Macadamia Husk Compost Improved Physical and Chemical Properties of a Sandy Loam Soil

Dembe Maselesele 1, John B.O. Ogola 1,*, and Romeo N. Murovhi 2

1 Department of Crop Science, University of Venda, Private Bag X5050, Thohoyandou 0950, South Africa; dmaselesele@gmail.com
2 Agricultural Research Council, Institute for Tropical and Sub-Tropical Crops, P.O. Box 247, Levalu 0929, South Africa; Romeo@arc.agric.za
* Correspondence: ochanda@univen.ac.za or ochandaogola@yahoo.com; Tel.: +27-15-9629005

Abstract: Poor soil fertility caused mainly by low and declining soil organic carbon is one of the major constraints limiting crop productivity in tropical and subtropical regions of South Africa. We evaluated the effect of macadamia husk compost (MHC) on selected chemical and physical properties of a sandy loam soil in NE South Africa in two successive seasons. The treatments, laid out in randomised, complete block design and replicated four times, were: (i) zero control, (ii) inorganic fertilizer (100:60:60 NPK Kg ha$^{-1}$), (iii) MHC at 15 t ha$^{-1}$, and (iv) MHC at 30 t ha$^{-1}$. Soil bulk density; water holding capacity; soil pH; electrical conductivity (EC); organic carbon; total N; and available P, K, Ca, Mg, Al, Zn, and Cu were determined at 0–15 cm soil depth. Macadamia husk compost application decreased bulk density and increased water holding capacity. MHC and inorganic fertilizer increased soil pH, organic carbon, total N, C:N ratio, available P, exchangeable cations, and micronutrients but the effect was more pronounced under MHC treatments in both seasons. The positive effect of MHC on soil physicochemical properties was associated with an increase in soil organic carbon due to MHC application; hence, MHC may offer a sustainable option of increasing soil productivity, particularly in areas characterised by low SOC.

Keywords: C:N ratio; exchangeable cations; macadamia husk compost; organic matter; soil fertility

1. Introduction

The productivity of cropping systems in the North Eastern (NE) region of South Africa, which is characterised by semi-arid climate, is limited by the physical constraints of inadequate water, high temperatures, and poor soils, amongst other factors. The poor fertility of soils in the region is associated mainly with low and declining soil organic carbon (SOC), which is exacerbated by extreme climatic conditions as well as poor soil management such as continuous monoculture, excessive burning of veld, uncontrolled grazing, and low organic matter application [1]. Most soils in this region have relatively low levels of organic carbon [2,3], which are below the threshold level for sustaining soil quality [4,5]. Poor soil management leads to destruction of ecological soil processes, depletion of soil quality, loss of biodiversity, and direct loss of soil [6]. Therefore, carbon (C) input is usually necessary to either decrease or reverse C loss in agricultural soils.

Increasing carbon inputs through agricultural management is likely to improve the quality of the soil's organic matter [7], soil quality, and crop productivity in NE South Africa. Indeed, the importance of soil organic matter in a soil ecosystem, and more specifically in alleviating soil degradation, has been documented [8]. Greater organic input into the soil has been associated with high soil nutrient concentration, high water retention, and high crop yield [9,10]. Therefore, soil organic input management is important for soil quality improvement and the development of sustainable low agriculture input systems [11] as well as sequestration of atmospheric C that leads to climate change mitigation [12].
Organic materials (such as biochar, compost, and green manure legumes) may be used to improve and/or sustain SOC and consequently soil fertility and productivity of cropping systems, especially in areas characterized by low SOC [2,13–15]. However, most smallholder farmers do not have the capacity to produce biochar nor ready access to biochar manufactured elsewhere. Earlier efforts to incorporate green manure legumes in smallholder farming systems were largely unsuccessful due to their lack of immediate benefits [16]. The use of compost may offer a sustainable option of improving soil organic carbon and soil fertility, especially in smallholder farms. However, the effects of compost vary with soil type, compost type, compost quality, application rate, application method, and the crop being grown [17].

A wide range of raw materials (including crop residues, livestock and poultry manure, and organic wastes) are used as feedstock for production of organic composts. However, the use of compost may be limited by the availability of feedstock material. The northeastern region of South Africa is a major producer of macadamia nuts. After harvesting, the farms generate enormous quantities of organic waste, in the form of macadamia husks (the outer coating of the nut-in-shell), which end up being dumped as waste. Therefore, the use of macadamia husk for making compost would not only contribute to a sustainable improvement of soil fertility and crop productivity, but also provide farmers with a sustainable and cost-effective way to dispose of the macadamia husk waste [18].

