Open Journal of Soil Science, 2023, 13, 457-473
https://www.scirp.org/journal/ojss
ISSN Online: 2162-5379
ISSN Print: 2162-5360

Effect of Organic Amendment on the Growth of *Artemisia annua* in the North of Côte d'Ivoire

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How to cite this paper: Konaré, S., Alui, K.A., Silué, S. and Soro, A. (2023) Effect of Organic Amendment on the Growth of *Artemisia annua* in the North of Côte d'Ivoire. *Open Journal of Soil Science*, **13**, 457-473.
https://doi.org/10.4236/ojss.2023.1311021

Received: September, 2023
Accepted: November 11, 2023
Published: November 14, 2023

Abstract

Malaria causes many deaths around the world, particularly in Africa, which ultimately affects the socio-economic development of African countries. The resistance of *Plasmodium falciparum* to quinine-based drugs led to new studies showing the efficiency of new artemisin-based drugs. The molecule artemisin is extracted from *Artemisia annua* a plant from China that has been used for decades in traditional Chinese medicine. The purpose of this study is to improve the production of sweet wormwood (*Artemisia annua*) using organic fertilizers in the north of Côte d'Ivoire. To do so, a morpho-pedological characterization of the study site was firstly performed to determine the soil type and their fertility level. Then, a randomized complete block system including two factors (the quantity of compost and the plant density) was implemented to test the effect of organic amendment and plant arrangement on the growth of *Artemisia annua*. Six treatments were set up: a control plot (no compost) where the plants are arranged in square (T0D1) and the plants are arranged in staggered (T0D2). Then, a treatment with compost addition of 25 t/ha where the plants are arranged in square (T1D1) and in staggered (T1D2). A treatment with compost addition of 50 t/ha where plants are arranged in square (T2D1) and in staggered (T2D2). Our results showed that the soils hosting our experimentation are Arenithic Plinthic Ferrasols with a very low level of fertility, prone to leaching and erosion. T1D2 and T2D2 treatments obtained the highest yields of 2.82 t/ha and 3.91 t/ha, respectively. Our findings indicate that a high dose of organic amendment combined with a staggered plant arrangement strongly improves the biomass production of sweet wormwood. This is in agreement with previous studies showing that the addition of organic matter can restore the level of soil fertility by increasing soil porosity and the activity of micro and macroorganisms.

Keywords

Artemisia annua, Compost, Soil Fertility, Korhogo, Côte d'Ivoire

1. Introduction

According to estimates by the World Health Organization (WHO), malaria killed nearly 429,000 people worldwide in 2015. This disease, mainly affecting African countries (approximately 90% of the 212 billion cases estimated worldwide in 2015), considerably alters their social and economic development. *Plasmodium falciparum* populations, one of the most virulent malaria pathogens (responsible for 99% of deaths), became resistant to antimalarial drugs based on quinine, chloroquine, mefloquine, or sulfadoxine-pyrimethamine in Asia and Africa [1] [2] [3] [4]. However, many studies conducted by the WHO since 2001, showed the efficiency of artemisinin-based combination therapy, a molecule extracted from an annual herbaceous Chinese plant *Artemisia annua* L., commonly known as sweet wormwood [5].

The *Artemisia annua* plant from the family of Asteraceae, has been used in traditional Chinese medicine for thousands of years to cure fevers [6] [7]. The discovery of the antimalarial properties of the extracts of this plant in the early 1970s led to the isolation of its active substance, artemisinin. This led to the development of a new class of antimalarial drugs whose combinations with other antimalarials have greatly improved chemotherapy for simple cases of malaria [8]. This molecule has demonstrated its efficacy and has virtually no side effects [5]. Unlike standard medicine, this plant has a very low toxicity and has been shown to be more efficient in the treatment of malaria. However, despite these results, the WHO does not recommend the direct uptake of *Artemisia annua* in the treatment of malaria. Because artemisinin production was not sufficient to meet the increasing global demand and its high price in China made the cure inaccessible to poor people, production chains were established in the early 2000s, first in Vietnam and then in East Africa [9]. But now it is produced in many countries, particularly in temperate (Europe, North America and North Africa) and subtropical zones [3].

Studies tend to show that the uptake of the whole plant, in the form of tea or capsules, would be more effective against malaria than artemisinin-based drugs [10] [11] [12] [13]. In Africa, faced with the reluctance of the WHO, a mobilization of researchers and organizations has been conducted to use the plant in the form of teas. Indeed, the uptake of sweet wormwood may allow poor populations to direct access to an effective and inexpensive antimalarial drug.

