

Article

Impact of Different Macadamia Husk Compost (MHC) Application Rates on Leaf Nutrient Content, Tree Yield, and Nut Quality in a Macadamia Nut Orchard

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Abstract

Compost derived from macadamia husks provides a sustainable alternative for improving soil fertility, nutrient uptake, and crop productivity. This study evaluated the effects of different macadamia husk compost (MHC) application rates on nut yield, nut quality, and leaf nutrient concentration in macadamia trees. Compost application significantly ($p < 0.05$) increased leaf potassium (K), magnesium (Mg), and zinc (Zn) concentrations, with the highest values recorded at 12 t ha⁻¹. Other nutrients (N, P, Ca, Cu, Mn, Fe, and B) were not significantly affected. Nut yield increased with compost application, with the highest yield observed at 12 t ha⁻¹ (63.10 kg tree⁻¹), followed by 8 t ha⁻¹, 4 t ha⁻¹, and the control. Similarly, nut-in-shell yield improved with increasing compost rates. Compost application enhanced key nut quality parameters, including sound kernel recovery, total kernel recovery, and first grade nuts, while maintaining insect damage and immature nuts within acceptable industry standards. Overall, nut quality improved in 2022 compared to 2021. These findings demonstrate that macadamia husk compost is an effective organic amendment for improving yield, nut quality, and selected leaf nutrient concentrations, contributing to sustainable macadamia production.

Keywords: South Africa; subtropical climate; nutrient uptake; sustainable agriculture; crop performance; soil fertility management

1. Introduction

Macadamia production in the subtropical Vhembe District in South Africa faces several agronomic challenges, primarily poor soil fertility and inadequate rainfall. To overcome these limitations, farmers often rely on inorganic fertilizers, which, although effective, are associated with environmental degradation and potential health risks [1]. Local farmers have identified both limited access to commercial fertilizers and a shortage of organic manure as key factors contributing to declining soil fertility. According to Du Preez et al. 2011 [2], South African soils are generally characterized by low organic matter content, although this varies with geographic location and climatic conditions. Despite these limitations, South Africa remains the world's largest producer of macadamia nuts, and its output is highly valued for meeting strict international quality standards [3]. Statistics in 2025 showed that the annual production was estimated at 87,000 metric tons for South Africa, with orchards expanding in Limpopo, Mpumalanga, KwaZulu-Natal, and the Eastern Cape [4].



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Several studies have linked macadamia yield and nut quality to factors such as soil preparation, climatic conditions, altitude, fertilization, irrigation practices, and harvesting techniques [5]. According to Cavaletto, [6], quality can be broadly defined as the set of attributes that confer value or a degree of excellence to a product. In the case of macadamia nuts, however, quality definitions vary across international markets. For instance, the United States market emphasizes food safety standards, while European markets prioritize low chemical residue levels. In contrast, the Chinese market values large nut size and a lower proportion of unsound kernels [7–10]. For the purposes of this study, macadamia nut quality was assessed based on specific parameters, including sound kernel recovery (SKR), unsound kernel recovery (USKR), total kernel recovery (TKR), first grade nuts (1st G), commercial grade (COM), early insect damage (EID), late insect damage (LID), and the number of immature nuts (IN). Beyond its effects on yield and quality, compost applications have been widely recognized for enhancing nutrient uptake, thereby improving overall crop performance [11,12]. This benefit is largely attributed to compost's richness in essential nutrient elements, which serve as fundamental building blocks for plant growth and tree productivity [13]. Leaf nutrient analysis plays a crucial role in macadamia cultivation by directly assessing the nutritional condition of the trees. It helps determine if the nutrients applied through soil amendments are effectively absorbed and used by the plant. While soil tests show the nutrients available in the soil, leaf analysis reveals what the tree takes up, uncovering hidden deficiencies or imbalances that might restrict growth, yield, and nut quality. In recent decades, considerable efforts have been directed toward reducing the reliance on synthetic fertilizers by promoting the development and use of compost derived from organic materials [14–16]. Compost is decomposed organic matter that has undergone biological breakdown into simpler organic and inorganic compounds through composting [17]. Compost is produced from the biological conversion of organic residues into a soil-like material that functions as a nutrient-rich fertilizer. Compost not only contributes to soil fertility but also promotes nutrient cycling by stimulating microbial activity, thereby supporting plant nutrition [17,18].