Despite the availability of macadamia husks in macadamia-growing areas and the potential benefits of macadamia husk compost (MHC), there is limited information in the literature on the effect of soil-incorporated MHC on SOC and overall soil productivity. For example, in an earlier study [18], macadamia husk was mixed with cattle manure. In another study, MHC was applied as surface mulch rather than being incorporated into the soil [19]. More recently, macadamia husk powder did not affect plant–parasite interactions or beneficial nematodes in a laboratory experiment [20]. Clearly, there is a need for more extensive field studies on the effect of soil-incorporated macadamia husk compost on soil fertility and other soil-related properties, especially in soils characterized by low SOC.

Therefore, the objective of this study was to quantify the effect of soil-incorporated macadamia husk compost on the physicochemical properties of a sandy loam soil under field conditions in NE South Africa. We hypothesized that MHC would improve selected chemical and physical properties of the soil by increasing SOC. To the best of our knowledge, this is the first field study to assess the response of physicochemical properties of a sandy loam soil characterized by low SOC to soil-incorporated MHC.

2. Materials and Methods
2.1. Study Location
A field experiment was conducted at the Agricultural Research Council (ARC) Farm, Levubu (25° 27’ S and 30° 58’ E, and 877 m asl) in Limpopo Province, South Africa in 2018 (season I) and 2019 (season II). The site is characterized by a sandy loam soil classified as Rhodic ferralsols [21]. Levubu receives an annual rainfall of approximately 752 mm, with most of the rain occurring between November and February [22]; as such, the site is characterized by wet summers and dry winters. The daily temperatures in Levubu vary from about 24 °C to 40 °C in summer and between 20 °C and 26 °C in winter with an average minimum and maximum temperature of 10 °C and 30 °C, respectively [22].

2.2. Field Experiment and Sampling Design
The experiment was laid out in a randomized complete block design with four treatments, i.e., zero control, inorganic fertilizer (IF), 15 t ha⁻¹ macadamia husk compost (MHC1), and macadamia husk compost at 30 t ha⁻¹ (MHC2) replicated three times. Individual experimental plot sizes measured 2.7 m × 5 m. The plots were separated by 1 m alleys to avoid encroachment of macadamia husk compost and inorganic fertilizer. The inorganic fertilizer was applied at a rate of 100 kg N ha⁻¹, 60 kg P ha⁻¹, and 60 kg K ha⁻¹, based on previous studies [23]. MHC was incorporated into the soil a month before plant-
ing at a depth of 15 cm and inorganic fertilizer was applied 2 weeks after planting by ringing around Chinese cabbage (*Brassica rapa* L. Chinensis), which was the test crop.

The chemical properties of the MHC used are given in Table 1. The pH of macadamia husk compost was slightly acidic, with a high level of total C; low N; moderate C:N ratio; moderate levels of P, K, Na, Mg, Ca, Mn, and Al; and very low Zn and Cu levels (Table 1). On the basis of the chemical composition, MHC1, supplied 267 kg N ha\(^{-1}\), 855 kg P ha\(^{-1}\), 418.5 kg K ha\(^{-1}\), 570 kg Ca ha\(^{-1}\), 4500 kg Mg ha\(^{-1}\), 249 kg Na ha\(^{-1}\), 42 kg Zn ha\(^{-1}\), 33 kg Cu ha\(^{-1}\), 478.5 kg Mn ha\(^{-1}\), and 474 kg Al ha\(^{-1}\) in each season, with MHC2 supplying double these amounts (Table 1).

### Table 1. Chemical composition of macadamia husk compost.

| Chemical Properties | Values        |
|---------------------|--------------|
| pH (H\(_2\)O)       | 6.6          |
| Total N (g kg\(^{-1}\)) | 17.8        |
| Total C (g kg\(^{-1}\)) | 312        |
| Available P (mg kg\(^{-1}\)) | 570       |
| K (g kg\(^{-1}\))    | 27.9         |
| Ca (g kg\(^{-1}\))   | 380          |
| Mg (g kg\(^{-1}\))   | 300          |
| Na (mg kg\(^{-1}\))  | 166          |
| Zn (mg kg\(^{-1}\))  | 28           |
| Cu (mg kg\(^{-1}\))  | 22           |
| Mn (mg kg\(^{-1}\))  | 319          |
| Al (mg kg\(^{-1}\))  | 316          |
| C:N ratio           | 17.5         |
| Moisture (%)        | 70.7         |

2.3. Determination of Soil Physical Properties

Selected soil physical properties (bulk density and water holding capacity) were determined prior to planting (just after ploughing) and after harvesting in both seasons. Bulk density of the soil was determined using the core method [24]. Soil samples were randomly collected from three points in each experimental plot at 0–15 cm soil depth, on each occasion, using a core sampler with a 98.17 cm\(^3\) core ring (5 cm inner diameter and 5 cm height). The samples were then taken to the laboratory and oven-dried at 105 °C for 24 h. Bulk density was calculated using Equation (1) [24].