Artemisia annua L. grows easily in temperate climates and high altitudes in the tropics [2], but it remains difficult to grow this plant under low-altitude tropical conditions. Moreover, with the current issue of food security and sustainable agriculture, organic fertilizers are increasingly used to reduce the use of chemical substances and optimize crop production while preserving the environment. The use of fertilizers is one of the most important agronomic management decisions for farmers. The main function of organic fertilizers is to improve or restore soil fertility by stimulating soil microorganisms activity, which consequently favors the presence of nutrients essential for plant growth. In addition, organic inputs improve or maintain soil physical and biological qualities depending on the level of soil degradation. Composting is an old technique consisting of reusing organic waste in the form of humus. A regular supply of compost can play an important role in soil structural stability by contributing to the formation of stable aggregates and the clay-humic complex. The clay-humic complex is considered as a soil nutrient reservoir for crops because its negative charge attracts a high quantity of free cations (Ca^{2+}, K^+, Na^+, etc.) present in the soil solution and necessary for plant growth [14]. In addition to soil structure, compost also improves soil porosity, leading to better soil aeration and, consequently, the development of biological activity [15]. Compost also affects soil chemistry by preventing soil acidification and chemically stabilizing the soil. Taken together, the addition of compost to the soil positively modifies the physical structure, chemistry and soil biology and contains substances that can improve the resistance of plants to some pathogens [16]. Besides the type of fertilization, plant density is also an important aspect of crop management. Indeed, it strongly influences the level of competition, the resource use efficiency, and the crop system production [17]. Knowing all these effects of compost and plant density on soil fertility, the main objective is to improve the production of *Artemisia annua* using compost in the North of Côte d'Ivoire. More specifically, this study aims to 1) assess the soil characteristics of the study site, 2) assess the effects of different doses of compost and different plant density through different plant arrangements on the growth of *Artemisia annua* and 3) determine the correlation between all growth parameters of sweet wormwood.

2. Materials and Methods

2.1. Site Description

The study site is located in the department of Korhogo (between 5˚16W and 6˚16W and 8˚32N and 10˚20N) in the North of Côte d'Ivoire (**Figure 1**). The department of Korhogo has a dry tropical climate, of Sudano-Sahelian type [18] characterized by two main seasons: a long dry season (from November to April) and a long rainy season (from May to October). The mean annual temperature is 27˚C and the annual rainfall is approximately 1200 mm/year. The vegetation of Korhogo is a Sudanese vegetation type divided into two sectors (Sudanese and sub-Sudanese) depending on the duration of the dry season and the cumulative water deficit. This vegetation is mainly composed by open forests and a mosaic

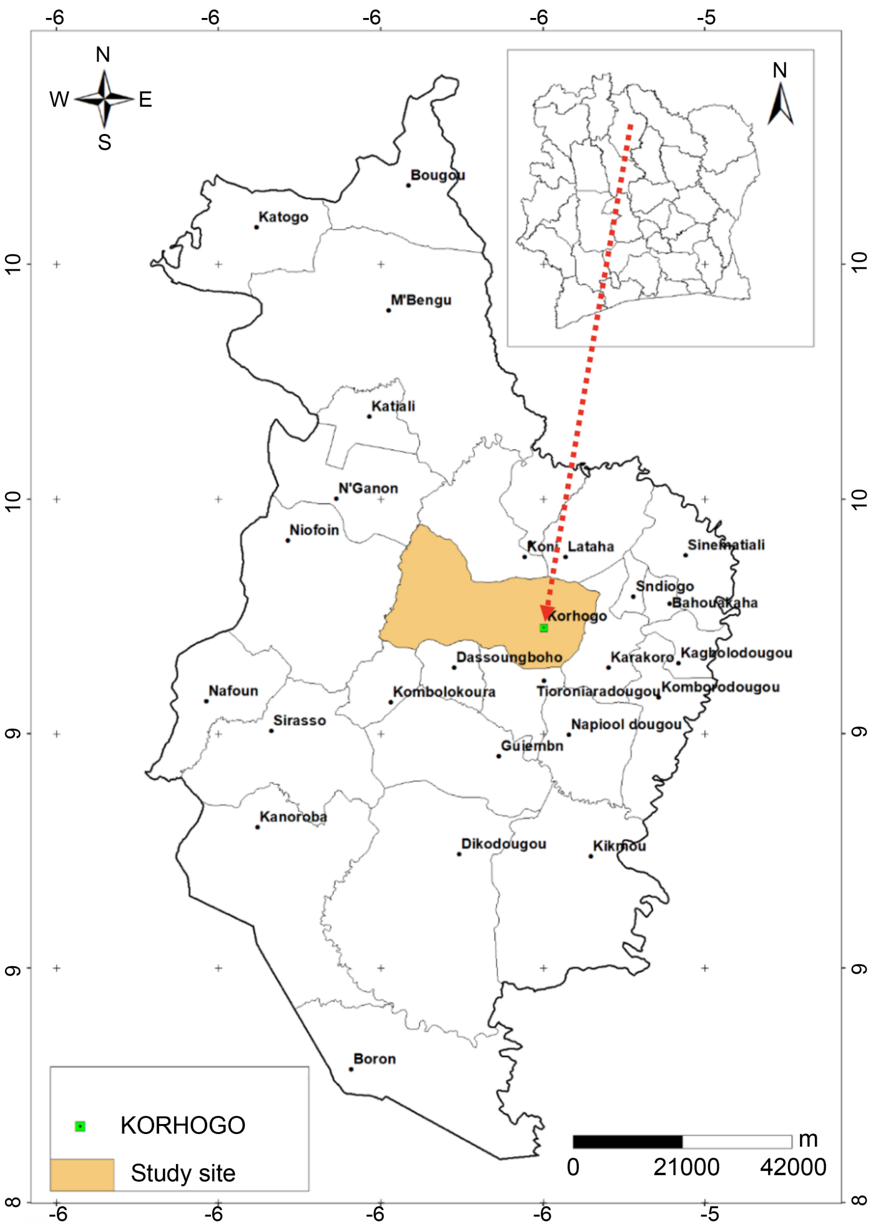

Figure 1. Location of study site.

of savannas with various tree densities. The department of Korhogo is covered by moderately and highly denatured ferralitic soils.