A key advantage of compost application is its content of essential macronutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), which are critical for crop growth and development [19,20]. For enhancing both yield and quality while promoting sustainability in agricultural systems, the use of compost is increasingly recognized as a vital management practice. Moreover, compost can address common challenges faced by farmers, particularly the decline in soil fertility [21]. The presence of beneficial microorganisms in compost further enhances plant resilience, helping crops better withstand environmental stress and disease pressure [22]. One notable initiative toward sustainable macadamia production is the use of compost derived from macadamia husks. Many farmers have begun replacing synthetic fertilizers with macadamia husk compost in their orchards, citing positive impacts on soil fertility and crop performance [16,23]. However, despite these benefits, there remains no established consensus on the optimal application rate of macadamia husk compost needed to maximize soil fertility and enhance both yield and nut quality. The application of macadamia husk compost has the potential to modify key soil properties, thereby supporting the growth and productivity of macadamia trees. Like other tree crops, macadamias require regular fertilization to meet their nutritional demands and ensure optimal yield. These nutrients can be supplied through either organic or inorganic fertilizers. Notably, macadamia trees require relatively low levels of P and calcium (Ca), but high levels of iron (Fe). Iron deficiency can lead to reduced canopy density and, in severe cases, tree dieback [24].

Compared to inorganic fertilizers, compost applications are increasingly regarded as a superior alternative for farmers aiming to improve crop productivity [25]. Compost supplies a broad spectrum of essential nutrients that support optimal plant development [26,27]. For instance, Gamal, 2009 [28] reported that higher compost application rates significantly enhanced corn crop quality, while [29] found that fruit yield in tomato plants treated with compost was increased compared to untreated controls. However, to be effective, the compost application rate must be sufficient to improve soil fertility without negatively affecting crop yield or product quality. In macadamia production, achieving this balance is particularly important. Therefore, this study aimed to evaluate the effects of different macadamia husk compost application rates on nut yield, nut quality, and leaf nutrient content in macadamia trees.

2. Materials and Methods

2.1. Characteristics of the Study Site

The study was conducted at the Agricultural Research Council (ARC) research farm in Levubu, Limpopo Province, South Africa (23.085° S, 30.284° E). The area experiences a subtropical climate with an average annual rainfall of 752 mm and temperatures ranging from 10 °C to 40 °C. The soil is classified as a sandy loam Rhodic Ferralsol. The average relative humidity is about 52%. Notably, the area is generally frost-free, making it highly suitable for the cultivation of subtropical crops, including macadamia.

2.2. Experimental Design and Treatments

The field experiment was arranged in a Completely Randomized Block Design (RCBD) with four treatments and four replications, resulting in a total of 16 experimental plots. Prior to establishing the treatments, random soil samples were collected at the experimental site to characterize the soil for selected physical and chemical properties (Table 1). The treatments comprised a control (no organic amendment) and three application rates of macadamia husk compost: 4, 8, and 12 t ha⁻¹. Each plot contained three uniformly managed macadamia (*Macadamia integrifolia*) trees, and the compost treatments were applied uniformly by plot according to the assigned treatment level. The compost material was applied in August 2020 and August 2021 using a banded surface application method, strategically placed within the active root zone to maximize nutrient uptake efficiency and minimize nutrient loss through volatilization. The band application was approximately 1–2 m wide, compost was applied to the soil surface without as a mulch without incorporation. The compost formulation consisted of macadamia husk (35%), wood chips (35%), and pine bark (30%) by volume. These proportions were selected based on the complementary physicochemical properties of the components. The orchard was irrigated using a microsprinkler irrigation system according to standard farm management practices. Irrigation scheduling was done two times a week for 4 h to avoid water stress. All treatments received the same irrigation water throughout the study period. Macadamia husk is rich in carbon and stimulates microbial biomass; pine bark and wood chips enhance moisture retention, aeration, and gradual nutrient release due to their high lignocellulosic content and slow decomposition rates. This mixture was composted under controlled conditions prior to field application to promote partial decomposition, reduce phytotoxicity, and enhance microbial activity.

Table 1. Soil properties of the experimental site.

Soil Properties	Values
pH (H ₂ O)	6.06
Organic C (%)	1.19
Total N (%)	0.04
C:N ratio	27.1
EC (dSm ^{−1})	2.3
OM (%)	2.12
Available P	11.43
K (mg kg ^{−1})	122
Ca (mg kg ^{−1})	920
Mg (mg kg ^{−1})	220
Na (mg kg ^{−1})	7
Al (mg kg ^{−1})	6.9
Zn (mg kg ^{−1})	112
Mn (mg kg ^{−1})	0.68
Sand (%)	65
Clay (%)	8
Silt (%)	27
Soil textural class	Sandy loam soil

EC = Electrical Conductivity, OM = Organic Matter, P = Phosphorus, K = Potassium, Ca = Calcium, Mg = Magnesium, Na = Sodium, Al = Aluminum, Zn = Zinc, Mn = Manganese.

