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Impact of Terroir on Some Morphophysiological Parameters of Grapevines in Four Agroecological Zones of Côte d'Ivoire

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Abstract

Grapes are the main reason why the grapevine (*Vitis vinifera* L.) is cultivated. However, climate, soil conditions, vegetation and anthropogenic effects on the soil greatly affect grapevine production. The organoleptic properties of grape-derived products, such as wine, are influenced by these factors, which are becoming increasingly popular in Africa. Thus, grapevines, which are commonly grown in warm regions, are acclimatized in Africa using grapevine varieties that can adjust to tropical conditions. This study, which was carried out in 2019, aimed to promote grapevine cultivation in Côte d'Ivoire by examining the influence of pedoclimatic factors on the agro-physiological characteristics of grapevines. In Côte d'Ivoire, there were four distinct agro-ecological zones (North, South, Southeast and West) where three grapevine varieties, Bequignol, Muscat Rouge and Aleatico, were grown. Grapevine plants could grow robustly in morpho-physiological ways because the soils had sufficient fertility, as revealed by the analysis of experimental sites. Grapevine varieties have successfully adapted to different terroirs, with the exception of Muscat Rouge, which only displayed favorable morphological characteristics in the Man zone (West). Regardless of the grape variety, the regions with the best grapevine-growing conditions were Man (West), followed by Aboisso (Southeast). Consequently, grapevine development was less favorable in Korhogo (North) and Abidjan (South) zones. Thus, the cultivation of grapevine varieties in Côte d'Ivoire was greatly influenced by terroir.

Keywords

Vitis vinifera, Pedoclimatic Factors, Bequignol, Muscat Rouge, Aleatico

1. Introduction

Climate change has contributed to the recent increase in the number of people experiencing food insecurity and is expected to exert new pressures on agricultural systems [1]. By 2050, rising temperatures will affect agricultural production, stability and food accessibility. This situation may worsen due to the irregularity of agricultural production cycles, resulting in unstable production and changes in production areas [2]. Therefore, ensuring long-term food and nutrition security requires the adaptation of agricultural systems through resilience strategies [3]. Urgent action must be taken to achieve the sustainable development goals set by the United Nations. This can be accomplished by introducing economically viable crops, such as grapevines [4], into the agricultural systems of developing countries like Côte d'Ivoire.

Indeed, grapevines add value to local products and can address the growing demand for diverse wine products, making them a strategic option for rural development and agricultural diversification in Côte d'Ivoire [5]-[7]. In addition, grapevine cultivation could contribute to job creation and boost rural tourism, thereby strengthening the local economy in areas where it is cultivated [8]. However, despite grapevine's potential, sub-Saharan African countries such as Côte d'Ivoire are struggling to introduce it into their agricultural systems. And yet, although rare in sub-Saharan Africa, grapevine cultivation holds significant potential for Côte d'Ivoire, where certain agro-ecological zones possess the necessary conditions for producing high-quality grapes [6] [9] [10]. Grapevines thrive in many climates, and the potential of this crop relies, in particular, on the adaptation of varieties to local conditions, as well as on sunshine, a determining factor in grape quality [5] [8]. However, for successful integration into agricultural systems, it is essential to identify suitable terroirs that promote optimal vine growth and high-quality grape production [11] [12]. The concept of terroir refers to an area where collective knowledge, interactions between a discernible physical and biological environment, and applied viticultural practices contribute to distinctive characteristics of products originating from that area [11]. Thus, terroir is a crucial factor for vine productivity and the valorization of high-quality wines. In fact, the quality of wine depends on the ability to synthesize phenolic compounds in grapevine, hence the phenolic content of the grapes [13]. In general, the potential for synthesizing phenolic compounds in grapevines depends on factors such as climate, soil type, foliage balance, and grape production [14]. Therefore, identifying suitable terroirs that promote the synthesis of these molecules is necessary to enhance the production and valorization of high-quality wine. The aim of this study was to evaluate the impact of pedoclimatic factors (*In situ* physical characterization; Soil Granulometry; Soil Water pH; Soil organic matter, Mineral content; organic carbon content; Soil absorbent complex characterization and chemical equilibrium; Trends in annual relative humidity; Rainfall and Crop Seasons etc.) on experimental sites on some pedo-physiological characteristics of grape varieties cultivated in Côte d'Ivoire.

2. Materials and Methods

2.1. Plant Material

The plant material consisted of 44-day-old grapevine seedlings of the Aleatico, Bequignol and Muscat rouge varieties. These grape varieties were selected based on their hardiness at the Nangui Abrogoua University experimental farm nursery, according to Yao *et al.* [10].

2.2. Methods

2.2.1. Plot Selection

The plots were chosen based on the microclimate of the area, the overall appearance, and the surface characteristics of the soil. In this regard, cold (daily average temperature ranging from 15 to 22˚C), sunny (from 23 to 29˚C) and hot (from 30 to 40˚C) climates were selected. The general aspect of the plot focused on sites with very low or no risk of flooding and drought during the dry season and were mostly flat or lacked steep slopes. As for the surface characteristics of the soil (obtain at a depth of 20 cm), the selection was made for rocky, loamy-sandy, and sandy-loamy plots. Finally, to accommodate each experimental plot, four contrasting agro-ecological zones, namely the North, South, Southeast, and West, were chosen with the corresponding areas of Korhogo, Abidjan, Aboisso, and Man, respectively.

2.2.2. Plot Establishment

The plots were established on previously cleared fallow land. Staking was carried out with a spacing of 3 meters both along and between rows. Subsequently, young grapevine plants were sown in squares at a rate of 3,000 plants per hectare. The actual transplanting involved inserting leafy plants from the nursery into 30 cm in diameter and 30 cm deep holes, which were then covered with soil.

2.2.3. Physico-Chemical Characterization of Soil from Experimental Sites

1) Soil sampling

Soil samples were collected using the method described by [15]. Composite soil samples were taken at a depth of 20 cm using a cylindrical tube and then dried in plastic tubes or root-trainers in the laboratory. They were finely ground in laboratory mortars, sieved using 2 mm Ø mesh sieves, and stored in labeled polyethylene bags for analysis.

2) Physical characterization of soil

The structure of the crop soils was characterized by their cultural profile. Deep pedological pits, 1 m deep and 1.5 m long [16], were dug perpendicular to the direction of tillage on each experimental plot (**Figure 1**). These pits allowed for the determination of the thicknesses of the various soil horizons in each experimental plot. The particle size analysis was conducted using the densimetric method described by [17].

