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# Use of Carbonized Fallen Leaves of *Jatropha Curcas* L. as a Soil Conditioner for Acidic and Undernourished Soil

**Takafumi Konaka [1], Shin Yabuta [2], Charles Mazereku [3], Yoshinobu Kawamitsu [4], Hisashi Tsujimoto [1,5], Masami Ueno [4] and Kinya Akashi [1,5,6,*]**

[1] United Graduate School of Agricultural Sciences, Tottori University, Tottori 680-8553, Japan; takafumi.konaka@gmail.com (T.K.); tsujim@alrc.tottori-u.ac.jp (H.T.)
[2] Faculty of Agriculture, Kagoshima University, Kagoshima 890-8580, Japan; syabuta@agri.kagoshima-u.ac.jp
[3] Department of Agricultural Research, Ministry of Agriculture, Private Bag 0033 Gaborone, Botswana; charmazereku@gmail.com
[4] Faculty of Agriculture, University of the Ryukyus, Okinawa 903-0213, Japan; kawamitu@agr.u-ryukyu.ac.jp (Y.K.); ruenom@agr.u-ryukyu.ac.jp (M.U.)
[5] Arid Land Research Center, Tottori University, Tottori 680-0001, Japan
[6] Faculty of Agriculture, Tottori University, Tottori 680-8553, Japan
[*] Correspondence: akashi.kinya@tottori-u.ac.jp; Tel.: +81-857-315352

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**Abstract:** Jatropha (*Jatropha curcas* L.) represents a renewable bioenergy source in arid regions, where it is used to produce not only biodiesel from the seed oil, but also various non-oil biomass products, such as fertilizer, from the seed cake following oil extraction from the seeds. Jatropha plants also generate large amounts of fallen leaves during the cold or drought season, but few studies have examined the utilization of this litter biomass. Therefore, in this study, we produced biochar from the fallen leaves of jatropha using a simple and economical carbonizer that was constructed from a standard 200 L oil drum, which would be suitable for use in rural communities, and evaluated the use of the generated biochar as a soil conditioner for the cultivation of Swiss chard (*Beta vulgaris* subsp. *cicla* "Fordhook Giant") as a model vegetable in an acidic and undernourished soil in Botswana. Biochar application improved several growth parameters of Swiss chard, such as the total leaf area. In addition, the dry weights of the harvested shoots were 1.57, 1.88, and 2.32 fold higher in plants grown in soils containing 3%, 5%, and 10% biochar, respectively, compared with non-applied soil, suggesting that the amount of biochar applied to the soil was positively correlated with yield. Together, these observations suggest that jatropha fallen leaf biochar could function as a soil conditioner to enhance crop productivity.

**Keywords:** jatropha; biochar; arid region; acidic undernourished soil; fallen leaves

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## 1. Introduction

Jatropha (*Jatropha curcas* L., Euphorbiaceae) has non-edible oils in its seeds that serve as a feedstock for biodiesel production. Furthermore, since this drought-tolerant species can thrive under a wide range of rainfall regimes, from 200 to over 1500 mm per annum [1,2], and can grow in poor soils, on eroded land, and on wasteland [3–6], jatropha seed oil also represents a promising feedstock for renewable energy in arid lands [7–9].

The utilization of non-oil biomass products of jatropha has also been evaluated from the perspective of whole-crop biorefineries [10]. Several studies have reported on the production of an organic fertilizer from the seed residues following oil extraction (the seed cake) [4,11–13] and have investigated use of the seed cake for bioenergy production, e.g., bio-oil and solid fuel [14–16]. Furthermore, the utilization of jatropha wood biochar as an energy source has been described [17]. The effects of jatropha leaf extracts as a herbal ointment [18], mite [*Rhipicephalus (Boophilus) annulatus*] repellent [19], and therapeutic agent [20] have been studied, and the positive effects of a biochar amendment made from a mixture of jatropha stems and leaves on jatropha seedling growth have been demonstrated [21]. Recently, production of catalytic biocarbons from jatropha biomass has been demonstrated [22,23].

Jatropha plants growing in the temperate zone are deciduous, losing their leaves in the cold season, so the fallen leaf biomass of this species cannot be neglected when considering whole-crop biorefineries [5,24,25]. A cultivation trial in Patancheru, India, estimated that jatropha trees produce 550 g of fallen leaves per plant at one year old and 1450 g at three years old, while the total plant biomass for four-year-old trees was estimated at 6.14 kg plant$^{-1}$ [26], suggesting that fallen leaves make up a major proportion of the biomass that is produced during jatropha cultivation.

