agriculture

MDPI

Article

Can Organic Amendments Improve Soil Physical Characteristics and Increase Maize Performances in Contrasting Soil Water Regimes?

Phimmasone Sisouvanh [1,*], Vidhaya Trelo-ges [1], Supat Isarangkool Na Ayutthaya [2,*], Alain Pierret [3], Naoise Nunan [4,5], Norbert Silvera [3], Khampaseuth Xayyathip [3] and Christian Hartmann [3]

[1] Department of Soil Science and Environment, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand; vidtre@kku.ac.th
[2] Department of Horticulture, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand
[3] Department of Agricultural Land Management (DALaM), Institute of Ecology and Environmental Sciences of Paris (iEES–Paris) UMR IRD 242, Ban Nongviengkham, Vientiane, Laos; alain.pierret@ird.fr (A.P.); norbert.silvera@ird.fr (N.S.); kxayyathip@gmail.com (K.X.); christian.hartmann@ird.fr (C.H.)
[4] Institute of Ecology and Environmental Sciences of Paris (iEES–Paris), Sorbonne Université, Place Jussieu, 75005 Paris, France; naoise.nunan@sorbonne-universite.fr
[5] Department of Soil and Environment, Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden
* Correspondence: p.sisouvanh@nuol.edu.la (P.S.); isupat@kku.ac.th (S.I.N.A.)

Abstract: Organic amendments are believed to help increase the soil carbon storage and therefore improve soil quality, which may be important in the context of climate change. However, the added value of organic amendments for farmers must be clearly demonstrated in order to convince them of the utility of their use. The aims of this study were: (i) to investigate the impact on maize of compost and vermicompost combined with two levels (negligible and significant) of plant water stress; and (ii) to determine how the organic amendments affected the soil's physical properties and maize productivity. Water stress levels were imposed by controlling the matric potential of soil columns in which cultivated soil characteristics was mimicked (10 cm topsoil with organic amendments, above a 50 cm subsoil without any inputs containing the majority of the roots). Plant and soil characteristics were monitored daily for 70 days. Our results show that the use of organic amendments is profitable for farmers as: (i) maize performances were increased in both moisture regimes; and (ii) the improvement was particularly striking in terms of yield. No additional benefits were measured when using vermicompost instead of compost. The data suggest that the improvement in plant characteristics did not result from increased water storage in the soils with organic amendments, but rather from better access to the water, resulting in faster root development in the macroporosity of the amended soils.

Keywords: compost; vermicompost; soil matric potential; porosity; pore size distribution; root; plant water stress

Citation: Sisouvanh, P.; Trelo-ges, V.; Isarangkool Na Ayutthaya, S.; Pierret, A.; Nunan, N.; Silvera, N.; Xayyathip, K.; Hartmann, C. Can Organic Amendments Improve Soil Physical Characteristics and Increase Maize Performances in Contrasting Soil Water Regimes?. *Agriculture* **2021**, *11*, 132. https://doi.org/10.3390/agriculture11020132

Academic Editor: Riccardo Scotti
Received: 29 December 2020
Accepted: 2 February 2021
Published: 5 February 2021

1. Introduction

During the last decade, successive scientific reports dedicated to the assessment of soils worldwide have drawn attention to their accelerated degradation [1–3]. Intensive agriculture has often been identified as a primary cause of the degradation. Although the agricultural intensification that occurred during the Green Revolution drastically increased food production, it also had a negative impact on many ecosystems, and may in the near future result in a decrease in the yield of cultivated plants [4]. This problem is increasingly recognized in political spheres, and has led to several international initiatives that aim to increase soil protection and rehabilitation: for example, the Global Soil Partnership from FAO [5,6] and the Land Degradation Neutrality of the United Nations Convention to Combat Desertification [7]. To limit the negative impact of intensive practices implemented during the Green Revolution, while maintaining food production, the adoption of practices inspired from agro-ecology is often put forward, such as management at the scale of the landscape, crop rotations reducing runoff and erosion, biological pest control, etc. [8]. Agroecology covers various concepts [9], but for the FAO, it consists of the application of ecological principles to the interactions between human beings and their environment: (i) to ensure the sustainable renewal of natural resources (water, soil, biodiversity, etc.) which are necessary for food production; and (ii) to reduce the use of non-renewable resources, e.g., the gradual elimination of the use of mineral fertilizers through the development of organic farming [10,11]. Other national and international institutions have also strongly promoted the use of organic amendments (OA) with the twin objectives of: (i) improving soil properties to maintain food production over the long term; and (ii) increasing global soil carbon stocks, in order to mitigate the effects of anthropogenic emissions of greenhouse gases [12,13]. If the implementation of such initiatives is to be widespread, the reticence that farming communities can have to the adoption of what scientists and politicians consider to be best management practices must also be accounted for. This reticence is particularly strong if farming communities do not clearly perceive short-term benefits for themselves [14–17].

In tropical regions, the problems related to soil degradation are particularly pronounced, as the soils of these regions are often less fertile, from both chemical and physical points of view [18]. Soils in this region are more depleted in mineral elements than temperate soils, but they also have a lower carbon contents, resulting in lower structural stability, lower biological activity and infiltration rates, and overall, productivity. Moreover, climate change projections for tropical regions suggest changes in rainfall regimes with an increase in the number of storm rainfall events during the dry season and an increase in the number and duration of dry periods during the rainy season, all of which can directly affect soil productivity [19–21]. Most farmers in these regions are smallholders, and their production depends directly on rainfall patterns, as their incomes are too low to cover the cost of installing and maintaining irrigation or drainage systems [22]. Consequently, for these small holders, in order to control the soil water status, it is necessary to find economically affordable and technically feasible alternatives to irrigation and drainage practices.

In this specific context, the use of OA can be attractive, with limited expenses, and the farmers can recycle some of the by-products of their activities (manure, crop residues, etc.), thereby reducing reliance on chemical inputs [23], as well as improving water management [24]. A large number of experiments have been conducted worldwide to test for the benefits of the use of a diverse range of agricultural by-products on plant productivity [25]. In China, cow or chicken manure has been shown to maintain or increase maize production relative to chemical fertilizer treatments [26,27]. In more arid zones, poultry manure applied to wheat and sorghum have also resulted in similar improvements [28]. Compared with fresh manure, compost and vermicompost can be more convenient for the farmers. Composting is an aerobic bio-oxidative process that has a thermophilic phase, during which temperatures can rise to 60 °C, associated with a significant water loss; vermicomposting is also an aerobic bio-oxidative processes, but it is done at ambient temperature by anecic earthworms [29]. In both processes, the fragmentation and decomposition induce dramatic changes to the physical and chemical properties of the original manure material. In particular, compared to manure, there is a reduced mass and volume to be transported to the field. Pathogens, parasites and weed seeds are also eliminated, and during the oxidative process, the mineral nutrients are accessible so they can be faster released into the soil solution [30]. However, the majority of experiments that have been conducted to date on the benefits provided by OA to soils and plants have not tested the interactions with different rainfall regimes. Moreover, the improvement of physical soil properties and their consequences for plant water supply were rarely considered.

The aims of this study were twofold: (i) to investigate the impact of two types of OA (compost and vermicompost) combined with two different moisture regimes (imposing negligible and significant water stress) on maize productivity; and (ii) to determine whether the OA affected the physical properties, and whether this could explain the impact on maize productivity.

2. Material and Methods

To obtain maximum control of the soil characteristics and of the water regime, our experiment was conducted on irrigated soil columns mimicking cultivated soil characteristics, i.e., a thin topsoil where inputs are added above a larger subsoil without any inputs, and in which the majority of the root system develops.

2.1. Soil Column Preparation

Approximately 1000 kg of soil was collected from an agricultural field on the campus of the Faculty of Agriculture of the National University of Laos located at Nabong (18°7′25″ N & 102° 47′34″ E, 30 km northeast of Vientiane city). The soil of this field is an acidic sandy-loam Alfisol (USDA Soil Taxonomy) with a very low carbon and nutrients content (the first 10 cm were removed to ensure that there was no organic debris present, and soil material was collected to a depth of 30 cm). The samples were collected three days after a heavy rainfall event, meaning that the water content of the soil was slightly below field capacity (FC). FC corresponds to a soil previously saturated (all pores being filled with water after a rainfall event or irrigation), in which fast downward water movements under the effect of gravity have stopped, what is generally observed after two days of drainage. The water content measured immediately after soil collection was ≈0.16 g water g^{-1} soil. The soil was then sieved (<30 mm) and kept in small plastic bags (20 kg each). The water content of all bags was controlled before sealing, and where necessary, it was adjusted to 0.16 g g^{-1}. In five randomly selected bags, around 100 g of soil was collected, mixed, dried at 105 °C for 2 days, crushed and sieved at 2 mm and analyzed according to the standard methods detailed in Pansu et al. [31]. Particle size distribution was carried out using the pipette method after organic matter destruction using H_2O_2. Soil pH was measured in 1:2.5 soil:water and KCl suspensions with a glass electrode pH meter. Organic matter was determined using the Walkley and Black's method. Total nitrogen was determined by Kjeldalh's method, while available phosphorus was extracted by Bray II method. Exchangeable potassium was determined by extraction with neutral 1N NH_4OAc. The soil main characteristics are presented Table 1.

Table 1. Main physical and physico-chemical properties of the soil used in the experiment.