3) Soil Analysis

The soil pH was measured using CEAEQ methods [18]. Soil organic matter (OM) content was determined using the method of M'Sadak *et al.* [19]. Organic carbon was deduced from organic matter. Total nitrogen (N) was determined using the Kjeldahl method [20], which involves attacking the extract with concentrated sulfuric acid. Phosphorus (P) was determined using the atomic absorption spectroscopy method in the presence of vanadomolybdate reagent [19]. The exchangeable bases potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) were determined using the AOAC method, with a flame photometer. Sulfur (S) and soil trace elements (Fe, B, Zn, Mn, Cu) were analyzed using X-ray fluorescence spectrometry [21].

O: organic horizon; A: organo-mineral horizon; B: mineral horizon; NAU: Nangui Abrogoua University; PGCU: Peleforo Gon Coulibaly University.

Figure 1. Soil profiles carried out on the experimental plot.

2.2.4. Foliar Diagnosis

1) Leaf sampling

The first two leaves from the base of the branches were collected and placed in small plastic bags, then placed in ice inside a thermos. This thermos was transported to the laboratory and the leaves were placed in an oven at 60˚C for 72 hours. Dried leaves were ground into powder, alcohol was added, and the mixture was stirred for a few minutes [22]. The resulting filtrate was used for analysis and stored in a hermetically sealed jar.

2) Analysis of mineral elements

Nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca), recognized as major elements for their importance in grapevine development, were assayed by X-Ray fluorescence spectrometry [23].

2.2.5. Evaluation of the Effect of Some Environmental Parameters

Rainfall, temperature, and relative humidity were the only climatic parameters for which measurements could be obtained from the meteorological structure (SODEXAM) in Côte d'Ivoire during this study period from November 2019 to October 2020. These data were collected from SODEXAM weather station observations, located in the various study areas.

2.2.6. Influence of Growing Site or Terroir on Grapevine Growth Parameters

1) Plant growth dynamics

Evaluation of plant growth dynamics (PGD) began one week after planting. This allowed the grapevines to acclimatize to their new environment following the shock of transfer to the soil. After recovery, they were trellised vertically, and their flexible ends were bent and tied horizontally 70 cm above the ground. The length of the nursery plants was used as a reference (0 months) before planting. Plant height, corresponding to the distance from the collar to the cauline apex, was determined using a tape measure every four months over a 12-month period. Plant growth dynamics (PGD) were determined as before, using the following formula:

$$PGD = \left(FiLe - InLe\right)/InLe \quad (1)$$

With, *FiLe*: Final Length; *InLe*: Initial Length

2) Grapevine collar diameter and span

One week after planting grapevine, collar diameter (CoDi) of grapevine was measured using the caliper every four months over a 12-month period. With regard to grapevine span, one year after planting, the plant span (PlSp) corresponding to the width of the biomass twisted on ropes acting as stakes were determined using a tape measure. The measurement of this parameter made it possible to monitor changes in the biomass width of grapevine varieties in each experimental field.

3) Grapevine plant water content

Three plants per grapevine variety were carefully uprooted. The roots were thoroughly rinsed with tap water to remove the sand. Subsequently, the plants were blot-dried with blotting paper and individually wrapped in aluminum foil. The plants were weighed using a precision balance to determine the fresh weight matter (PFW). They were then placed in an oven at 60˚C until a constant weight was obtained, which represented the plant's dry matter (PDM). Plant water content (PWC) was determined using the following formula [24]:

$$PWC = \left[\left(PFW - PDM\right)/PFW\right] \times 100 \quad (2)$$

With, *PFW*: fresh weight matter; *PDM*: plant dry matter.

4) Statistical analysis

Data obtained from the evaluation of morpho-physiological parameters of the six different grape varieties were analyzed using Statistica 7.1 software. The mean values of the measured parameters were compared to each other through one or two classification criteria of variance analysis (MANOVA). Percentage data, which are non-parametric values, were angularly arcsin transformed (√x) before any variance analysis (the angular transformation is used to stabilize variance and improve the normality of data, especially for data expressed as percentages or proportions. These types of data often have variance that depends on the mean (non-homogeneous) and may deviate from normality. The angular transformation tends to bring the distribution closer to a normal curve, which is a key requirement for parametric tests). In case of significant differences between means, the Newman-Keuls multiple comparison test at 5% was performed to classify the means into homogeneous groups.

3. Results

3.1. Physical Characterization of Sites

3.1.1. *In Situ* Physical Characterization

The thickest organic horizon was obtained at the Aboisso site (11 cm), followed by Man (10 cm), Korhogo (9 cm) and Abidjan (8 cm). In contrast, the organo-mineral horizon was greatest at the Abidjan site (58 cm), followed by Man (50 cm), Korhogo (31 cm) and Aboisso (30 cm). As for the mineral horizon, the greatest was recorded at the Korhogo site (60 cm), followed by Aboisso (59 cm). On the other hand, the Man site (40 cm) and the Abidjan site (34 cm) had the thinnest mineral horizons. Furthermore, the soils at the four experimental sites are sufficiently deep and well drained for proper development of the grapevine's root system. With regard to texture, the soils at Abidjan, Korhogo and Man have a sandy-silty texture, while those at Aboisso have a silty-sandy texture (**Table 1**).

Table 1. In situ morphological analysis of soils at various experimental sites.

Experimental plots	Soil morphological characteristics				
	Soil horizon	Dimension (cm)	Drainage (cm)	Texture	Internal drainage
Abidjan	O	08 ± 0.10^{e}	100 ± 0.30^{a}	Sandy-loam	Good
	A	58 ± 0.60^{a}			
	B	34 ± 0.55^{d}			
Aboisso	O	11 ± 0.11^{e}	100 ± 0.60^{a}	Silty-sandy	Good
	A	30 ± 0.20^{d}			
	B	59 ± 0.19^{a}			
Man	O	10 ± 0.15^{e}	100 ± 0.85^{a}	Sandy-silty	Good
	A	50 ± 0.40^{b}			
	B	40 ± 0.60^{c}			
Korhogo	O	09 ± 0.23^{e}	100 ± 0.50^{a}	Sandy-silty	Good
	A	31 ± 0.57^{d}			
	B	60 ± 0.71^{a}			

O: organic layer; A: organo-mineral layer; B: mineral layer; Means followed by the same letter in the same column are not significantly different (Test of Newman-Keuls at 5%); ±S: Standard error.

