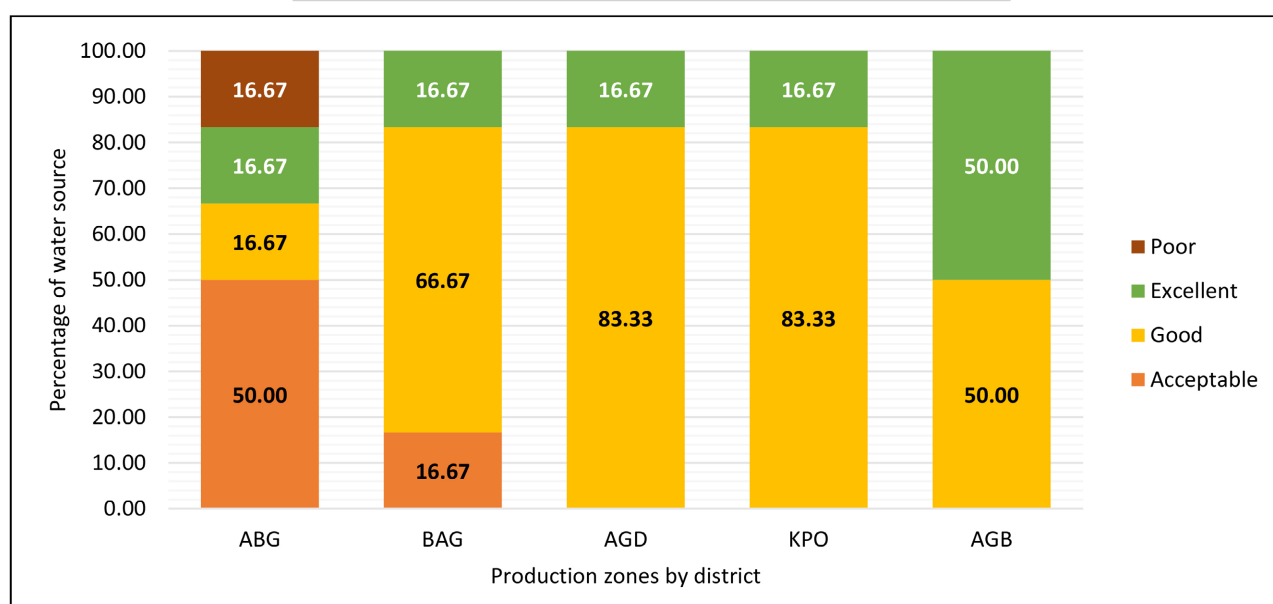
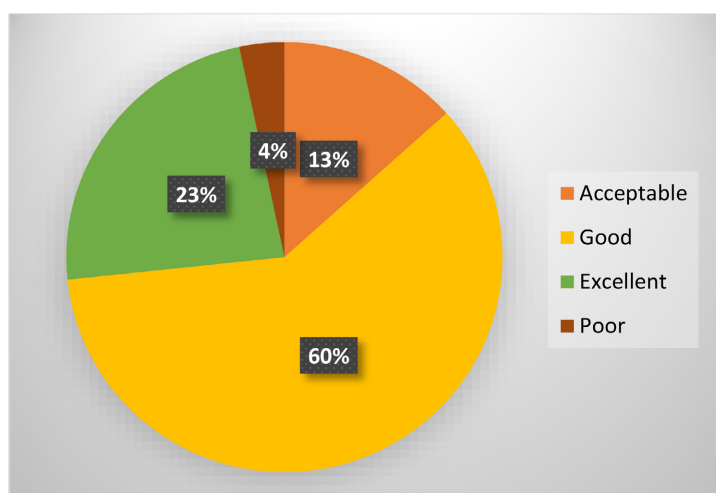


**Figure 11.** Wilcox' diagram of the water tables in the production areas of the Togolese coastal strip.

Considering the Wilcox' diagram, the majority of the groundwater exploited on the Togolese barrier beach has a good suitability for market garden irrigation, with a low risk of salinization by sodium (**Figure 12**).