Parameters	Values
Clay (g kg^{-1})	223
Silt (g kg^{-1})	306
Sand (g kg^{-1})	471
pH (H_2O)	4.16
pH (KCl)	4.09
OM (%)	0.80
Total N (%)	0.04
Available P (mg kg^{-1})	2.24
Exchangeable K (mg kg^{-1})	11.53

The columns were designed to mimic the reality of soil preparation by farmers in the field, where fertilizers and OA are applied only to the surface layer. This means that much of the root system grows without contact with the OA. Thirty soil columns were prepared using PVC tubes (20 cm internal diameter and 60 cm height). At the bottom of the columns, a 1 cm metallic mesh covered with a mosquito net was fitted to ensure that there was no soil loss whilst allowing excess water, if any, to drain out. The subsoil of all soil columns was prepared by filling them with the sieved soil at a dry bulk density of 1.30 Mg m^{-3}, i.e., a 0.392 cm^3 g^{-1} (approximately 50% porosity). This was achieved by adding 4.57 kg of the sieved soil and gently packing it to get a 10 cm-thick layer, and repeating this another four times to obtain soil columns of 50 cm in height (Figure 1).

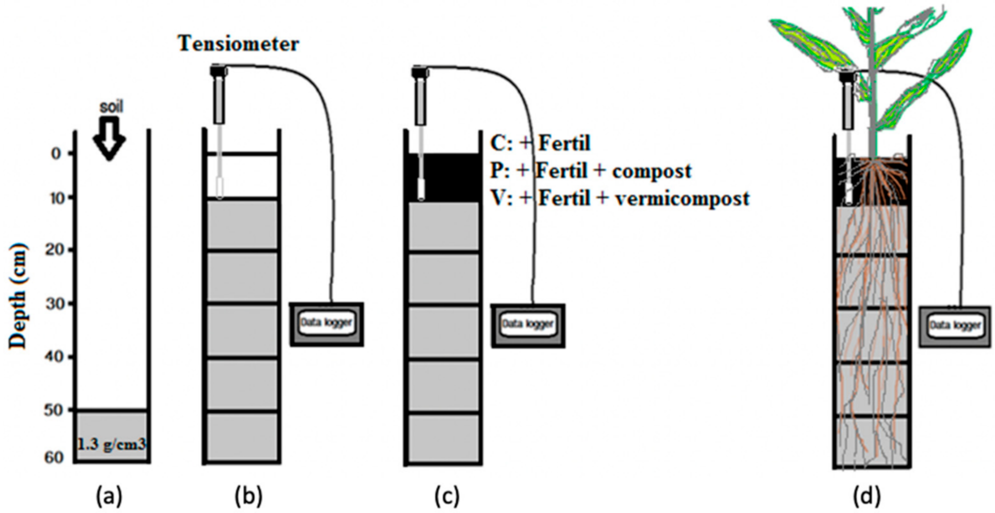

Figure 1. Preparation of soil columns: (**a**) soil was placed on the bottom of the column and gently packed to a 10 cm thick layer with a bulk density of 1.3 g cm^{-3}. (**b**) Additional layers were added in the same way and a micro-tensiometer connected to a data logger was installed before adding the top layer. (**c**) The preparation of the top layer followed the same procedure after the addition of fertilizers (C, control treatment) or fertilizers plus organic amendments (P and V, compost and vermicompost treatments, respectively). (**d**) The experiment was stopped at 71 days after planting (DAP) when the roots reached the bottom of some columns.

The topsoil (i.e., the last upper layer) consisted in 4.57 kg sieved soil at the same dry bulk density, to which one of the following was added:

- chemical fertilizers (control treatment that was unamended–C),
- chemical fertilizers + compost (compost treatment–P),
- chemical fertilizers + vermicompost (vermicompost treatment–V).

Ten columns were prepared per treatment.

The amount of chemical fertilizers followed the recommendations of the Pacific Seeds (Thai) Company Ltd., Saraburi, Thailand, i.e., 15-15-15 (N-P_2O_5-K_2O) at 2.9 g $plant^{-1}$ and 46-0-0 (N-P_2O_5-K_2O) at 2.3 g $plant^{-1}$. Micronutrients were also added and consisted in Photonic Premium plant nutrition (Merck Company, Darmstadt, Germany) containing S (13%), Fe (7.50%), Mn (8%), Cu (2.30%), Zn (4.50%), B (1.35%) & Mo (0.04%), and this was prepared at a concentration of 0.25 g L^{-1}. Lime was also applied at 7 g $plant^{-1}$. Before seedling planting, 100% of 15-15-15 and 50% of 46-0-0 fertilizer and 100% of lime were mixed to the 0–10 cm soil layer. At 21 days after planting (DAP), 50% of 46-0-0 was applied at the same time as irrigation. Every week, micronutrients were applied at 100 mL $plant^{-1}$ until flowering.

2.2. Organic Amendments Preparation

The OA, i.e., compost and vermicompost, were prepared from a similar mixture of cow dung and coconut fiber (ratio 2:1 by volume). After two weeks of pre-composting, half of the material continued the composting process for 50 days, when the other half was vermicomposted for the same period, using African Nightcrawler (*Eudrilus eugeniae* at a density of 100 g earthworms for 31 L organic amendments at 70% water). The chemical characteristics of compost (P) and vermicompost (V) were determined according to the methods presented in FCQAO [32] (Table 2).

Table 2. Main chemical properties of compost and vermicompost made from the same constituents (cow dung and coconut fiber mix in the ratio 2:1 by volume) and used in the experiment.

Parameters	Compost	Vermicompost
pH (H_2O)	7.1 ± 0.1	6.6 ± 0.3
C/N	19.6 ± 1.0	20.1 ± 1.4
Organic carbon (OC (%))	31.2 ± 1.2	29.6 ± 2.1
Total N (%)	1.60 ± 0.03	1.46 ± 0.09
Total P_2O_5 (%)	1.45 ± 0.29	1.26 ± 0.21
Total K_2O (%)	0.77 ± 0.13	0.85 ± 0.14
Total Na (%)	0.22 ± 0.06	0.20 ± 0.05
Total CaO (%)	2.62 ± 0.18	2.34 ± 0.46
Total MgO (%)	0.68 ± 0.08	0.69 ± 0.18
Total S (%)	0.16 ± 0.03	0.22 ± 0.06
EC (dS m^{-1})	2.0 ± 0.3	2.8 ± 0.6

The amount of compost or vermicompost per column was 63 g, which is equivalent to 20 t ha^{-1}, as found in several previously published experiments (for example [33,34]). At the end of the preparation, the 30 columns were installed under a shelter covered by a transparent plastic sheet.

2.3. Maize Transplanting

The maize (*Zea mays*) variety used in the experiment was the 'Pacific 999′ hybrid from Pacific Seeds Ltd. (Thailand). It is commonly used by the farmers of the region, and is adapted to a wide range of hot, dry, tropical and sub-tropical conditions, according to the information provided by the company. The seeds with the largest diameter were germinated, and after three days, the largest shoots were planted in the soil columns. Two shoots were planted per column (3 cm below the soil surface) on 30 April 2016. At five DAP, only the most vigorous seedling was kept, while the other was removed.

2.4. Control of the Soil Matric Potential by Irrigation

Our objective was to test the impact of two types of OA on maize plants under two different water regimes, thereby inducing two levels of water stress: negligible and significant water stress. Plants need to take up water from the soil to meet evaporative demand. The water movement and availability are determined by the soil matric potential Ψm (expressed in hPa or pF), which is related to the pore size (Figure S1)

$$d \approx \frac{3000}{-\Psi\mathrm{m\ (hPa)}} = \frac{3000}{10^{\Psi\mathrm{m\ (pF)}}}$$

with d the equivalent pore diameter (µm) [35]. In case of insufficient water supply, plants respond to that stress by closing their stomata, reducing their photosynthetic activity and biomass production [36].

To control the level of plant water stress in each individual column, the soil matric potential was monitored by one micro-tensiometer located 10 cm below the soil surface (tensiometer reference: SMS 2030S3, SDEC company, Reignac-sur-Indre, France). The micro-tensiometers were installed during the column preparation and consisted in a porous ceramic pipe (12 mm in diameter, 32 mm in length, reference: SDEC850) connected by a 30 cm-long flexible tube to the water reservoir located approximately 20 cm above the soil level. The ceramic was laid on the surface of the so-called 'subsoil', before the so-called 'topsoil' (the last soil layer) was added (Figure 1). At the top of the tensiometer water reservoir, an electronic sensor measuring negative pressures (air pressure sensor 26PCCFA6D Honeywell company, USA) was installed and connected to a data logger (CR1000, Campbell, UK) recording the soil matric potential (Ψm) every 10 min. After one day equilibration following their installation, all the tensiometers indicated a similar matric potential close to −200 hPa, confirming that all the columns were homogeneously prepared not only with a similar water content of 0.16 g g^{-1}, but also with similar matric potentials that were slightly above field capacity.

Our objective was to impose a negligible water stress to half of the columns and a significant stress to the other half, two levels which are generally observed in 'wet' and 'dry' soils, i.e., moisture contents below or above the field capacity. Thus, we imposed two moisture regime treatments, one in which the matric potential was maintained close to −150 hPa (pF ≈ 2.2), and another in which the matric potential was maintained close to −500 hPa (pF ≈ 2.7). They were termed the wet (W) and dry (D) treatments, respectively. In the wet treatment, pores up to 30 µm were filled with water and were regularly refilled (up to two times a day if necessary). The water located in those large pores was only slightly retained by capillary forces, thus allowing sufficiently fast water uptake (from soil to the roots and then to the shoots) to fulfill the plants' demand. In the dry treatment, however, the pores between 30 and 2 µm were emptied of water, and only the pores of <2 µm contained water. In these small pores, water movements are slow and controlled by Ψm gradients (from highest to the lowest Ψm). Thus, in wet treatment it was expected that water transfer from soil to roots would be too slow to completely fulfill plants' demand (Figure S2).