Previous studies have shown that biochar can contribute to agricultural production through improvement of the soil physicochemical properties [21,27,28] and fertilizing effects [29–31], and that the application of biochar derived from wood or organic waste has positive impacts on the growth of many crops, such as rice (*Oryza sativa*) and maize (*Zea mays*) [32–34]. Biochar derived from fallen leaves has also been investigated for several species—for example, biochars made from the fallen leaves of ginkgo (*Ginkgo biloba*) and maple (*Acer* spp.) trees have been studied as materials for the stabilization of heavy metals in polluted soils [35,36], and the physicochemical properties of fallen leaf biochars made from maple [37] and *Eucalyptus saligna* [38] have been reported. However, to the best of our knowledge, the use of biochar made from jatropha fallen leaves in the production of edible crops and vegetables has been limited.

In this study, fallen leaves of jatropha derived from a cultivation trial in Botswana [24,25] were pyrolyzed and applied to an acidic and undernourished soil to evaluate the use of jatropha fallen leaves as a feedstock for producing a soil conditioner. In addition, we investigated the performance of a simplified and inexpensive oil-drum carbonizer for the production of jatropha fallen leaf biochar to facilitate the implementation of biochar production in resource-poor villages in rural areas [39–41]. We chose to use Swiss chard (*Beta vulgaris* subsp. *cicla*) as a model plant for evaluating the impact of jatropha fallen leaf biochar on crop production because this is commonly grown in Botswana.

## 2. Materials and Methods

### 2.1. Production and Analysis of Jatropha Fallen Leaf Biochar

Fallen leaves of jatropha were collected in July (winter) 2016 from a jatropha cultivation site [24] located approximately 4 km northeast of the Department of Agricultural Research station in Gaborone, Botswana. The cold-induced defoliation of jatropha in this climatic region has been described previously [24,25]. The fallen leaves were dried in the sun and subsequently used for biochar production.

A simplified carbonizer was constructed from a used oil drum of standard 200 L capacity (572 mm diameter, 851 mm high). The lid of the drum was removed and replaced with a custom-made steel lid that contained a funnel (15 cm high, 7 cm internal diameter) in the center (Figure 1A). Several holes were then made in the bottom of the drum at approximately 10–15 cm intervals for ventilation (Figure 1B) and the drum was placed on top of four bricks to ensure air flow from the bottom at the beginning of ignition.

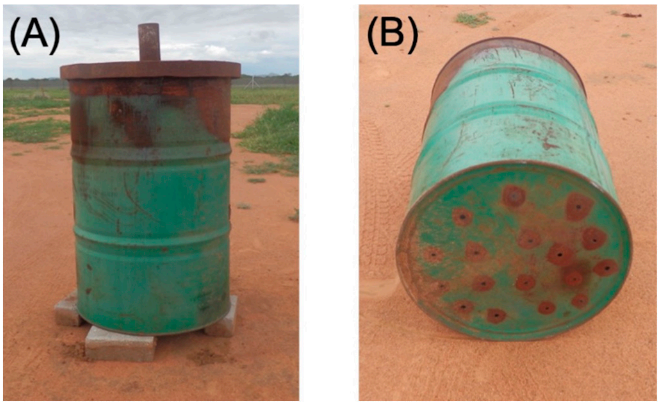

**Figure 1.** Jatropha fallen leaf biochar production using an oil-drum carbonizer. (**A**) Side view of the carbonizer. An oil drum was placed on top of bricks and covered with a custom-made lid with a funnel. (**B**) Bottom view of the carbonizer. Several ventilation holes were made in the bottom of the oil drum.

Approximately 44 kg of the jatropha fallen leaves were tightly packed into the drum up to the height of the upper rim by stamping them down with the body weight of an adult. A pilot burner was then provided by placing a burning piece of paper on top of the piled leaves in the drum. After 30 min of burning, the lid was placed on top of the drum and 1 h later, the top funnel was sealed by a brick and the bottom ventilation was closed by filling the area between the bricks and the bottom of the drum with soil, to suppress combustion inside the drum by blocking the in-flow of the air. The drum was maintained for the next 46.5 h to promote carbonization, during which time the internal temperature of the carbonizer was continuously measured by three thermocouple sensors with a measurable temperature range of −50 to 800 °C (TL-13K; Sato Shouji, Tokyo, Japan), which were inserted laterally into the center of the drum through small holes at heights of 15, 45, and 75 cm from the bottom, and a data logger (Ondotori MCR-4; T&D Corporation, Nagano, Japan). Then, 48 h after ignition, the carbonization was stopped by opening the lid manually using refractory gloves, and immediately applying approximately 10 L of water to the top of the pile. The drum was then left for 6 h, after which time the resulting biochar was spread out on a steel sheet in the open air and left to dry for 10 days, and then mixed extensively with a shovel to ensure homogenization. The surface structure of the biochar was then observed under a VHX-D500 scanning electron microscope (Keyence, Osaka, Japan).

