



Influence of Morphopedological Conditions on the Agronomic Characteristics of Black Pepper (*Piper nigrum* L.) in Azaguié, Guibéroua, and Niablé, Côte d'Ivoire

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The pepper plant is cultivated in tropical areas. Its fragrant, pungent berries make it a quality spice, considered the queen of spices, consumed worldwide. This study was initiated to assess the impact of morpho-pedological factors on the agronomic performance of black pepper in three localities (Azaguié, Guibéroua, Niablé) in Côte d'Ivoire. The present study, carried out in Azaguié, Guibéroua and Niablé, aimed to assess the morphopedological conditions of these localities in Côte d'Ivoire and to evaluate the agronomic parameters of pepper berries.

To this end, chemical analyses were carried out on pepper berries and soil samples taken from the 0-60 cm stratum of four (4) soil pits opened in pepper plantations in each of the three localities. The results show that the soils in the study areas are generally Ferralsols with a silty clay-sandy texture on the surface and clay at depth in Azaguié and Guibéroua. At Niablé, the texture is silty on the surface and silty-clayey at depth. The hydrodynamic properties of the soils are characterised by high useful reserves in Azaguié ($R_u = 169$ mm) compared with Guibéroua ($R_u = 139$ mm) and Niablé ($R_u = 142$ mm). Soils are strongly acidic in Guibéroua ($pH < 5$), moderately to weakly acidic in Niablé ($5.22 < pH < 5.6$) and Azaguié ($5.4 < pH < 6.5$).

Organic matter content decreases with depth, and is higher overall at Azaguié, with an average value of 1.86%, compared with 1.69% at Niablé and 1.43% at Guibéroua.

In terms of agronomic properties, the berries obtained in Azaguié had a high diameter (5.37 mm) and piperine content (6.42g/100g), while water (11.69%) and ash (3.59%) contents were low. At Guibéroua and Niablé, grain diameters (4.16 mm and 4.33 mm) and piperine (4.61 and 4.76g/100g) and ash (4.37%) contents are similar. Grain moisture content was 13.49% at Niablé and 12.47% at Guibéroua.

These values comply with black pepper quality standards. These three localities, therefore, offer conditions conducive to the production of good-quality black pepper. In conclusion, the study found that black pepper grown in three regions of Côte d'Ivoire adapts well to local soils and lower rainfall, producing berries that meet quality standards. Azaguié showed the highest piperine content, and only Niablé exceeded the moisture limit, indicating good potential for high-quality pepper production.

Keywords: Ferralsol, black pepper; morphopedological conditions; agronomic properties; Ivory Coast; agronomic potential.

1. INTRODUCTION

Black Pepper (*Piper nigrum* L.) belongs to the *Piperaceae* family, popularly known as the "king of spices". There are many other spices in the family of *Piperaceae*, among which black pepper is unique due to piperine, the principal pharmacological component. Due to the export value, black pepper is also called "Black Gold". And it is the most traded spice in the world (Visakh & Ramchandra, 2023). Pepper, scientific name *Piper nigrum* L., is a perennial plant with a woody stem, a climbing liana that can grow up to 8 to 10 m high (El-Sayed et al., 2021). This plant is cultivated in tropical areas. Its fragrant, pungent berries make it a quality spice, considered the queen of spices consumed worldwide (FIRCA, 2020). Pepper berry quality can be assessed through its piperine content (pungency) and the diameter of its seeds.

However, this quality is influenced by a number of factors, including soil parameters, climatic conditions in growing areas and terroir (John et al., 2022). Chemical characterisation of soils is fundamental for assessing their quality and proposing agricultural practices to ensure high productivity and quality of the crops. In this sense, we evaluate the chemical profile of soils from the black pepper cultivation (Ferde et al., 2021; Tran et al., 2022). The climate and physico-chemical characteristics of the soil are important for pepper cultivation. Rainfall influences soil fertility and facilitates the availability of essential nutrients for plant development and berry quality. In addition, texture and pH are determining factors influencing symbiotic actions between soil and plant (Li et al., 2022). Peppers prefer clayey or sandy-clay soils that drain easily (Diagne & Raj, 2021). pH also influences the availability of

essential nutrients such as nitrogen, phosphorus and potassium. A pH that is too acidic or too alkaline can impair the uptake of these nutrients, affecting plant health and berry quality (Diagne & Raj, 2021). Previous studies have shown that well-drained, nutrient-rich soils promote better berry development. On the other hand, sandy soils, with their often-excessive drainage, and clay soils, with their compaction, can hinder pepper tree growth and thus present specific challenges in terms of water retention and nutrient uptake (Thomas, 1996). Consequently, knowledge of the pedoclimatic factors in the experimental zones is a prerequisite in the quest for sustainable pepper production, from an agronomic, economic and environmental point of view. This study was therefore initiated to assess the impact of morpho-pedological factors on the agronomic performance of black pepper in three localities (Azaguié, Guibéroua, Niablé) in Côte d'Ivoire. The first step was to determine the morphopedological characteristics of the growing areas and the agronomic characteristics of the peppers.

2. MATERIALS AND METHODS

2.1 Study Areas

The study was conducted in the localities of Azaguié in the south, Guibéroua in the west, and Niablé in the east of Côte d'Ivoire (Fig. 1). The Azaguié site (5°39'1" N and 3°59'42" W) is located in a forest area in the Agnèby-Tiassa region in southeastern Côte d'Ivoire. The climate is hot and sunny with four seasons divided into

two rainy seasons from April to July and October to November, and two dry seasons from December to March and August to September. Rainfall in the western Agnèby watershed is 1,600 mm per year (Diomandé et al., 2018). In Azaguié, the vegetation consists of dense, semi-deciduous forest. The soil formations are dominated by Dystric Ferralsols with a sandy-clay to clay texture (Thomas, 1996). As for the experimental site in Guibéroua (6°18'43" N and 6°9'5" W), it is characterized by a humid tropical climate with two seasons, including a dry season from December to February with a maximum temperature of 27.67°C, and a rainy season from March to November with a maximum monthly rainfall of 206.9 mm. The average annual temperature ranges between 26 and 27°C. In Guibéroua, Eutric Ferralsols are found in areas with low rainfall and highly desaturated Ferralsols in areas with high rainfall (Koffi et al., 2022). The Niablé site, located at 6°44'8" N and 3°16'45" W, is situated in the Indénie-Djuablin region in eastern Côte d'Ivoire. The area is covered with dense mesophilic forests in the north and dense rainforests in the south. The climate is tropical, humid and is characterised by four seasons of unequal length (Coulibaly et al., 2024). There is a long rainy season from mid-March to mid-July, a short rainy season between September and November, a long dry season that begins in December and ends in mid-March, and finally a short dry season in August. The average annual rainfall is 1241.45 mm. The soils, developed on a peneplain, are Eutric Ferralsols on schist, mica schist, or granite (IUSS, 2014).