3.1.2. Soil Granulometry

The results of the granulometric analysis reveal that the mineral fraction of the soils consists of sand, silt, and clay. However, the soils have a significant proportion of sand (>60%). Indeed, the Abidjan site is the richest in sand with 80.22%, followed by the Korhogo site (78.23%), Man (67.72%), and Aboisso (62.31%). On the other hand, the Aboisso site showed the highest clay content (20.53%), followed by Man (11.32%). Korhogo and Abidjan had the lowest clay contents at 8.82% and 5.28%, respectively. Regarding silt, the soil at the Man site had the highest percentage (21.11%), followed by Aboisso (17.33%), while the soil at the Abidjan (14.58%) and Korhogo (12.36%) sites had the lowest silt content (Table 2).

Table 2. Granulometric composition of soils from different experimental sites.

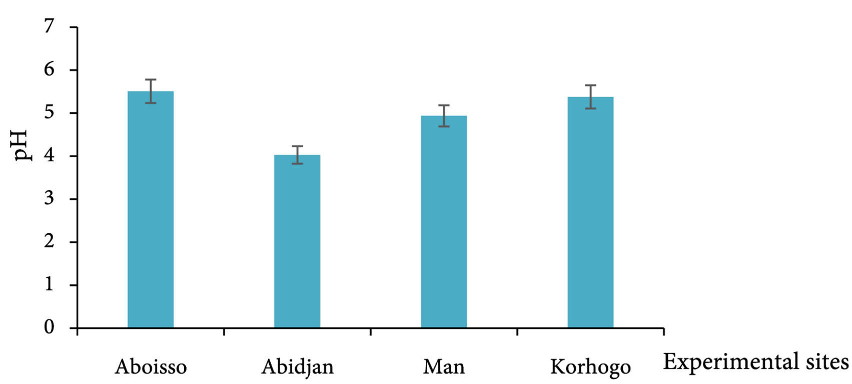
Soil elements (%)	Experimental sites			
	Abidjan	Aboisso	Man	Korhogo
Clay	05.28 ± 0.01^{d}	20.53 ± 0.01^{a}	11.32 ± 0.01^{b}	08.82 ± 0.01^{c}
Slit	14.58 ± 0.01^{c}	17.33 ± 0.01^{b}	21.11 ± 0.01^{a}	12.36 ± 0.01^{d}
Fine sand	20.12 ± 0.01^{c}	25.10 ± 0.45^{b}	29.31 ± 0.01^{a}	18.11 ± 0.01^{d}
Coarse sand	60.10 ± 0.45^{a}	37.13 ± 0.01^{a}	38.41 ± 0.01^{b}	60.12 ± 0.01^{c1}
Total sand	80.22 ± 0.04^{a}	62.31 ± 0.02^{b}	67.72 ± 0.02^{b}	78.23 ± 0.03^{a}
Soil texture	Sandy-silty	Silty-sandy	Sandy-silty	Sandy-silty

Means followed by the same letter in the same column are not significantly different (Test of Newman-Keuls at 5%). ±S: Standard error.

3.2. Chemical Characteristics of Soils from Different Experimental Sites

3.2.1. Soil Water pH

The results of the analysis of soil water pH for the different experimental sites are presented in (Figure 2). Analysis of variance revealed that soil water pH varied significantly according to experimental site. However, all the studied soils were



Histograms topped by the same letter are not significantly different (Test of Newman-Keuls at 5%). Bars represent standard error.

Figure 2. Soil water pH of experimental sites.

generally acidic, with pH below 6. Nevertheless, the soil at the Abidjan site was found to be more acidic (pH = 4.03) in comparison to the Man site (pH = 4.94). Soils at the Aboisso site (pH = 5.51) and Korhogo site (pH = 5.38) had higher pH values, which were statistically identical.

3.2.2. Soil Organic Matter and Organic Carbon Content

Soil organic matter content was highest at the Aboisso site (15.00%), followed by Man (11.74%). In contrast, the soil at the Abidjan (7.45%) and Korhogo (7.47%) sites had the lowest levels. As for organic carbon, the soil of Aboisso site recorded 6.03%, followed by that of Man (5.06%), Abidjan (4.98%) and Korhogo (4.64%). However, no statistical differences were observed between soil contents (Table 3)

Table 3. Organic matter and carbon content of soils from the four experimental sites.

Organic elements (%)	Experimental sites			
	Abidjan	Aboisso	Man	Korhogo
Organic matter	07.45 ± 0.01^{c}	15.00 ± 0.10^{a}	11.74 ± 0.01^{b}	07.47 ± 0.03^{c}
Total carbon	04.98 ± 0.01^{a}	06.03 ± 0.63^{a}	05.06 ± 0.01^{a}	04.64 ± 0.01^{a}

On a line, means followed by the same letter are not significantly different (Test of Newman-Keuls at 5%); ±S: Standard error.

3.2.3. Mineral Content of Experimental Site Soils

Table 4 presents the content of nitrogen (N), sulfur (S), phosphorus (P), and trace elements (Fe, B, Zn, Mn, Cu), as well as C/N ratio of soils from the four different experimental sites. The highest nitrogen content was observed in Aboisso, at 0.75%. Man (0.56%) followed, and then Abidjan (0.42%), and Korhogo (0.32%) had the lowest contents. On the other hand, the Korhogo site recorded the highest

Table 4. Chemical composition of experimental site soils.

Mineral constituents	**Mineral content of experimental site soils (%)**			
	Abidjan	**Aboisso**	**Man**	**Korhogo**
N	0.42 ± 0.01^{c}	0.75 ± 0.01^{a}	0.56 ± 0.01^{b}	0.32 ± 0.01^{d}
P	0.53 ± 0.01^{c}	1.44 ± 0.01^{a}	0.55± 0.02^{c}	0.64 ± 0.03^{b}
S	Ni	Ni	Ni	Ni
Fe	23.47 ± 0.01^{c}	52.41 ± 0.01^{a}	2.78 ± 0.01^{d}	41.65 ± 0.01^{b}
B	0.01 ± 0.00^{a}	0.07 ± 0.00^{a}	0.01 ± 0.00^{a}	0.01 ± 0.00^{a}
Zn	0.02 ± 0.00^{b}	0.20 ± 0.01^{a}	0.01 ± 0.00^{b}	0.01 ± 0.00^{b}
Mn	0.03 ± 0.00^{b}	0.43 ± 0.00^{a}	0.02 ± 0.00^{b}	0.02 ± 0.00^{b}
Cu	0.01 ± 0.00^{c}	0.04 ± 0.00^{a}	0.02 ± 0.00^{b}	0.01 ± 0.00^{c}
C/N	11.85 ± 0.01^{b}	8.04 ± 0.52^{c}	9.03 ± 0.01^{c}	14.50 ± 0.01^{a}

N: nitrogen; P: phosphorus; S: sulfur; Fe: iron; B: boron; Zn: zinc; Mn: manganese; Cu: copper; Ni: not identified; On a line, means followed by the same letter are not significantly different (Test of Newman-Keuls at 5%); ±S: Standard error.