2.3. Compost Preparation and Analysis

Fresh macadamia nut husks were collected from processing facilities during the commercial harvest period, which typically spans May to July in the Levubu region. The raw husks were manually stockpiled into aerated static piles, approximately 2.0 m in height and 2.5 m in base diameter, situated on a concrete platform to prevent nutrient leaching and facilitate drainage. To promote aerobic microbial activity and ensure homogeneity of the composting mass, the piles were mechanically turned once weekly during the initial thermophilic phase (first four weeks) and thereafter biweekly during the mesophilic and maturation phases for a total active composting duration of five months. Moisture content was maintained within the optimal range (50–60%) using a sprinkler irrigation system, operated twice weekly, to sustain microbial metabolic activity and control pile temperature. The composting process was conducted under open-field conditions with passive aeration and monitored for nine (9) months, allowing sufficient time for lignocellulosic breakdown and stabilization of the organic matter.

At the end of the composting period, composite samples ($n = 3$) of the mature compost were collected from multiple points within each pile using a stratified random sampling method and homogenized for laboratory analysis (Table 2). The samples were air-dried, sieved to 2 mm, and analyzed for key chemical parameters using standard analytical protocols. pH and electrical conductivity (EC) were measured in a 1:2.5 compost-to-distilled water suspension following the Food and Agriculture Organization [30]. Macronutrients, including total N, were analyzed by Kjeldahl digestion [31]; available P and exchangeable K were determined using Mehlich-3 extraction [32] followed by inductively coupled plasma optical emission spectrometry (ICP-OES). Secondary nutrients and micronutrients—calcium, magnesium, sodium, sulfur, iron, zinc, manganese, copper, and boron—were also quantified via ICP-OES following acid digestion [33]. Total organic carbon (C) was measured using the Walkley–Black dichromate oxidation method [34], and the carbon-to-nitrogen (C:N) ratio was calculated accordingly. These parameters were used to evaluate compost maturity, nutrient availability, and the suitability of macadamia husk compost as a soil amendment in subtropical orchard systems.

Table 2. Chemical composition of macadamia husk compost.

Chemical Properties	Values
pH (H ₂ O)	6.6
Total N (%)	1.78
Total C (%)	31.2
Available P (mg kg ^{−1})	570
K (mg kg ^{−1})	27.9
Ca (mg kg ^{−1})	380
Mg (mg 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

Total N = total nitrogen; Total C = total carbon; Available P = available phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Na = sodium; Zn = zinc; Cu = copper; Mn = manganese; Al = aluminum; C:N ratio = carbon-to-nitrogen ratio.

2.4. Leaf Sampling and Analysis

Leaf tissue sampling was conducted in accordance with the Agricultural Research Council (ARC-TSC) protocol for macadamia nutrient diagnostics. Leaf samples were collected in November 2021 and November 2022 from each selected tree within the experimental plots. Sampling was conducted during the post-flowering/nut development period, which is the standard timing recommended for macadamia leaf nutrient assessment because nutrient concentrations are relatively stable and suitable for comparison with established sufficiency standards. Following the method described by [35], the fourth pair of leaves from the first fully expanded leaf whorl on non-fruiting terminals of primary branches was selected for sampling, ensuring consistency across all trees and treatments. Immediately after collecting, the leaves were rinsed with distilled water to remove surface contaminants (e.g., dust and pesticide residues), and then oven-dried at 70 °C for 60 h to achieve constant weight. The dried samples were ground into a fine powder using a Wiley mill (1 mm sieve), purchased from MCL (Monitoring and Control Laboratories) in Johannesburg South Africa, to facilitate homogeneity for chemical analysis. Prepared samples were analyzed for total carbon, total N, P, K, Ca, Mg, Zn, Fe, Cu, Mn, and B. These foliar nutrient contents were used to assess the nutritional status of macadamia trees under different compost amendment treatments.

2.5. Macadamia Harvesting and Yield Determination

Nut yield was quantified after the harvesting season, which occurs annually between May and July in the Levubu region. The study utilized the ‘Beaumont’ cultivar, characterized by a late-maturing phenology and a strong nut-pedicel attachment that prevents natural nut abscission at maturity. To facilitate uniform nut drop, trees were chemically induced using ethephon (2-chloroethylphosphonic acid) from Rochele chemicals and lab in Johannesburg South Africa, a plant growth regulator known to stimulate ethylene release and accelerate abscission. A solution of 600 mL Ethephon 480 SL was diluted in 400 L of water and applied as a canopy spray using high-pressure sprayers. Nut detachment typically occurred within 7 days post-application. Nuts remaining attached to the canopy were manually dislodged using bamboo poles to minimize mechanical damage and maintain consistency across treatments.