In order to facilitate seedling development, for the first eight days of the incubation, Ψm was maintained at >−150 hPa by irrigating each of the 30 soil columns with 200 mL water; irrigation was done by gently pouring irrigation water on filter paper protecting the soil surface. From the 9th DAP forwards, Ψm was checked twice daily (early morning and late afternoon) and the soils irrigated when necessary. If the threshold Ψm was reached in a column, then it was irrigated. Figure S3 presents as an example the Ψm recorded between 6 and 20 DAP for one wet (left) and dry (right) treatment. It shows a temporary Ψm increase during or immediately after irrigation, which corresponded to the drainage by gravity of the irrigation water through the largest pores, until a new equilibrium was reached at the threshold Ψm. The Ψm values, recorded in each columns during the 70 days of the experiment, are presented in Figure S4. The data logger was also connected to a meteorological station installed nearby the shelter, so that the air temperature, air relative humidity and solar radiation were recorded at the same frequency as the matric potential (Figure S5).

2.5. Plant and Soil Characteristics

During the period of plant development (until 52 DAP), the maximum height, the number of leaves and the length of each leaf (measured by hand using a ruler) of each plant were recorded every morning. The total length of a maize plant was calculated by adding the length of all existing leaves.

The experiment was stopped at 70 DAP, when we observed roots reaching the bottom of some of the columns. The plants were harvested and separated into stems, leaves, flowers and corn ears, weighed and then dried at 65 °C for 48 h and weighed again.

In each 10 cm layer (i.e., 0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm) of each column, seven undisturbed soil cylinders (100 cm^3, 5 cm height & diameter) were collected. Five of these cylinders were used to determine the root biomass (g), soil bulk density (g cm^{-3}) and specific pore volume as follows. Immediately after sampling, the cylinders were weighed, the soil inside the cylinders was fragmented and the roots it contained were collected by hand using tweezers. The roots and the soil were dried for 48 h at 65 °C and 105 °C, respectively.

The two remaining undisturbed soil cylinders were used to establish water retention curves at −10, −33, −100, −330, −1000 and −16,000 hPa (i.e., pF = 1, 1.5, 2, 2.5, 3, 3.5, 4.2). In each layer, after the cylinders were sampled, the nodal roots were taken out of the remaining soil and counted.

2.6. Statistical Analyses

Table 3 shows the six elementary treatments that correspond to two types of organic amendments plus one unamemded control crossed with two levels of water stress, and with five replicates for each elementary treatment. Data were analyzed using R Studio "R version 3.3.0" (R Core Team, 2013). ANOVA, with Tukey's post hoc test ($p \leq 0.05$), was used to compare the six treatments.

Table 3. The experimental treatments and their codes.

Water Potential	Treatments and Codes		
	Chemical Fertilizer	Chemical Fertilizer + Compost	Chemical Fertilizer + Vermicompost
$\Psi \approx -150$ hPa	Cd	Pd	Vd
$\Psi \approx -500$ hPa	Cw	Pw	Vw

3. Results

3.1. Irrigation Volumes

Figure 2 presents the average cumulative irrigation volume for each treatment. During the first eight days of the incubation, the cumulative amount of irrigation water was 1.6 L in all columns, as similar daily irrigation of 200 mL daily irrigation was applied during that period. From 9 DAP forwards, the increase in irrigation water was greater ($p < 0.05$) in wet compared to dry treatment, and in OA added compared to unamended controls. The difference in cumulative irrigation between control columns (unamended) and OA added columns started at 22 DAP for the wet treatments and 34 DAP for the dry treatment, and then this difference increased regularly until harvesting. At the end of the experiment (70 DAP), 36.7 L of irrigation water was used in the control columns of the wet treatment, and 52.4 L (+43%) and 52.7 L (+44%) in the compost and vermicompost columns of the wet treatment, respectively. The control columns of the dry treatment received an average of only 16.4 L (i.e., −55% compared to the wet control), and 23.9 and 22.9 L were added to the compost and vermicompost columns of the dry treatment, respectively, which represents +45 and +40% compared to the dry control. The organic amendments added to the topsoil increased the plant use of water by 40–45% compared to the unamended control columns in both wet and dry conditions. Furthermore, there were no significant differences in the irrigation between compost and vermicompost treatments.

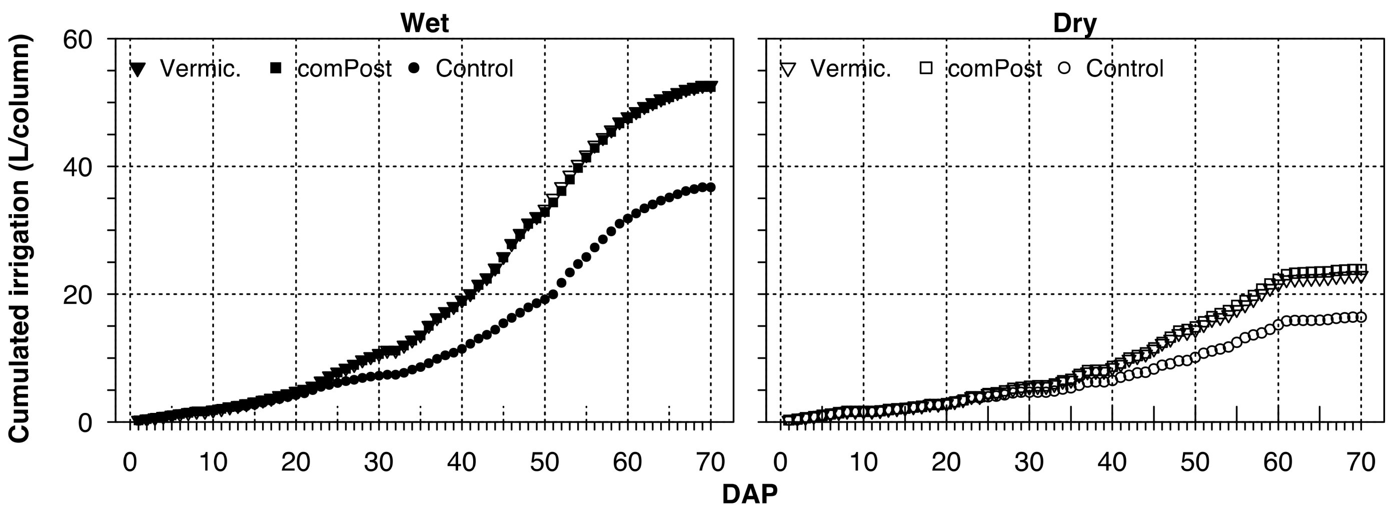

Figure 2. Cumulated amount of irrigation water (L of water per column), during all the experiment (1 to 70 DAP). Values are means ($n = 5$) and error bars represent the standard deviation, but they were not presented as they were smaller than the symbols.

3.2. Plant Development

The development of the maize plants, i.e., changes with time of average plant height, number of leaves and total leaf length, is presented in Figure 3. These three plant characteristics were greatly affected by Ψm and by the use of OA, but only slightly affected by the type of OA. Plant development was faster in the wet treatment and in the OA treatments relative to the controls.