2.2. Composting

A series of nine pits (2 m × 1 m × 1 m) were dug for composting. The pits were placed in the shade, a few meters from a water source. The bottom of the pits was lightly watered before filling the first pit, followed by spreading a thin layer of ash. The filling began with a 20 - 30 cm thick spread of coarse plant debris. This was followed by abundant watering and tamping. Then, a second layer of material that was more easily decomposable (10 to 20 cm thick) was added. Chicken droppings and cow purse were then added. The previous steps were repeated until the pit was filled. Once filled, the pit was carefully covered with straw. After the pit was filled, the compost was regularly watered (at least 2 - 3 times a week) and turned every 30 days. All the compost that is formed in one pit is transferred to the next pit during turning. After 90 days, the mature compost is removed from the pit, dried, sieved, and used for experimentation.

2.3. Soil Morpho-Pedological Characteristics

The soil pit was opened depending on soil homogeneity or heterogeneity (flat surface or not). The open pit was 1.20 m deep, 1 m long, and 0.80 m wide. The soil profile was described using the "ORSTOM" approach [19], based on the observation of morphological features such as horizon depth or thickness, soil color, presence or absence of organic matter, soil moisture, soil texture, type and content of coarse elements, general structure and flow structure, general cohesion and aggregate cohesion, general porosity and pore size, root abundance (size and preferred orientation), drainage class determined by the observation of hydromorphic stains, transition between each horizon. Soil samples were taken from 0 - 30 cm soil depth and then constituted into composite samples for laboratory analyses. The sampling depths took into account the rooting depth of the crop.

2.4. Soil Physico-Chemical Characteristics

A fine quantity of soil was sampled before setting experimental design to carry out soil granulometric and chemical analyses including pH, macroelements (N, C, and P) according to standard methods (AFNOR NF ISO 10-390).

Total nitrogen content in the soil was determined using the Kjeldahl method according to AFNOR ISO 11-261.

2.5. Experimental Design

The experimental design used was a randomized complete block system with a total surface of 187 m^2 (17 m × 11 m) divided into four (04) blocks separated by 1 m aisles. Each block contained six treatments and each treatment was installed on 4 m^2 (2 m × 2 m) elementary plots separated from each other by 1 m aisles. The number of subplot repetitions is 4 per treatment. During this experiment, two doses of compost and two densities were tested. Plant densities are expressed as × plants/square meter. Plant density was considered through two plant arrangements, square and staggered: 9 plants/4m^2 (square arrangement) and 6 plants/4m^2 (staggered arrangement) (**Figure 2**). Square and staggered arrangements were performed at equal distances, in a straight line. The distance between each plant was taken from axis to axis (from the center of each plant). The total plant density for square and staggered plots was respectively 22,500 plants per hectare (ha) and 15,000 plants/ha. Although the spacing between and within rows was identical in the square layout, it was completely different in the staggered plot. The two factors considered here are the dose of compost (three

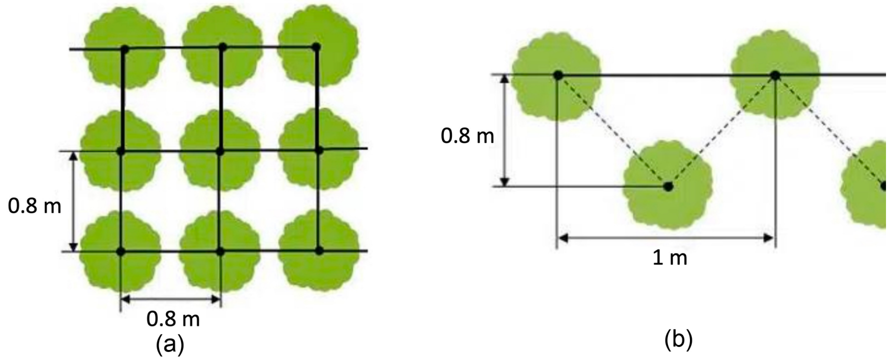

Figure 2. Schematic representation of the plant arrangement with panel a representing a square arrangement and panel b representing a staggered arrangement.

levels of modalities) and the plant density (two levels of modalities). In total, six (06) treatments were set up to test the effects of different doses of compost (T0, T1 and T2, respectively, 0, 25 and 50 t/ha) and different plant density (D1 and D2, respectively, square and staggered arrangement) on the growth of *Artemisia annua*. This leads to the following combinations: T0D1: control (no compost application) with plants arranged in square, T0D2: control with plants arranged in staggered rows, T1D1: compost application (25 t/ha) with plants arranged in square, T1D2: compost application (25 t/ha) with plants arranged in staggered, T2D1: compost application (50 t/ha) with square plant arrangement, and T2D2: application of compost (50 t/ha) with staggered plant arrangement. Biofertilizer (organic amendment) was applied to each unit using the spread technique prior to seedbed preparation. To maintain the experimental design, manual weeding was performed two weeks after sowing. The weeding sessions were repeated. No phytosanitary treatments were carried out.