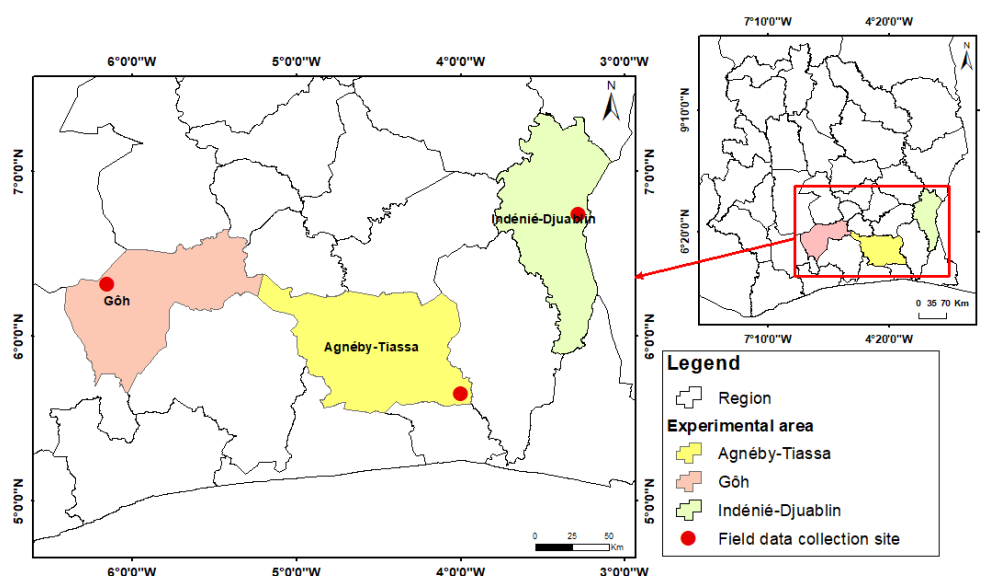


Fig. 1. Study areas

2.2 Materials

Soil science equipment: The soil material consists exclusively of Ferralsol samples taken from open soil pits in the various study areas for physical and chemical analysis. Ferralsols are highly altered soils typical of humid tropical regions. They are derived from highly weathered material on old stable geomorphological surfaces, where intense and deep weathering produces residual concentrations of resistant primary minerals, sesquioxides, and kaolinite. Their great depth, good permeability, and stable microstructure make them less susceptible to erosion than most other heavily weathered tropical soils (Mathian *et al.*, 2020). They are well-drained but can suffer from temporary drought due to their low water retention capacity. The chemical fertility of Ferralsols is low, with rare or absent alterable minerals and weak cation retention by the mineral fraction of the soil (Kirsten *et al.*, 2021). Ferralsols also have low levels of basic cations and trace elements (Koffi *et al.*, 2021).

Plant material: The plant material used consists of cultivars of black pepper (*Piper nigrum* L), Lampung and Muntok, collected from farms in the study areas. The main pepper varieties found in Ivorian pepper farms are the "Lampung" or "Kawur" type, with large leaves, long spikes, and an estimated yield of between 1,500 and 2,500 kg/hectare, and small berries, and the "Muntok" or "Bangka" variety, which has small leaves, short spikes, and large berries, with a yield of 1,200-2,000 kg/hectare (CNRA, 2016).

2.3 Methods

2.3.1 Physicochemical characterisation of soils

Soil description: Soil data collection was carried out during the dry season between November and February. The study was conducted on cultivated plots covering areas of 1 hectare in Guibéroua, 3 hectares in Niablé, and 4 hectares in Azaguié, all of which were more than seven years old. A one-hectare plot was marked out and four pits measuring 1x0.80x1.5m were dug at each site along a 270° north-facing strip. Subsequently, the soil profiles were described in situ by determining the thickness of the horizons using a tape measure, the colour using a Munsell code, the texture using the dough ball method, and the drainage class. Finally, soil samples were taken to a depth of 60 cm, in 20 cm layers

from the surface: 0-20; 20-40; 40-60 cm. For each horizon, soil samples were taken and mixed together to form a composite sample for physical and chemical analysis in the laboratory.

Determination of soil water content: The soil water supply was assessed by determining the available water supply (RU) based on the water-holding capacity (CR) and the permanent wilting point (WP). The available water reserve is the amount of water available to plants. It is the water content between the water-holding capacity and the permanent wilting point (Gubiani *et al.*, 2024). It is assessed using the following formula:

$$RU = CR - WP \quad (1)$$

With: RU (% or mm/m) = Useful reserve; CR = Field capacity; WP = Permanent wilting point.

Physical and chemical analyses: To determine the physicochemical potential of soils under pepper cultivation, composite samples weighing one kilogram each were collected from each site and then dried at room temperature (25 to 30°C) for 72 hours. The coarse elements were then separated from the fine soil using a 2 mm diameter sieve, followed by grinding to standardise and homogenise the samples. The analyses focused on determining the textural class of the soils, the pH of the water, and the content of organic carbon (Org-C), total nitrogen (Nt), available phosphorus (P-ass.), exchangeable bases (P, K, Ca, Mg), and cation exchange capacity (CEC). The pH was determined using a glass electrode in a 1/2.5 ratio, as described by Heering *et al.* (2024). The organic carbon content of the soil was determined using the Walkley and Black method as described by Bolo *et al.* (2023). Assimilable phosphorus-Bray I was determined using the method described by Rodrigo *et al.* (2024). Exchangeable bases (Ca, Mg, and K) were determined by extraction with ammonium acetate buffered at pH 7 before reading with an atomic absorption spectrometer (Ca, Mg) and flame spectrometer (K). Total nitrogen (N-total) was determined by the Kjeldahl method as described by Belhadj (2020).

Climate characteristics: The rainfall and temperature data used come from the NASA POWER platform, which acquires, processes, and archives them. These data were collected over a period of 32 years (1990-2022). The processing method used is based on statistical

processing techniques (Model Output Statistics, MOS) as developed by (Maximilian et al., 2024).

Agronomic characterisation of black pepper:

The physical and chemical quality criteria for peppercorns concerned grain diameter, moisture content, ash content, and piperine content. These criteria were determined on the basis of essential composition and quality factors as defined in the Codex Alimentarius (FAO, 2017).

2.3.2 Determination of agronomic parameters

The quality criteria for pepper were determined at the physical and chemical levels based on the quality criteria established in the Codex Alimentarius. In this study, the quality criterion used was the diameter of the grains for physical parameters. The chemical parameters of pepper were determined by assessing the moisture content, ash content, and piperine content of the peppercorns.