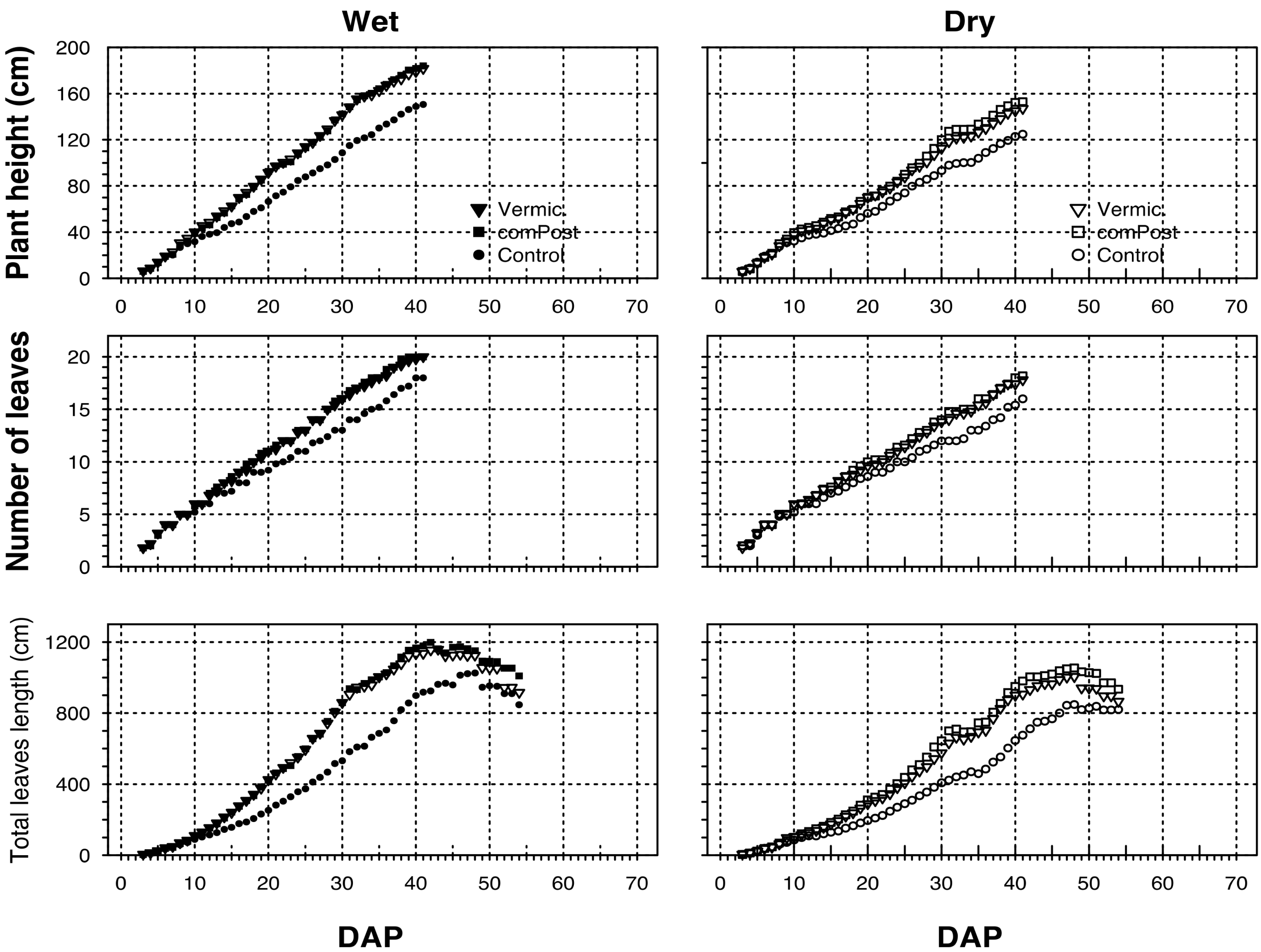

Figure 3. Daily record of the plant height (in cm, **top**), number of leaves (**middle**), total leaves length (in cm, **right**) for the wet (**left**) and dry (**right**) treatments. Values are means (n = 5), error bars represent the standard deviation, but they were not presented as they were smaller than the symbols.

Table 4 shows the days at which the different treatments became significantly different ($p \leq 0.05$) for the first time. The impact of OA on plant height was significant from 10 DAP onwards. This was the case for the number of leaves and the total leaves length from 16 DAP onwards. The impact of matric potential was observed from 16 DAP onwards. The control columns in wet and dry treatments were significantly different for all three plant characteristics. These differences remained significant, and increased with time.

At the end of the vegetative period, plant height was increased by 18–23% and the leaf number by 11–14% in the OA treatments; this difference was similar in both wet and dry treatments. However, the impact of OA addition on leaf length depended on the Ψm: in the wet conditions, this difference ranged from 18 to 23%, while it ranged from 34 to 45% in the dry treatment.

Table 4. Plant characteristics (height in cm, number of leaves, total leaves length in cm) at three periods of the monitoring (10, 16 and 41 DAP) in wet and dry treatments (i.e., columns in which matric potential maintained close to −150 and −500 hPa respectively) for the unamended control, compost and vermicompost added columns.

Plant Characteristics	DAP	Wet						Dry					
		C		P		V		C		P		V	
		av	sd	av	sd	av	sd	av	sd	av	sd	av	sd
Plant height (cm)	10	31.80	1.8 b	38.90	4.2 a	40.00	2.4 a	32.30	1.9 b	39.60	2.8 a	37.90	2.9 a
	16	48.80	2.6 b	68.90	3.7 a	69.90	5.2 a	43.20	3.3 c	53.20	3.0 b	52.10	3.0 b
	41	150.60	6.1 b	184.00	4.5 a	181.60	7.5 a	124.80	5.6 c	153.00	5.4 b	147.00	5.1 b
Number of leaves	10	5.20	0.4 b	5.80	0.4 ab	6.00	0.0 a	5.20	0.4 b	5.80	0.4 ab	6.00	0.0 a
	16	8.00	0.0 b	9.00	0 a	9.00	0.0 a	7.20	0.4 c	8.00	0.0 b	8.20	0.4 b
	41	18.00	0.0 cd	20.00	0 a	20.00	0.0 a	16.00	0.0 d	18.20	0.4 b	17.80	0.4 bc
Total leaves length (cm)	10	89.50	11.4 b	104.90	14.5 ab	110.70	10.2 a	85.50	3.0 b	100.80	13.9 ab	102.80	10.2 ab
	16	178.20	13.2 b	275.60	21.7 a	277.30	17.0 a	135.50	17.1 c	202.60	12.9 b	193.60	10.8 b
	41	917.60	37.1 bc	1178.40	31.1 a	1135.00	58.1 a	676.00	31.2 d	980.60	27.3 bc	905.80	49.1 c

DAP: day after ploughing; C: control (unamended), P: compost added; V: vermicompost add, av: average (n = 5), sd: standard deviation. In each row, letters are indicative of Tukey's post test.

3.3. Shoot and Root Biomass at Harvesting

In both wet and dry treatments, the addition of either of the composts had a dramatic effect on the shoot biomass at harvesting (70 DAP), as it was double compared to the unamended controls (Table 5). The compost had a slighter higher impact (113 and 110% increase in wet and dry columns, respectively) than the vermicompost (95 and 76% increase in wet and dry columns, respectively). The different above-ground plant organs were not similarly impacted: the differences in leaf and stem biomass between control and OA treatment were in the range of 35–70% where it was 259–301% for the corn ears. Compost provided systematically higher ($p \leq 0.05$) benefit than vermicompost, and this was especially observed for the corn ears: +350% and +260% (in wet and dry conditions, respectively). Compared to the impact of OA addition, the impact of Ψm was much lower. In the drier conditions, total biomass was decreased by 30% for the control columns and by 40% in the OA columns, while the corn ears biomass decreased by 40% for the control (from 19.0 to 10.9 g) and for the compost (85.7 to 48.1 g), and by 50% for the vermicompost (70.4 to 38.6 g).

Table 5. Dry biomass (g per plant) of the shoot (separated in flower, stem, leaves and corn ears) and root at harvesting (70 DAP), in the wet and dry treatments (i.e., columns in which matric potential maintained close to −150 and −500 hPa respectively) for the unamended control, compost and vermicompost added columns.

Biomass (g)		Wet								Dry							
		C		P			V			C		P			V		
		av	sd	av	sd	Δ (P/C)	av	sd	Δ (V/C)	av	sd	av	sd	Δ (P/C)	av	sd	Δ (V/C)
Shoot	Flowers	3.60	0.60	4.40	0.60	22%	3.90	0.9	7%	2.90	0.40	3.30	0.50	11%	3.20	1	8%
	Stem	41.90	1.4 b	64.30	7.4 a	54%	63.90	4.4 a	53%	25.10	4.0 c	42.60	4.3 b	70%	36.50	2.9 b	45%
	Leaves	32.30	1.6 c	51.90	5.4 a	61%	50.30	2.8 a	55%	24.50	3.1 d	38.90	2.5 b	59%	33.00	3.5 bc	35%
	Corn ear	19.00	4.9 c	85.70	15.8 a	351%	70.40	8.5 a	270%	10.80	3.3 c	48.10	5.4 b	347%	38.60	5.6 b	259%
	Total	96.90	5.40	206.40	27.50	113%	188.50	14.4	95%	63.30	8.40	132.90	8.70	110%	111.30	6.8	76%
Root		37.10	13.40	92.70	20.40	150%	72.20	21.4	95%	18.00	4.50	31.60	6.90	76%	24.50	1.50	36%

C: control (unamended), P: compost added; V: vermicompost add, av: average (n = 5), sd: standard deviation. Δ (P/C) and Δ (V/C) indicate the increase (in %) of the average value of the treatments (P and V, respectively) compared to the average value of the control. In each row, letters are indicative of Tukey's post hoc test with $p \leq 0.05$.

In both wet and dry treatments, the addition of either of the OA had a significant effect on the root biomass at harvesting (70 DAP), but it was much more pronounced in the wet compared to the dry conditions, and for compost than for vermicompost (Table 5). In the wet conditions, the OA increased the root biomass by 122% (37.1 and 82.0 g for control and OA added, respectively), and in the dry conditions, it was increased by 56% (18.0 and 28.0 g for control and OA added, respectively). The root biomass was increased by 126% in compost treatments (27.5 and 62.1 g in control and compost added, respectively) and by 76% in vermicompost treatments (27.5 and 48.4 g in control and vermicompost added, respectively).

3.4. Root System Distribution with Depth

No significant differences in nodal roots were observed between treatments (wet and dry, with and without OA) (Figure 4). Nodal roots only reached a depth of 30 cm in all treatments, with their number being highest in the top layer (ranging from 10–15) and decreasing with depth (ranging from 5–10 roots in the 20–30 cm layer). Fine root density in the top layer (0–10 cm) was also the same in all treatments with average values in the range of 10–15 g L^{-1}. Below the top layer, large differences were observed between wet and dry columns. In the wet controls, the root density decreased regularly with depth (from 15 g L^{-1} in the 10–20 cm layer to less than 1 g L^{-1} at the bottom of the column). In the wet OA treatments, however, the root density was in the range 15–20 g L^{-1} in all layers down to 40–50 cm depth. It is only in the deepest layer that roots in the compost amended columns were almost absent. The vermicompost treated columns, however, still had a root density of 15 g L^{-1} (the huge standard deviations indicates a large dispersion between the five columns, with some of them containing no roots in that layer when others still contained a large amount).

In the dry columns maintained at $\Psi m < -500$ hPa, no significant difference was observed between the control and the treated columns. The root density decreased regularly with depth similarly for control (unamended) and OA added columns; at the bottom of all the columns, the roots were nearly absent.