2.6. Data Collection and Measurements

During this study, the average height, the number of plant branching and the crown diameter (diameter projected onto the ground) of *Artemisia annua* plants were measured. These observations were made on a few randomly selected plants from all elementary plots. The diameter was measured from the collar on the narrowest side of the stem. The fresh mass of *Artemisia annua* was taken after digging up and rinsing the plants. An electronic balance was used to determine the plant weight to obtain the average yield per elementary plot and, therefore, per treatment. All these data were collected at the end of the 90-day experiment.

2.7. Data Analysis

All analyses were performed using R software version 4.2.2 [20]. Generalized linear mixed models (GLMM) were used to evaluate the effect of different types of fertilization on the growth parameters of sweet wormwood, with the quantity of compost and the density of plants as fixed effects and block as a random effect with the glme package [21]. The Tukey procedure was used for pairwise comparisons to determine which treatments were significantly different from each other. The Pearson correlation coefficient (r) was used to study the correlation between the different parameters for each treatment. The *cor* function from stats package in R was used to calculate Pearson s coefficient between plant length, diameter and number of plant branching. We used generalized linear models to predict the relation between the yield and other plant parameters. The significance threshold for all statistical tests was set at 0.05.

3. Results

3.1. Soil Characteristics

Regarding morpho-pedological characteristics, the soil of the study site has a brown superficial horizon apparently rich in humus, sandy, loose with a lumpy structure and a good drainage (drainage class 1.3). Moreover, the surface layer is porous with many millimetric roots in a sub-horizontal orientation. The deeper pale brown horizons are characterized by good drainage (drainage class 1.5 to 2.1). They are also fresh, not very coherent, loose, apparently non-rich in humus, sandy-silty-clay and sandy-silt, pellicular grain structure with the observation of a few millimetric roots of sub-horizontal orientation. Taken together, our study site soils are Arenic Plinthic Ferralsols. They are deep, rich in humus in the surface layers, generally sandy with a high infiltration rate. The medium and deep horizons are more prone to leaching.

Regarding soil hydraulic characteristics, the Readily Available Water (RAW) represents approximately 1/3 of the Available Water Capacity (AWC) in the first 60 cm for a well-rooted crop and is equal to 110.18 mm with a high permeability coefficient (K = 218.05 mm/h), which implies a very high soil permeability (**Table 1**). All these parameters suggest that the soils investigated in this study have a low level of irrigation (**Table 1**).

Table 2 presents the results of soil physico-chemical analyses of our study site. These analyses show that the soils of our study site have predominantly clayey-sandy texture, with a sand (S) content around 46.05%. The pH values range from 5.4 to 5.9, suggesting that site soils are moderately acidic. Additionally, these soils have a low content of organic matter and total nitrogen, with respective values of 0.67% (below 2%) and 0.02%, leading to a high value of the C/N ratio (C/N = 19.50), indicating a low decomposition of soil organic matter. The soil slaking index (SI) is quite high (SI = 1.67), indicating the presence of

Table 1. Hydrodynamic properties of study site soils.

Soil type	Bulk density	Soil porosity (P)	Available Water Capacity (AWC)	Readily Available Water (RAW)	Permeability coefficient (K)	Irrigation level
Arenithic Plinthic Ferrasols	0.66	74.76%	165.28 mm	110.18 mm	218.95 mm/h	Low

Table 2. Physico-chemical characteristics of study site soils. Cl: Clay, FL: Fine silt, CL: Coarse silt, FS: Fine sand and CS: Coarse sand.

Soil type	Granulometry (%)					Acidity, nitrogen, carbon and organic matter (%)					Phosphorus ($mg \cdot kg^{-1}$)	Slacking Index	Cationic Exchange Capacity ($cmol^{+}/kg$)	Salinity ($\mu S \cdot cm^{-1}$)
	Cl	Fl	CL	FS	CS	pH	C	OM	N	C/N	P_2O_5	SI	CEC	
Arenithic Plinthic Ferrasols	17.36	17.06	19.53	25.85	20.20	5.4	0.39	0.67	0.02	19.5	41.11	1.67	4.33	0.307

slaking at this site.

Moreover, soil salinization, which is both natural (primary) and a consequence of anthropogenic processes (secondary), is one of the main land degradation processes. The salinity level of the site soils is very low (S = 0.307 $\mu S\ cm^{-1}$). The cation exchange capacity (CEC) characterizing the capacity of the soil to fix nutrients, is 4.32 $cmol^{+}/kg$, which induces a relatively low chemical fertility. The estimated saturation rate (V) is of the order of 62.73%. This implies a soil desaturation, probably due to its continuous soil exploitation.