The pH of the biochar was measured using a Laqua D-51 pH meter (HORIBA Scientific, Kyoto, Japan) at a biochar to water ratio of 1:50 (*w*/*v*) and the electrical conductivity (EC) of the biochar was measured with a JENCO VisionPlus meter (JENCO, San Diego, CA, USA). The cation exchange capacity (CEC) of the biochar was measured as described previously [42] with the following modifications. Biochar (1 g) was placed in a centrifuge tube and 25 mL of 1 M ammonium acetate was added. The tube was then shaken for 1 h and centrifuged at 830× *g* for 5 min, following which the supernatant was removed and 80% ethanol was added. The tube was then further shaken for 5 min and recentrifuged as described above. This ethanol washing procedure was repeated three times. After the final centrifugation, the supernatant was removed and 25 mL of 10% sodium chloride was added. The tube was then shaken for 1 h and centrifuged at 830× *g* for 5 min, following which the supernatant was taken into an Erlenmeyer flask and 5 mL of 18% formaldehyde aqueous solution and 200 µL of 1% of thymol blue were added. The solution was then titrated with 0.1 N sodium hydroxide. The CEC value was calculated using a previously described formula [43].

### 2.2. Experimental Soil

To evaluate the effect of biochar on soils that would otherwise be unsuitable for vegetable cultivation, an experimental soil with acidic, Cu/Ni-rich, and nutrient-poor characteristics [44] was collected from a suburb of Selebi-Phikwe in the central district of Botswana. The organic carbon content of the soil was measured using the potassium dichromate method [45] with a UVD 2950 spectrophotometer (LABOMED, Los Angeles, CA, USA).

### 2.3. Plant Material and Monitoring of Growth

Seeds of Swiss chard 'Fordhook Giant' were purchased from Sakata Seed Southern Africa (Lindsay, South Africa). The seeds were initially germinated on a horticulture soil (Potting soil, New Frontiers, Lobatse, Botswana) in a plastic seed tray, where they were grown for 2 weeks until their second true leaves emerged. The seedlings were then transplanted into 2 L plastic pots filled with the experimental soil supplemented with 0% (control), 3%, 5%, or 10% (*w*/*w*) biochar. The plants were provided with 0.5 L of water every second day.

The length of the longest leaf on each plant was measured weekly using a steel measuring tape. Then, at 44 days after transplantation to the experimental soil, the number of expanded leaves on each plant was counted and the aerial and underground tissues were harvested. The total leaf area was measured with an area meter (LI-3100; LI-COR, Lincoln, NE, USA), following which the whole tissues were dried in an oven at 70 °C for 2 days and the dry biomass was weighed using an electric balance.

### 2.4. Mineral Nutrient Assays

The unamended soil was decomposed by concentrated sulfuric acid as described previously [46] and their mineral contents were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (SPECTRO CIROS CCD; SPECTRO Analytical Instruments GmbH, Nordrhein-Westfalen, Germany). The biochar and aerial parts of the harvested plants were decomposed as described previously [47] with the following modifications. Dry samples of the biochar (0.2 g) and aerial parts (0.1 g) were dissolved in 10 mL of concentrated nitric acid in a flask and digested on a hot plate for 1 h at each of 90 °C, 140 °C, and 190 °C. The solutions were then evaporated at 220 °C (biochar) or 240 °C (aerial parts) until the volume was reduced to approximately 1 mL and analyzed by ICP-AES as described above. The water-soluble ions $NO_3^-$ and $NH_4^+$ were extracted from the soils by mixing 5 g of soil with 50 mL of distilled water for 1 h and were quantified using an RQflex 10 reflectometer (Merck, Darmstadt, Germany).

### 2.5. Evaluation of the Water-holding Capacities of the Soils

After harvest, the experimental soils were spread onto a sheet in a greenhouse with a daily maximum temperature that ranged from approximately 40 to 49 °C and were dried out for 1 month. Then, 1 kg of the soils were poured back into the original pots and 500 mL of water was added. The pots were maintained in the greenhouse and their weights were measured on a daily basis from the day after water addition to estimate the water-holding capacities of the amended and unamended soils.

## 3. Results and Discussion

### 3.1. Properties of the Jatropha Fallen Leaf Biochar

The 200 L oil-drum carbonizer that was used in this study (Figure 1A,B) was completely filled with dried jatropha leaves and ignited from the top of the piled leaves. Then, 1.5 h after ignition, both top and bottom ventilation holes were closed, and the biomass inside was subjected to pyrolysis in an oxygen-limited condition. The heating scheme employed in this study is based on the auto-thermal process, in which burning part of the raw biomass material with a controlled air inlet provides the energy necessary for the pyrolysis process [48].