The diameter of the peppercorns was determined by gravimetric analysis in accordance with standard CXS 326-2017. This is a standardised method used to determine the particle size distribution of spices by measuring the distribution of particles according to their size through sieving on a series of sieves of varying sizes ranging from 0.5 cm to 9 cm. (Nikolic et al., 2021).

The determination of piperine is based on High Performance Liquid Chromatography (HPLC). This method allows the isolation, fractionation, and identification of piperine-type compounds from Piper species and the accurate quantification of piperine (Nikolic et al., 2021). Thus, 100 g of black pepper was ground into a fine powder, then piperine was extracted using ethanol as a solvent and extracted to remove impurities. The extract was then introduced into the HPLC system using a C18 reverse-phase column and a mobile phase composed of a mixture of water and methanol. Piperine was detected at a wavelength of 340-343, and for quantification, the piperine peaks were compared to a calibration curve made from piperine standards of known concentration.

The water content of peppercorns was determined using the AOAC method. Five grams of black pepper were weighed in metal crucibles

of known mass M0 using a precision balance accurate to 0.001 g. The assembly (crucible and sample) was placed in an oven at 105°C for 24 hours. The crucible was then removed and placed in a desiccator to cool (Belhadj, 2020). The dry matter content expressed as a percentage by mass was determined using equation (2). The water content (Te) was obtained by subtracting the dry matter content from the total matter content, i.e., 100%, using equation (3) (ESA, 2018).

$$MS = \frac{M2-M0}{M1} \times 100 \quad (2)$$

Where MS % = dry matter content; M0 = mass in grams of the empty crucible (g);

M1 = mass in grams of the test sample before drying (g);

M2 = mass in grams of the crucible and test sample after drying (g).

$$Te (\%) = 100 (\%) - MS (\%) \quad (3)$$

Where Te (%) = Water content

The ash content is determined by incinerating a sample of black pepper until a whitish residue is obtained. Five grams of dried pepper (P0) are placed in porcelain incineration capsules of known mass (P1). The assembly (capsule + pepper powder) is heated in a muffle furnace and then incinerated at 550°C for 12 hours. The capsules are then removed from the furnace and cooled in an AOAC Official Method of Analysis desiccator (ESA, 2018). The mass (P2) of the crucible-ash assembly is determined by weighing. The ash content (C) is obtained in g per 100 g of dry matter using the following equation 3:

$$Ash (\%) = \frac{P2-P1}{P0} \times 100 \quad (4)$$

P0 = Mass of pepper powder (g)

P1 = Mass of empty capsules (g)

P2 = Mass of crucible + ashes (g)

2.4 Statistical Analyses

The average values of the parameters (climatic, agronomic, pedological) evaluated per site were compared using a two-factor analysis of variance (ANOVA) with a significance threshold of 5% using RStudio software version 4.4.1 in order to highlight any significant differences. Thus, when a difference is observed between factors, the

least significant difference (LSD) test is performed. The correlation matrix was used to quantify the relationships between parameters based on Pearson's correlation coefficient (r).

3. RESULTS

3.1 Soil Parameters

Textural evolution of soils: The granulometric analysis of soil samples taken at Azaguié revealed significant variation in texture depending on depth. The surface layers (0-20 cm) have a high proportion of sand (53.54%), followed by clay (28.17%) and silt (18.29%), giving these horizons a Sandy-Clay-Silt texture. In the underlying horizons (20-40 cm), the proportion of sand decreases (47.41%), while the clay (30.17%) and silt (22.42%) contents increase slightly, maintaining a Sandy-Clay-Silt texture, but with a tendency towards enrichment in fine particles. In contrast, the deep horizons (40-60 cm) are characterised by a high clay content (71.19%), combined with reduced proportions of silt (11.81%) and sand (17%), thus defining a Clayey texture.

Textural analysis of Guibérroua soils reveals marked pedological differentiation depending on depth. In the surface horizons (0-20 cm), the dominant grain size fraction is sand (47.80%), followed by clay (33.65%) and silt (18.55%), resulting in a Sandy-Clay-Silt texture. In the intermediate horizons (20-40 cm), there is a significant increase in the clay fraction (41.30%), accompanied by a decrease in silt (12.50%), while the sand content remains at 46.20%, giving a Sandy-Clay texture. Finally, in the deep horizons (40-60 cm), the textural stratification reaches its maximum with a clear predominance of clay (47.53%), associated with reduced proportions of sand (31.80%) and silt (20.67%), characterising a typical clayey texture.

The granulometric analysis of Niablé soils shows a differentiated distribution according to depth: the surface horizons have a Silt texture (41.49% silt, 34.34% sand, 24.17% clay), while the intermediate and deep horizons evolve towards a Clay-Silt texture (38.80% silt/31.10% clay/29.94% sand and 35.40% clay/32.10% silt/32.5% sand, respectively), revealing a gradual increase in the clay fraction with depth (Table 1).

Chemical composition of soils: Table 2 shows that the soils in Niablé and Guibérroua are highly acidic ($4.5 < \text{pH} < 5.6$), while those in Azaguié are moderately acidic ($5.4 \leq \text{pH} \leq 6.5$). The organic matter content decreases with depth and is generally higher in Niablé ($0.72\% \leq \text{OM} \leq 3.46\%$) than in Azaguié ($1.49\% \leq \text{OM} \leq 2.12\%$) and Guibérroua ($0.70\% \leq \text{OM} \leq 2.75\%$).

The soils in the study areas consistently have very low nitrogen content ($\text{N} < 1\%$), although the surface horizons at Niablé (0.19%) and Azaguié (0.13%) show relatively higher concentrations. Ratios of $9 < \text{C/N} < 12$ indicate optimal mineralisation of organic matter at all sites. This mineralisation appears particularly high in the intermediate and deep horizons of Azaguié, the intermediate horizon of Guibérroua, and the deep horizon of Niablé.

The soil absorbent complex has a high cation exchange capacity (CEC) ($8 \text{ cmol.kg}^{-1} < \text{CEC} < 15 \text{ cmol.kg}^{-1}$) for most horizons and locations, with the exception of the surface and intermediate horizons of Azaguié and the surface horizon of Guibérroua, where the CEC is normal ($3 \text{ cmol.kg}^{-1} < \text{CEC} < 8 \text{ cmol.kg}^{-1}$). Calcium contents vary significantly, with an average ($1 \text{ cmol.kg}^{-1} \leq \text{Ca}^{2+} \leq 2.5 \text{ cmol.kg}^{-1}$) in the soils of Azaguié and Niablé, but remain particularly low ($\text{Ca}^{2+} < 0.5 \text{ cmol.kg}^{-1}$) in the deep horizons of Azaguié. With regard to potassium, only the soils of Azaguié have normal levels ($0.15 \text{ cmol.kg}^{-1} < \text{K}^+ < 0.40 \text{ cmol.kg}^{-1}$), while those in Guibérroua and Niablé show moderately low values ($\text{K}^+ > 0.1 \text{ cmol.kg}^{-1}$). Magnesium concentrations are moderately low in Azaguié and Guibérroua ($0.5 \text{ cmol.kg}^{-1} < \text{Mg}^{2+} < 1 \text{ cmol.kg}^{-1}$), but normal in Niablé ($1.76 \text{ cmol.kg}^{-1}$ on average).