The cross-analysis of the quality of irrigation water on the Togolese coast based on Richards and Wilcox diagrams makes it possible to establish an overall diagnosis of its suitability for irrigation:

- According to Richards' diagram, 93.33% of the samples belong to classes C3S1 and C2S1, reflecting a virtual absence of salinity that can be used without major constraints. Only 6.67% of the water is considered mediocre.
- The Wilcox' diagram, based on electrical conductivity and sodium concentration, shows an equally favourable quality: 83.33% of the samples are classified as “excellent” and “good”, with a low risk of sodium salinity. A minority of waters (16.67%) require vigilance, particularly in the context of sensitive soils.



ABG = Ablogame; BAG = Baguida; AGD = Agodeke; KPO = Kpogan; AGB = Agbavi.

**Figure 12.** Classification of the slicks used by producers according to the Wilcox' diagram.

### 3.4.3. Conclusion on the Use of Groundwater in Market Gardening

The analyses carried out indicate that the vast majority of groundwater exploited for market gardening purposes along the Togolese coast is suitable for irrigation. Despite the proximity of the sea, the main quality parameters usually used to assess the suitability of water for irrigation (pH, temperature, electrical conductivity, total dissolved solids, as well as concentrations of calcium, magnesium, sodium, ammonium, bicarbonates, chlorides, sulphates and nitrites) comply with the guide values recommended by WHO and FAO. These results reflect a low or even negligible salinity, making these water resources favourable for use in market gardening.

However, high concentrations of potassium and nitrates were found at all the sites studied, exceeding the thresholds of 0.31 and 0.81 meq/L set by international standards, respectively. This situation deserves special attention, because of the

potential risks associated with the accumulation of these ions in soils and their transfer to crops.

In addition, the FAO/WHO water quality classification shows that the water points studied have levels ranging from “excellent” to “acceptable” for irrigation. However, the Ablogamé site is distinguished by higher ion concentrations, which result in higher electrical conductivity and TDS than those observed in other areas.

In summary, the physico-chemical quality of the groundwater on the Togolese coast is found to comply with WHO and FAO guidelines, except for potassium and nitrates. These resources thus constitute an important basis for vegetable production, while requiring reinforced monitoring, particularly on sites with higher ion concentrations.

#### 4. Discussion

The heterogeneity of the groundwater resources used by market gardeners suggests a generalized exploitation of different hydrogeological units. The shallow sandy water table characteristic of this coastal zone remains shallow and the water tables are particularly vulnerable to anthropogenic and environmental influences [26] [27]. The significant difference between the depths of the water tables on the different sites studied confirms this variability in access to water resources. Thus, the spatial distribution of boreholes reveals two contrasting areas in terms of proximity to the coast: an area further from the sea (Ablogamé, Baguida) and an area closer to the sea (Agodékè, Kpogan, Agbavi).

Indeed, [28] explains that proximity to the sea can be a risk factor for the quality of exploited groundwater, particularly in connection with saline intrusion. This intrusion is a well-documented phenomenon in coastal areas where shallow water tables are directly influenced by sea level rise, tides, and excessive pumping [29].

In areas such as Kpogan or Agbavi, located in the immediate vicinity of the sea, the overexploitation of water tables could theoretically unbalance the natural hydraulic gradient and promote the upwelling of saline water. However, the results indicate that, in the current context, the waters analysed remain in compliance with WHO and FAO standards and do not show signs of marked salinization. This situation contrasts with other coastal regions of West Africa where cases of progressive salinization have been reported, directly affecting agricultural practices [30] [31]. Thus, although the risk exists, it is not yet evident in the area studied.

In short, the depth of the water tables and their geographical location in relation to the sea play a decisive role in vulnerability to salinization. A differentiated and preventive management of water resources, taking into account this spatial configuration, is necessary to ensure the sustainability of market gardening activities in this region.

The variation in the temperature of water resources, although small in appearance, is statistically very significant and seems to be directly related to the geographical position of the sites in relation to the coast. The lowest temperatures were recorded in Ablogamé and Agbavi, located inland, while the highest temper-

atures were measured in Agodékè and Kpogan, closer to the sea. This spatial distribution obtained on the Togolese coast suggests a thermal effect of maritime proximity, probably due to a warmer and humid coastal microclimate, the influence of warmed runoff, and denser urbanization in coastal areas that can amplify the urban heat island effect [32] [33]. In addition, the thermal conductivity of soils and the depth of water tables could play a role in the variability observed [34].