3.2. Effect of Different Quantities of Compost and Plant Density on *Artemisia annua* Growth

The compost treatment and plant density through plant arrangements affect the growth parameters and the yield of *Artemisia annua* (**Figure 3**). The plant length is higher in treatments with compost T1D2 (113 ± 46.91 cm; $p < 0.001$), T2D1 (93.19 ± 46.66 cm; $p < 0.01$), T2D2 (100.94 ± 47.35 cm; $p = 0.00102$) than in treatments without compost T0D1 (40.31 ± 36.27 cm) and T0D2 (56.56 ± 36.91 cm) (**Table 3**). We observe the same tendencies for the plant diameter. The plant diameter is higher in treatments T1D2 (1.18 ± 0.62 cm; $p = 0.00125$), T2D1 (1.20 ± 0.65 cm; $p < 0.001$), T2D2 (1.54 ± 0.47 cm; $p < 0.001$) than in treatments without compost T0D1 (0.46 ± 0.31 cm) and T0D2 (0.77 ± 0.43 cm). There is no significant difference between the square arrangement and the staggered arrangement when no compost is added (T0D1 and T0D2) for all parameters (**Table 4**). Furthermore, when we provide compost to the soil (T1:25 t/ha), the square plant arrangement is not significantly different from the non-compost treatments (T0D1 and T0D2) for all parameters. However, we observe a significant difference between plant arrangement regarding the yield. Increasing the dose of compost increases the yield, but this effect depends on the plant arrangement. The yield is higher in the staggered arrangement T1D2 (2.82 ± 0.31 t/ha; $p = 0.00245$), T2D2 (3.91 ± 0.65 t/ha; $p < 0.001$) than in the square arrangement T1D1 (0.9 ± 0.09 t/ha), T2D1 (1.43 ± 0.28 t/ha). Treatments without compost have the lowest yields but always with a higher value in the staggered arrangement, respectively for the square arrangement T0D1 (0.31 ± 0.06 t/ha) and the staggered arrangement T0D2 (0.70 ± 0.25 t/ha). The number of plant

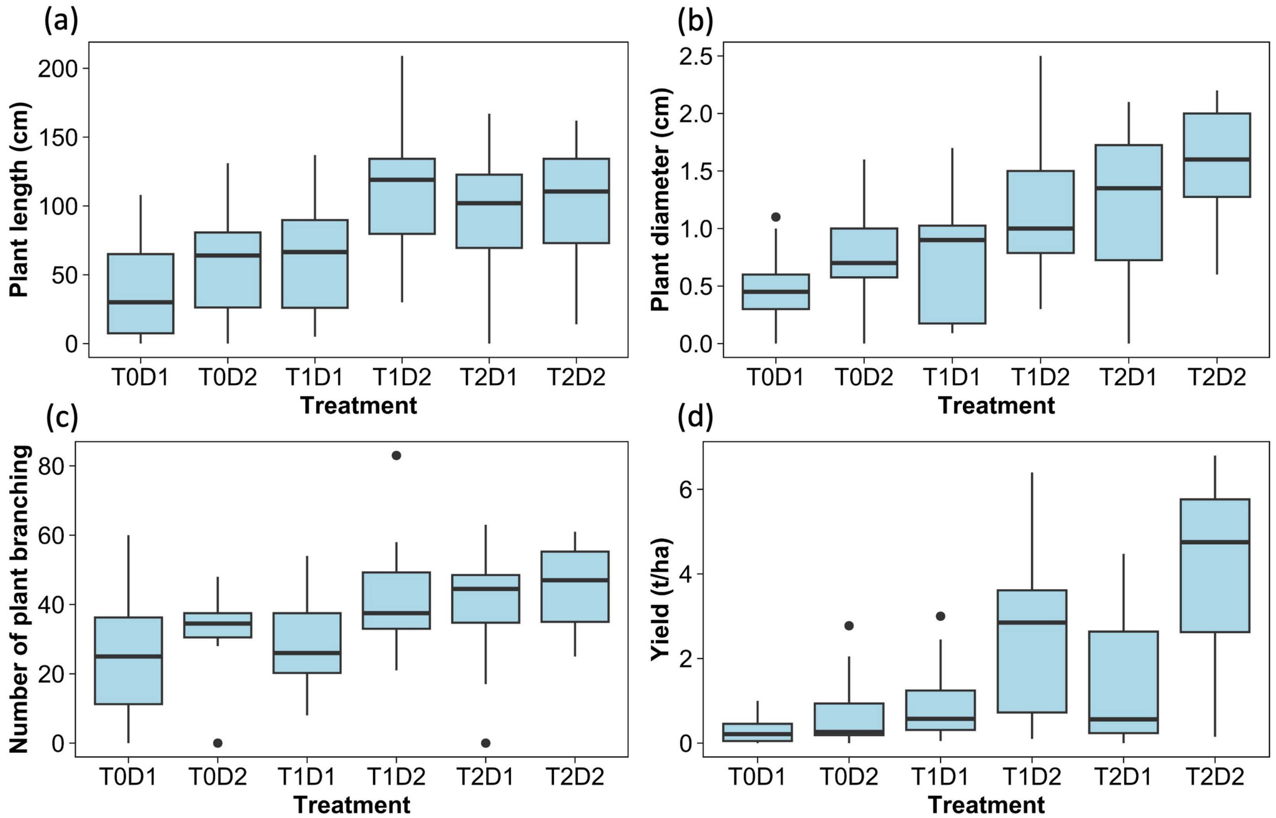

Figure 3. Plant parameters depending on fertilization treatments. Panels a, b, c and d respectively represent the plant length (cm), plant diameter (cm), number of plant branching and yield (t/ha).