During the heating process, the internal temperature of the drum was monitored at three different heights (Figure 2). In the upper part of the drum (75 cm from the bottom), the temperature increased immediately after ignition to reach a maximum temperature of 395.1 °C at 6 h after ignition (HAI), after which it dropped sharply to <100 °C at 10–15 HAI. In the middle of the drum (45 cm from the bottom), the temperature increased from around 1–2 HAI to reach a small peak of 156 °C at 7 HAI.

The temperature was then maintained between 120 and 200 °C at 8–42 HAI, after which it sharply increased to 370 °C at 48 HAI. In the lower part of the drum (15 cm from the bottom), the temperature increased sharply at 6–18 HAI to exceed 400 °C, after which it was maintained at 396–454 °C until the pyrolysis was extinguished. The maximum temperature in the bottom part was 454 °C at 46 HAI.

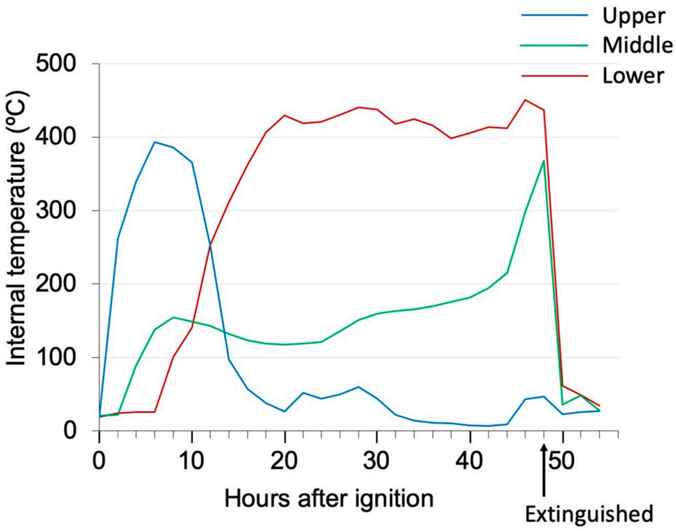

**Figure 2.** Temporal changes in the internal temperature of the oil-drum carbonizer at three different heights of 15 cm (lower), 45 cm (middle), and 75 cm (upper) from the bottom of the drum. The pyrolysis was terminated at 48 h after ignition (vertical arrow).

The timing of a sharp decrease in temperature from 365.3 to 26.3 °C in the upper part of the drum (at 10–20 HAI) appeared to be synchronized with a sharp increase in temperature from 25.6 to 429.5 °C in the bottom part of the drum (at 6–20 HAI), suggesting that the spatial location of the pyrolysis reaction migrated downward at this time. It is noteworthy that only a modest decreased in temperature from 137.7 to 118.5 °C was observed in the middle part of the drum at 6–18 HAI. The reason for this behavior is currently unknown, but one possibility is that the heat was transmitted downward via a peripheral route, bypassing the central axis of the drum where the mid-height sensor was located. It is also interesting to note that the temperature in the bottom part of the drum remained high for a prolonged period of time (18–48 HAI). The mechanism driving this phenomenon is also unclear, but it may have been related to a higher density of jatropha leaves occurring at the bottom of the drum due to compression under their own weight, allowing a high temperature to be sustained. The internal temperature profile of the drum suggested that the biomass was subjected to modestly high temperatures in the range of 100–450 °C. This temperature range was similar to those related to the degradation of polymers of hemicellulose, cellulose, and lignin during pyrolysis of plant biomass [22].

When the pyrolysis was terminated by applying water on top of the pile, soot and smoke at a height of approximately 50 cm evolved from the pile, but vapor explosion did not occur. Since the temperature profile suggested that the pyrolysis products in the drum were heterogeneous, the jatropha biochar was extensively mixed with a shovel for homogenization once the pyrolysis had been completely terminated. The resulting biochar had a mosaic appearance consisting of dark and light brownish fragments and grains of different sizes (Figure 3A), and scanning electron microscopy showed that the surface of subsets of these fragments had a porous structure (Figure 3B), which is a common hallmark of biochar [49].

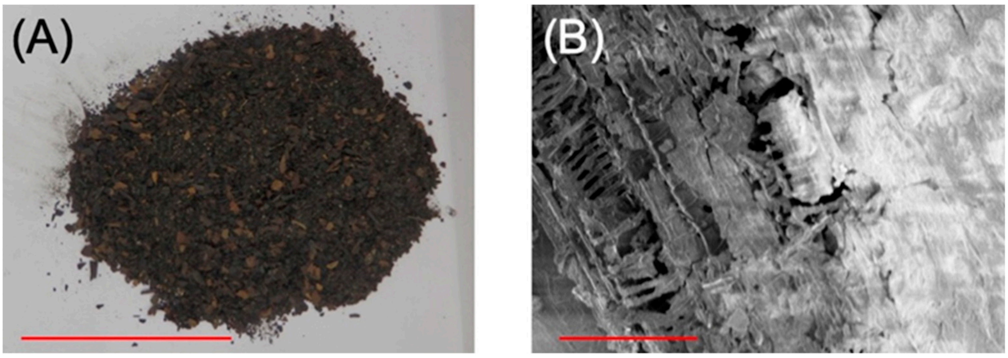

**Figure 3.** (**A**) Top view of the jatropha fallen leaf biochar that was produced by the carbonizer. Red scale bar represents 5 cm. (**B**) Close-up view of the surface of the jatropha fallen leaf biochar observed under an electron microscope. Red scale bar represents 100 μm.