Harvested nuts were collected into ventilated field crates, then transported to the post-harvest processing facility. At the packhouse, nuts were stored temporarily in aerated wooden bins prior to processing. Nuts-in-husk (NIH) were subsequently subjected to mechanical de-husking, a process involving the mechanical separation of the exocarp and mesocarp (husk) from the endocarp (shell) using a rotating drum de-husking unit. The de-husked nuts were sorted, weighed, and recorded for yield analysis. The discarded husk material, constituting a significant organic by-product, was collected and transported to the composting site.

2.6. Nut Quality Analysis

A representative nut sample of approximately 3 kg was collected from each treatment replicate after harvest and submitted to Royal Macadamia (Levubu, South Africa) for post-harvest quality evaluation. The samples were mechanically cracked to separate the kernel from the shell, after which the kernels were graded and sorted into quality classes according to standard industry protocols. Nut quality was evaluated following standard grading methods used in the macadamia industry. Sound Kernel Recovery (SKR) indicated kernels that were healthy and free of defects, while Unsound Kernel Recovery (USKR) covered kernels showing signs of insect damage, mold, germination, discoloration, or immaturity. Total Kernel Recovery (TKR) was obtained by adding SKR and USKR together. Nuts classified as First Grade (1st G) met premium quality criteria, whereas Commercial Grade (COM) nuts were suitable for processing but did not fulfill first-grade requirements. Early Insect Damage (EID), Late Insect Damage (LID), Early Germination (EG), and Immature Nuts (IN) were identified through visual inspection. All quality measures were reported as a percentage of the total sample weight. Each component was weighed, and quality data was calculated and expressed as a percentage of the total in-husk nut mass for consistency across treatments. This allowed for comparison of nut quality performance as influenced by the compost application rates. In addition to kernel grading, the macadamia nutshell, a by-product of the de-husking and cracking process, was noted for its potential secondary value in industrial applications, including use as a carbon filter, biomaterial precursor, nano-powder feedstock, and renewable energy source (e.g., biochar or charcoal).

2.7. Data Analysis

Analysis of variance (ANOVA) was performed on leaf nutrient content, yield, and nut quality data using the General Linear Model (GLM) procedure of GenStat version 17 (VSN International, Hemel Hempstead, UK). Mean comparisons were conducted using Fisher's Least Significant Difference (LSD) test when treatment effects were significant at $p < 0.05$.

3. Results

3.1. Macadamia Nut and Husk Yields

Treatment had a statistically significant effect ($p < 0.05$) on both nut-in-husk (NIH) yield and nut-in-shell (NIS) yield. However, no significant treatment effect was observed for husk yield (Table 3). Additionally, neither year nor the year $\times$ treatment interaction significantly influenced any of the measured yield components. Table 4 shows the influence of macadamia husk compost application rate on NIH yield, NIS yield and husk biomass per tree. Compost application significantly affected both NIH and NIS yields ($p < 0.05$), indicating a positive effect of compost amendment on nut productivity. In contrast, husk yield was not significantly affected by treatment ($p > 0.05$), suggesting that compost application enhanced economic yield rather than total husk biomass production. The highest NIH yield was recorded at 12 t ha⁻¹ (63.10 kg tree⁻¹), while the control treatment produced the lowest yield (42.90 kg tree⁻¹). The 4 and 8 t ha⁻¹ treatments resulted in intermediate

yields (51.09 and 57.22 kg tree⁻¹, respectively). According to the LSD mean separation test, the 12 t ha⁻¹ treatment differed significantly from the control, whereas the 4 and 8 t ha⁻¹ treatments did not differ significantly from either the control or the highest compost rate. Similarly, NIS yield increased with compost application rate. The highest NIS yields were obtained at 12 t ha⁻¹ (30.40 kg tree⁻¹) and 8 t ha⁻¹ (25.05 kg tree⁻¹), which did not differ significantly from each other but were significantly higher than the control (17.75 kg tree⁻¹). The 4 t ha⁻¹ treatment (20.47 kg tree⁻¹) was intermediate and did not differ significantly from either the control or the higher compost rates. No significant year effect was observed for any yield component, among NIH, HUSK, and NIS in the year 2021 or 2022 (Table 5). Although NIH consistently produced higher numerical yields than HUSK and NIS, all treatments were statistically similar.

Table 3. Mean square values from analysis of variance (ANOVA) for macadamia yield parameters.

Source of Variation	df	NIH (kg)	Husk (kg)	NIS (kg)
Year (Y)	1	110.45 ns	140.07 ns	1.64 ns
Treatment (T)	3	597.44 *	148.80 ns	238.91 *
Y × T	3	0.001 ns	17.36 ns	14.58 ns
Error	18	91.67	53.01	63.92

df = degrees of freedom; NIH = nut-in-husk yield; NIS = nut-in-shell yield; Y = year; T = treatment; Y × T = interaction between year and treatment; * indicates significance at $p \leq 0.05$; ns = not significant.