Changes in the available water reserve (Ru) in the soil at the three study sites: Fig. 2 shows the seasonal variation in available water reserves (AWR) in soils under pepper cultivation in Azaguié, Guibérroua, and Niablé over the period 1990-2022 during the pepper production period (January to April). Analysis of variance (location and month) reveals significant differences ($p < 0.05$) between monthly WTR averages, but no significant variation between locations ($p = 0.089$), indicating the absence of a local effect on this hydrodynamic parameter. On the other hand, the temporal factor (month) significantly influences RU ($p < 0.05$), highlighting marked seasonal variability.

Table 1. Proportion of physical elements in different soil horizons

c	Horizon	Particle size distribution (%)			Texture
		A	(Lf+Lg)	(Sf+Sg)	
AZAGUIE	0 – 20	28.17	18.29	53.54	Sandy-Clay-Silt
	20 – 40	30.17	22.42	47.41	Sandy-Clay-Silt
	40 - 60	71.19	11.81	17	Clay
GUIBEROUA	0 – 20	33.65	18.55	47.80	Sandy-Clay-Silt
	20 – 40	41.30	12.50	46.20	Sandy-Clay
	40 - 60	47.53	20.67	31.8	Clay
NIABLE	0 – 20	24.17	41.49	34.34	Silt
	20 – 40	31.10	38.80	29.94	Clay-Silt
	40 - 60	35.40	32.10	32.5	Clay-Silt

H: Horizon; A: Clay; Lf: Fine silt; Lg: Coarse silt; Sf: Fine sand; Sg: Coarse sand

Table 2. Proportion of chemical elements in different soil horizons

Localities	Horizon	pH	Organic Matter (%)			Pass (g/Kg)	Absorbent complex (cmol/kg)			
			C	N	C/N		Ca ²⁺	Mg ²⁺	K ⁺	CEC
AZAGUIE	0 – 20	6	1.23	0.13	9.18	53	3.19	0.86	0.17	6.2
	20 – 40	5,4	1.15	0.09	12.77	39	2.17	0.52	0.19	7.90
	40 - 60	6,5	0.87	0.07	12.42	17	2.01	0.27	0.19	11.27
GUIBEROUA	0 – 20	4,5	1.60	0.14	11.42	32	1.51	0.82	0.01	7.44
	20 – 40	4,7	0.49	0.04	12.25	28	0.05	0.19	0.02	13.20
	40 - 60	5,1	0.41	0.04	10.25	31	0.06	0.17	0.02	11.36
NIABLE	0 – 20	5,5	2.01	0.19	10.57	70	2.72	1.96	0.10	11.42
	20 – 40	5,22	0.52	0.05	10.4	10	1.22	1.47	0.04	10.16
	40 - 60	5,6	0.42	0.03	14	10	1.41	1.87	0.03	10.46

%; percentage; C: Carbon; N: Nitrogen; C/N: carbon/nitrogen ratio; Pass: assimilable phosphorus; Ca²⁺; Mg²⁺; K⁺; CEC: Cation Exchange Capacity

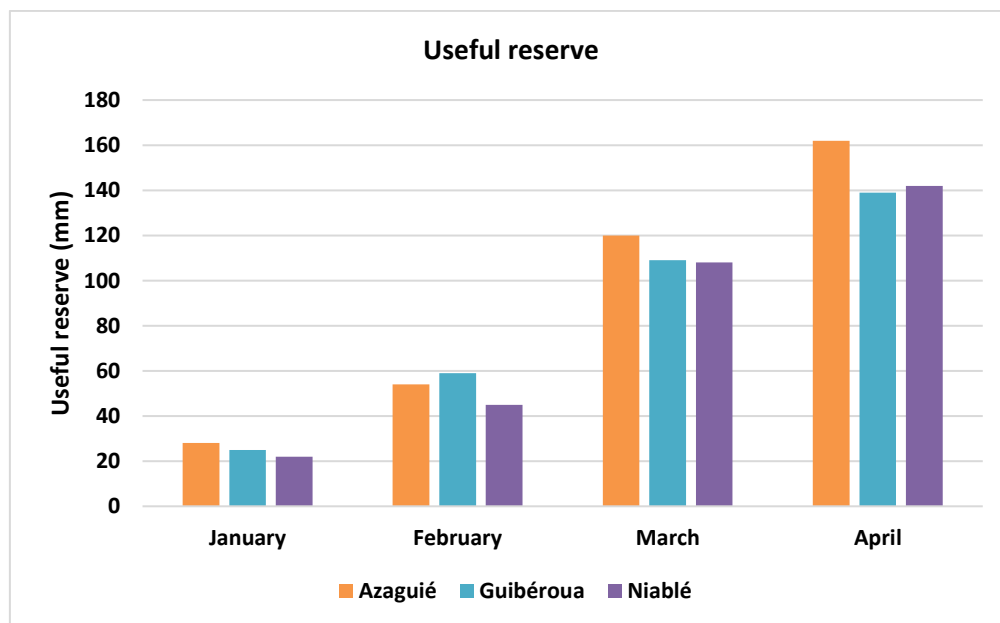


Fig. 2. Useful reserve for the localities of Azaguié, Guibéroua, and Niablé during the months of January to April

3.2 Changes in Climate Parameters

Rainfall trends: Fig. 3 illustrates the average rainfall distribution (1990-2022) for the areas studied. Average annual rainfall is 1,329.80 mm in Azaguié (maximum: 1,613.45 mm in 2015; minimum: 1,021 mm in 2002), 1,331.71 mm in Guibérroua (maximum: 1,998.62 mm in 2014; minimum: 973.64 mm in 1992) and 1331.98 mm in Niablé (maximum: 1851.04 mm in 2022; minimum: 949.23 mm in 1998). The analysis reveals that Niablé has the highest average rainfall, followed by Guibérroua and Azaguié, while the most extreme rainfall is observed in Guibérroua with an absolute maximum of

1,998.62 mm and an absolute minimum of 973.64 mm.

Temperature change: Fig. 4 shows the monthly evolution of average temperatures in the three locations studied. In Azaguié, temperatures vary between 24.86°C in July (minimum) and 29.04°C in February (maximum). The locality of Guibérroua has its maximum temperature in March (28.46°C) and its minimum in July (25.07°C). Niablé records its highest temperature in March (29.3°C) and its lowest in August (25.07°C), revealing characteristic seasonal variations for each site.