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BD = \frac{M}{V},
\]

where BD is dry bulk density (g cm\(^{-3}\)), M is the mass of the dry soil (g), and V is the volume of the soil (cm\(^3\)).

For determination of potential available water (PAW), soil samples were randomly collected, before planting and after harvesting, from three points in each individual plot at 0–15 cm soil depths using a soil augur. The pre-planting samples were bulked together and homogenized while the post-harvest samples were handled per experimental plot. All the samples were taken to the laboratory, air-dried, and sieved through a 2 mm sieve. Water holding capacity of the soil was determined using the filter paper method [25]. In brief, tubes were clamped to the bottom of a funnel that was attached to a ring stand. Thereafter, a filter paper (Whatman No. 42) was placed in the funnel, which was then filled with a 50 g soil sample. Then, 100 mL of water was measured out using a graduated cylinder and was gradually added to the soil sample in the funnel. Samples were stirred gently and let to sit until they were fully saturated. The clamp was released, and excess water was collected in the graduated cylinder, and the PAW was calculated according to [25].
2.4. Determination of Soil Chemical Properties

Selected soil chemical properties (pH; EC; soil organic carbon; total N, P, K, Ca, Mg, Na, Zn, and Mn) were determined prior to planting as well as after harvesting in both seasons. Composite samples were collected from 0–15 cm depths from each plot before planting and were homogenized thoroughly, air-dried, and used for the determination of the initial soil chemical properties. Soil samples were also collected (0–15 cm depth) from each experimental plot; the samples from each plot were analysed separately to evaluate the effects of MHC and IF on the selected soil chemical properties.

Soil pH and EC (1:2, soil/water) were determined using a glass electrode pH meter [26] and a conductivity meter [27], respectively. Soil organic carbon (SOC) was determined using the Walkley and Black method [28]. Total N was determined using the Kjeldahl method [29], and available P was extracted using the Bray I method [30]. The exchangeable cations (K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), and Na\(^{2+}\)) were determined using the ammonium acetate extraction procedure [31], while Zn, Mn, and Al were determined using the EDTA titration method [32].

2.5. Data Analysis

The data were subjected to analysis of variance (single factor ANOVA) using the general linear model (GLM) of GenStat software version 18. Fisher’s least significant difference (LSD) test was used to separate means where significant (\(p < 0.05\)) effects of the treatments were detected. Pearson’s correlation analysis was conducted to assess the relationship between the various physical and chemical properties of the soil.

3. Results

3.1. Physicochemical Properties of Soil before MHC\(_1\) Application

The initial physical and chemical properties of the soil prior to imposing the treatments in 2018 and 2019 are shown in Table 2. In the first season, soil had low pH and bulk density; low levels of N and total C, OM, P, Na, Al, Zn, and EC; moderate levels of Mg, Ca, and Mn; and a high C:N ratio. A similar trend was observed in the second season.

Table 2. Physicochemical properties of soil before macadamia husk compost application at Levubu in 2018 (Year 1) and 2019 (Year 2).

| Soil Properties       | 2018; Year 1 | 2019; Year 2 |
|-----------------------|--------------|--------------|
| pH (H\(_2\)O)         | 6.1 ± 0.02   | 6.2 ± 0.04   |
| Organic C (%)         | 1.1 ± 0.02   | 1.1 ± 0.03   |
| Total N (%)           | 0.04 ± 0.010 | 0.05 ± 0.017 |
| C:N ratio             | 27.0 ± 0.58  | 22.0 ± 1.53  |
| EC (dSm\(^{-1}\))     | 2.3 ± 0.17   | 2.4 ± 0.15   |
| OM (%)                | 1.9 ± 0.02   | 2.0 ± 0.02   |
| Available P (mg kg\(^{-1}\)) | 6.7 ± 0.15 | 8.3 ± 0.20 |
| K (mg kg\(^{-1}\))    | 53 ± 2.08    | 62 ± 0.58    |
| Ca (mg kg\(^{-1}\))   | 483 ± 3.00   | 561 ± 2.65   |
| Mg (mg kg\(^{-1}\))   | 132 ± 1.53   | 144 ± 2.31   |
| Na (mg kg\(^{-1}\))   | 7 ± 1.16     | 10 ± 1.53    |
| Al (mg kg\(^{-1}\))   | 8 ± 1.00     | 10 ± 1.73    |
| Zn (mg kg\(^{-1}\))   | 2.9 ± 0.04   | 3.1 ± 0.23   |
| Mn (mg kg\(^{-1}\))   | 112 ± 1.53   | 128 ± 1.53   |
| Bulk density (g cm\(^{-3}\)) | 1.0 ± 0.01 | 1.0 ± 0.1   |
| Sand (%)              | 69.8 ± 0.12  | 69.4 ± 0.20  |
| Silt (%)              | 3.2 ± 0.12   | 3.2 ± 0.15   |
| Clay (%)              | 27.0 ± 0.06  | 27.4 ± 0.20  |
| Soil textural class   | Sandy loam   | Sandy loam   |
3.2. Effect of Macadamia Husk Compost and Inorganic Fertilizer on Soil Physical Properties