Even moderate groundwater warming can affect the physicochemical and microbiological quality of water, with implications for public health and the sustainable management of water resources in a context of increasing population pressure and climate change [35] [36]. In the context of market gardening, the temperature of the irrigation water is also a significant parameter for plant growth. Temperatures that are too low or too high can induce physiological stresses in plants, affect nutrient solubility and slow down soil biological processes [37].

The temperatures observed in this study, which are compatible with the requirements of vegetable crops, therefore indicate that water resources on the Togolese coast are not a limiting factor in terms of thermal conditions. Unlike surface water, groundwater does not experience sudden increases in daytime temperature, which limits potential thermal shocks during irrigation.

Measurements of the electrical conductivity (EC) of irrigation water in the market gardening sites studied reveal significant variations between zones. EC, a key indicator of water salinity, directly influences the availability of nutrients to plants and their ability to absorb water [38] [39].

The maximum value obtained at Ablogamé could be explained by anthropogenic factors such as increasing urbanization, domestic discharges or the uncontrolled use of agricultural inputs. As this site is further from the sea, the salinity seems to be more of anthropogenic origin than the result of marine saline intrusion. Conversely, the low levels observed at Agbavi and Kpogan, located on the seashore, indicate almost absent or negligible salinization, although these areas remain vulnerable to future intrusion in the event of overexploitation of the water table [40].

The notable internal variability recorded in Ablogamé, Baguida and Kpogan could result from a mixture of several water supply sources (groundwater, reclaimed water, etc.), but also from uneven borehole management or local differences in geology and land use [41]. This heterogeneity poses a particular challenge for water quality management in urban agriculture, where practices are often informal and poorly regulated. The intermediate values observed in Agodéké and Baguida indicate a transitional situation, possibly linked to average pressure on the resource, both in terms of exploitation and exposure to sources of pollution.

According to [42], human activity, particularly intensive irrigation and agricultural practices, can have a major impact on groundwater salinity. Excessive exploitation of water tables in dense urban or agricultural areas can lead to an increase in conductivity, unlike natural saline intrusion, which occurs more slowly and locally.

Referring to the [43] classification, electrical conductivities between 0.750 mS/cm and 2.250 mS/cm correspond to slightly saline waters. The waters used by market gardeners on the Togolese coast therefore fall broadly into this category. However, this water is generally suitable for the majority of crops, provided that a reasoned management of irrigation is implemented. This reflects an overall favourable situation, in contrast to other coastal regions heavily affected by salinisation.

Thus, in Morocco, in the Chaouia region, the electrical conductivities of groundwater near the shore reach values greater than 3 mS/cm [44]. Similarly, in the Dakar region, [45] revealed elevated EC levels, suggesting marked saline intrusion. On the Beninese coast, [46] reported values ranging from 0.7 to 2 mS/cm, reflecting mild to moderate salinity. Comparatively, the situation on the Togolese coast appears to be much more favourable, as salinity is not yet a limiting factor for irrigation.

This relative stability could be attributed to several factors, including natural hydrostatic pressure that maintains a separation between fresh and salt water [47]. Freshwater recharge by rainfall and rivers also plays a key role in preserving the hydrogeological balance and limits the risk of saline intrusion.

In short, although local variations exist, the electrical conductivity of groundwater on the Togolese coast remains generally compatible with the requirements of market gardening. These results underline the positive potential of the resource, while recalling the need to put in place preventive management mechanisms in order to limit possible future degradation.

The results indicate that the groundwater used is generally soft, with concentrations of total dissolved salts ( $\text{TDS} \leq 1000 \text{ mg/L}$ ) in perfect correlation with electrical conductivity. This situation, observed in Agbavi, Kpogan, Ablogamé, Baguida and Agodéké, reflects the combination of environmental, anthropogenic and seasonal factors influencing the composition of groundwater [48] [49].

In Ablogamé, the higher concentrations reflect slightly more mineralized water, probably related to the use of well water or surface water tables rich in soluble salts. Conversely, the lower levels recorded in Agbavi and Kpogan reflect good quality water resources, from less mineralized springs and therefore better suited to market gardening.