3.5. Soil Physical Characteristics

Table 6 presents the water retention for the top layer (0–10 cm) at the onset of the experiment, in the control and OA treatments (compost and vermicompost) at different Ψm ranging from −10 hPa to −1.4 MPa (from pF = 1 to 4.2). After compost addition, the water retention increased at all matric potentials, and the increase was the largest at high matric potential (close to 0). At $\Psi m = -10$ hPa (pF = 1), the increase was 35–37%, when it was only 19% at $\Psi m = -30$ hPa (pF = 1.5), and only 7–8% at $\Psi m = -100$ hPa (pF = 2). At lower Ψm, the increase in water content between OA-added columns and unamended control columns ranged from 12 to 31%, with a median value of 19% for compost and 13% for vermicompost.

Table 6. Water content (g water g^{-1} soil) at different matric potentials in the top layer of the unamended control, compost and vermicompost added columns.

Range of the Matric Potential			Pore Size µm	Water Content g water g^{-1} soil							
hPa		pF		C		P		Δ (P/C)	V		Δ (V/C)
				av	sd	av	sd		av	sd	
−10	=>−30	1.0–1.5	300–100	0.033	0.012	0.083	0.020	153%	0.088	0.0233	167%
−30	=>−100	1.5–2.0	100–30	0.035	0.009	0.065	0.011	83%	0.067	0.0092	88%
−100	=>−300	2.0–2.5	30–10	0.052	0.006	0.049	0.009	−6%	0.047	0.0064	−11%
−300	=>−1000	2.5–3.0	10–3	0.017	0.005	0.011	0.007	−33%	0.021	0.0064	23%
−1000	=>−3000	3.0–3.5	3–1	0.011	0.007	0.011	0.006	0%	0.013	0.0099	17%
−3000	=>−16000	3.5–4.0	1–0.2	0.024	0.011	0.017	0.007	−31%	0.013	0.0123	−44%

C: control (unamended), P: compost added; V: vermicompost add, av: average (n = 5), sd: standard deviation. Δ (P/C) and Δ (V/C) indicate the increase (in %) of the average value of the treatments (P and V, respectively) compared to the average value of the control.

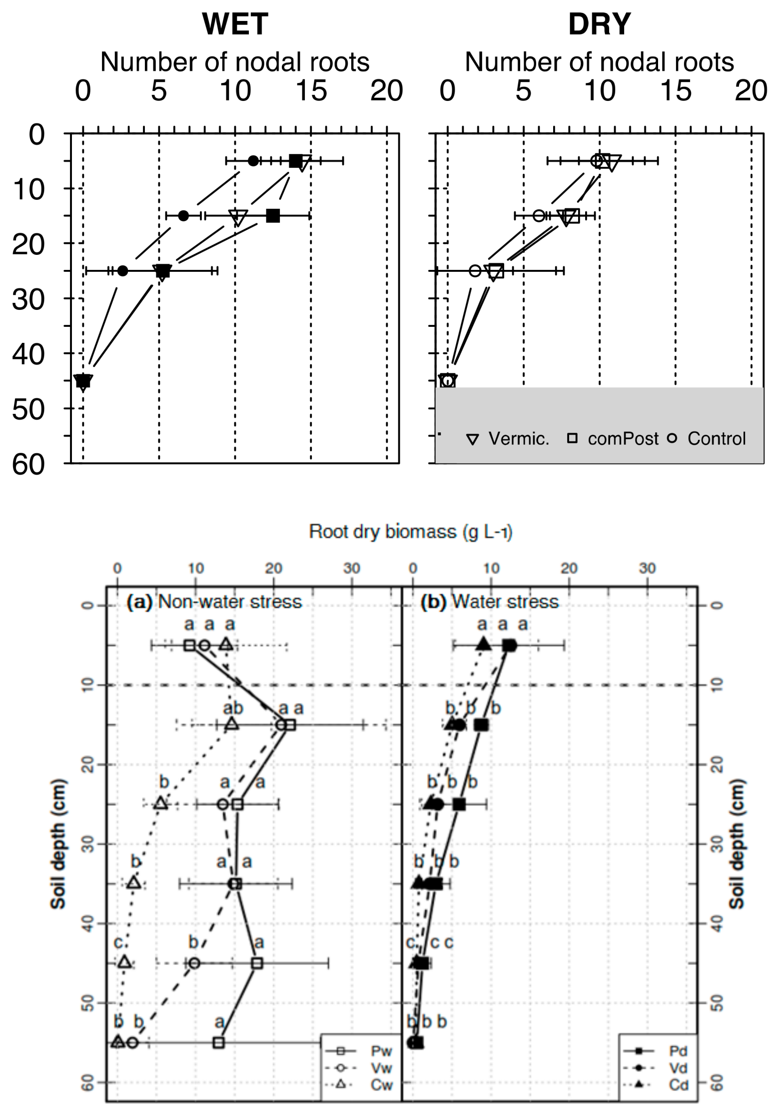

Figure 4. Number of nodal roots (**up**) and dry biomass (g L^{-1}) of fine roots (**bottom**) measured at four depths, the days following the plant harvesting. Error bars represent the standard deviation (n = 5); different letters (along horizontal direction) indicate statistically significant differences ($p < 0.05$) between treatments.

4. Discussion

The objectives of this study were to test the impact of compost and vermicompost topsoil amendments on maize biomass and yield under two levels of water stress (negligible and significant).

4.1. Water Stress Control

In experiments dealing with water stress, the standard practice has been to define treatments based on a given percentage of water relative to field capacity or maximum water-holding capacity [37]. Although this method has often proved useful, it also has the major disadvantage that plants are not sensitive to the amount of water in soil (Θ), but are to the matric potential (Ψm), which is the force with which water is held in the soil porosity. There is a relation (Θ = Ψm) called the water retention curve, which is different for each soil type as it depends on many variables, such as texture, structure organic matter content, etc. [38,39]. Consequently, the results of experiments based on Θ in a particular soil type are difficult to generalize to different soil types. To circumvent this problem, an increasing number of recent experiments have controlled the level of plant water stress by controlling and monitoring the soil Ψm [40–42]. However, the water-stress threshold values of Ψm varies depending on soil properties and the plant type. In a horticultural medium, Newby et al. [42] used a Ψm ranging from −20 to −100 hPa as non-stressing conditions for growing flowers. Valença et al. [43] indicated that Ψm ranging from −40 to −120 hPa caused water stress for papaya, but not for lettuce. For vegetable crops growing in a loamy sand, Bonachela et al. [40] considered −100 to −200 hPa, −200 to −300 hPa and −300 to −500 hPa as high, conventional and low soil water availability, respectively. For an experiment in which maize plants were grown on a sandy material for a short time, Ahmed et al. [44] set the Ψm (during 16 days) to −20 to −30 hPa to get non-stressing conditions, when Dowd et al. [41] set the Ψm (during 9 days) to −1,000 hPa and −3,000 hPa for non-stressing and mildly stressing conditions, respectively.

In our experiment, we wanted to mimic possible future rainfall conditions during which the soil could be maintained continuously wet or continuously dry, whilst avoiding a saturated soil, which would reduce the maize yield not due to water stress, but due to anoxic conditions [45]. The soil used here was a coarse textured sandy loam, and by setting the bulk density at 1.3 g cm^{-1} (i.e., around 50% porosity), we expected the largest pores to drain rapidly after irrigation, thus remaining air filled most of the time and avoiding anoxic conditions and related problems. Results presented in Figures S3 and S4 show that saturation never lasted >10 min. We wanted also to avoid excessively dry soil that would induce excessive water stress and stomata closure, and would stop the plant functioning. Thus, we set the negligible and significant stressing conditions close to field conditions, slightly above and below it, i.e., at Ψm = −150 and −500 hPa.

Originally, we planned to determine the impact of the two moisture levels on the extent of plant water stress in real time, by using a porometer to measure the stomatal conductance [43,46]. Measurements were made by clamping a chamber on a leaf and estimating stomatal conductance as leaf water loss. In order to do so however, the atmosphere in the chamber must be dried. Our experiment was carried out in the rainy season, making it impossible to dry the atmosphere in the chamber and obtain reliable results. Consequently, we could not measure the impact of Ψm on plant water stress in real time, and so we estimated it by measuring the impact on the plant development at the end of the incubation period.

Water stress has a negative impact on metabolic processes, the most sensitive being cellular expansion and development, resulting in specific morphological traits, i.e., reduced leaf elongation, reduced leaf area and stem diameter, among others [47]. By comparing the morphological characteristics of plants grown at the same moment and in the same location, but with different soil water conditions, a diagnosis of the occurrence of a water stress and its intensity can be made [48]. The reduced growth and development in the dry treatment compared to the wet treatment (Figure 3) confirmed the higher plant stress in the dry treatment, and consequently validated our technique of managing the timing and amount of irrigation by controlling Ψm, as well as validating the threshold Ψm of −500 hPa to impose a slight water stress and −150 hPa for negligible stress.

4.2. Benefit of OA Addition; Compost Vs Vermicompost

The results presented in Figure 3 and Table 5 confirmed our hypothesis that OA can improve both maize development and the production of plant biomass in both water stressing and non-stressing conditions. They are also in agreement with the results from Abd El-Mageed et al. [49], who reported a 10 to 20% increase in sorghum shoot biomass after compost addition (15 or 30 t ha^{-1}) to a sandy loam, in both water stressed and unstressed conditions. However, no such compost effect was observed on quinoa and pea biomass under water stressed conditions in a field experiment on a loamy soil [46]. The lack of an effect may have been due to the stressing conditions being more extreme in the latter study, negating the organic matter effect. This suggests that it would be necessary to determine the threshold value, above which OA addition does not provide any benefit for plant productivity.