Table 4. Effect of different levels of macadamia husk compost on the nut and husk yield.

Treatment (t ha ⁻¹)	NIH (kg)	Husk (kg)	NIS (kg)
Control (0)	42.90 ^b	23.65 ^a	17.75 ^b
4 t ha ⁻¹	51.09 ^{ab}	30.62 ^a	20.47 ^{ab}
8 t ha ⁻¹	57.22 ^{ab}	32.17 ^a	25.05 ^a
12 t ha ⁻¹	63.10 ^a	33.24 ^a	30.40 ^a

Means within each parameter with similar letters are not significantly different by the LSD (T-Grouping test) at 5% ($p < 0.05$) level of probability, NIH = nut-in-husk, NIS = nut-in-shell.

Table 5. Main effect of year on nut and husk yield across macadamia husk compost application rates.

Year	NIH (kg)	HUSK (kg)	NIS (kg)
2021	55.43 ± 19.26 ns	32.01 ± 11.64 ns	24.44 ± 8.61 ns
2022	51.72 ± 20.8 ns	27.83 ± 12.26 ns	23.15 ± 9.64 ns

ns = not significant, NIH = nut-in-husk, NIS = nut-in-shell.

3.2. Macadamia Nut Quality

Table 6 shows the effect of macadamia husk compost levels on nut quality. Application of macadamia husk compost significantly influenced key nut quality parameters (Table 6). The highest first grade nut percentage was observed with 12 t ha⁻¹ compost. While immature nuts (INs) were lowest in the control, commercial-grade nuts (COM) and early insect damage (EID) did not differ significantly among treatments (Table 7). The highest values, although not statistically significant, were observed at the 12 t ha⁻¹ compost application rate, with shelling kernel (SKR) at 24.45% and TKR at 28.1%. These values fall within the recommended industry standards of 20–30% for SKR and 25–30% for TKR. Similarly, the percentage of first grade nuts peaked at 21.15%, which is within the optimal range of 15–25%. The percentage of USKR remained below the acceptable threshold of 6% across treatments. While LID decreased with compost application, the lowest proportion of IN occurred under the 12 t ha⁻¹ rate (Table 7). However, no statistically significant differences were found among treatments for COM and EID. These results suggest that compost applications, particularly at higher rates, enhance macadamia nut quality while

maintaining pest-related damage within acceptable limits. Table 8 presents the effect of macadamia husk compost on nut quality parameters over two consecutive years. Apart from first grade nuts and total kernel recovery, most quality parameters showed notable improvement in 2022 compared to 2021. The proportion of late insect damage (LID) was significantly lower in 2022, while early germination (EG) was numerically lower but not significantly different between years indicating a positive trend toward better nut quality over time. SKR sound kernel recovery increased significantly from 16.58% in 2021 to 22.33% in 2022, indicating improved kernel development and processing quality. Unsound kernel also increased significantly, from 3.98% to 5.92%, suggesting a rise in defective kernels despite improvements in other parameters. Although TKR values differed numerically between years (28.47% in 2021 and 28.25% in 2022), the difference was not statistically significant, and both values remained within the recommended industry standard range for macadamia kernel recovery. The first grade significantly decreased from 21.73% to 18.62%, a decline that may reflect an increase in unsound kernels in 2022. COM increased significantly (from 2.57% to 3.71%), suggesting improved classification or sorting efficiency. EID and LID significantly decreased in 2022, while EG showed a numerical decrease but was not significantly different between years. Immature nuts significantly increased from 0.28% to 1.20%, possibly due to environmental stress or uneven maturity during harvest.

Table 6. Mean square of analysis of variance for macadamia nut quality parameters.

Source	Df (%)	SKR (%)	USKR (%)	TKR (%)	1st G (%)	COM (%)	EID (%)	LID (%)	EG (%)	INs (%)
Year (Y)	1	40.79 **	30.13 **	0.39 **	22.35 **	10.48 **	65.84 **	447.75 **	13.38 ns	6.26 **
Treatment (T)	3	15.48 **	3.91 **	5.06 **	8.35 *	0.28 *	5.17 ns	135.85 **	16.74 ns	0.15 **
Y × T	3	1.93 ns	1.29 ns	1.32 ns	4.72 ns	1.58 ns	0.11 ns	5.27 ns	1.19 ns	0.32 ns

** significant at $p < 0.01$ level of probability, * Significant at $p < 0.05$ level of probability, ns = not significant at $p < 0.05$ level of probability, SKR = sound kernel recovery, USKR = unsound kernel recovery, TKR = total kernel recovery, 1st G = first grade, COM = commercial grade, EID = early insect damage, LID = late insect damage, EG = early germination, INs = immature nuts.