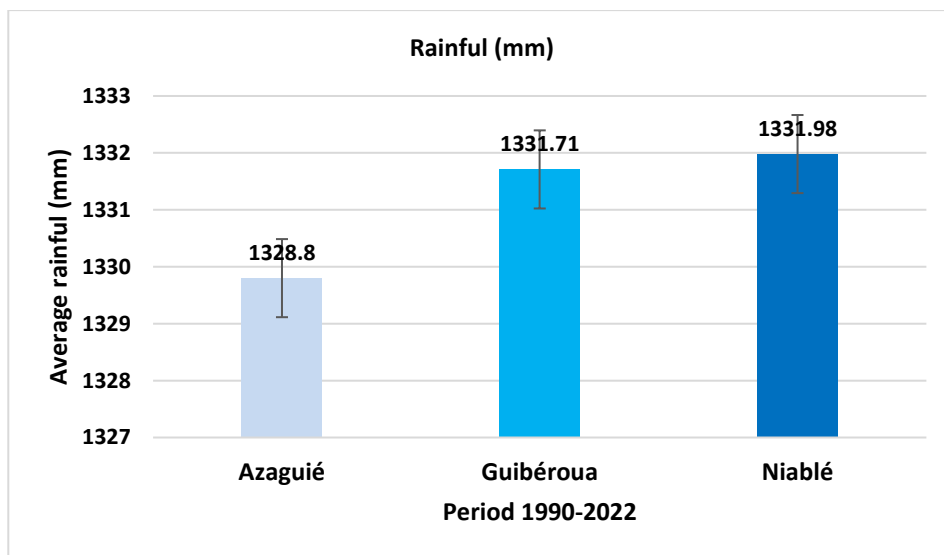


Fig. 3. Average rainfall trends in Azaguié, Guibérroua, and Niablé over the period 1990–2022

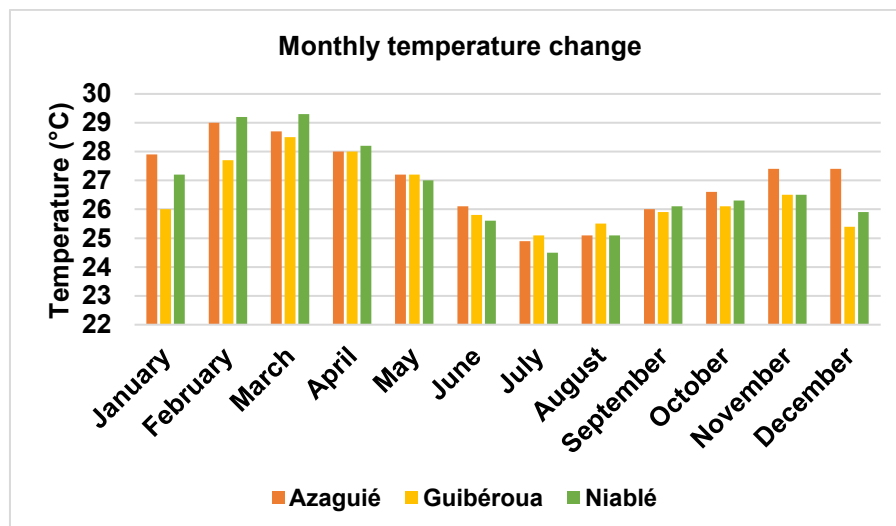


Fig. 4. Monthly changes in average temperatures over the period 1990-2022 in the localities of Azaguié, Guibérroua, and Niablé

3.3 Agronomic Parameters

Peppercorn diameter: Analysis of the diameter of black peppercorns reveals significant differences between locations (ANOVA, $p < 0.05$), with a larger average size in Azaguié (5.00 mm) compared to Guibéroua (4.16 mm) and Niablé (4.33 mm) (Fig. 5).

Water content of peppercorns: The average water content of black peppercorns is 11.69% in the Azaguié locality. In Guibéroua, the average water content of peppercorns is around 12.47%, and the water content of Niablé peppercorns is 13.49%. ANOVA reveals significant differences ($p < 0.05$) between the water contents of the three localities. These results demonstrate the

significant influence of locality on the water content of peppercorns (Fig. 6).

Piperine content of peppercorns: The variation in piperine content in peppercorns according to location is shown in Fig. 7. It can be seen that the locality of Azaguié stands out from the other localities with a significantly higher piperine content (6.42 g/100 g) compared to the localities of Guibéroua (4.61 g/100 g) and Niablé (4.76 g/100 g). Furthermore, ANOVA reveals highly significant differences ($p = 1.64 \times 10^{-13}$) between the piperine contents of the three localities, with almost zero variability between groups (0.0003), suggesting that the piperine content varies from one locality to another.