Application of MHC decreased soil bulk density by 20–40% (season 1) and 20–30% (season 2), with greater increases at MHC2 compared to that at MHC1 (Table 3). In contrast, inorganic fertilizer (IF) did not affect soil bulk density in either season (Table 3).

Table 3. Effect of macadamia husk compost and inorganic fertilizer (IF) on soil physical properties in 2018 (Year 1) and 2019 (Year 2).

| Treatments    | Bulk Density (g cm$^{-3}$) | Potential Available Water (%) |
|---------------|----------------------------|-------------------------------|
|               | 2018 (Year 1)              |                               |
| Control       | 1.0 ± 0.00 a               | 16.3 ± 2.08 b                 |
| IF            | 1.0 ± 0.00 a               | 15.7 ± 1.53 b                 |
| MHC1          | 0.8 ± 0.06 b               | 19.7 ± 0.58 a                 |
| MHC2          | 0.6 ± 0.06 c               | 20.3 ± 0.58 a                 |
| LSD (0.05)    | 0.08                       | 2.55                          |
| $p$ (F-test)  | $p < 0.01$                 | $p < 0.01$                    |
| CV (%)        | 4.8                        | 7.7                           |
|               | 2019 (Year 2)              |                               |
| Control       | 1.0 ± 0.01 a               | 11.5 ± 0.70 b                 |
| IF            | 1.0 ± 0.01 a               | 12.0 ± 1.00 b                 |
| MHC1          | 0.8 ± 0.02 b               | 26.0 ± 1.00 a                 |
| MHC2          | 0.7 ± 0.01 c               | 26.3 ± 1.52 a                 |
| LSD (0.05)    | 0.02                       | 2.10                          |
| $p$ (F-test)  | $p < 0.01$                 | $p < 0.01$                    |
| CV (%)        | 1.2                        | 4.8                           |

Values are means ± standard deviation; $n = 12$; within a column, items bearing the same letter are not statistically different; Control = no fertilizer, IF = 100:60:60 kg NPK ha$^{-1}$, MHC1 = Macadamia husk compost at 15 t ha$^{-1}$, MHC2 = Macadamia husk compost at 30 t ha$^{-1}$.

The soil PAW increased with application of macadamia husk compost in both seasons, but the magnitude of the increase was greater in the second season where MHC application more than doubled the water holding capacity of the soil (Table 3). Contrary to the effect of macadamia husk compost, IF did not affect the soil’s water holding capacity in either season (Table 3).

3.3. Effect of Macadamia Husk Compost on Soil Chemical Properties

3.3.1. pH and EC

The application of macadamia husk compost (MHC1 and MHC2) and inorganic fertilizer increased soil pH by 0.1 and 0.27 units, respectively, in the first season (Table 4). In the second season, in contrast, soil pH increased (by 0.54 units) only in plots where 30 t ha$^{-1}$ of macadamia husk compost, MHC2, was applied (Table 5). Unlike soil pH, the effect of macadamia husk compost and inorganic fertilizer on soil salinity was not significant in either season (Tables 4 and 5).
### Table 4. Effect of macadamia husk compost and inorganic fertilizer (IF) on soil chemical properties in 2018 (Year 1).