The jatropha fallen leaf biochar had a pH of 9.84 ± 0.08 (Table 1), which was notably higher than that reported by Awasthi et al. [50] for jatropha leaves (pH 8.85). The EC of the biochar produced in this study was 575 ± 108 μS $cm^{-1}$, which was slightly lower than the reported value of 920 μS $cm^{-1}$ for jatropha leaves [50], and the CEC of the biochar was 169 ± 19 mmol $kg^{-1}$, which was higher than the reported average values for wheat/barley biochar (103 mmol $kg^{-1}$) but lower than the average values for corn and rice straw/husk biochar (607 and 212 mmol $kg^{-1}$, respectively) [51].

**Table 1.** Properties of the jatropha fallen leaf biochar produced in this study.

| **Property** | **Value** [1] |
|---|---|
| pH | 9.84 ± 0.08 |
| EC (μS $cm^{-1}$) | 575 ± 108 |
| CEC (cmol $kg^{-1}$) | 16.9 ± 1.9 |
| Element content (mg $kg^{-1}$) | |
| Al | 52,900 ± 700 |
| C | 227,000 ± 12,000 |
| Ca | 18,000 ± 1000 |
| Cd | 1.19 ± 0.03 |
| Co | 16.4 ± 0.2 |
| Cr | 29.8 ± 6.8 |
| Cu | 9.39 ± 0.66 |
| Fe | 5080 ± 340 |
| K | 6220 ± 530 |
| Mg | 741 ± 62 |
| Mn | 617 ± 46 |
| N | 15,000 ± 1000 |
| Ni | 43.4 ± 3.4 |
| P | 1450 ± 230 |
| Pb | 18.0 ± 0.5 |
| Sn | <0.1 |
| Ti | 121 ± 3 |
| Zn | 80.1 ± 6.7 |

[1] Values are means ± standard deviations ($n = 3$). EC, electrical conductivity; CEC, cation exchange capacity.

The chemical constituents of biochars are influenced by the feedstock source and the pyrolysis temperature [29,33]. The jatropha fallen leaf biochar that was produced in the present study had P and K contents of 1450 ± 230 and 6220 ± 530 mg $kg^{-1}$, respectively (Table 1), which were higher than the reported average values for rice straw/husk biochar (1200 and 700 mg $kg^{-1}$, respectively) but lower than those for corn biochar (2350 and 19,000 mg $kg^{-1}$, respectively) [51].

High concentration of Al was observed in fallen leaf biochar (52,900 ± 700 mg $kg^{-1}$). Reasons for this high abundance is currently unknown; one possibility is that jatropha fallen leaves feedstock might be contaminated with Al-rich soil particles during harvest in the field. Alternatively, Al in fallen leaf biochar might be derived from intrinsic Al accumulated within jatropha leaves, although absorption and accumulation of Al in plant leaves are normally inefficient due to its phytotoxicity. The third possibility is that Al might be derived from leaching from the surface of the used oil drum. Although we extensively washed the inside of drum before usage, this possibility is not totally excluded. Origin of Al in the fallen leaf biochar should be examined in future studies.

### *3.2. Effects of Jatropha Fallen Leaf Biochar on Vegetable Growth in an Acidic and Undernourished Soil*

The experimental soil that was collected from Selebi-Phikwe, Botswana, was highly acidic, with a pH of 3.39 ± 0.03 (Table 2), and it is well known that crop growth is generally retarded in acidic soils [52,53]. Furthermore, the experimental soil contained markedly lower contents of the major nutritious elements (e.g., P, 2.67 ± 0.91 mg $kg^{-1}$; K, 5.87 ± 2.76 mg $kg^{-1}$; Ca, 98.2 ± 8.5 mg $kg^{-1}$; and Mg, 20.7 ± 12.0 mg $kg^{-1}$; Table 2) than typical soils [54], suggesting that it was poor in nutrients. By contrast, the contents of Cu (772 ± 8 mg $kg^{-1}$) and Ni (249 ± 2 mg $kg^{-1}$) were particularly high in the experimental soil (Table 2).