C/N ratio (14.50), while the lowest C/N ratio was observed at the Aboisso site (8.04). The highest phosphorus content was found in the soil of the Aboisso experimental site (1.44%), followed by the Korhogo site (0.64%), while the lowest was noted in the Abidjan (0.53%) and Man (0.55%) sites. Regarding iron, the highest content was detected in the Aboisso site (52.41%), followed by Korhogo (41.65%), and then Abidjan (23.47%). In contrast, the Man site had the lowest iron content (2.78%). The soils from all experimental sites showed the same low boron content. Except for Aboisso site, which had a relatively high zinc content (0.20%), Abidjan, Man, and Korhogo sites had the lowest but statistically identical zinc contents (0.01%). As for manganese, Aboisso site recorded the highest content (0.43%), unlike the other three sites (Abidjan, Man and Korhogo), which had the same low content (0.2%). Regarding copper, although it was present in trace amounts in these soils, Aboisso site recorded the relatively highest content (0.04%), followed by Man (0.02%). In contrast, Abidjan and Korhogo sites had the lowest levels (0.01%).

3.2.4. Soil Absorbent Complex Characterization and Chemical Equilibrium

The characteristics of the absorbent complex and the chemical equilibrium of the soils at the various experimental sites are given in (**Table 5**). With regard to the absorbent complex, soils from the Aboisso and Man experimental sites expressed the highest levels of CEC (21.51 and 20.61 meq/100g respectively), followed by Abidjan (18.52 meq/100g) and Korhogo (17.86 meq/100g). Regarding potassium, the highest levels were recorded in the soil at the Man site (0.79%), followed by Abidjan (0.66%). Korhogo (0.49%) and Aboisso (0.37%) recorded the lowest values. Sodium content was highest in Man (0.38%), followed by Aboisso (0.35%),

Table 5. Characteristics of the absorbent complex and soil chemical balance at grapevine experimental sites.

Study area	Absorbent complex and chemical balance							
	CEC (meq/100g)	K (%)	Na (%)	Ca (%)	Mg (%)	SBE (%)	(SBE + 6,15)/N	Mg/K
Abidjan	18.52 ± 1.00[b]	0.66 ± 0.01[b]	0.28 ±0.01[c]	4.71 ± 0.01[c]	12.0 ± 1.00[b]	17.65 ± 0.01[b]	56.66 ± 0.01[c]	18.18 ± 0.56[c]
Aboisso	21.51 ± 1.00[a]	0.37 ± 0.01[d]	0.35 ±0.01[b]	62.7 ± 0.01[b]	6.37 ± 0.46[c]	69.79 ± 0.01[d]	101.5 ± 0.01[d]	17.21 ± 0.01[d]
Man	20.61 ± 1.00[a]	0.79 ± 0.01[a]	0.38 ±0.01[a]	65.5 ± 0.01[a]	14.78 ± 0.01[a]	78.21 ± 0.01[a]	150.6 ± 0.01[a]	19.67 ± 0.01[b]
Korhogo	07.86 ± 0.01[c]	0.49 ± 0.01[c]	0.02 ± 0.01[d]	0.77 ± 0.01[d]	15.49 ± 0.01[a]	16.77 ± 0.01[c]	69.75 ± 0.01[b]	31.61 ± 0.01[a]
Standards	0 - 12 Light soil 12 - 20 Medium soil >20 Heavy soil	3.50%	0.30%	60 - 85%	10 - 16%	>15 %	≥8.90 %	≥3.0

CEC: cation exchange capacity; K: potassium; Na: sodium; Ca: calcium; Mg: magnesium; SBE: sum of exchangeable bases; within a column, means followed by the same letter are not significantly different (Test of Newman-Keuls at 5%); ±S: Standard error.

Abidjan (0.28%) and Korhogo (0.02%). As for calcium, the Aboisso and Man sites registered the highest levels (62.7 and 65.5%, respectively. On the other hand, calcium content was lower at the Abidjan (4.71%) and Korhogo (0.77%) sites. Soils from the Man (15.54%) and Korhogo (15.49%) sites expressed statistically the same magnesium content. They were followed by soils from the Abidjan site (12%) and Aboisso (6.37%), which had the lowest magnesium content. Concerning chemical equilibria, the SBE values were, were significantly higher in the soils of the Man (78.21%) and Aboisso (69.79%) sites compared to those of Abidjan (17.65%) and Korhogo (16.77%). (SBE + 6.15)/N was highest in Man (150.6), followed by Aboisso (101.5). Korhogo (69.75) and Abidjan (56.66) recorded the lowest values. As regards the Mg/K ratio, the Korhogo experimental site showed the highest value (31.61), followed by Man (19.67), Abidjan (18.18) and Aboisso (17.21).

3.3. Climatic Characteristics of Experimental Sites

3.3.1. Trends in Annual Relative Humidity

Overall, Man is the most humid site, with the highest relative humidity (92.80%) in June 2020, while Korhogo is the least humid, with the lowest relative humidity (16%) in January 2020. For this site, relative humidity consistently increased after January 2020, reaching its peak (85.20%) in August 2020. Additionally, at the Aboisso and Abidjan sites, the recorded relative humidity was similar and remained practically constant throughout the cultivation period (November 2019 to October 2020). Similar to the Man site, the Aboisso and Abidjan sites experienced their highest humidity levels in June, which is the rainiest month of the year, reaching 90% and 89.1%, respectively.

3.3.2. Rainfall and Crop Seasons

Both experimental sites of Aboisso and Abidjan record two dry seasons separated by two rainy seasons. The first dry season is long, extending from November to mid-May. The second is short, running from mid-June to October. As for the Man and Korhogo sites, they are characterized by a long dry season from November to July for the former and from November to June for the latter. The period from mid-May to mid-July was the rainiest for the Aboisso and Abidjan sites. In addition, the warmest period was from July to October at the Man site and from June to October at the Korhogo site.