Table 3. Mean values ± sd of plant characteristics depending on the fertilization treatments.

Parameters	T0D1	T0D2	T1D1	T1D2	T2D1	T2D2
Plant length (cm)	40.31 ± 36.27	56.56 ± 36.91	62.56 ± 36.80	113 ± 46.91	93.19 ± 49.66	100.94 ± 47.35
Plant diameter (cm)	0.46 ± 0.31	0.77 ± 0.43	0.77 ± 0.56	1.18 ± 0.62	1.20 ± 0.65	1.54 ± 0.47
Number of plant branching	25.31 ± 18.73	33 ± 10.23	28.69 ± 14.07	41.87 ± 14.76	39.75 ± 16.42	44.75 ± 11.80
Yield (t/ha)	0.31 ± 0.06	0.70 ± 0.25	0.9 ± 0.09	2.82 ± 0.31	1.43 ± 0.28	3.91 ± 0.65

branching is higher in compost treatments with staggered arrangement T1D2 (41.87 ± 14.76; $p = 0.017$), T2D2 (44.75 ± 11.80; $p = 0.00234$) than in the treatment without compost T0D1 (25.31 ± 18.73).

3.3. Correlation between Plant Parameters

The correlation is generally high ($r > 0.6$) between all parameters, regardless of the treatment (Table 5). Regarding T0D1 treatment (without compost and square plant arrangement), the plant length has a high correlation with diameter, the number of branching and the yield (respectively $r = 0.89$, $r = 0.81$ and $r = 0.67$). The plant diameter is strongly related to the number of plant branching

Table 4. Statistical results (GLMM) of the effect of compost dose and plant density on the growth parameters of *Artemisia annua*. All bold values represent significant differences.

Treatments	Plant length	Plant diameter	Number of plant branching	Yield
T0D2 – T0D1	0.895	0.534	0.672	0.973
T1D1 – T0D1	0.691	0.536	0.987	0.857
T1D2 – T0D1	**<0.001**	**0.001**	**0.017**	**<0.001**
T2D1 – T0D1	**0.007**	**<0.001**	0.058	0.238
T2D2 – T0D1	**0.001**	**<0.001**	**0.002**	**<0.001**
T1D1 – T0D2	0.999	1.000	0.961	0.999
T1D2 – T0D2	0.003	0.227	0.520	**<0.001**
T2D1 – T0D2	0.156	0.177	0.781	0.710
T2D2 – T0D2	**0.042**	**<0.001**	0.204	**<0.001**
T1D2 – T1D1	**0.012**	0.225	0.109	0.002
T2D1 – T1D1	0.338	0.176	0.266	0.903
T2D2 – T1D1	0.119	**<0.001**	**0.023**	**<0.001**
T2D1 – T1D2	0.786	1.000	0.998	0.074
T2D2 – T1D2	0.969	0.351	0.994	0.278
T2D2 – T2D1	0.996	0.423	0.928	**<0.001**

Table 5. Correlation between plant characteristics for each treatment.

Plant parameters	Treatments					
	T0D1	T0D2	T1D1	T1D2	T2D1	T2D2
Plant length—Plant diameter	0.89	0.76	0.73	0.93	0.68	0.43
Plant length—Number of plant branching	0.81	0.65	0.89	0.89	0.79	0.78
Plant length—Yield	0.67	0.75	0.78	0.92	0.71	0.86
Plant diameter—Number of plant branching	0.87	0.70	0.70	0.85	0.71	0.28
Plant diameter—Yield	0.71	0.71	0.55	0.90	0.41	0.45
Number of plant branching—Yield	0.69	0.43	0.61	0.76	0.52	0.73

and the yield (respectively $r = 0.87$, $r = 0.71$). The correlation between the number of plant branching and the yield is about 0.63. Regarding T0D2 treatment (without compost and staggered plant arrangement), the plant length has a high correlation with diameter, the number of branching and the yield (respectively $r = 0.76$, $r = 0.65$ and $r = 0.75$). There is also a high correlation between plant diameter and the number of plant branching (r = 0.70) and the yield (r = 0.71). The lowest correlation is observed between the number of plant branching and the yield (r = 0.43). Regarding T1D1 treatment, the plant length has a high correlation with diameter, the number of branching and the yield (respectively r = 0.73, r = 0.89 and r = 0.78). The correlation is relatively high between the plant diameter and the number of plant branching (r = 0.70) but low between plant diameter and the yield (r = 0.55). The correlation between the number of plant branching and the yield is about 0.61. There is a high correlation among all parameters for T1D2 treatment (r > 0.75). We also observe that T2D2 treatment has the highest correlation values for all combinations of parameters. The correlation is high between all parameters except between the plant diameter and the yield (r = 0.41) and between the number of plant branching and the yield (r = 0.52) for T2D1 treatment, between the plant length and the plant diameter (r = 0.43), between the plant diameter and the number of plant branching, and the yield (respectively r = 0.28 and r = 0.45) for the treatment T2D2.