| Treatments | pH  | SOM (%) | EC (dS m⁻¹) | SOC (%) | Total N (%) | C:N Ratio | P (mg kg⁻¹) | K (mg kg⁻¹) | Ca (mg kg⁻¹) | Mg (mg kg⁻¹) | Na (mg kg⁻¹) | Al (mg kg⁻¹) | Zn (mg kg⁻¹) | Mn (mg kg⁻¹) |
|------------|-----|---------|-------------|---------|-------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Control    | 6.5 ± 0.00 c | 1.4 ± 0.08 c | 1.0 ± 0.21 | 1.0 ± 0.28 b | 0.06 ± 0.02 b | 15.8 ± 2.82 b | 15.3 ± 0.12 d | 80.7 ± 2.16 d | 685.0 ± 3.00 c | 141.7 ± 2.08 d | 21.0 ± 2.00 d | 9.0 ± 0.00 c | 6.1 ± 0.06 c | 49.4 ± 0.43 c |
| IF         | 6.6 ± 0.04 b | 1.7 ± 0.21 c | 1.1 ± 0.16 | 1.2 ± 0.44 b | 0.09 ± 0.02 a | 13.3 ± 3.70 b | 25.1 ± 0.12 b | 134.7 ± 1.53 c | 763.3 ± 2.00 b | 159.3 ± 1.53 c | 25.3 ± 1.15 c | 5.3 ± 0.57 d | 3.4 ± 0.06 d | 48.2 ± 0.32 d |
| MHC1       | 6.8 ± 0.06 a | 2.1 ± 0.15 b | 1.0 ± 0.15 | 1.3 ± 0.18 b | 0.08 ± 0.04 a | 15.8 ± 2.82 b | 22.2 ± 0.15 c | 162.7 ± 2.20 b | 966.0 ± 2.00 b | 254.7 ± 2.31 b | 30.3 ± 1.15 b | 16.0 ± 0.57 b | 7.6 ± 0.00 b | 52.0 ± 0.05 b |
| MHC2       | 6.8 ± 0.02 a | 3.5 ± 0.15 a | 1.0 ± 0.2 | 2.2 ± 0.14 a | 0.09 ± 0.08 a | 38.0 ± 8.72 a | 35.4 ± 0.20 a | 287.0 ± 1.173 a | 1270.6 ± 2.08 a | 274.3 ± 4.04 a | 50.0 ± 2.00 a | 17.7 ± 0.00 a | 9.9 ± 0.06 a | 65.1 ± 0.10 a |
| p (F-test) | p < 0.01 | p < 0.01 | rs | p < 0.05 | p < 0.05 | p < 0.01 | p < 0.01 | p < 0.01 | p < 0.01 | p < 0.01 | p < 0.01 | p < 0.01 | p < 0.01 |
| LSD (0.05) | 0.08 | 0.32 | 0.32 | 0.54 | 0.009 | 10.542 | 0.28 | 3.88 | 4.58 | 5.01 | 3.07 | 0.77 | 0.09 | 0.52 |
| CV (%)     | 0.61 | 7.4 | 15.9 | 18.5 | 2.9 | 24.8 | 0.61 | 1.2 | 0.26 | 1.3 | 5 | 3.4 | 0.74 | 0.51 |

Values are means ± standard deviation; n = 12; within a column, items bearing the same letter are not statistically different; Control = no fertilizer; IF = 100:60:60 kg NPK ha⁻¹; MHC1 = Macadamia husk compost at 15 t ha⁻¹; MHC2 = Macadamia husk compost at 30 t ha⁻¹.

### Table 5. Effect of macadamia husk compost and inorganic fertilizer (IF) on soil chemical properties in 2019 (Year 2).

| Treatments | pH  | SOM (%) | EC (dS m⁻¹) | SOC (%) | Total N (%) | C:N Ratio | P (mg kg⁻¹) | K (mg kg⁻¹) | Ca (mg kg⁻¹) | Mg (mg kg⁻¹) | Na (mg kg⁻¹) | Al (mg kg⁻¹) | Zn (mg kg⁻¹) | Mn (mg kg⁻¹) |
|------------|-----|---------|-------------|---------|-------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Control    | 6.5 ± 0.31 b | 5.0 ± 0.14 c | 0.8 ± 0.57 | 1.4 ± 0.34 b | 0.09 ± 0.00 c | 15.7 ± 1.34 | 15.9 ± 0.14 b | 108.0 ± 5.00 c | 824.5 ± 29.50 b | 167.3 ± 43.54 c | 38.3 ± 0.70 c |
| IF         | 6.9 ± 0.02 a | 5.6 ± 0.06 c | 1.2 ± 0.5 | 2.0 ± 0.49 a | 0.10 ± 0.01 bc | 21.8 ± 5.45 | 19.4 ± 0.66 ab | 156.0 ± 28.21 b | 936.7 ± 66.66 b | 238.7 ± 15.14 bc | 44.3 ± 2.51 b |
| MHC1       | 6.9 ± 0.14 ab | 6.5 ± 0.14 b | 1.2 ± 0.5 | 2.0 ± 0.34 a | 0.11 ± 0.03 b | 19.1 ± 4.06 | 22.6 ± 2.73 b | 243.3 ± 13.32 a | 1283.3 ± 45.09 a | 303.0 ± 47.57 b | 44.8 ± 0.96 b |
| MHC2       | 7.0 ± 0.07 a | 8.1 ± 0.81 a | 1.0 ± 0.0 | 2.2 ± 0.59 a | 0.12 ± 0.04 a | 18.5 ± 4.09 | 25.3 ± 6.34 a | 281.0 ± 34.39 a | 1375.0 ± 190.91 a | 417.0 ± 59.43 a | 54.7 ± 1.44 a |
| p (F-test) | p < 0.05 | p < 0.01 | rs | p < 0.05 | p < 0.05 | rs | p < 0.05 | p < 0.05 | p < 0.01 | p < 0.01 | p < 0.01 |
| LSD (0.05) | 0.47 | 1.26 | 0.6 | 0.87 | 0.008 | 9.45 | 6.13 | 38.9 | 149.9 | 98.02 | 3.38 |
| CV (%)     | 3.1 | 10 | 8.6 | 20.4 | 2.9 | 25.2 | 11.8 | 9.9 | 6.2 | 17.4 | 3.8 |