3.4. Chemical Characterization of Grapevine Leaves

The chemical analysis of leaves from grapevine plants cultivated at four different experimental sites (Korhogo, Man, Aboisso, and Abidjan) allowed for the characterization of five macroelements and five microelements.

3.4.1. Macroelements

The analysis of leaves from the three grapevine varieties (Muscat Rouge, Aleatico and Bequignol) reveals the presence of five macroelements: nitrogen, phosphorus, potassium, magnesium, and calcium. In all study sites, magnesium was the most abundant mineral, followed by nitrogen, potassium, and calcium. Additionally, for the Muscat Rouge, magnesium content was higher only at the Man site, while it remained consistent across the three other sites (Aboisso, Abidjan, and Korhogo). For the Aleatico, leaf nitrogen content was highest at the Aboisso site, followed by the Man, Korhogo and Abidjan sites. Regarding Bequignol plants, the nitrogen content in their leaves did not vary with the experimental site. Except for the Man site, which favored the nitrogen content of Muscat Rouge leaves, those from the Abidjan, Aboisso, and Korhogo sites exhibited consistently low levels. Potassium and calcium are also abundant in the leaves of Aleatico and Bequignol plants at the Aboisso site, followed by those in the Man, Abidjan, and Korhogo sites. On the other hand, with the exception of the Man site, the content of these minerals was lower in Muscat Rouge plants at the different study sites. However, except for the Man site, the content of these minerals was lower in the leaves of Muscat Rouge plants across the various study sites (**Table 6**)

Table 6. Macroelement composition of grapevine leaves by experimental site.

Type of macro-element	Grapevine varieties	Trace element content in leaves (%)			
		Experimental site			
		Abidjan	Aboisso	Man	Korhogo
N	Aleatico	6.61 ± 0.01^{b}	11.45 ± 0.01^{a}	9.18 ± 0.01^{b}	6.75 ± 0.01^{b}
	Bequignol	4.97 ± 0.01^{a}	5.98 ± 0.01^{a}	5.05 ± 0.01^{a}	4.88 ± 0.01^{a}
	Muscat Rouge	0.97 ± 0.01^{b}	0.57 ± 0.01^{b}	6.51 ± 0.01^{a}	1.07 ± 0.01^{b}
P	Aleatico	0.09 ± 0.00^{a}	Ni	0.17 ± 0.00^{b}	0.08± 0.00^{b}
	Bequignol	0.44 ± 0.00^{a}	Ni	0.48 ± 0.00^{a}	Ni
	Muscat Rouge	0.01 ± 0.00^{a}	Ni	Ni	Ni
K	Aleatico	4.01 ± 0.00^{b}	6.86 ± 0.00^{a}	4.58 ± 0.00^{b}	1.76 ± 0.01^{c}
	Bequignol	3.67 ± 0.00^{b}	8.84 ± 0.00^{a}	5.05 ± 0.00^{b}	1.84 ± 0.01^{c}
	Muscat Rouge	2.13 ± 0.00^{b}	1.95 ± 0.00^{b}	4.60 ± 0.00^{a}	2.42 ± 0.01^{b}
Mg	Aleatico	90.8 ± 0.01^{b}	88.29 ± 0.02^{c}	91.3 ± 0.01^{b}	95.2 ± 0.01^{a}
	Bequignol	93.5 ± 0.01^{b}	86.63 ± 0.03^{c}	81.6 ± 0.03^{d}	94.7 ± 0.01^{a}
	Muscat Rouge	20.1 ± 0.00^{c}	19.2 ± 0.01^{d}	89.2± 0.02^{a}	29.3 ± 0.00^{b}

Continued

Ca	Aleatico	2.75 ± 0.00^{b}	4.29 ± 0.00^{a}	3.71 ± 0.00^{b}	2.52 ± 0.00^{b}
	Bequignol	1.75 ± 0.01^{b}	4.03 ± 0.00^{a}	3.68 ± 0.00^{a}	2.32 ± 0.00^{b}
	Muscat Rouge	1.03 ± 0.00^{b}	0.97 ± 0.00^{b}	5.48 ± 0.00^{a}	1.05 ± 0.00^{b}

N: nitrogen; P: phosphorus; K: potassium; Mg: magnesium; Ca: calcium; Ni: not identified; on a line, means followed by the same letter are not significantly different (Test of Newman-Keuls at 5%).

3.4.2. Trace Element

The analysis of grapevine leaves cultivated in the four different experimental sites allowed the characterization of five trace elements: iron (Fe), boron (B), copper (Cu), zinc (Zn), and manganese (Mn). Except Fe, which was slightly assimilated by the grapevines on each experimental site, B, Cu, Zn, and Mn are hardly assimilated. Furthermore, B was practically absent in grapevines on all four experimental sites, except for the Aleatico plants on the Abidjan site, which assimilated a very small amount of B. As for Cu, Zn and Mn, they were present in very low concentrations in all grapevines, regardless of the experimental site (Table 7).

Table 7. Trace elements in grapevine leaves by experimental site.