We also made the hypothesis that different OA would affect crops differently. Zamani et al. [50] have already demonstrated the differential effects of OA, from which sewage sludge decreased maize growth, whereas solid waste compost increased it. If only solid wastes are considered, vermicompost has a higher impact, but this is difficult to generalize as vermicomposts and composts were often prepared with different materials and technologies [51]. When vermicompost and compost are prepared with the same material, vermicompost is generally found to be more beneficial. In a pot experiment, Kalantari et al. [52] reported that maize biomass was decreased (around 50%) when using a compost, and increased (+120%) when using a vermicompost. Using cassava waste material also in a pot experiment, Oo et al. [53] observed that the application of compost and vermicompost amendments increased plant height significantly by 10 to 30%, compared with the unamended control treatment, and that vermicompost had systematically higher benefit compared to compost. In a field experiment, Roy et al. [54] used compost and vermicompost made with rice straw and cow dung, which was applied at a rate of 4 t ha^{-1}. At 60 DAP, they observed an increase of approximately 100% in the dry biomass compared to the control plot, and a trend of higher results for the vermicompost compared to the compost. Our results were in agreement with these results obtained in the field, especially concerning the dramatic biomass improvement obtained after OA addition. In our case, the improvement was even >100%, but we have used five times more OA compared to them. In this study, however, the compost provided systematically better results; the potential causes of this difference are discussed below.

4.3. Organic Amendments Reduced Plant Water Stress

It could be argued that the reduced water stress in the OA treatments was due to higher water additions in these treatments. In this experiment, the differences in evapotranspiration within each moisture treatment were related to plant functioning as the environmental conditions were the same. The hypothesis that the mineral nutrition was not a limiting factor due to the addition of fertilizers to all treatments is highly probable. Before the growth stage V6 (six leaves) N uptake by corn is relatively slow. Significant differences in plant height between the control and OA-added columns were observed at 10 DAP, when the number of leaves was ranging from 5.2 (control) to 5.8 and 6 (compost and vermicompost, respectively) (Table 4). Consequently, it is additional access and use of water (not nitrogen) that can explain the faster growth. Moreover, when available N reaches a certain level, although plant tissue N concentration continues to increase, grain yield does not respond to increased soil N supply [55]. The fertilizers added at planting and 21 DAP had the objective to reach that certain level, in order to limit the impact of additional N provided by OA (compost and vermicompost) on plant growth, as well as on plant yield. In several pot experiments conducted on tropical sandy loams in which maize was grown, after similar additions of mineral fertilizers, no significant differences were found in soil exchangeable ammonium and nitrate 45 days after planting [56], nor in the plant nitrogen content 30 days [57], or six weeks after sowing [58], when compared to AO addition (compost or vermicompost) treatments. It can be concluded that the improved plant properties observed during the early stages of plant growth did not result from improved mineral nutrient uptake, but were associated with a higher water availability. This may be possible firstly as the access to soil water was facilitated, or secondly due to the amount of soil water being increased by the addition of organic amendment, in both wet as well as dry treatments.

The addition of organic amendments generally decreases the bulk density, i.e., increases the total pore volume and thus the possibility of soil water storage. Liu et al. [59] reported that after adding 20 t ha^{-1} compost in a Cambisol (FAO Soil Taxonomy) with a loamy-sand texture, the plant available water (between field capacity and wilting point) was increased twofold, from 6 to 12%. Many similar examples can be found [50,60,61]. However, a recent meta-analysis conducted on 60 published papers by Minasny and McBratney [62] reported that after OA addition, the total increase in available water capacity was generally very small (1.16 mm H_2O 100 mm soil^{-1}), and the water capacity increase was larger at saturation, followed by field capacity and wilting point. The latter result indicates that all pore sizes were not similarly affected: the largest pores, in which water flows under the effect of gravity, are the most affected by OA, followed by mesopores in which water is hold by capillary forces but still easily accessible to the plants, and finally by micropores (in which water is less available to plants). The water retention measured in the top-layers of our experiment (Table 6) fits with this general pattern. Table 6 presents the water content in different ranges of matric potential (in hPa and in pF) and the corresponding ranges of equivalent pore size (diameter in µm) and the increase in pore volume after OA addition in the different classes of pores. A large increase (>200%) was observed for pores of >30 µm which were filled with water only when the matric potential was >−100 hPa; in comparison, the increase in the volume occupied by smaller pores was negligible. During our experiment, in wet and dry conditions, the matric potential was maintained below −150 hPa, meaning that the large pores created by the OA addition were filled with air, and not with water. As a consequence, the reduced water stress in OA columns did not result from a higher soil water storage in the organic amended soils.

Although the large macropores were likely not responsible for water storage, they could facilitate root growth at early stages in the top layer that received the OA. The addition of OA has increased the macropores' volume, and perhaps also their continuity, facilitating the elongation of some roots [63,64] and resulting in the faster development of the root system as a whole, and thus also resulting in a faster use of the available water. The hypothesis of faster root growth after OA addition is consistent with the better plant characteristics observed since the early stages of the experiment (Table 4), when there was still no difference in the cumulated amount of irrigation water (Figure 2).

The dramatic increase in the weight of corn ears after OA addition indicates a better water supply at reproductive stages [65]. Such improved water supply for OA-added columns compared to the unamended control is consistent with our hypothesis of larger root development, as it would give access to a larger soil volume and finally provide more water to the plant at any stage of its development, including the critical stages of grain filling.

When the soil was maintained in dry conditions ($\Psi m \approx -500$ hPa), the geometry of the pore volume was the same as in wet conditions, but the mechanical resistance of the solid phase was dramatically increased, making the root elongation more difficult [66]. Even if the elongation was more difficult in dry conditions, the number of large macropores in OA-added layers was higher than in unamended control layers anyway. Consequently, OA addition provided a faster root development at the early stages until the reproductive stages or grain filling stages, so that maize development and yield improved. It must be noted that increased access to a larger volume of soil probably also increased the uptake of nutrients from soil solution, but the impact on the growth potential is difficult to estimate in absence of plant analyses [55,67].

The differences in the impact of compost and vermicompost could result from different sizes of the elementary organic particles. Vermicompost is made from smaller particles than compost [68], but the small particles can also form aggregates in the soil, and thus have the same impact as larger particles [29]. Such differences in the size of the OA particles could result in different geometry of the pore size, thus different conditions of root elongation, and finally have different consequences on the plant water stress and development. As the size of organic particles in the OA could partly determine the impact of the OA, it is a characteristic that should be measured and controlled in future experiments.

5. Conclusions

Our results, obtained on soil columns mimicking cultivated soil characteristics, show that the use of OA in poor tropical soils could be particularly beneficial for farmers in the context of climate change and in the absence of irrigation infrastructure, as maize biomass and yield were increased in both moisture conditions. The improvement was particularly striking in terms of yield, but is in agreement with other experiments conducted on maize grown in the fields [54]. In continuously dry conditions, the biomass and yield of treated columns were similar to those of the control columns in wet conditions, suggesting that the organic matter amendments helped overcome limitations imposed by the water stress. However, there were no clear differences induced by the two types of OA tested (compost and vermicompost), suggesting that in this situation at least, the extra time and effort necessary for the production of vermicompost is not worthwhile. Compared to the increase in yield, the biomass increase was less impressive but is a valuable improvement, as the additional biomass production can contribute to produce the next compost batch. By recycling the organic wastes, the farmers could limit their expenses and make the best use of available water and mineral nutrients.

The data suggest that the improvement in plant characteristics did not result from increased water storage in the OA-treated soils, but rather from better access to water, resulting in faster root development. This increased the soil volume that was colonized by the plant, improved water supply and reduced water stress during the important stages of plant development. This better access to water seems possible when the soil is maintained wet or dry, meaning that farmers can benefit from OA under a large range of rainfall patterns.

To generalize our results, they need to be confirmed in different conditions. It would be necessary to study soils with different textures, as the addition of OA is likely to have differential impacts on the pore size distribution, as well as on soil mechanical resistance to penetration. Furthermore, testing plants with a different photosynthetic pathway and different root morphology would also be useful. Maize uses the C_4 photosynthetic pathway, which allows for a more efficient use of water than in plants that use the C_3 pathway [69]. One might therefore expect the impact of water stresses on C_3 plants (rice, wheat, soybean, etc.) to be different. Finally, plants with different root systems (branching, lateral growth, etc.) should also be tested.

For these additional experiments, using soil columns similar to which we did (a thin topsoil where inputs are added above a larger subsoil without any inputs but with a drastic control of soil physical characteristics), with real-time control of the soil matric potential and real-time monitoring of the plant water stress, would be an easy and efficient way to test the impact of different rainfall patterns on various soils, OA and plants types, and provide relevant recommendations allowing farmers to get the highest benefit from the time spent on preparing and spreading OA in their fields.

Supplementary Materials: The following are available online at https://www.mdpi.com/2077-0472/11/2/132/s1, Figure S1: Schematic presentation of the relation between pore size and the soil water matric potential expressed in hPa and in pF, Figure S2: Schematic presentation of the water location in relation to pore equivalent diameter and the expected flux of water between root and shoot in the wet (left) and dry (right) treatments, Figure S3: Examples of matric potential recordings in a wet and in a dry column, from 6 to 20 DAP, Figure S4: Matric potential (hPa) recorded during all the experiment in the 30 columns, dry (d) treatment (3 upper rows), and wet (w) treatments (3 bottom rows), Figure S5: Recording of the meteorological characteristics during the 70 days of the experiment.