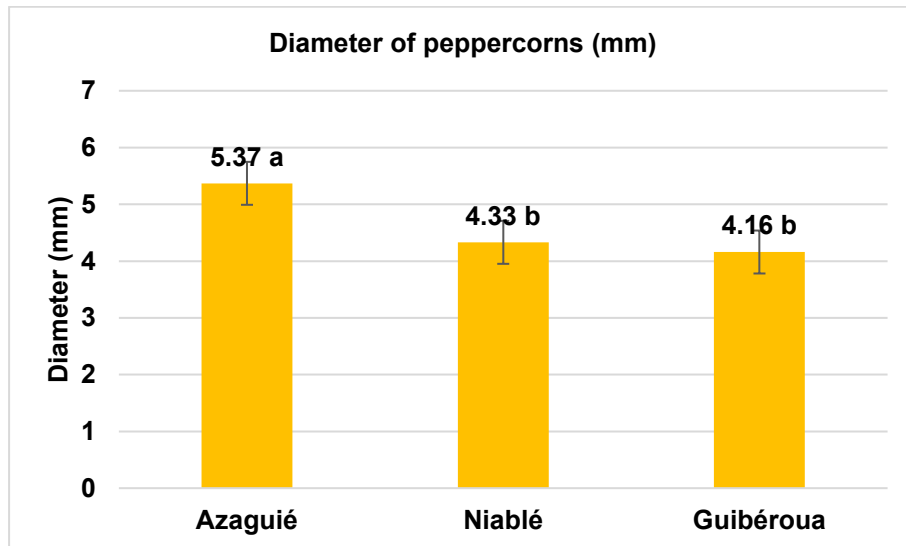


Fig. 5. Diameter of black peppercorns by site

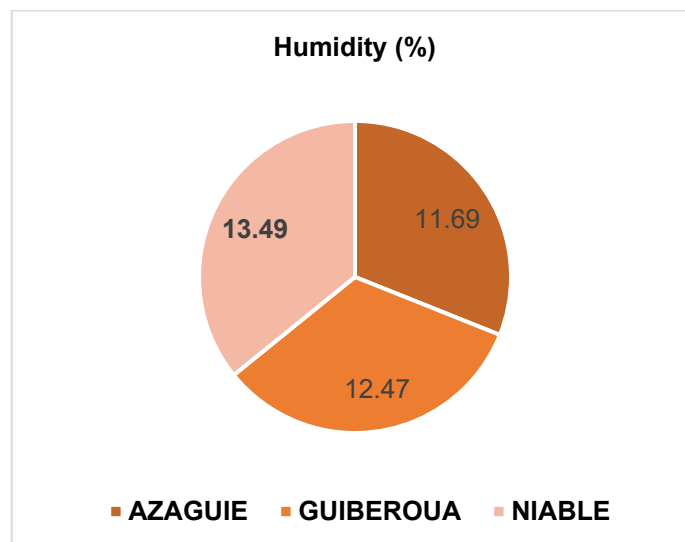


Fig. 6. Water content of peppercorns by location

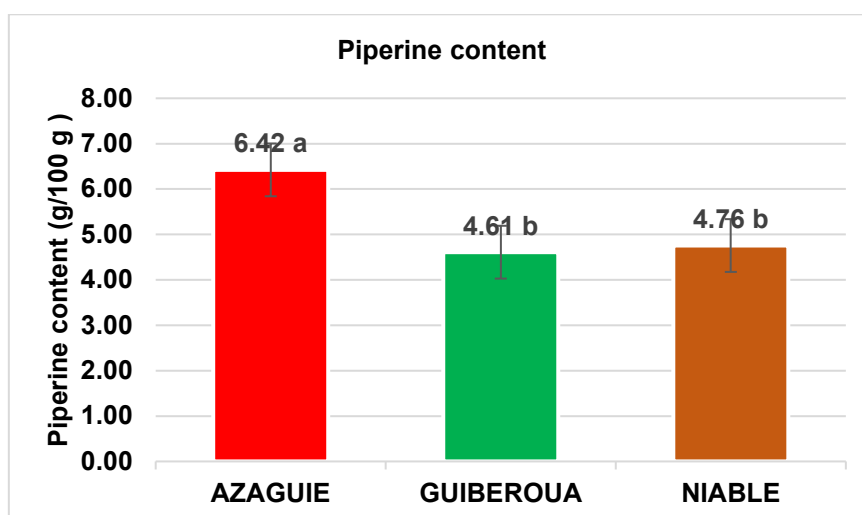


Fig. 7. Piperine content of peppercorns by site

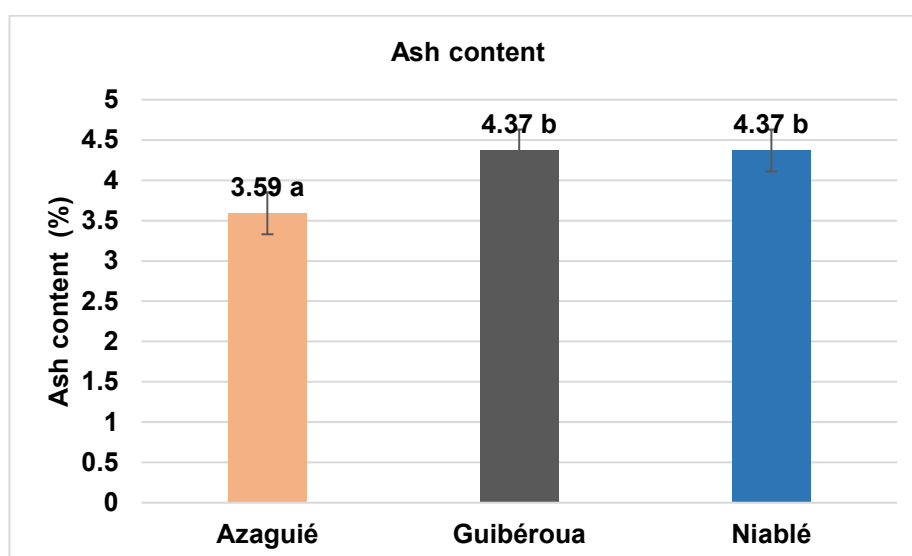


Fig. 8. Ash content of peppercorns by site

Ash content of peppercorns: Fig. 8 shows the variation in ash content of peppers according to growing area. ANOVA reveals significant differences, $p < 0.05$, in the ash content of black peppers according to their growing area. The samples from Azaguié have a significantly lower ash content (3.59%) than those from Guibéroua and Niablé (4.37% each).

Relationship between climatic parameters and physical parameters of pepper: Correlations are established between climatic and agronomic parameters. Analysis of Table 3 shows a linear relationship across different levels of correlation between variables. There is a strong positive correlation between grain

diameter and available soil water ($r=0.99$). With regard to climatic parameters, the results show that there is a strong positive correlation between rainfall and grain diameter (0.90) and a strong negative correlation between rainfall and pepper grain water content (-0.84). With regard to rainfall-available water interactions, there is a strong positive correlation between rainfall and available soil water ($r=0.92$). Temperature shows a strong positive correlation with pepper grain water content ($r=0.85$). It also shows a strong positive correlation with black pepper grain diameter ($r=0.84$). With regard to grain size, there is a strong positive correlation between grain diameter and water content ($r=0.99$).

Table 3. Correlation matrix between climatic parameters and agronomic parameters

	Peppercorns diameter	Peppercorns moisture content	Rainfall	Useful reserve	Temperature
Peppercorns diameter	1.00				
Peppercorns moisture content	0.99	1.00			
Rainfall	0.90	-0.84	1.00		
Useful reserve	0.99	-0.99	0.92	1.00	
Temperature	0.84	0.85	0.45	0.51	1.00

Table 4. Correlation matrix between soil chemical parameters and pepper

	Mg_pepper	Mg_Soil	P_pepper	P.ass	K_pepper	K_Sol	Ca_pepper	Ca_soil	Cu_pepper	Cu_Soil	Fe_pepper	Fe_Soil	Piperine
Mg_pepper	1.00												
Mg_Soil	0.62	1.00											
P_pepper	0.94	-0.61	1.00										
Pass	-0.20	0.11	0.81	1.00									
K pepper	0.91	-0.59	0.86	-0.19	1.00								
K_Sol	-0.16	0.11	-0.14	0.04	0.61	1.00							
Ca_pepper	0.90	-0.59	0.84	-0.20	0.99	-0.15	1.00						
Ca_sol	-0.22	0.12	-0.19	0.12	-0.20	0.04	0.82	1.00					
Cu_pepper	0.90	-0.59	0.85	-0.20	0.99	-0.15	0.99	-0.20	1.00				
Cu_Soil	-0.12	0.10	-0.10	0.03	-0.12	0.02	0.99	0.02	-0.19	1.00			
Fe_pepper	0.90	-0.59	0.85	0.03	0.99	-0.15	-0.12	-0.19	1.00***	-0.11	1.00		
Fe_Soil	-0.16	0.11	-0.14	0.04	-0.15	1.00***	0.99	0.04	-0.15	0.02	-0.15	1.00	
Piperine	0.90	0.86	0.85	0.91	0.99	0.51	0.99	0.92	0.99	0.61	0.99	-0.15	1.00