Values are means ± standard deviation; n = 12; within a column, items bearing the same letter are not statistically different; Control = no fertilizer; IF = 100:60:60 kg NPK ha⁻¹; MHC1 = Macadamia husk compost at 15 t ha⁻¹; MHC2 = Macadamia husk compost at 30 t ha⁻¹.
3.3.2. Soil Organic Carbon, Total N, and C:N Ratio

The application of 30 t ha$^{-1}$ MHC increased SOC in both seasons; in contrast, MHC1 and IF increased SOC in the second season only (Tables 4 and 5).

Total N was significantly increased by MHC1 (2 g kg$^{-1}$) and MHC2 (3 g kg$^{-1}$), relative to the control, in both seasons (Tables 4 and 5). In contrast, the increase (by 3 g kg$^{-1}$; 33%) in total N by IF, relative to the control, was only significant in the first season (Tables 4 and 5). Total N was greater (by 20%; 2 g kg$^{-1}$) at MHC2 compared to IF, but there was no difference in total N between MHC1 and IF in the second season (Table 5).

Application of inorganic fertilizer and 15 t ha$^{-1}$ of macadamia husk compost did not have a significant effect on the C:N ratio in either season (Tables 4 and 5). In contrast, application of 30 t ha$^{-1}$ of macadamia husk compost resulted in a 2.4-fold increase in the C:N ratio in the first season but had no significant effect on the C:N ratio in the second season (Tables 4 and 5).

3.3.3. Available P and Exchangeable Cations

Application of macadamia husk compost increased soil P by 45% (6.0 mg kg$^{-1}$) and 130% (20.1 mg kg$^{-1}$), respectively, for MHC1 and MHC2 in the first season (Table 4). Similarly, soil P was 64% (9.8 mg kg$^{-1}$) greater with inorganic fertilizer application compared with that of the unfertilized control in season 1 (Table 4). Contrary to the first season, IF did not have a significant effect on soil available P in the second season, but application of MHC increased soil available P by 42–59% (6.7–9.4 mg kg$^{-1}$) with the greater increase at MHC2 compared to MHC1 (Table 5).

Both macadamia husk compost and inorganic fertilizer significantly increased soil K content, relative to the unfertilized control, in each of the two seasons (Tables 4 and 5). The increases in soil K due to IF, MHC1, and MHC2 were 67% (54 mg kg$^{-1}$), 102% (82 mg kg$^{-1}$), and 256% (206.3 mg kg$^{-1}$), respectively, over the control in 2018 (Table 4). The corresponding increases in available K content in 2019 were 44% (48 mg kg$^{-1}$), 125% (135.3 mg kg$^{-1}$), and 160% (173 mg kg$^{-1}$), respectively (Table 5).

Soil Ca content was increased by the application of IF (11%; 7.8 g kg$^{-1}$), MHC1 (44%; 30.1 g kg$^{-1}$), and MHC2 (85%; 58.5 g kg$^{-1}$), relative to the zero control, in the first season (Table 4). In the second season, in contrast, IF did not have a significant effect on soil Ca, but MHC increased soil Ca content by 56–67% (4.6–5.5 g kg$^{-1}$) with a greater increase at the higher rate of MHC application (Table 5). A similar trend was observed with Mg in 2018 and 2019 (Tables 4 and 5).

Na content of the soil increased with application of both IF and MHC in the two seasons, but the increase was greater with MHC2 (138% and 43%) compared with MHC1 (44% and 17%) and IF (21% and 16%) in 2018 and 2019, respectively (Tables 4 and 5).

The micronutrients (Al, Zn, and Mn) were assessed only during the first season. Compared to the unfertilized control, IF decreased the concentrations of the micronutrients, but the application of MHC increased Al, Zn, and Mn contents with a greater increase at MHC2 compared to that at MHC1.