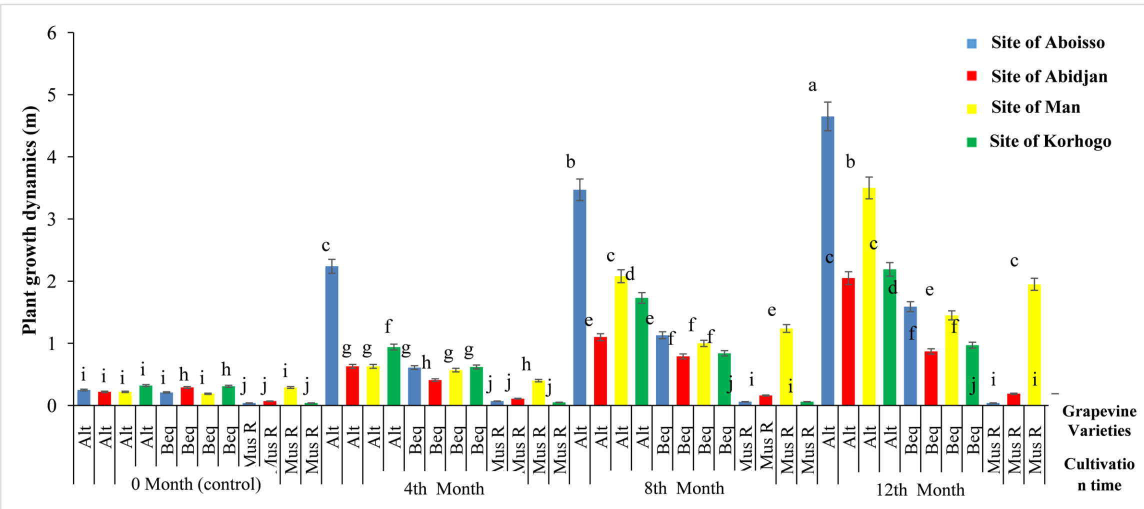
Type of trace element	Grapevine varieties	Trace element content in leaves (%)		
		Experimental site		
		Abidjan	Aboisso	Man
Fe	Aleatico	0.13 ± 0.00^{b}	0.17 ± 0.00^{a}	0.11 ± 0.00^{c}
	Bequignol	0.29 ± 0.00^{a}	0.20 ± 0.00^{b}	0.13 ± 0.00^{c}
	Muscat Rouge	0.04 ± 0.00^{b}	0.02 ± 0.00^{b}	0.25 ± 0.00^{a}
B	Aleatico	0.002 ± 0.00^{a}	Ni	Ni
	Bequignol	Ni	0.001 ± 0.00^{a}	Ni
	Muscat Rouge	Ni	Ni	Ni
Cu	Aleatico	0.004 ± 0.00^{b}	0.006 ± 0.00^{a}	0.005 ± 0.00^{b}
	Bequignol	0.002 ± 0.00^{a}	0.003 ± 0.01^{a}	0.003 ± 0.01^{a}
	Muscat Rouge	0.002 ± 0.00^{a}	0.002 ± 0.00^{a}	0.003 ± 0.01^{a}
Zn	Aleatico	0.007 ± 0.00^{b}	0.013 ± 0.01^{a}	0.007 ± 0.01^{b}
	Bequignol	0.004 ± 0.00^{b}	0.009 ± 0.01^{a}	0.007 ± 0.01^{a}
	Muscat Rouge	0.002 ± 0.00^{b}	0.003 ± 0.00^{b}	0.007 ± 0.01^{a}
Mn	Aleatico	0.034 ± 0.00^{b}	0.070 ± 0.01^{b}	0.037 ± 0.01^{b}
	Bequignol	0.035 ± 0.00^{b}	0.070 ± 0.01^{b}	0.038 ± 0.01^{b}
	Muscat Rouge	0.025 ± 0.00^{d}	0.032 ± 0.00^{b}	0.038 ± 0.01^{a}

Fe: Iron; B: Boron; Cu: Copper, Zn: Zinc; Mn: Manganese; Ni: not identified; on a line, means followed by the same letter are not significantly different (Test of Newman-Keuls at 5%); ±S: Standard error.

3.5. Influence of Growing Site on Grapevine Development Parameters

3.5.1. Plant Growth Dynamics

Figure 3 illustrates that plant growth of the three-grapevine evolved progressively on each experimental site. However, the Aleatico variety exhibited the most significant growth across all experimental sites. Moreover, after 12 months of cultivation, Aleatico reached an average height of 4.65 m compared to 1.59 m for Bequignol and 0.04 m for Muscat Rouge on the Aboisso site. For the same variety, plants were shorter at the Abidjan site than that of Aboisso. Aleatico plants reached a height of 2.05 m, followed by Bequignol (0.87 m) and Muscat Rouge (0.19 m). In comparison to the plants on the Abidjan site, those in Man exhibited a considerable increase in height. However, they are smaller than those on the Aboisso site, except for the Muscat Rouge plants. Thus, Aleatico plants expressed the greatest height (3.5 m), followed by Muscat Rouge (1.95 m) and Bequignol (1.45 m). Plants at the Korhogo experimental site have a growth dynamic in height slightly more significant than those on the Abidjan site. Conversely, the growth is less significant than that of the plants on the Man and Aboisso sites. Plants of the Aleatico grape variety recorded an average height growth of 2.19 m, while Bequignol and Muscat rouge achieved heights of just 0.97 and 0.18 m respectively.



Alt: Aleatico; Beq: Bequignol; Mus R: Muscat Rouge; Means followed by the same letter are not significantly different (Newman-Keuls test at 5%); Bars represent standard error.

Figure 3. Growth dynamics of grapevine plants grown on experimental sites versus cultivation time.

3.5.2. Plant Span

The largest plant spans were recorded at the Aboisso experimental site (Table 8). Depending on the grapevine variety, Aleatico plants exhibited the greatest span (44.40 cm); Bequignol plants had a medium span (17.31 cm), while Muscat Rouge plants showed the smallest span (5.55 cm). Plants at the Aboisso site developed more vigorous growth than those in Abidjan. Thus, Aleatico plants developed the largest span (23.97 cm), followed Bequignol plants (12.89 cm), while Muscat

Rouge plants exhibited the smallest (5.30 cm). A comparison of experimental sites shows that the Man site developed the widest span of plants, followed by the Abidjan and Korhogo sites. However, with the exception of Muscat Rouge plants (22.08 cm), showing superior growth compared to the Aboisso plot, Bequignol (16.48 cm) and Aleatico (38.07 cm) plants exhibited more vigorous growth at the Aboisso site than that of Man. Moreover, plants at the Korhogo site struggled to thrive compared to those at the Aboisso and Man experimental sites. Nevertheless, they exhibited greater growth than those in the Abidjan site. Aleatico, Bequignol and Muscat Rouge plants developed an average span of 31.47 cm, 14.42 cm and 7.53 cm respectively.

Table 8. Changes in the span of grapevine plants grown on experimental sites.

Grapevine varieties	Span of grapevine plants (cm)			
	Experimental site			
	Aboisso	Abidjan	Man	Korhogo
Aleatico	44.40 ± 18.06[a]	23.97 ± 06.89[c]	38.07 ± 05.48[b]	31.47 ± 07.28[b]
Bequignol	17.31 ± 08.40[d]	12.89 ± 03.03[e]	16.48 ± 09.98[d]	14.42 ± 07.53[de]
Muscat rouge	05.55 ± 01.31[f]	05.30 ± 01.39[f]	22.08 ± 11.78[c]	07.53 ± 02.33[f]

Means followed by the same letter are not significantly different (Newman-Keuls test at 5%); ±S: Standard error.