In the geographical context of the Togolese coast, TDS concentrations could be expected to lead to progressive soil salinization, with a negative impact on plant growth. Indeed, the accumulation of dissolved salts in the soil can increase electrical conductivity and reduce water availability for roots, due to reverse osmosis phenomena [50]. However, the results of this study show the opposite: the measured values remain within a range favourable to the majority of crops, confirming the good suitability of the groundwater of the Togolese coast for irrigation.

These observations are consistent with those reported in other regions where, despite the proximity of the sea, the water tables remain relatively spared from salinization thanks to efficient freshwater recharge and favorable hydro-geological

conditions [45] [47]. This situation is a major asset for the sustainability of coastal market gardening, while stressing the importance of regular monitoring in order to prevent any risk of adverse developments.

The pH of irrigation water is an essential parameter for assessing its quality. According to FAO guidelines, the recommended pH range for irrigation is between 6.5 and 8.4. Thus, the values measured in this study (7.18 to 7.50) are comfortably within this range, indicating irrigation water of acceptable quality [51]. A slightly basic pH is generally favourable for the majority of vegetable crops, as it optimises the availability of essential nutrients. For example, a pH between 6.5 and 7.5 is often considered optimal for the availability of micronutrients such as iron, manganese, and zinc.

Although the measured pH values are within the acceptable range, it is important to note that variations in pH can affect the operation of irrigation systems. For example, a high pH can lead to the formation of limescale deposits in pipes, while a low pH can accelerate the corrosion of equipment. However, the values measured in this study do not suggest such immediate risks [52].

With regard to the chemical quality of water resources on the Togolese coast, the low variability of ions such as calcium, magnesium, ammonium, nitrites and sulphates, as well as slightly basic pH values, suggests a water table that is little affected by major anthropogenic intrusions, such as domestic discharges or agricultural effluents rich in nitrogenous matter. With respect to nitrates, it should be noted that they result from the natural process of nitrification of ammonium by the action of bacteria of the genus *Nitrosomonas* and *Nitrobacter* [53]. However, the literature indicates that the presence of nitrates in drinking water is very often attributable to human activities: the use of mineral fertilizers and manure, associated with intensive farming, as well as animal manure or deficient septic systems, are important sources [54]. The risk of contamination is all the more marked when the soil covering the water table is sandy and the water table is shallow, conditions that favour the infiltration and rapid migration of nitrates.

However, the coastal area studied corresponds precisely to an area of intensive market gardening, where the use of chemical inputs and organic composts (from poultry droppings and cattle manure) is common. It is characterized by a low, sandy coast, subject to strong erosion to the east of the main jetty of the port of Lomé, with a pronounced departure of sediments [19]. Sandy soils [20] accentuate this vulnerability. These contextual elements suggest that, although the concentrations measured in this study do not indicate marked pollution, the area remains at increased risk of nitrate contamination due to its soil characteristics and agricultural uses.

At the international level, high nitrate levels in groundwater are a widely documented problem, particularly in relation to agricultural practices, and concern many OECD countries [55]. In fact, the most readily available forms of nitrogen are nitrate and ammonium, but nitrate ( $\text{NO}_3^-$ -N) is most commonly found in irrigation water. Ammonia nitrogen rarely exceeds 1 mg/L, except when ammonia

fertilizers or wastewater are added to the water resource. The concentration in most surface and groundwater is generally less than 5 mg/L of  $\text{NO}_3^-$ -N, but some specific groundwater may contain amounts exceeding 50 mg/L. Drainage water from the area below the root system frequently has higher nitrogen levels due to deep fertilizer leaching [56]. Reducing groundwater contamination by nitrates requires the implementation of adapted agricultural practices focused on improved nitrogen management in the field. Among the most relevant measures is targeted nitrogen fertilization, which involves adjusting fertilizer inputs to the actual needs of crops and their growth cycle. This approach, based on nitrogen balance assessment and the use of monitoring tools (sensors, soil analyses, fertility mapping), minimizes excess nitrogen that could be leached into groundwater [56]. Splitting applications, avoiding fertilization before heavy rainfall, and covering the soil between crop cycles are complementary practices that enhance the effectiveness of this strategy.