4. Discussion

Organic matter is a source of nutrients and microbial activity in the soil, and it affects water holding capacity, soil structure, infiltration rate, soil aeration, and soil porosity [33,34]. The increase in SOC with the addition of compost, including MHC, to the soil has been reported previously and this was attributed to the high organic carbon in the compost [19,35,36] and an increase in the rate of carbon sequestration [14,37,38]. In the current study, the increase in soil organic carbon with compost application was likely due to the high C of the macadamia husk compost (Table 1), which is consistent with recent findings that carbon inputs from compost resulted in greater SOC at lower soil depths [15]. In addition, an increase in SOC with biochar application was associated with the high carbon content of the biochar used [39].
The effect of inorganic fertilizer on soil C is generally less pronounced, particularly in the short-term, since it increases C indirectly by improving crop growth [40]. Consistent with our findings, Lusiba et al. [2] did not observe a significant effect of inorganic fertilizer on SOC in clay (both seasons) and loamy sand (one season) soils in NE South Africa, and Jalal et al. [39] reported no effect of inorganic nitrogen fertilizer on soil carbon in a clay loam characterised by low organic matter. Similarly, soil amended with compost had higher SOC compared to that of soil treated with inorganic fertilizer [41,42].

Macadamia husk compost increased the soil potential available water (PAW) in both seasons, while the effect of inorganic fertilizer was non-significant, as expected. The greater PAW with application of MHC was likely due to a similar increase in soil organic matter [43,44] as reflected by the significant positive correlation between SOM and PAW (Table 6). Organic matter affects water holding capacity by improving soil structure, soil aggregate stability, particle size, and total porosity [45]. However, we did not determine aggregate stability, particle size, and total porosity, which is one of the limitations of the current study. Similar results have been reported with soil surface-applied MHC [19] and other organic wastes [46–49] where the increase in water holding capacity was attributed to increased SOM, but our study is the first to report on the positive effects of soil-incorporated MHC on PAW of sandy loam soil that is characterized by low SOC.

Addition of organic amendments to soil reduces soil bulk density by increasing total soil organic carbon, which causes an increase in stable soil aggregates and soil porosity [2,34,50–53]. In this study, application of macadamia husk compost reduced soil bulk density, probably due to an increase of soil organic carbon (Table 6). Although we did not determine aggregate stability and soil porosity in the current study, the effect of MHC on soil bulk density was consistent with that on WHC.

Soil organic matter and SOC play a significant role in both soil fertility and soil quality management [36,54]. Application of MHC increased total N in the soil, soil available P, exchangeable cations, and micronutrient levels in the soil in the current study (Tables 4 and 5). The observed increase in soil available phosphorus with MHC application was probably due to a similar increase in SOC with MHC application (Tables 4 and 5) and high concentration of P of the MHC (Table 1). MHC supplied 855–1710 kg P ha$^{-1}$ in each season, which may in part explain the greater effect of MHC on soil available P compared to that of IF [55,56]. Moreover, it is likely that MHC released various organic acids, which led to increased P solubilization [57]. In support of the association of high soil available P with high SOC due to MHC application, we observed a highly significant positive correlation between SOC and available P (Table 7). More recently, application of rice straw biochar and rice husk ash led to a significant increase in available P and K in both surface and subsurface soil layers due to the high P and K content of these soil amendments [58].

The application of soil amendments may increase total soil N either through a reduction in soil N losses via leaching and denitrification [59], direct addition of N contained in the soil amendments [58], or an increase in SOC [60]. In the current study, the increase in total soil N due to MHC could be attributed to a combination of the high N content of the MHC (Table 1), increase in SOC as evidenced by the highly significant positive correlation between total N and SOC (Table 7), and a decrease in leaching losses. Although we did not explicitly determine the leaching losses in our study, MHC increased PAW (Table 3). Previous studies with MHC compost have not been conclusive. For example, Cox et al. [19] observed an increase in total N content in the 2–10 cm soil layer due to surface-applied MHC. In contrast, application of 10 t ha$^{-1}$ macadamia husk/cattle manure compost decreased soil nitrate levels and leaf nitrogen content in macadamia orchards [18]. These contrasting results, which are likely due to the huge variability in compost quality, suggests the need for more widespread studies with MHC.
Table 6. Correlation between selected soil physicochemical properties.

| Variables | Bulk Density | WHC | N    | SOC   | OM   | pH   | P    | Ca   | Mg   | K    | Na   | EC   | C:N |
|-----------|--------------|-----|------|-------|------|------|------|------|------|------|------|------|-----|
| Bulk Density | 1          | -0.35 ns | -0.52 ** | -0.89 *** | -0.89 *** | 0.58 ** | -0.10 ns | -0.77 *** | -0.81 *** | 0.84 *** | -0.77 *** | -0.17 ns | -0.10 ns |
| PAW       | -0.35 ns    | 1    | -0.03 ns | 0.56 ** | 0.97 *** | 0.03 ns | 0.15 ns | -0.15 ns | -0.13 ns | 0.42 *    | -0.15 ns | -0.23 ns | 0.46 * |

* = p < 0.05, ** = p < 0.01, *** p < 0.001, n = 12. The significant correlations are highlighted in bold.