Table 7. Effect of different rates of compost on quality parameters of macadamia nuts.

Parameter	Control	4 t ha ⁻¹	8 t ha ⁻¹	12 t ha ⁻¹
SKR (%)	21.8 ^b	24.1 ^a	24.2 ^a	24.5 ^a
USKR (%)	5.7 ^a	5.0 ^{ab}	4.8 ^{ab}	4.2 ^b
TKR (%)	27.4 ^b	28.7 ^a	29.6 ^{ab}	28.8 ^{ab}
1st G (%)	18.9 ^b	20.0 ^{ab}	20.6 ^a	21.2 ^a
COM (%)	3.0 ^a	3.2 ^a	3.3 ^a	3.4 ^a
EID (%)	5.5 ^a	3.9 ^a	4.2 ^a	4.1 ^a
LID (%)	11.7 ^a	8.2 ^b	7.9 ^b	6.5 ^b
EG (%)	6.1 ^a	5.0 ^{ab}	4.5 ^b	3.8 ^b
INs (%)	1.1 ^a	0.9 ^a	1.0 ^a	0.8 ^a

Means within each parameter with similar letters are not significantly different by the T-Grouping test at 5% ($p < 0.05$) level of probability, SKR = sound kernel recovery, USKR = unsound kernel recovery, TKR = total kernel recovery, 1st G = first grade, COM = commercial grade, EID = early insect damage, LID = late insect damage, EG = early germination, IN = immature nuts.

Table 8. Effects of different compost application rates on macadamia nut quality parameters across two years.

Parameter	2021 (Mean ± SD)	2022 (Mean ± SD)	Significance	Interpretation
SKR (%)	16.58 ± 1.29	22.33 ± 2.79	*	Significant improvement in 2022
USKR (%)	3.98 ± 1.07	5.92 ± 1.84	*	Increased unsound kernels in 2022
TKR (%)	28.47 ± 0.96	28.25 ± 1.23	ns	numerical difference is small
1stG(%)	21.73 ± 1.65	18.62 ± 2.53	*	Slight decrease in first-grade nuts
COM (%)	2.57 ± 1.00	3.71 ± 1.14	*	Significant increase in commercial grade nuts

Table 8. Cont.

Parameter	2021 (Mean $\pm$ SD)	2022 (Mean $\pm$ SD)	Significance	Interpretation
EID (%)	6.12 $\pm$ 2.65	3.25 $\pm$ 1.61	*	Significant reduction in early insect damage
LID (%)	12.06 $\pm$ 5.02	4.58 $\pm$ 2.52	*	Significant reduction in late insect damage
EG (%)	5.23 $\pm$ 3.39	3.94 $\pm$ 1.96	ns	Not significantly different
INs (%)	0.28 $\pm$ 0.20	1.20 $\pm$ 0.35	*	Significant increase in immature nuts

* Significant at $p < 0.05$ level of probability, ns = not significant at $p < 0.05$ level of probability, SKR = sound kernel recovery, USKR = unsound kernel recovery, TKR = total kernel recovery, 1st G = first grade, COM = commercial grade, EID = early insect damage, LID = late insect damage, EG = early germination, INs = immature nuts.

3.3. Concentration of Nutrients in the Leaves of Macadamia Trees

The mean square of analysis of variance for leaf nutrient concentration on the leaves of macadamia trees is presented in Table 9. Compost application significantly ($p < 0.05$) increased leaf K, Mg, and Zn concentrations, with the highest values generally recorded at 12 t ha⁻¹. However, year had a significant effect on leaf P, Zn, Cu, and Fe concentrations. Table 10 shows the effect of compost rates on the concentration of macro nutrients in the leaves of macadamia trees amended with different rates of compost (i.e., N, P, K, Ca, and Mg). Application of compost did not have a significant effect on the concentration of micronutrients (Cu, Mn, Fe, and B) on the leaves of macadamia trees except for Zn (Table 11). There was a significant ($p < 0.05$) effect of year on the concentration of P, Zn, Cu, and Fe in the leaves of macadamia trees (Table 12). Maximum leaf P (0.06%), leaf Zn (11.60 mg kg⁻¹), and Cu (3.61 mg kg⁻¹) were observed in 2022, indicating that the concentration of nutrient elements in leaves was increasing with time. Maximum leaf Fe (165.7 mg kg⁻¹) was recorded in 2021 compared with 2022. However, there was no significant difference between the two years (2021 and 2022) with respect to leaf N, K, Ca, N, and B concentration.