3.5.3. Plant Vigor

The highest vigor indices were obtained in Aleatico grapevine plants on each experimental site (Table 9). However, the Aboisso (226.11) and Man (221.50) sites allowed Aleatico plants to express the highest vigor indices, followed by Korhogo (147.87) and then Abidjan (130.98). Bequignol grapevine plants were less vigorous than Aleatico plants on all study sites. However, on the Aboisso (169.14) and Man (167.82) sites, the most vigorous grapevine plants were favored, followed by those in Korhogo (143.06) and Abidjan (114.04). As for Muscat Rouge plants, their highest vigor indices were obtained in Man (154.88), followed by Korhogo (55.38), Abidjan (51.35) and Aboisso (16.99).

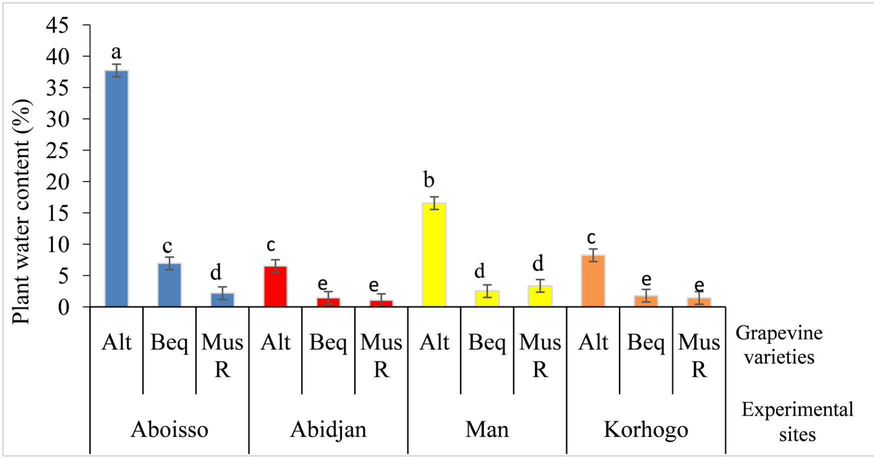
Table 9. Vigor of grapevines based on variety and growing site.

Grapevine varieties	Vigor of grapevines			
	Experimental site			
	Aboisso	Abidjan	Man	Korhogo
Aleatico	226.11 ± 66.51[a]	130.98 ± 74.19[b]	221.50 ± 68.86[a]	147.87 ± 51.16[b]
Bequignol	169.14 ± 72.30[b]	114.04 ± 88.81[b]	167.82 ± 52.09[b]	143.06 ± 19.27[b]
Muscat Rouge	16.99 ± 33.89[d]	51.35 ± 08.67[c]	154.88 ± 72.88[b]	55.38 ± 06.37[c]

Means followed by the same letter are not significantly different (Newman-Keuls test at 5%); ±S: Standard error.

3.5.4. Plant Water Content

Analysis of the results revealed that Aleatico grapevine plants exhibited a high-water content on each experimental site (**Figure 4**). However, those in the Aboisso experimental site recorded the highest water content (37.73%). Those in the Man (16.56%), Korhogo (8.25%), and Abidjan (6.53%) sites follow it. Compared with Aleatico plants, Muscat Rouge and Bequignol plants registered low water content at each experimental site. However, Bequignol plants located at the Aboisso site slightly recorded higher water content than those on the other sites.



Alt, Aleatico; Beq, Bequignol; Mus R, Muscat rouge; Means followed by the same letter are not significantly different (Newman-Keuls test at 5%); bars represent standard error.

Figure 4. Variation in the water content of plants of three grapevine varieties grown on four experimental sites.

4. Discussion

In the case of grapevines, as with many plants, morphological and physiological characteristics depend on pedoclimatic factors (terroir) that influence their growth and development [25]. The results showed that the three grapevine varieties studied (Aleatico, Bequigno and Muscat Rouge) exhibit morphophysiological behaviors that differ based on the four agro-ecological zones where the cultivation trials were implemented in Côte d'Ivoire (Korhogo, Man, Aboisso, and Abidjan). This variation in growth may be linked either to the plant itself, or to environmental conditions (especially soil and climate) that are specific to each study area [26]. The physico-chemical characteristics of the soil influence the ability of roots to absorb nutrients. Similarly, the impact of climate (light, temperature and rainfall) is crucial in the plant's mineral nutrition. All physiological functions of the plant are regulated by climatic factors [22].

According to the triangular diagram of textural classes [27], the soils studied generally exhibit a sandy-loamy or loamy-sandy texture (combined topsoil and subsoil). This indicates that the soils in different experimental sites are light, permeable, and easy to work with [28]. This type of soil allows for an acceptable level of fertility, promoting the good growth of plants. Therefore, the observed morpho-physiological variation in the sites is likely due to their silt content, which helps maintain fertility. Additionally, the acidic pH of the soil is an important factor, facilitating the release of nutrients from the soil [29]. However, mineral absorption varied between different cultivation sites and grapevine varieties. The Aboisso and Man soils released more of the necessary minerals, resulting in greater plant growth than at the other two sites. In addition, the experimental site appears to have an effect on the agro-physiological parameters of grapevine plants, influencing height and canopy size. This measurable increase over time begins with cell divisions in the meristematic zones of plants, such as the shoot and root apices. The cells resulting from divisions undergo elongation before differentiating into the characteristic tissues of the organs [30]. These mitotic activities and cell differentiation explain the elongation of stems and the size of vegetative parts in these plants. Furthermore, the growth or elongation of these organs varies from one terroir to another. If the pedoclimatic conditions of a cultivation zone are not conducive to a particular species, its organs struggle to develop [31]. Our results have shown that the Aboisso and Man sites favored the growth dynamics (height and canopy size) of different grapevine varieties in the studied sites. However, Muscat Rouge plants only thrived on the Man site. This suggests that Muscat Rouge is well adapted to the soil and climatic conditions of the Man site. In addition, our work has shown that the site has good soil fertility and the highest relative humidity. The combination of these parameters probably favored the growth of Muscat Rouge [32]. Consequently, it could be suggested that Muscat Rouge needs fertile soils and good humidity conditions to express its agronomic potential [33]. The vigorous growth of grapevines in Man site could be attributed to the high organic matter content in these two sites. Organic matter is a key factor in improving soil fertility, facilitating the release, adsorption, storage, and release of minerals for optimal plant nutrition [34]. On the other land, the low growth dynamics (plant height and span) observed at the Korhogo and Abidjan sites may be explained by their relatively low organic matter content. Indeed, Verdoodt and Van Ranst **[35]** have reported that low organic matter content can reduce soil quality and act as a limiting factor for plant growth. Among the different sites, the Aboisso site was the most favorable for vine plant growth, with the exception of Muscat Rouge, which showed the best growth on the Man site. The significant morphological growth of the three grape varieties seems to be explained by the high silt content, which is considered a fertilizer, as reported by [22]. As for the Muscat Rouge grapevines, they exhibited their best growth on the Man site, characterized by its richness in mineral elements such as potassium, sodium, and calcium. Several studies have emphasized the importance of these three minerals (potassium, sodium, and calcium) in the vegetative growth of vines [36]-[40]. The influence of terroir on the three grapevine varieties is also manifested through environmental factors such as water (rainfall), temperature, and relative humidity due to their crucial roles in various physiological processes of plants [41]. Thus, the difference in the growth of the three grape varieties' plants is attributable to climatic fluctuations existing between the four experimental sites (temperature, rainfall and humidity) [32] [42] [43]. Physiologically, Aleatico is the grapevine variety that exhibited the best vegetative growth in terms of both height and span. This significant vegetative growth might be explained by its high drought tolerance, as reported by [44]. Aleatico plants also proved to be the most robust. As for the Muscat Rouge variety, its growth was affected differently depending on the experimental site, which itself was influenced by climatic factors. Indeed, Muscat Rouge plants showed the best vegetative growth and greater vigor on the Man site. This result in the Man cultivation site could be attributed to its high relative humidity, a crucial factor for the growth and development of certain grape varieties. According to Egon [45], adequate relative humidity increases mineral absorption and reduces water loss in plants. On the other hand, on the Abidjan, Korhogo, and Aboisso sites, Muscat Rouge plants exhibited low growth dynamics with small height and spread. Compared to that of Man, the low performance of this grape variety observed in the other regions could well be linked to the very little rainfall recorded during the growing seasons, from November to April, which characterizes the dry season in these regions. This situation significantly disrupted the cutting's regrowth, delaying the vegetative growth of the plants and indicating a low robustness ratio of Muscat Rouge plants. Moreover, Zhu [46] reported that drought is the most significant limiting factor for vegetative growth and plant vigor.