Author Contributions: P.S., C.H., A.P., N.S. and S.I.N.A. designed the experiment, all authors have analyzed and interpreted the data; P.S. managed and controlled all the work done in the green house and in laboratory; N.S. designed and maintained all the instruments for the electronic monitoring; K.X. made all the activities about soil physics (soil cylinders collection, water retention curves, etc.); P.S., C.H., N.N. and A.P. drafted the manuscript; V.T.-g., S.I.N.A. and A.P. contributed to all aspects related to plant physiology; and N.N. (native English speaker) edited the final version. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by IRD (Institut de Recherche pour le Développement, France) through the LMI-LUSES (Laboratoire Mixte International 'Impact of Rapid Land Use Change on Soil Ecosystem Services'), which covered the cost of the experiment, and also through the JEAI (Jeune Equipe Associée à l'IRD) 'EcoRubber', a cooperation project between the Faculty of Agriculture of the

National University of Laos (NUOL, Lao PDR), the Department of Agricultural Land Management (DALaM, ministry of Agriculture, Lao PDR) and the Faculty of Agriculture of the Khon Kaen University (KKU, Thailand) which supported the PhD registration.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are openly available in DataSuds at https://doi.org/10.23708/6QSN6Q.

Acknowledgments: P.S. would like to thank the IRD staff and all members of the 'LUSES' and 'EcoRubber' projects for their scientific and administrative supports; NUOL for granting leave permission. Somchai Chansavang, Thanyakan Sengkhrua and Nopmanee Suvannang for providing compost and vermicompost and exchange most useful knowledge. All authors would like to express their gratitude to the Department of Agricultural Land Management (DALaM, Lao PDR) for providing access to greenhouse, equipment and analytical facilities. All authors would like to thank Phonepasith Phongmala & Xayasone Keobandith, students at NUOL faculty of agriculture, who were in charge of many practical aspects (soil and column preparation, daily irrigation, plant measurements) and did outstanding work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cherlet, M.; Hutchinson, C.; Reynolds, J.; Hill, J.; Sommer, S.; von Maltitz, G. (Eds.) *World Atlas of Desertification*; Publication Office of the European Union: Luxembourg, 2018; 248p, ISBN 978-92-79-75350-3.
2. IPBES. *The IPBES Assessment Report on Land Degradation and Restoration*; Montanarella, L., Scholes, R., Brainich, A., Eds.; Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services: Bonn, Germany, 2018; 744p.
3. IPCC. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustaina-ble Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Summary for Policymakers*; IPCC: Geneva, Switzerland, 2020; 41p.
4. Millennium Ecosystem Assessment (Program). *Ecosystems and Human Well-Being: Synthesis*; Island Press: Washington, DC, USA, 2005; ISBN 978-1-59726-040-4.
5. Montanarella, L.; Vargas, R. Global governance of soil resources as a necessary condition for sustainable development. *Curr. Opin. Environ. Sustain.* **2012**, *4*, 559–564. [CrossRef]
6. Montanarella, L. The Global Soil Partnership. *IOP Conf. Ser. Earth Environ. Sci.* **2015**, *25*, 12001. [CrossRef]
7. IUCN. *Land Degradation Neutrality: Implications and Opportunities for Conservation*, Technical Brief, 2nd ed.; IUCN: Nairobi, Kenya, 2015; 19p.
8. Wezel, A.; Casagrande, M.; Celette, F.; Vian, J.-F.; Ferrer, A.; Peigné, J. Agroecological practices for sustainable agriculture. A review. *Agron. Sustain. Dev.* **2014**, *34*, 1–20. [CrossRef]
9. Altieri, M.A.; Nicholls, C.I.; Henao, A.; Lana, M.A. Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.* **2015**, *35*, 869–890. [CrossRef]
10. FAO. *Final Report for the International Symposium on Agroecology for Food Security and Nutrition*; FAO: Rome, Italy, 2015; 41p.
11. FAO. *FAO'S Work on Agroecology. A Pathway to Achieving the SDGs*; FAO: Rome, Italy, 2018; p. 28.
12. Awasthi, M.K.; Sarsaiya, S.; Wang, Q.; Wang, M.; Chen, H.; Ren, X.; Kumar, S.; Zhang, Z. Mitigation of global warming po-tential for cleaner composting. In *Biosynthetic Technology and Environmental Challenges*; Varjani, S.J., Parameswaran, B., Kumar, S., Khare, S.K., Eds.; Springer: Singapore, 2018; pp. 271–305. ISBN 978-981-10-7433-2.
13. Minasny, B.; Malone, B.P.; McBratney, A.B.; Angers, D.A.; Arrouays, D.; Chambers, A.; Chaplot, V.; Chen, Z.-S.; Cheng, K.; Das, B.S.; et al. Soil carbon 4 per mille. *Geoderma* **2017**, *292*, 59–86. [CrossRef]
14. Amundson, R.; Biardeau, L. Opinion: Soil carbon sequestration is an elusive climate mitigation tool. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 11652–11656. [CrossRef]
15. Luangduangsitthideth, O.; Limnirankul, B.; Kramol, P. Farmers' knowledge and perceptions of sustainable soil conservation practices in Paklay district, Sayabouly province, Lao PDR. *Kasetsart J. Soc. Sci.* **2018**. [CrossRef]
16. Wang, Y.; Zhu, Y.; Zhang, S.; Wang, Y. What could promote farmers to replace chemical fertilizers with organic fertilizers? *J. Clean. Prod.* **2018**, *199*, 882–890. [CrossRef]
17. Alexander, K.S.; Greenhalgh, G.; Moglia, M.; Thephavanh, M.; Sinavong, P.; Larson, S.; Jovanovic, T.; Case, P. What is technology adoption? Exploring the agricultural research value chain for smallholder farmers in Lao PDR. *Agric. Hum. Values* **2020**, *37*, 17–32. [CrossRef]
18. Sanchez, P.A. *Properties and Management of Soils in the Tropics*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2019.
19. Huang, P.; Xie, S.-P.; Hu, K.; Huang, G.; Huang, R. Patterns of the seasonal response of tropical rainfall to global warming. *Nat. Geosci.* **2013**, *6*, 357–361. [CrossRef]