3.4. Global Relation between the Yield and Other Plant Parameters

This level of correlation between each parameter is in agreement with the results of the prediction models of the yield. Indeed, a positive relationship was observed between the yield and the plant length, the plant diameter, and the number of branching (p < 0.001 and R^2 = 0.65 for the plant length; p < 0.001 and R^2 = 0.5 for the plant diameter; p < 0.001 and R^2 = 0.39 for the number of plant branching) (Figure 4). Although the yield significantly increases with all these parameters, the value of R^2 is higher for the plant length than for the plant diameter and the number of plant branching (Figure 4). The complete model including all parameters (Plant length + Plant diameter + Number of plant branching) has a higher R^2 (R^2 = 0.67) (Table 6). This shows that 67% of the yield is explained by the combination of the plant length, plant diameter and

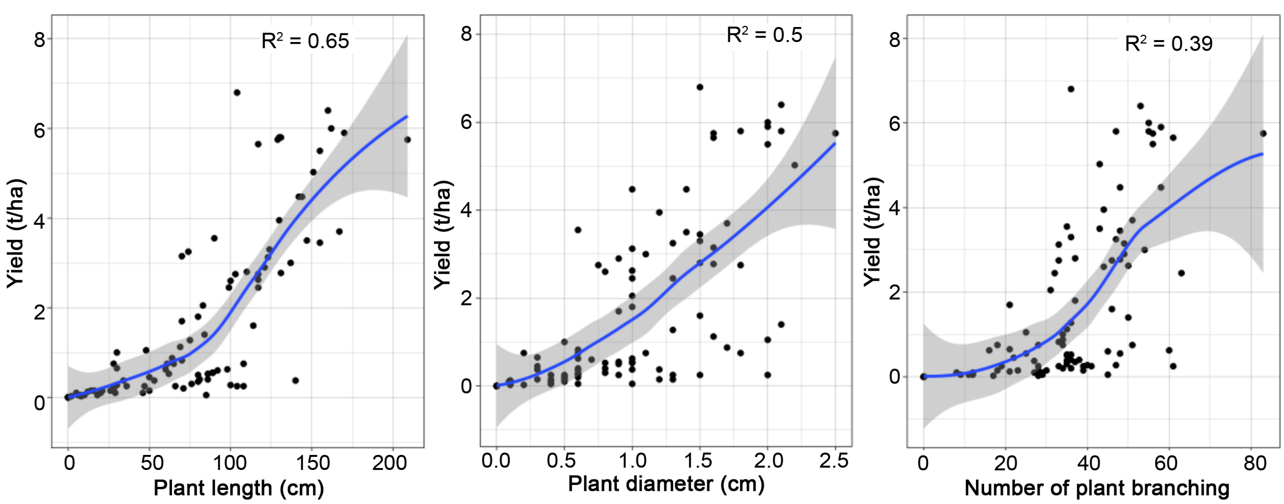

Figure 4. Relation between the yield and the plant length, plant diameter and number of plant branching.

Table 6. Squared-R and *p* values for GLM.

Predictors	R^2	p
Plant length	0.65	<0.001
Plant diameter	0.50	<0.001
Number of plant branching	0.39	<0.001
Plant length + Plant diameter + Number of plant branching	0.67	<0.001

number of plant branching while the model with only plant length explains 65% of the yield (R^2 = 0.65). Even if the complete model has a higher prediction, the plant length is considered here to be the best predictor of the yield.

4. Discussion

The analysis of morpho-pedological characteristics indicates that the soils of the study site are Arenic Plinthic Ferralsols. The results of the hydrodynamic analyses of these soils showed that these soils have a relatively high coefficient of permeability (K = 218.05 mm/h) and total porosity (*P* = 74.76%) suggesting that these soils have a very high permeability. The level of organic matter is very low, as the obtained values (0.67%) are below 2% followed by a low total nitrogen content (N = 0.02%), which subsequently leads to a high value of C/N ratio (C/N = 19.50). This low soil fertility may be due to soil degradation and low biological activity that prevents the decomposition of organic matter. This low soil fertility is in accordance with the low value of the cation exchange capacity (CEC = 4.32 $cmol^+/kg$) and shows that these soils are poor in nutrients. Consequently, all hydrodynamic, physical and physico-chemical characteristics of the Arenic Plinthic Ferralsols confirm that the soils of the study site are very degraded. This is probably due to overgrazing and continuous soil exploitation, which largely reduces plant cover and organic matter levels. This phenomenon of soil degradation is very common in the north of Côte d'Ivoire [22]. The low concentration of soil organic matter shows that these soils may not be sequestering enough CO_2. Indeed, soil degradation, particularly the low level of organic matter, contributes to the release of CO_2, and reduces soil porosity and water retention capacity. This lack of air in the soil due to low porosity decreases oxygen concentration in deeper soil layers and, consequently slows down the activity of soil microorganisms responsible of the mineralization of soil organic matter and thus the release of mineral nutrients necessary for plant growth.