**Table 2.** Properties of the experimental soil used in this study.

| **Property** | **Value** [1] |
|---|---|
| pH | 3.39 ± 0.03 |
| Organic carbon (%) | 0.12 ± 0.00 |
| Nitrogen content (mg $kg^{-1}$) | |
| $NO_3^-$ | 0.12 ± 0.04 |
| $NH_4^+$ | 0.10 ± 0.01 |
| Element content (mg $kg^{-1}$) | |
| Al | 69,400 ± 900 |
| Ca | 98.2 ± 8.5 |
| Cu | 772 ± 8 |
| Fe | 38,300 ± 100 |
| K | 5.87 ± 2.76 |
| Mg | 20.7 ± 12.0 |
| Ni | 249 ± 2 |
| P | 2.67 ± 0.91 |
| Zn | 40.4 ± 0.2 |

[1] Values are the means ± standard deviations of three samples for all parameters except pH and organic carbon, which were derived from two samples.

To examine the effect of jatropha fallen leaf biochar as a soil amendment, the biochar was applied to the experimental soil at rates of 3%, 5%, and 10% (*w*/*w*) and the growth of Swiss chard was examined. Swiss chard was chosen as a model crop because it is one of the major vegetables grown in Botswana. Plants that were grown in soil containing 5% and 10% biochar had significantly longer leaves than control plants at both 28 days after transplantation (DAT) (7.33 ± 0.58 cm and 9.67 ± 0.58 cm, respectively, versus 5.67 ± 0.58 cm, corresponding to 1.29 and 1.71 fold increases) and 44 DAT at harvest (9.33 ± 1.53 cm and 11.0 ± 1.00 cm, respectively, versus 6.00 ± 1.00 cm, corresponding to 1.56 and 1.83 fold increases) (Figure 4A).

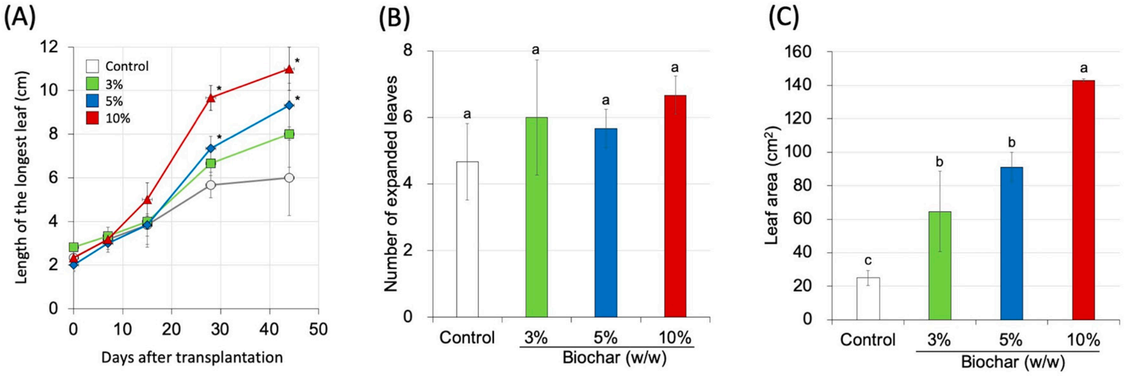

**Figure 4.** Effects of jatropha fallen leaf biochar application to the experimental soil on the growth of Swiss chard plants. Biochar was applied to the experimental soil at three levels (3%, 5%, and 10% (*w*/*w*)) and the growth of Swiss chard plants in the amended soils and unamended control soil was compared. (**A**) Temporal changes in the length of the longest leaf after transplantation in the biochar-amended soils. (**B**) Number of expanded leaves and (**C**) total leaf area per plant at harvest (44 days after transplantation). Values are means ± standard deviations ($n = 3$ plants). Significant differences are indicated by asterisks in (**A**) (*t*-test, $p < 0.05$) and different letters in (**B**,**C**) (Holm's test, $p < 0.05$).

The plants were harvested at 44 DAT and the number of leaves, total leaf area, and dried biomass weight were measured. Plants grown in soils supplemented with 3%, 5%, and 10% biochar had a similar total number of leaves to control plants (6.00 ± 1.73, 5.67 ± 0.58, and 6.67 ± 0.58 leaves, respectively, versus 4.67 ± 1.15; Figure 4B) but 2.58, 3.64, and 5.71 fold higher leaf areas, respectively, than the control plants (Figure 4C). Furthermore, although biochar treatment had no significant effect on the root dry biomass weight, the shoot and the total dry biomass weights were 1.57, 1.88, and 2.32 fold higher in the 3%, 5%, and 10% biochar-amended soils, respectively, compared with the unamended control soil (Figure 5). These observations indicate that the application of jatropha fallen leaf biochar to the acidic experimental soil improved the growth performance of stalk and leaves of Swiss chard.