The values observed in the study area are therefore part of a more global dynamic, with no direct link to specific local anthropization, but the environmental and agricultural context of the Togolese coast calls for particular vigilance. Finally, potassium levels appear to be associated more with the ecological characteristics of the water table than with anthropogenic inputs, which confirms the good general chemical quality of the groundwater analysed. These findings suggest that in the absence of marked urbanization, groundwater quality could be significantly better [57].

The high potassium concentrations observed can be explained by both natural sources and anthropogenic inputs. On the one hand, the release of  $\text{K}^+$  can result from the weathering of potassium-rich minerals (feldspars, micas) in aquifer formations, and from leaching facilitated by favorable hydrological and textural conditions (example, high infiltration, irrigation, sandy soils). For example, one study shows that irrigating a sandy soil resulted in K losses of up to  $387 \text{ kg}\cdot\text{ha}^{-1}$  to the aquifer [58]. Another study, in a semi-arid basin, identified the use of potassium fertilizers (KCl) as a significant source of K in the groundwater [59]. On the other hand, the use of soluble potassium fertilizers can directly feed the water table by percolation: a soil column experiment recorded significant K leaks after the addition of KCl [60].

Unlike chloride, sodium, potassium, bicarbonate and nitrate ions, the higher concentrations of these ions at Ablogamé could be attributed to several factors: the proximity of the sea and the possible overexploitation of the water table can promote an upwelling of saline water, as suggested by the high levels of chlorides and sodium. However, it is important to emphasize that the concentrations measured are still much lower than those of seawater, whose electrical conductivity is around 50 mS/cm and the total dissolved solids (TDS) content is about 35,000 mg/L [48] [61]. On the contrary, the water tables studied have EC and TDS values compatible with fresh water, confirming that no major salinization is observed despite the immediate proximity of the Atlantic Ocean. A second factor would be

the intensive use of fertilisers: nitrate and potassium concentrations can result from a more intensive use of mineral fertilisers, which are often rich in these elements. The market gardeners of Ablogamé could have more intensive cultivation practices than in other areas. Another factor would also be increasing urbanization: as Ablogamé is on the outskirts of Lomé, it is likely that urbanization and soil sealing will modify the local hydrogeochemical regime. These observations are in line with the results of [62], which found higher concentrations of dissolved ions in peri-urban areas of Togo, due to increasing anthropogenic pressures.

The relatively stable concentrations of calcium, magnesium, sulphates and ammonium reflect a homogeneous chemical composition of the water table exploited for irrigation. This constancy, independent of geographical areas, suggests a common underground supply or one that is little influenced by anthropogenic inputs. Similar results have been observed in coastal water tables in West Africa, particularly in Benin, where concentrations of these ions have remained stable at comparable market gardening sites [63]. These levels are consistent with good water quality for irrigation, in accordance with the thresholds set by the Food and Agriculture Organization of the United Nations (FAO), which considers calcium and magnesium concentrations below 20 meq/L to be non-limiting for irrigation [43].

The pH indicates a slight basicity, which is favourable to the bioavailability of nutrients in the soil for the majority of vegetable crops [38]. In addition, the low nitrite concentration is a reliable indicator of water with low levels of organic matter or domestic discharge, which is essential for the safety of irrigated vegetable crops.

The concentrations of certain elements such as sodium, potassium, chlorides, bicarbonates and nitrates show a high spatial variability, especially with significantly higher concentrations at Ablogamé. This situation suggests a marked anthropogenic influence in Ablogamé, probably linked to the intensive use of nitrogen fertilizers, uncontrolled irrigation practices, and saline intrusions linked to the overexploitation of the water table [62]. It could also result from domestic or industrial effluents (salt-rich wastewater), as the site is located in the immediate vicinity of an industrial zone in Lomé. These concentrations raise potential risks of soil salinization (particularly by sodium and chlorides), as well as nutritional imbalances (excess nitrates and bicarbonates) that can affect crop growth and quality [38] [64] [65].