Our results show that different compost doses and plant density through different plant arrangements significantly affect growth parameters and biomass production (yield) of *Artemisia annua*. Indeed, the high values of yield are observed in staggered arrangement with high amount of compost, respectively corresponding to T1D2 and T2D2 treatments. Compared to the square arrangement, the staggered arrangement enhances the yield of *Artemisia annua*.

T1D2 and T2D2 treatments achieved the highest yields of 2.82 t/ha and 3.91 t/ha respectively, while average yields were observed in treatments T1D1 and T2D1, with values of 0.9 t/ha and 1.43 t/ha respectively. The lowest yields were recorded in control treatments without compost, with values of 0.31 t/ha for T0D1 and 0.7 t/ha for T0D2. These low yields are partly due to the level of soil degradation due to leaching and soil erosion. We observe that the higher the dose of compost, the higher the yield. This shows that the response of plants to compost is dose dependent [23], as high concentrations of organic matter can significantly prevent soil nutrient leaching by improving soil capacity to retain nutrients [24]. Moreover, according to previous studies carried out at this site by [25], the low yields observed in the control treatments can be explained by the presence of aluminum oxide. Indeed, aluminum-rich soils create toxicity in plants, resulting in a decrease in plant growth due to the precipitation of aluminum phosphates in the roots and blocking of cell division in root terminal meristems and aerial buds. Besides, exchangeable aluminum strongly inhibits the activity of soil microflora and particularly prevents the development of rhizobia [26].

The increase in plant yield observed after the addition of compost (T1D2 and T2D2) shows that the addition of organic matter reduces aluminum toxicity by complexing aluminum ions within organic matter, particularly with humic and fulvic acids. This is supported by the results of [27] that showed that organic matter reduces toxicity by complexing ions, including aluminum, which improved soil fertility and the maize yield in the brown soils of the city of Toumodi (center of Côte d'Ivoire). Our results are also in agreement with those achieved by [28] on the application of organic manure to improve rice yield. Similar results were reported by [29] after using compost enriched with poultry droppings for lettuce production on a ferrallitic soil. Furthermore, compost favors the formation of clay-humic complexes, which stabilizes soil structure and, subsequently improves soil porosity and water retention capacity [30]. As a result, the soil is well aerated, less prone to compaction, leaching, and erosion by rain and watering, and stores water more easily: all these factors contribute to the soil fertility, whatever its nature. Moreover, the structural role of humus ensures a good air penetration and therefore a better oxygenation in deeper soil layers, stimulating the activity of soil macrofauna and microfauna [31]. This also enhances the penetration of roots more easily and deeper, improving their soil exploration, and their acquisition of water and nutrients. The results showed that the yields under the staggered arrangement are higher than those under the square arrangement. This suggests that the staggered arrangement reduces the level of intraspecific competition. Contrary to the staggered arrangement, the square arrangement leads to a high plant density (9 plants/4m^2) that induces high stress on the plant and increases the competition for light, water and nutrients [32] and thus decreases the yield. Moreover, to improve the production of *Artemisia annua*, smallholder farmers need visual clues indicating the state of their crop system. Our results showed that the plant length explains 65% of the yield of *Ar-*

temisia annua. The plant length plays an important role in influencing the yield and can therefore alert farmers on the performance of their crop system.

5. Conclusion

The use of fertilizer and plant density are major points to take into account in agronomic management decisions. The main objective of this study was to improve the yield of sweet wormwood (*Artemisia annua*) by assessing the effects of compost concentration and plant density through different plant arrangements on the plant growth parameters. The results showed that the soils of the study site are from the Ferralsol group. Moreover, the addition of compost increases the yield and is higher under the staggered arrangement than under the square arrangement. By enhancing the production of *Artemisia annua*, smallholder farmers with low revenue can therefore directly access to antimalarial drugs. However, because of the reluctance of the WHO to use this plant directly in tea form, studies are necessary to better control its dosage in the treatment of malaria. There is also an optimum concentration of compost that varies depending on crops. It would thus be necessary in the next studies to determine the optimal dose of compost to reach a better yield of *Artemisia annua*. Beyond the influence on the sweet wormwood yield, the use of organic fertilizers allowed reconstituting the soil fertility of the study site by improving the level of organic matter concentration, which increases soil porosity and the activity of soil micro and macroorganisms. Compared to chemical fertilizers, the use of organic fertilizers represents a sustainable way to restore the fertility of soils in the North of Côte d'Ivoire while preserving the environment. Thus, it would be interesting in future studies to repeat the experiment on other nutrient-poor soils subjected to soil erosion and continuous soil exploitation and to test the effects of compost and leguminous plants combination on soil fertility and crop production.

Conflicts of Interest

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

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