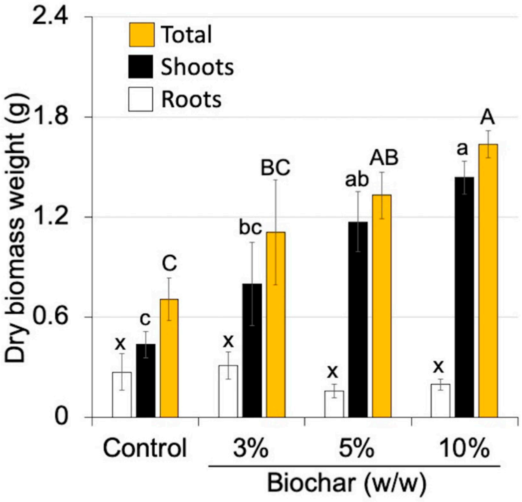

**Figure 5.** Effects of jatropha fallen leaf biochar application to the experimental soil on the dry biomass weight of Swiss chard plants at harvest (44 days after transplantation). Values are means ± standard deviations of three independent plants. Sets of bars with different letters are significantly different (Holm's test, $p < 0.05$).

The improved growth performance of Swiss chard in the biochar-amended experimental soils prompted us to examine the soil conditions and foliar mineral contents of the plants after harvest.

Biochar application caused the acidic experimental soil (pH 4.03 ± 0.21) to become more neutral in a concentration-dependent manner, reaching pH 6.62 ± 0.28 in the soil containing 10% biochar (Figure 6A). Furthermore, although the soil $NH_4^+$ levels were not affected by biochar application, the 5% and 10% biochar treatments resulted in a small but significant increase in the $NO_3^-$ concentration (Figure 6B,C), suggesting that biochar application improved the nitrogen availability. Examination of the foliar mineral levels at harvest showed that the majority of minerals were not significantly affected by the biochar treatment, but potassium exhibited 2.17, 3.76, and 4.00 fold increases following the application of 3%, 5%, and 10% biochar, respectively (Table 3), which may reflect the relatively high potassium content of the jatropha fallen leaf biochar that was used in this study (6220 ± 530 mg kg$^{-1}$; Table 1).

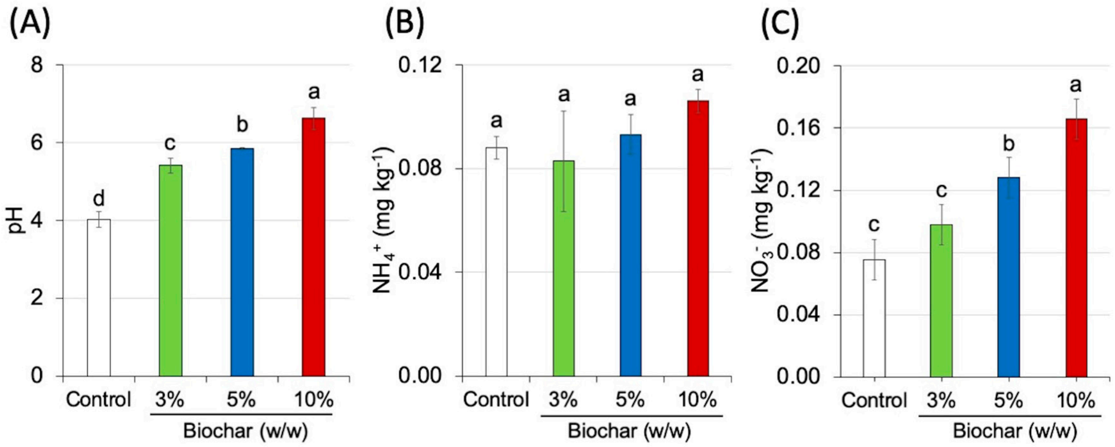

**Figure 6.** Soil pH and concentration of major inorganic nutrients in the jatropha biochar-amended soils at the time of harvest. The soil pH (**A**) and ammonium ion (**B**) and nitrate ion (**C**) contents are shown. Values are means ± standard deviations ($n$ = 3 pots). Bars with different letters are significantly different (Holm's test, $p < 0.05$).