Variations in the chemical composition of groundwater cannot be understood solely from the perspective of anthropogenic inputs; geological factors play an equally crucial role. Indeed, the nature of the aquifer formations (sands, clays, sandstones, marine deposits) directly influences mineral weathering reactions, basal mineralization, and ion exchange within the aquifer. For example, in the Atlantic Coastal Plain (United States), the distribution of hydrochemical facies shifts from a Ca-Mg-HCO<sub>3</sub> type in well-drained areas to a Na-Cl type towards the coast, linked to mineral dissolution, cation exchange, and seawater intrusion. Similarly, in a coastal alluvial plain in China, the transition from a Ca-HCO<sub>3</sub> hydrotype to a

highly mineralized Na-Cl hydrotype towards the sea has been attributed to evaporite dissolution, concentrated evaporation, and seawater infiltration [66]. These studies illustrate that the concentrations of major ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ) result from a combination of natural processes (weathering, dissolution, cation exchange, marine intrusion) and not solely from agricultural or urban impacts. Indeed, the study area is characterized by Quaternary deposits consisting primarily of marine and coastal sands, forming poorly consolidated sandbars—an environment particularly permeable to infiltration. These formations therefore offer strong infiltration pathways for groundwater, which would explain why ion exchange reactions, the dissolution of sedimentary minerals and the coastal marine influence would significantly modulate the levels of major ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ) in these aquifers.

The assessment of the quality of irrigation water on the Togolese coast, through Richards and Wilcox's diagrams, highlights convergent and generally positive perceptions of the suitability of these waters for agricultural use.

The Richards diagram [24], based on electrical conductivity (EC) and sodium adsorption ratio (SAR), helps to assess both the level of total salinity and the risk of soil sodization. More than 90% of the water analysed reflects a moderate risk of salinity, suitable for crop growth and the preservation of soil structure in the long term [38]. These classes require relatively flexible management, even for less salt-tolerant species, contrary to the recommendations of [67], which recommend drainage, organic amendments, and gypsum to limit sodium accumulation. A study of the Mnasra plain water table (Morocco) obtained similar results, with a majority of samples classified as “good to acceptable” according to SAR and %Na [68].

The Wilcox diagram [25], based on CE and %Na, offers another perspective focused on immediate ionic toxicity. Here, 86.67% of the samples are rated as “excellent to good” quality, while only 3.33% are rated as poor. This optimistic view is probably related to the lack of consideration of SAR, which allows for the assessment of long-term effects on soil structure [69]. In an example in Ethiopia (Koga area), the waters were classified as C1S1 to C2S2 (low to moderate salinity and sodium), thus largely suitable for irrigation [70].

These two approaches are therefore complementary. Richards is more conservative and better suited to a sustainable vision, while Wilcox is pragmatic, relevant in short-cycle or immediate-use systems. Other studies confirm this complementarity: the joint analysis of these diagrams in the Senegal Valley (Lower Delta) has made it possible to map the potential impact on soil degradation by salinization and sodization [71].

Ultimately, the waters of the Togolese coast are a resource that is generally favourable to irrigation and offer significant potential to support market gardening. Their integrated and proactive management including regular monitoring of physicochemical parameters, the choice of adapted crops and the implementation of resilient cultural practices (localized irrigation, organic amendments, rotations,

etc.) can further enhance their agronomic value. Some areas such as Ablogamé, where ionic variability is more marked ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ), appear to be strategic spaces for developing innovative water and soil management solutions. The special attention paid to these sites is therefore not only a constraint, but an opportunity to improve soil fertility and consolidate the sustainability of market gardening production in the medium and long term.

## 5. Conclusions

The study highlights, through an overall assessment, a favorable physico-chemical quality of irrigation water along the Togolese coast, characterized by low salinity and a composition well adapted to the needs of the crops. Analysis using the Richards and Wilcox diagrams confirms this suitability, while also pointing out some limitations related to dissolved salt content and nutrient imbalances. Finally, characterization by production area reveals significant spatial variability, which is more closely related to geological and environmental conditions and local agricultural practices than to direct saline intrusion.

While this water quality is an asset for the sustainability of market gardening, the high concentrations of nitrates reflect the impact of anthropogenic inputs and underscore the need for rational fertilizer management. In this context, continuous monitoring and a localized approach to groundwater management appear essential to anticipate changes and prevent degradation. Preserving these resources requires appropriate agricultural practices, integrated water and soil management, and strategies to protect the fragile boundary between freshwater and saline water, especially in the face of increasing demographic and climatic pressures.

## Conflicts of Interest

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

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