20. Fischer, E.M.; Sedláček, J.; Hawkins, E.; Knutti, R. Models agree on forced response pattern of precipitation and temperature extremes. *Geophys. Res. Lett.* **2014**, *41*, 8554–8562. [CrossRef]
21. Sheldon, K.S. Climate Change in the Tropics: Ecological and Evolutionary Responses at Low Latitudes. *Annu. Rev. Ecol. Evol. Syst.* **2019**, *50*, 303–333. [CrossRef]
22. Unver, O.; Wahaj, R.; Lorenzon, E.; Mohammadi, K.; Osias, J.R.; Reinders, F.; Wani, S.; Chuchra, J.; Lee, P.; Sangjun, I. Key and Smart Actions to Alleviate Hunger and Poverty through Irrigation and Drainage. *Irrig. Drain.* **2018**, *67*, 60–71. [CrossRef]
23. Nigussie, A.; Kuyper, T.W.; De Neergaard, A. Agricultural waste utilisation strategies and demand for urban waste compost: Evidence from smallholder farmers in Ethiopia. *Waste Manag.* **2015**, *44*, 82–93. [CrossRef]
24. Yazdanpanah, N.; Mahmoodabadi, M.; Cerdà, A. The impact of organic amendments on soil hydrology, structure and microbial respiration in semiarid lands. *Geoderma* **2016**, *266*, 58–65. [CrossRef]
25. Bundhoo, Z.M. Solid waste management in least developed countries: Current status and challenges faced. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 1867–1877. [CrossRef]
26. Geng, Y.; Cao, G.; Wang, L.; Wang, S. Effects of equal chemical fertilizer substitutions with organic manure on yield, dry matter, and nitrogen uptake of spring maize and soil nitrogen distribution. *PLoS ONE* **2019**, *14*, e0219512. [CrossRef]
27. Li, H.; Feng, W.-T.; He, X.-H.; Zhu, P.; Gao, H.-J.; Nan, S.; Xu, M. Chemical fertilizers could be completely replaced by manure to maintain high maize yield and soil organic carbon (SOC) when SOC reaches a threshold in the Northeast China Plain. *J. Integr. Agric.* **2017**, *16*, 937–946. [CrossRef]
28. Mohamed, W.S.; Hammam, A.A. Poultry manure-derived biochar as a soil amendment and fertilizer for sandy soils under arid conditions. *Egypt. J. Soil Sci.* **2019**, *59*, 1–14. [CrossRef]
29. Fornes, F.; Mendoza-Hernández, D.; García-De-La-Fuente, R.; Abad, M.; Belda, R.M. Composting versus vermicomposting: A comparative study of organic matter evolution through straight and combined processes. *Bioresour. Technol.* **2012**, *118*, 296–305. [CrossRef] [PubMed]
30. Larney, F.J.; Sullivan, D.M.; Buckley, K.E.; Eghball, B. The role of composting in recycling manure nutrients. *Can. J. Soil Sci.* **2006**, *86*, 597–611. [CrossRef]
31. Pansu, M.; Gautheyrou, J. *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods*; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 2006; ISBN 978-3-540-31210-9.
32. FCQAO. *Methods Book for the Analysis of Compost*; Federal Compost Quality Assurance Organization: Stuttgart, Germany, 2003; ISBN 978-3-928179-33-1.
33. Ferreras, L.; Gomez, E.; Toresani, S.; Firpo, I.; Rotondo, R. Effect of organic amendments on some physical, chemical and biological properties in a horticultural soil. *Bioresour. Technol.* **2006**, *97*, 635–640. [CrossRef] [PubMed]
34. Joshi, R.; Singh, J.; Vig, A.P. Vermicompost as an effective organic fertilizer and biocontrol agent: Effect on growth, yield and quality of plants. *Rev. Environ. Sci. Bio/Technol.* **2015**, *14*, 137–159. [CrossRef]
35. Eden, M.; Gerke, H.H.; Houot, S. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: A review. *Agron. Sustain. Dev.* **2017**, *37*, 11. [CrossRef]
36. Osakabe, Y.; Osakabe, K.; Shinozaki, K.; Tran, L.-S.P. Response of plants to water stress. *Front. Plant Sci.* **2014**, *5*, 86. [CrossRef]
37. Khalil, A.M.; Murchie, E.H.; Mooney, S. Quantifying the influence of water deficit on root and shoot growth in wheat using X-ray Computed Tomography. *AoB Plants* **2020**, *12*, plaa036. [CrossRef]
38. Assouline, S.; Tessier, D.; Bruand, A. A conceptual model of the soil water retention curve. *Water Resour. Res.* **1998**, *34*, 223–231. [CrossRef]
39. Novák, V.; Hlaváčiková, H. *Applied Soil Hydrology*, 1st ed.; Theory and Applications of Transport in Porous Media; Springer International Publishing: Cham, Switzerland, 2019; ISBN 978-3-030-01806-1.
40. Bonachela, S.; González, A.M.; Fernández, M.; Cabrera-Corral, F.J. Vegetable Crops Grown under High Soil Water Availability in Mediterranean Greenhouses. *Water* **2020**, *12*, 1110. [CrossRef]
41. Dowd, T.G.; Braun, D.M.; Sharp, R.E. Maize lateral root developmental plasticity induced by mild water stress. I: Genotypic variation across a high-resolution series of water potentials: Lateral root developmental plasticity. *Plant Cell Environ.* **2019**, *42*, 2259–2273. [CrossRef]
42. Newby, A.F.; Altland, J.E.; Struve, D.K.; Pasian, C.C.; Ling, P.P.; Jourdan, P.S.; Kessler, J.R.; Carpenter, M. Integrating Moisture Characteristic Curves with Gravimetric Data in the Management of Substrate Moisture Content for Annual Vinca. *HortScience* **2018**, *53*, 1197–1202. [CrossRef]
43. Valença, D.D.C.; De Carvalho, D.F.; Azevedo, R.A.; De Pinho, C.F.; Medici, L.O.; Reinert, F. Automatically controlled deficit irrigation of lettuce in "organic potponics". *Sci. Agricola* **2018**, *75*, 52–59. [CrossRef]
44. Ahmed, M.A.; Zarebanadkouki, M.; Kaestner, A.; Carminati, A. Measurements of water uptake of maize roots: The key function of lateral roots. *Plant Soil* **2016**, *398*, 59–77. [CrossRef]
45. Cavero, J.; Medina, E.T.; Montoya, F. Sprinkler Irrigation Frequency Affects Maize Yield Depending on Irrigation Time. *Agron. J.* **2018**, *110*, 1862–1873. [CrossRef]
46. Hirich, A.; Choukr-Allah, R.; Jacobsen, S.-E. Deficit Irrigation and Organic Compost Improve Growth and Yield of Quinoa and Pea. *J. Agron. Crop. Sci.* **2014**, *200*, 390–398. [CrossRef]
47. Efeoğlu, B.; Ekmekçi, Y.; Çiçek, N. Physiological responses of three maize cultivars to drought stress and recovery. *S. Afr. J. Bot.* **2009**, *75*, 34–42. [CrossRef]

48. Parkash, V.; Singh, S. A Review on Potential Plant-Based Water Stress Indicators for Vegetable Crops. *Sustainability* **2020**, *12*, 3945. [CrossRef]
49. El-Mageed, T.A.A.; El-Samnoudi, I.M.; Ibrahim, A.E.-A.M.; El Tawwab, A.R.A. Compost and mulching modulates morphological, physiological responses and water use efficiency in sorghum (bicolor L. Moench) under low moisture regime. *Agric. Water Manag.* **2018**, *208*, 431–439. [CrossRef]
50. Zamani, J.; Afyuni, M.; Sepehrnia, N.; Schulin, R. Opposite effects of two organic wastes on the physical quality of an agricultural soil. *Arch. Agron. Soil Sci.* **2016**, *62*, 413–427. [CrossRef]
51. Tognetti, C.; Laos, F.; Mazzarino, M.; Hernández, M. Composting vs. Vermicomposting: A Comparison of End Product Quality. *Compos. Sci. Util.* **2005**, *13*, 6–13. [CrossRef]
52. Kalantari, S.; Hatami, S.; Ardalan, M.M.; Alikhani, H.A.; Shorafa, M. The Effect of Compost and Vermicompost of Yard Leaf Manure on Growth of Corn. *Afr. J. Agric. Res.* **2010**, *5*, 1317–1323.
53. Oo, A.N.; Iwai, C.B.; Saenjan, P. Soil Properties and Maize Growth in Saline and Nonsaline Soils Using Cassava-Industrial Waste Compost and Vermicompost with or without Earthworms. *Land Degrad. Dev.* **2015**, *26*, 300–310. [CrossRef]
54. Roy, S.; Arunachalam, K.; Dutta, B.K.; Arunachalam, A. Effect of organic amendments of soil on growth and productivity of three common crops viz. *Zea mays*, *Phaseolus vulgaris* and *Abelmoschus esculentus*. *Appl. Soil Ecol.* **2010**, *45*, 78–84. [CrossRef]
55. Subedi, K.D.; Ma, B.L. Corn crop production: Growth, fertilization and yield. In *Corn Crop Production Growth, Fertilization and Yield Corn Crop Production: Growth, Fertilization and Yield*; Danforth, A.T., Ed.; Nova Publisher: New York, NY, USA, 2011; p. 84. [CrossRef]
56. Latifah, O.; Ahmed, O.H.; Majid, N.M.A. Short Term Enhancement of Nutrients Availability in *Zea mays* L. Cultivation on an Acid Soil Using Compost and Clinoptilolite Zeolite. *Compos. Sci. Util.* **2017**, *25*, 22–35. [CrossRef]
57. Manolikaki, I.; Diamadopoulos, E. Positive Effects of Biochar and Biochar-Compost on Maize Growth and Nutrient Availability in Two Agricultural Soils. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 512–526. [CrossRef]
58. Ayanfeoluwa, O.E. Availability of nutrients from an accelerated compost for maize (*Zea mays*) production in two soil types. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 1476–1486. [CrossRef]
59. Liu, J.; Schulz, H.; Brandl, S.; Miehtke, H.; Huwe, B.; Glaser, B. Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. *Z. Pflanzenernähr. Bodenk.* **2012**, *175*, 698–707. [CrossRef]
60. Lynch, D.H.; Voroney, R.P.; Warman, P.R. Soil Physical Properties and Organic Matter Fractions Under Forages Receiving Composts, Manure or Fertilizer. *Compos. Sci. Util.* **2005**, *13*, 252–261. [CrossRef]
61. Mamo, M.; Moncrief, J.; Rosen, C.; Halbach, T. The Effect of Municipal Solid Waste Compost Application on Soil Water and Water Stress in Irrigated Corn. *Compos. Sci. Util.* **2000**, *8*, 236–246. [CrossRef]
62. Minasny, B.; McBratney, A.B. Limited effect of organic matter on soil available water capacity: Limited Effect of Organic Matter on Soil Water Retention. *Eur. J. Soil Sci.* **2018**, *69*, 39–47. [CrossRef]
63. Clark, L.J.; Whalley, W.; Barraclough, P. How do roots penetrate strong soil? *Plant Soil* **2003**, *255*, 93–104. [CrossRef]
64. Tardieu, F. Analysis of the spatial variability of maize root density. III. Effect of a wheel compaction on water extraction. *Plant Soil* **1988**, *109*, 257–262. [CrossRef]
65. Sangakkara, U.R.; Amarasekera, P.; Stamp, P. Irrigation Regimes Affect Early Root Development, Shoot Growth and Yields of Maize (*Zea mays* L.) in Tropical Minor Seasons. *Plant Soil Environ.* **2010**, *56*, 228–234.
66. Bengough, A.G.; McKenzie, B.M.; Hallett, P.D.; Valentine, T.A. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *J. Exp. Bot.* **2011**, *62*, 59–68. [CrossRef] [PubMed]
67. Doussan, C.; Pagès, L.; Pierret, A. Soil exploration and resource acquisition by plant roots: An architectural and modelling point of view. *Agronomie* **2003**, *23*, 419–431. [CrossRef]
68. Frederickson, J.; Howell, G.; Hobson, A.M. Effect of pre-composting and vermicomposting on compost characteristics. *Eur. J. Soil Biol.* **2007**, *43*, S320–S326. [CrossRef]
69. Way, D.A.; Katul, G.G.; Manzoni, S.; Vico, G. Increasing water use efficiency along the C_3 to C_4 evolutionary pathway: A stomatal optimization perspective. *J. Exp. Bot.* **2014**, *65*, 3683–3693. [CrossRef] [PubMed]