For the Bequignol grapevine variety, the growth dynamics of the plants in terms of height and canopy size were significantly shortened on each experimental site, negatively affecting the vigor of the plants. According to INRA [44], Bequignol is originally a fairly vigorous grapevine variety, showing resilience in drought conditions. However, excessively high temperatures could shorten its vegetative growth and reduce its vigor as well as its survival rate. In fact, Bois and Perard **[47]** reported that, due to the generally high temperatures in tropical climates, the grapevine's vegetative season, from bud-break to harvest, is considerably reduced.

Considering the vigor of grapevine plants after 12 months of cultivation, the Aleatico grapevine variety emerged as the most robust across all experimental sites. This result could be explained by Aleatico's ease of adaptation to any type of soil [48]. Indeed, even in the nursery, the plants developed long roots, promoting good mineral and water nutrition, thus fostering strong vegetative growth. For Bequignol, the plants were less robust. The root system appeared fasciculated, allowing the development of adventitious roots that explored only the superficial layer of the soil and were also susceptible to numerous physical (during weeding) and climatic (sunshine) stresses. According to Huglin and Schneider [49], roots have small masses of cells called meristems where cell divisions and growth are active. Disturbance of these processes can lead to the malfunctioning of physiological processes, resulting in either death or weak robustness of the plants. Muscat Rouge plants showed greater robustness only at the Man site. This result could be explained by the fact that the soil at this site is biologically healthy for the flourishing of plants of this grapevine variety [50].

From a physiological standpoint, the cultivation period on different experimental sites had a significant impact on the evolution of water content in various grapevine varieties. The results of this study revealed that, across all sites, Aleatico plants exhibited the highest water content. Following the extended warm period from November to April, the rainy season concludes. This sufficient distribution of precipitation could have contributed to the increased water content of Aleatico grapevine plants. A similar pattern was observed for Bequignol plants. Indeed, several authors have highlighted the crucial role of water in plant fresh matter production [51]-[53]. During the rainy season, cryptogamic attacks are more significant, potentially hindering grapevine plants from adequately accessing water [54] [55]. However, throughout the trials, no cryptogamic diseases were formally observed on the experimental sites. This suggests that the observed differential growth of the plants may be linked to the grapevine varieties' ability to extract mineral elements from the soil. Thus, terroir appears to play a crucial role in the growth and development of the grapevine, as indicated by several studies [56] [57]. From the above, the sites of Aboisso and Man have proven to be terroirs that favored the good morpho-physiological growth of grapevine plants. Although the growth of the Aleatico and Bequignol varieties was moderate in Abidjan and Korhogo, these terroirs also seem suitable for their cultivation. The plants appear to adapt well to sandy-loamy soils [58]. Thus, for the Aleatico and Bequignol varieties, all four agroecological zones tested appear conducive to their development and cultivation. Furthermore, viticulture would appear to be dependent on both terroir and grapevine [59], as the Muscat Rouge variety was only able to thrive on the Man site. Consequently, the development of viticulture would be possible in Côte d'Ivoire with the Aleatico and Bequignol varieties. This could be an opportunity for farmers to substantially diversify their income. For this to happen, a well-established technical itinerary needs to be made available, and potential outlets identified for grape by-products, the commercial raw material.

5. Conclusion

The soil fertility of the various experimental sites contributes to the grapevine plants' good morpho-physiological growth. Indeed, the Aleatico variety exhibited excellent performance in terms of vegetative and physiological growth across all four experimental sites: Man, Aboisso, Abidjan and Korhogo. However, the best growth was observed on the Aboisso and Man sites. For the Bequignol variety, the plants showed moderate growth on each experimental site, but growth was more significant on the Aboisso and Man sites. As for the Muscat Rouge variety, its plants expressed the best morpho-physiological parameters only on the Man site. Thus, the Aboisso and Man sites represent the most favorable terroirs for the morpho-physiological growth of grapevine plants, indicating a terroir effect. However, for the Aleatico and Bequignol grape varieties, the four agro-ecological zones tested in Côte d'Ivoire are favorable to their cultivation. Viticulture in Côte d'Ivoire is therefore possible, but is dependent on terroir and grapevine variety. It would be particularly relevant to conduct an in-depth comparative study of the phenolic compound content (anthocyanins, flavonoids, tannins) in grapes from the Man and Aboisso sites, which demonstrated the best growth performance.

This approach would help identify the agroecological zone most conducive to producing grapes with high phenolic content. Additionally, the findings could guide varietal selection and optimal cultivation practices to maximize grape quality in these areas.

Conflicts of Interest

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

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