**Table 3.** Amount of minerals in the aerial parts of the Swiss chard plants.

| Mineral | Content (mg plant$^{-1}$)[1] | | | |
|---|---|---|---|---|
| | Control | 3% Biochar | 5% Biochar | 10% Biochar |
| Al | 5.35 ± 1.75 $^{a}$ | 3.23 ± 1.41 $^{a}$ | 3.72 ± 3.72 $^{a}$ | 4.53 ± 2.82 $^{a}$ |
| Ca | 7.79 ± 2.72 $^{a}$ | 6.87 ± 1.96 $^{a}$ | 5.89 ± 2.09 $^{a}$ | 5.98 ± 1.47 $^{a}$ |
| Cu | 0.01 ± 0.01 $^{b}$ | 0.02 ± 0.00 $^{ab}$ | 0.02 ± 0.00 $^{a}$ | 0.01 ± 0.00 $^{ab}$ |
| Fe | 0.41 ± 0.20 $^{a}$ | 0.19 ± 0.10 $^{a}$ | 0.22 ± 0.21 $^{a}$ | 0.30 ± 0.18 $^{a}$ |
| K | 22.0 ± 0.8 $^{c}$ | 47.8 ± 14.5 $^{b}$ | 82.7 ± 14.8 $^{a}$ | 88.1 ± 9.7 $^{a}$ |
| Mg | 0.34 ± 0.04 $^{b}$ | 0.48 ± 0.10 $^{ab}$ | 0.68 ± 0.08 $^{a}$ | 0.68 ± 0.05 $^{ab}$ |
| Mn | 0.38 ± 0.10 $^{b}$ | 0.72 ± 0.24 $^{ab}$ | 0.89 ± 0.16 $^{a}$ | 0.78 ± 0.07 $^{ab}$ |
| Ni | 0.04 ± 0.02 $^{b}$ | 0.15 ± 0.06 $^{ab}$ | 0.20 ± 0.06 $^{a}$ | 0.04 ± 0.01 $^{b}$ |
| P | 23.1 ± 1.9 $^{a}$ | 19.9 ± 6.5 $^{a}$ | 19.8 ± 5.7 $^{a}$ | 21.8 ± 8.9 $^{a}$ |
| Ti | 0.01 ± 0.01 $^{a}$ | 0.00 ± 0.01 $^{a}$ | 0.01 ± 0.01 $^{a}$ | 0.01 ± 0.01 $^{a}$ |
| Zn | 0.27 ± 0.07 $^{a}$ | 0.28 ± 0.07 $^{a}$ | 0.19 ± 0.03 $^{a}$ | 0.15 ± 0.05 $^{a}$ |

[1] Values are means ± standard deviations ($n$ = 3 plants). Values with different letters within a row are significantly different (Holm's test, $p < 0.05$).

### 3.3. Effects of Jatropha Fallen Leaf Biochar on the Soil Moisture Content

The water-holding capacities of the experimental soils supplemented with different amounts of jatropha biochar were evaluated after harvest, by monitoring the pot weight after adding 500 mL of water to 1 kg of the dried soils. The weights of the pots containing biochar-applied soils increased in a concentration-dependent manner at each measurement time point (Figure 7). Furthermore, while the weights of the control pots had returned to their pre-watering levels at four days after water application, the pots that contained soils supplemented with 3%, 5%, and 10% biochar retained 3.3 ± 1.2 g, 16.3 ± 1.2 g, and 42.3 ± 2.1 g more water, respectively. These observations were consistent with those of previous studies [21,55,56] and suggest that the application of jatropha fallen leaf biochar improved the water-holding capacity of the experimental soil.

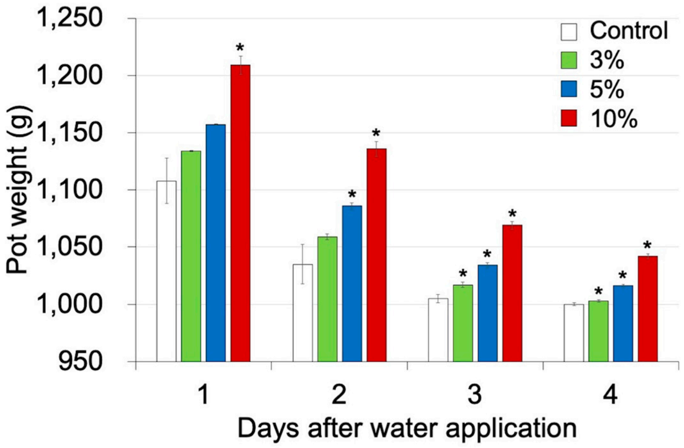

**Figure 7.** Effect of jatropha fallen leaf biochar application on the moisture contents of the experimental soils. The pot weights were measured daily to estimate the rates of water loss from the potted soils. Values are means ± standard deviations ($n$ = 3 pots per biochar concentration). Asterisks indicate significant differences from the control ($t$-test, $p < 0.05$).

## 4. Conclusions

This study described the production of jatropha fallen leaves biochar using a simplified oil-drum carbonizer, based on the auto-thermal process in which partial combustion of the biomass provided the energy necessary for the pyrolysis of the remaining biomass. Internal temperature of the drum was maintained in the range of 100–450 °C, and the resultant products had porous surface structure characteristics for biochar. Application of the biochar to an acidic and undernourished soil significantly improved the growth performance of the model vegetable Swiss chard. These findings suggest that jatropha has potential applications not only for producing renewable energy and industrial products, but also as a feedstock for soil conditioner to improve agricultural production.

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