Effect of soil chemical parameters on pepper chemical parameters:

Various interactions are established in the analysis of Table 4, which shows that there is a strong positive correlation between the piperine content and the content of all mineral elements in black peppercorns. This can be seen by studying the various correlation factors with correlation coefficient values ($0.85 < r < 0.99$). With regard to the interactions between the chemical composition of the soil and the chemical composition of black peppercorns, there is a weak positive correlation between the magnesium content of the soil and the magnesium content of black peppercorns ($r=0.62$). The assimilable phosphorus in the soil correlates positively with the phosphorus content of pepper grains ($r=0.81$). With regard to the relationship between soil potassium and pepper grain potassium, the analysis of the table shows a weak positive correlation ($r=0.61$). There is a strong positive correlation between soil calcium and the calcium content of pepper grains, with $r=0.82$. Soil copper and iron are very weakly correlated with those in pepper, with correlation coefficients of $r=-0.19$ for copper and $r=-0.15$ for iron.

4. DISCUSSION

Physical parameters of soils: Soil analysis shows that the soils in the study areas belong to the Cambisol group, with differences in exchangeable base content. This distinction highlights distinct pedogenetic and climatic characteristics between the sites studied.

The soils of Azaguié have a silty-clay-sandy texture in the top 20 centimetres, with a clear sandy dominance on the surface.

These results are corroborated by those of Ettien *et al.* (2022), which, through a study of the agronomic potential of soils in areas of land pressure in the locality of Azaguié, identified soils of intermediate texture ranging from sandy Silt to sandy Silt-clay. In addition, the soils at the study sites are characterised by a sandy texture with a particulate structure and high porosity, which is typical of unstable soils. This results in high permeability, making them susceptible to erosion. These results corroborate those of Koffi *et al.* (2021), which have shown that a high content of coarse sand makes the soil light and permeable, and this could give it low structural stability, making it highly susceptible to physical and chemical degradation.

In Guibérroua, the soils are silty-clayey-sandy in texture on the surface (0-20 cm), sandy-clayey in the intermediate horizon (20-40 cm), and clayey at depth (40-60 cm). Similar results were obtained during the work carried out in Kotaix *et al.* (2021), which have shown that the soil formations in the region are dominated by highly desaturated ferrallitic soils with a sandy-clay to clay texture.

In the Niablé area, the soils are Silty in texture on the surface (0-20 cm) and Silty-clayey in the intermediate and deeper horizons (20-60 cm). The same is true for the work of Kotaix *et al.* (2021), which showed that the slopes of the Abengourou soils are composed of silty-clay products covering blocks of ferruginous crust. Thus, the soils in the study areas are composed of a textural variability conducive to the cultivation and good productivity of pepper, as pepper plants prefer deep soils with a texture intermediate between clayey-siliceous, siliceous-clayey, and clayey-siliceous-silty. (Andrews *et al.*, 2013, N'Guessan *et al.*, 2015).

Chemical composition of soils: Soil pH analysis reveals highly acidic soils in Guibérroua ($\text{pH} < 5$), slightly acidic soils in Azaguié ($5 \leq \text{pH} \leq 5.5$), and optimal soils in Niablé ($5.5 \leq \text{pH} \leq 6$). According to Chad & Camberato. (2019), at low pH values, many phenomena harmful to vegetative growth occur in the soil, such as decreased nitrification, phosphorus deficiency, aluminium or manganese toxicity, low mobility of organic pollutants, and high availability of certain heavy metals (Andrews *et al.*, 2013; N'Guessan *et al.*, 2015). However, pepper is a hardy plant with a high degree of adaptability. This gives it a tolerance to soil pH, to such an extent that it grows satisfactorily at pH values between 4 and 6.5. As demonstrated by Lalanirainy (2011), this adaptability is particularly evident in its ability to thrive in generally acidic soils, while tolerating very acidic conditions ($\text{pH} = 4.5-5$). This adaptability also extends to other soil characteristics. In fact, poor soil chemistry is not a major obstacle to pepper cultivation, provided that the physical conditions are adequate. As pointed out by Nair (2004), compared to other perennial crops (cocoa, coffee, oil palm), *Piper nigrum* L. is better adapted to soils with low fertility potential (Kandiannan *et al.*, 2009). This peculiarity can be explained by the fact that the physical properties of the soil (depth, texture, aeration, water retention capacity) and climatic conditions take precedence over its chemical fertility.

Among these physical requirements, drainage is a crucial factor, as pepper plants are particularly sensitive to standing water. This is why forest land (rich in humus) with a slight slope, which promotes water runoff, is generally preferred. Boulet *et al.*, 1982 In terms of minerals, pepper plants mainly require nitrogen and potassium. In summary, although the optimal pH is slightly acidic, pepper plants can adapt to very acidic soils (pH = 4.5-5) while benefiting from humus input. Its soil preferences include deep, loose, cool soils with a clay-siliceous or siliceous-clay texture and a water table located more than 2 m below the surface, hence its preference for hillsides. These observations confirm that pepper plants can adapt to a relatively wide range of soil types, provided that one absolute requirement is met: good drainage (Kandiannan *et al.*, 2009).

Climate parameters: Climate analysis of the study areas reveals average annual rainfall of between 1329 and 1332 mm, combined with temperatures ranging from 24.86°C to 29.3°C. These parameters differ from the optimal conditions described in the Guide to Good Sanitary and Phytosanitary Practices for Penja Pepper (2000-4000 mm/year of rainfall and 25-30°C all year round) (Högberg *et al.*, 2007). However, they correspond to the observations of the FIRCA (2020) considers regions with temperatures of 25-33°C and annual rainfall of 1200-2500 mm to be suitable for pepper cultivation. This discrepancy suggests that pepper is remarkably adaptable, allowing it to thrive in climatic conditions that differ from those of traditional growing areas.

Agronomic parameters: Analysis of agronomic parameters reveals pepper grain diameters ranging from 4.33 mm to 5.37 mm, mainly resulting from the well-drained soils of the study areas, which promote optimal root system development and efficient nutrient absorption. The values observed fall within the quality range defined by Belhadj (2020), which describes black pepper as a round berry approximately 4 mm in diameter. As specified by Devi & Singh. (2023), *Piper nigrum* L. thrives particularly well in well-drained, slightly acidic soils, conditions that optimise nutrient absorption and thus improve the mineral quality of the grains. These observations confirm that the diameters measured in the study areas fully meet international quality standards for pepper.