Table 9. Mean square of analysis of variance for leaf chemical properties after the application of macadamia husk compost.

Source	Df	P (%)	K (%)	Mg (%)	Zn (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Fe (mg kg ⁻¹)
Year (Y)	1	0.001 *	0.014 ns	0.001 ns	230.43	4.55 **	36,597.3 **
Treatment (T)	3	0.0001 ns	0.009 *	0.0006 *	30.52 *	0.067 ns	324.06 ns
Year x Treatment (Y x T)	3	0.000001 ns	0.00009 ns	0.0002 ns	2.04 ns	0.331 ns	3178.75 ns

** significant at $p < 0.01$ level of probability, * Significant at $p < 0.05$ level of probability, ns = not significant at $p < 0.05$ level of probability, P = phosphorus, K = potassium, Mg = magnesium, Zn = zinc, Fe = iron.

Table 10. Effects of different rates of compost on leaf macro-nutrient concentration.

Nutrient	Observation	Statistical Significance	Interpretation
N	Increased from control to all compost treatments	Not significant (all treatments labeled “a”)	Compost application slightly increased N, but not significantly
P	Slight increases across treatments	Not significant (all “a”)	P levels were low and unaffected by compost rates
K	Increased from control to 12 t ha ⁻¹	Significant difference; control “b”, others “ba” or “a”	Compost improved K concentration, especially at higher rates
Ca	Steady increase across compost treatments	Not significant (all “a”)	No statistical difference, though trend shows compost may improve Ca
Mg	Slight increase with compost	Borderline significance; control “b”, others “ba” or “a”	Compost tends to improve Mg, though variability is high

N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium.

Table 11. Leaf micronutrient concentrations (mg kg^{−1}) in macadamia trees under different compost treatments.

Treatment	Zn (mg kg ^{−1})	Cu (mg kg ^{−1})	Mn (mg kg ^{−1})	Fe (mg kg ^{−1})	B (mg kg ^{−1})
Control	6.79 ± 4.65 ^b	3.32 ± 0.82 ^a	543.1 ± 283.18 ^a	128.37 ± 39.97 ^a	16.34 ± 2.55 ^a
4 t ha ^{−1}	7.73 ± 3.77 ^{ab}	3.07 ± 0.57 ^a	560.5 ± 223.64 ^a	130.59 ± 31.09 ^a	18.27 ± 4.46 ^a
8 t ha ^{−1}	10.46 ± 4.18 ^a	3.29 ± 0.55 ^a	702.5 ± 297.26 ^a	127.35 ± 48.96 ^a	18.18 ± 4.45 ^a
12 t ha ^{−1}	13.22 ± 4.68 ^a	3.17 ± 0.31 ^a	719.8 ± 300.52 ^a	141.21 ± 71.58 ^a	19.78 ± 4.05 ^a

Means within the column with similar letters are not significantly different at 5% ($p < 0.05$) level of probability by the T Grouping test, Mg = magnesium, Zn = zinc, Cu = copper, Mn = manganese, Fe = iron, B = boron.

Table 12. Effects of macadamia husk compost on the concentration of nutrient elements in the two years of study (2021 and 2022).

Year	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Zn (mg kg ^{−1})	Cu (mg kg ^{−1})	Mn (mg kg ^{−1})	Fe (mg kg ^{−1})	B (mg kg ^{−1})
2021	0.86	0.05	0.60	0.64	0.14	6.23	2.84	669.4	165.7	17.81
2022	0.94	0.06	0.64	0.56	0.13	11.60	3.61	593.5	98.06	18.39
Significance	ns	*	ns	ns	ns	*	*	ns	*	Ns

* Significant at $p < 0.05$ level of probability, ns = not significant at $p < 0.05$ level of probability, N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Zn = zinc, Cu = carbon, Mn = manganese, Fe = iron, B = boron.

4. Discussion

4.1. Macadamia Nut Yield and Husks

The study revealed that macadamia husk compost (MHC) significantly ($p < 0.05$) increased nut yield nut-in-husk (NIH) and nut-in-shell (NIS) due to enhanced nutrient availability, improved root development, and greater plant vigor [36]. Compost application at 8 and 12 t ha^{−1} supplied essential macro- (N, P, K, Ca, Mg) and micronutrients (Zn, Mn, Cu, B, Fe), positively affecting various growth and yield parameters. These results are consistent with findings from similar studies on other fruit crops, where compost application increased nutrient uptake and fruit yield. For example, eucalyptus-wood-based compost increased foliar nutrients and avocado yield in South Africa [12], and organic manure treatments significantly enhanced litchi yield and fruit set compared with control in litchi orchards [37,38]. Although no significant yield differences were observed between 2021 and 2022, this was likely attributable to a national decline in macadamia production caused by climatic stress, as temperature and precipitation patterns have been shown to strongly influence macadamia yields [39].