Table 7. Correlation between selected soil physicochemical properties.

| Variables | N    | C    | OM   | pH   | P    | Ca   | Mg   | K    | Na   | EC   | C:N  |
|-----------|------|------|------|------|------|------|------|------|------|------|------|
| N         | 1    |      |      |      |      |      |      |      |      |      |      |
| C         | 0.64 ** | 1    |      |      |      |      |      |      |      |      |      |
| OM        | 0.80 *** | 0.56 ** | 1    |      |      |      |      |      |      |      |      |
| pH        | -0.47 ** | 0.61 ** | 0.41 * | 1    |      |      |      |      |      |      |      |
| P         | 0.16 ns | 0.71 *** | 0.65 ** | 0.79 *** | 1    |      |      |      |      |      |      |
| Ca        | 0.25 ns | 0.78 *** | 0.70 ** | 0.66 ** | -0.07 ns | 1    |      |      |      |      |      |
| Mg        | 0.51 ** | 0.73 *** | 0.71 *** | 0.74 *** | 0.19 ns | 0.94 *** | 1    |      |      |      |      |
| K         | 0.24 ns | 0.72 *** | 0.60 ** | 0.41 * | 0.18 ns | 0.90 *** | 0.80 *** | 1    |      |      |      |
| Na        | 0.51 ** | 0.83 *** | 0.77 *** | 0.46 * | 0.03 ns | 0.82 *** | 0.73 *** | 0.84 *** | 1    |      |      |
| EC        | 0.76 *** | -0.28 ns | 0.24 ns | 0.37 ns | 0.13 ns | 0.53 ** | 0.61 ** | 0.41 * | 0.59 ** | 1    |      |
| C:N       | 0.06 ns | 0.77 *** | 0.10 ns | 0.15 ns | 0.50 ** | 0.47 * | 0.31 ns | 0.60 ** | 0.65 ** | -0.11 ns | 1    |

* = p < 0.05, ** = p < 0.01, *** p < 0.001, n = 12. The significant correlations are highlighted in bold.
The increase of exchangeable cations and micronutrients content in soil with compost application was likely due to the high content of these nutrients from the compost (Table 1) [56,61], an increase in adsorption of the cations, and a reduction in leaching losses [58,62]. Consistent with our findings, Bittenbender et al. [18] observed an increase in K, Ca, Mg, and Na with application of macadamia husk/cattle manure compost.

Exchangeable cations and micronutrients levels in the soil were greater in plots amended with MHC compared to those amended with IF, as expected. The IF used in our study supplied only N, P, and K while MHC contained high amounts of exchangeable cations and micronutrients (Table 1). Moreover, organic soil amendments have high cation exchange capacity, which bind more exchangeable cations [58,63]. The increase in exchangeable cations and micronutrients due to inorganic fertilizer application that we observed in the current study was unexpected since the mineral fertilizer used did not contain any exchangeable cations (other than K) or micronutrients.

Application of MHC increased soil pH in the current study probably due to (i) the high pH of the compost used (Table 1), which is consistent with previous findings [18,19], and (ii) a similar increase in exchangeable cations as shown by positive correlations between exchangeable K, Na, Ca, Mg, and soil pH (Table 7). Consistent with our findings, Macil et al. [64] attributed an increase in soil pH of both clay and loamy sand soils with the application of biochar to high ash content and pH of the biochar, and Ojobor et al. [38] concluded that application of rice husk compost increased soil pH due to the exchangeable Ca, Na, and K contained in the compost.

5. Conclusions

Application of macadamia husk compost improved soil fertility (N, P, K, organic C, exchangeable cations, and micronutrients) and overall soil health (pH, PAW, and bulk density). The large increase in SOC was particularly important due to the low SOC at this site. The beneficial effect of MHC on soil fertility and soil health, which was associated with the high content of carbon and other nutrient elements in the compost, was more pronounced at the higher compared to the lower application rate. Macadamia husk compost outperformed inorganic fertilizer, suggesting the huge potential of using MHC as a soil amendment in this region. However, we recommend further studies, which should include the 15–30 cm soil layer, across several sites with contrasting climate, soils, and cropping systems and in-depth analysis of soil physicochemical properties (e.g., aggregate stability, particle size, porosity, sodicity, etc.) that were not assessed in the current study.

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