The water content of peppers from Azaguié and Guibéroua is 11.69% and 12.42% in Guibéroua.

These moisture levels comply with the standards of the International Pepper Community (IPC), which sets the maximum threshold at 13% for high-quality pepper (Srinivasan *et al.*, 2018). In contrast, in Niablé, the water content reaches 13.49%, exceeding the recommended standard of 13%. As explained by Coulibaly, the drying method significantly influences residual moisture, as demonstrated by insufficient drying, which can not only maintain excessive moisture but also promote mould growth (Coulibaly *et al.*, 2024). In addition, excessive soil irrigation promotes water absorption by plants, leading to dilution of compounds and a higher initial water content before drying.

The piperine content varies significantly between the locations studied, with a maximum observed in Azaguié (6.42). g/100 g) compared to 4.61 g/100 g in Guibéroua and 4.76 g/100 g in Niablé, all of these values falling within the standard quality range (1.7-7.4 g/100 g) for piperine content, as highlighted byDjiwonou *et al.* (2019) which have shown that for good pepper quality, the piperine content must be between 1.7 and 7.4 g/100 g. Furthermore, the high piperine content in Azaguié compared to Guibéroua and Niablé can be explained by the mineral content of the soil in these areas. Potassium stimulates the synthesis of secondary metabolites, including piperine, which is a secondary alkaloid. Phosphorus (P) promotes berry development and piperine biosynthesis. These results are corroborated by Malav *et al* (2025) who, through his study on the influence of phosphorus and zinc nutrition on wheat growth and yield, demonstrates that phosphorus plays a key role in root development, energy conversion, and various vital metabolic processes in plants, resulting in an overall improvement in crop yield (Boulet *et al.*, 1982) Finally, nitrogen promotes the vegetative growth of pepper and the production of aromatic compounds (Ravindran, 2000). Conversely, the more acidic soils of Guibéroua and Niablé limit the bioavailability of these essential nutrients, thereby reducing piperine synthesis. These results highlight the decisive influence of soil characteristics on the quality of the pepper produced.

The analysis reveals ash contents of 3.59% for Azaguié pepper compared to 4.37% for Guibéroua and Niablé pepper. These values are consistent with those observed by Coulibaly, which showed that the ash content of peppers from the Maféré region was (3.54 ± 0.01%) (Coulibaly *et al.*, 2024). They also comply with

the quality standards for black pepper as defined by the Codex Alimentarius, which sets the ash content for high-quality black pepper at between 3.5 and 7%. In addition, ESA and IPC set the maximum ash content of dried pepper at 7% (IPC, 2017; ESA, 2018). These levels are indicative of grain mineralisation. They reflect the richness of the soil in assimilable mineral elements. Low pH values could produce phenomena in the soil that are harmful to vegetative growth, such as reduced nitrification, phosphorus deficiency, aluminium or manganese toxicity, low mobility of organic pollutants, and high availability of certain heavy metals. These phenomena can hinder the growth and production of pepper plants and result in poor-quality berries (Srinivasan *et al.*, 2018).

The analysis reveals ash contents of 3.59% for Azaguié pepper compared to 4.37% for Guibéroua and Niablé pepper. These values are consistent with those observed by Coulibaly (Coulibaly *et al.*, 2024) ($3.54 \pm 0.01\%$) for Maféré pepper, thus corresponding to the maximum threshold of 7% established by the ESA and the IPC (IPC, 2017; ESA, 2018). These levels are indicative of grain mineralisation. They reflect the richness of the soil in assimilable elements, although excessively acidic pH levels may, depending on Xiao *et al.* (2023), cause harmful phenomena (decreased nitrification, phosphorus deficiency, aluminium/manganese toxicity, reduced mobility of organic pollutants, and increased availability of heavy metals) that could compromise plant growth and pepper berry quality.

5. RELATIONSHIP BETWEEN SOIL AND PEPPER

The study of the correlation between available water and berry diameter shows that available soil water does not significantly influence pepper berry diameter. Thus, when soil water content increases, pepper berry diameter decreases. This observation correlates with that of Moussa *et al.* (2023), who demonstrated in their study on the evaluation of the physical properties of fresh and dried peppercorns grown in Côte d'Ivoire that the diameter of peppercorns is influenced by their moisture content. Furthermore, the moisture content of peppercorns is influenced by temperature (Mahmood *et al.*, 2023). Furthermore, the strong positive correlation between rainfall and available soil water reserves reflects favourable climatic and soil conditions. This observation correlates with the work of

d'Ehrhardt *et al.*, (2025), which shows that the readily available water supply in the soil comes from precipitation that feeds the soil.

The strong positive correlation between piperine content and mineral elements in peppercorns reflects a symbiosis of synthetic processes within the plant. These various mineral elements contribute to the synthesis of piperine. This is the case with potassium, which is crucial in the photosynthetic processes involved in producing the sugars needed to manufacture piperine. In addition, magnesium is responsible for the formation of chlorophyll, which is essential for photosynthesis. A lack of chlorophyll could lead to an energy deficiency in the plant and limit its ability to produce secondary metabolites such as piperine (Huimin *et al.*, 2025). The correlations between the chemical content of the soil and that of the peppercorns can be explained by the fact that the plant draws the minerals it needs for nutrition from the soil (c). These observations, therefore, reflect the richness of the soil in these different locations.

6. CONCLUSION

This study characterised the agronomic parameters of pepper (*Piper nigrum* L.) in three locations in Côte d'Ivoire (Azaguié, Guibéroua, Niablé), revealing significant variations related to local soil and climate conditions. The analyses showed that the soils have textures favourable to pepper cultivation. These characteristics, combined with high CEC ($8\text{--}15\text{ cmol.kg}^{-1}$) and variable mineral content (N, P, K), directly influence the growth and quality of the berries. Although annual rainfall ($1329\text{--}1333\text{ mm}$) is lower than traditional standards ($2000\text{--}4000\text{ mm/year}$), it confirms the adaptability of pepper plants to subtropical conditions. Piperine content ($4.61\text{--}6.42\text{ g/100 g}$) complies with quality standards, with Azaguié having a higher content due to the mineral richness of the soil. The ash content ($3.59\text{--}4.37\%$) complies with the thresholds of the Codex Alimentarius ($3.5\text{--}7\%$), reflecting adequate mineralisation. The moisture content of the peppercorns below the critical threshold of 13%, except in Niablé (13.49%), is probably due to drying methods that need to be optimised. These results highlight Côte d'Ivoire's potential for producing high-quality pepper.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models

(ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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