The benefits of the compost may also be attributed to its role in enhancing soil microbial activity and improving soil physical properties that support nutrient cycling and plant growth, increased microbial biomass and nutrient availability following compost and humic acid amendments have been shown to improve root and shoot development in legumes by modulating soil microbial densities and nutrient pools [40]. Humic substances present in organic amendments can stimulate root elongation and lateral root emergence, enhance nutrient uptake, and influence root plasma membrane activity, likely acting as bio-stimulants in the rhizosphere [41]. Although some studies report no significant yield benefit from compost applications, such discrepancies are likely due to differences in compost composition, humification level, and crop species responses under varying soil and environmental conditions [42]. This study highlights the need for further research to quantify humic acids and other bioactive compounds in macadamia husk compost that contribute to its effectiveness as a soil amendment.

4.2. Macadamia Nut Quality

Macadamia husk compost significantly improved the quality of macadamia nuts under field conditions. Trees amended with compost exhibited increased sound kernel recovery, total kernel recovery, and first grade nuts, while reductions were observed in unsound kernel recovery, early and late insect damage, and the number of immature nuts. These quality parameters are critical in determining the commercial value of macadamia nuts and are therefore of significant interest to producers. These findings are consistent with previous studies showing that improved soil fertility and orchard management enhance nut quality by promoting better kernel development and reducing defects [43]. The observed improvements are attributed to the nutrient-rich composition of MHC, which provides essential macro- (N, P, K, Ca, Mg) and micronutrients (Zn, Mn, Cu, B, Fe). These nutrients play vital roles in various physiological processes, including flowering, nut setting, oil accumulation, and pest resistance. The enhancement of nut quality with increasing compost application rates (particularly at 8 and 12 t ha⁻¹) aligns with prior findings across multiple horticultural crops, where compost has been shown to improve fruit quality and yield. Improved soil fertility increases in soil organic matter and nutrient availability has been widely reported to enhance crop productivity and quality through better plant physiological performance [16]. Additionally, compost applications significantly reduced insect damage to nuts. This may be due to improved plant health and the increased presence of beneficial soil microorganisms that suppress plant pathogens and reduce pest pressure. In macadamia systems specifically, soil fertility plays a critical role in nut retention, development, and overall quality, with poor soils leading to reduced yields and inferior kernel quality [5]. Given the high economic losses (estimated at R200 million annually) due to insect pests in the South African macadamia industry, compost application offers a viable integrated pest management strategy. Despite the positive effects of MHC on yield and quality, no significant difference in yield was observed between the two study years. In conclusion, macadamia husk compost has demonstrated potential as a sustainable soil amendment that enhances nut quality, suppresses pest damage, and reduces the need for chemical inputs.

4.3. Leaf Nutrient Concentration

The study found that leaf concentrations of N, P, Zn, Cu, and B in macadamia trees were below recommended norms, while K, Ca, Mg, Mn, and Fe were sufficient. The non-significant response of leaf N, P, and B concentrations to compost application may be attributed to the slow-release nature of organic amendments, whereby nutrient mineralization occurs gradually and may not coincide with peak plant demand. In addition, leaf sampling was conducted during flowering and nut development, when nutrients are actively translocated from leaves to developing nuts, potentially reducing foliar nutrient concentrations [44]. Similar findings have been reported in studies where compost improved crop performance without significantly increasing foliar nutrient concentrations [45]. Despite some nutrients being below recommended norms, no nutrient deficiency symptoms were observed across treatments, suggesting that macadamia husk compost contributed to maintaining adequate tree nutrition. To improve foliar nutrient concentrations, farmers may combine compost with targeted inorganic fertilization and apply compost at rates of 8–12 t ha⁻¹. These findings highlight the potential of macadamia husk compost as a sustainable nutrient management strategy that supports productivity while promoting waste recycling and reducing reliance on synthetic fertilizers.

5. Conclusions

Application of macadamia husk compost significantly improved macadamia nut yield, nut quality, and selected leaf nutrient concentrations, with the most consistent benefits

observed at 12 t ha^{−1}. While husk yield remained unaffected, compost application enhanced key nutrients such as K, Mg, and Zn, contributing to improved kernel development and reduced insect damage. The findings confirm that MHC functions as a slow-release nutrient source that supports sustained productivity under subtropical conditions. However, the limited response of certain nutrients, particularly N, P, and B, highlights the need for integrated nutrient management strategies.

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