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Valorization of Sugarcane Residues as a Bio-input for Sustainable Cultivation of *Cucurbita moschata* on the Northern Coast of Peru

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Abstract: The valorization of agro-industrial waste represents a pivotal strategy for enhancing the sustainability of horticultural systems in arid regions. This study evaluated the potential of compost derived from sugarcane residues as an ecological alternative to chemical fertilization in the cultivation of *Cucurbita moschata* (loche), a culturally and economically significant crop on the northern coast of Peru. Four fertilization treatments were compared: conventional mineral fertilization, compost from sugarcane residues enriched with efficient microorganisms, compost supplemented with digestive enzymes, and guano from islands. Physiological parameters (plant vitality, elongation, number of shoots, and SPAD index) and productive indicators (fruit number, length, diameter, and °Brix) were evaluated under dry climatic conditions. Significant differences were observed in SPAD values at 107 days after sowing, with conventional mineral fertilization exhibiting the highest index (51.39 ± 5.4). While yield related traits did not differ statistically among treatments, compost from sugarcane residues enriched with efficient microorganisms showed vegetative development comparable to that of the mineral treatment, along with a positive trend in plant length. No significant differences were observed in fruit quality or number. These results suggest that composted sugarcane residues, especially when enriched with microbial agents, can support crop growth without compromising productivity. This study constitutes the first formal report on the application of sugarcane waste compost in *C. moschata* cultivation. Its implementation could promote agroecological practices, reduce reliance on mineral

Key words: Sugarcane, sustainability, cucurbits.

Cucurbits represent a plant family of considerable agricultural, economic, and cultural importance in Latin

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America, due to their nutritional value and their long-standing presence in traditional farming systems (Delgado-Paredes and Rojas-Idrogo, 2014). Among them, *Cucurbita moschata* stands out as a species domesticated since pre-Columbian times (Barboza *et al*., 2012) and is widely cultivated in Peru through local varieties such as zapallo loche. This creole cultivar, native to the Lambayeque region, holds not only strong gastronomic and cultural value, but also significant commercial potential for the regional agro-industry (Arbizu *et al*., 2022).

Concurrently, Lambayeque stands as the second largest producer of sugarcane (*Saccharum officinarum*) in Peru (INEI, 2025), generating substantial amounts of agro-industrial waste annually. This waste, however, frequently remains underutilized. In this scenario, it is imperative to recover the value of this waste through processes such as composting, which transforms it into bio-inputs that can partially or totally replace synthetic fertilizers. This practice could represent a doubly beneficial strategy: reducing dependence on chemical inputs and closing nutrient cycles in local agricultural systems.

The intensive and prolonged use of mineral fertilizers, while contributing to increased agricultural productivity, has had negative impacts on the physical, chemical, and biological properties of the soil. These include a decrease in organic matter content, loss of microbial biodiversity, and water and soil contamination due to leaching and nitrate accumulation (Gu *et al*., 2015; Lv *et al*., 2020; Liu *et al*., 2021; Rekaby *et al*., 2024; Souza and Tavares, 2021; Zhang *et al*., 2015). Moreover, the high cost of these inputs threatens the economic sustainability of family farmers (Fang *et al*., 2021), particularly in contexts of climate and financial vulnerability.

In response to these challenges, the use of organic amendments, such as compost, has emerged as a viable alternative. A multitude of studies have demonstrated their capacity to enhance soil structure, augment nutrient availability, and sustain agricultural yields that are commensurate with synthetic fertilizers (Eghball and Power, 1999; Boudjeka *et al*., 2024). The effectiveness of these processes can be enhanced by incorporating efficient microorganisms (EM), which stimulate the decomposition of organic matter (Calvo *et al*., 2014; Hu and Qi, 2013), or by adding enzymes that accelerate the mineralization of key nutrients (Rekaby *et al*., 2024; Vessey, 2003). Conversely, guano from the islands, a conventional source of nitrogen and phosphorus utilized in Peruvian organic agriculture, persists as a viable alternative, though its efficacy varies contingent upon the specific crop and management practices (Havik *et al*., 2014).

Notwithstanding this potential, there is a knowledge gap regarding the comparative effect of different organic amendments on non-traditional crops, such as loche. To date, there has been a paucity of research evaluating the impact of these treatments on physiological (e.g., SPAD index or vegetative development), phenological (e.g., shoot formation), and productive (e.g., fruit yield and quality) variables of *Cucurbita moschata* grown under arid conditions, such as those prevailing on the northern coast of Peru.

In this context, the present study was designed to evaluate the effect of four nutritional treatments-conventional mineral fertilization, sugarcane residue compost with efficient microorganisms (EM), compost with enzymes, and guano from islands-on the vegetative development, physiological status, and fruit quality of *Cucurbita moschata* (Zapallo loche). The hypothesis posits that organic amendments derived from sugarcane residues can equal the agronomic performance of mineral fertilization, thereby serving as a viable strategy for achieving more sustainable and circular agriculture in arid agroecological contexts.

Material and Methods

The research was conducted at the Vista Florida Agricultural Experiment Station (EEA-VF) of the National Institute of Agrarian Innovation (INIA), located in the district of Picsi, province of Chiclayo, department of Lambayeque, at 6.731°S latitude and 79.788132° W longitude (see Fig. 1). The study was carried out over a six-month period, from March to August 2024. The study area is characterized by a temperate, dry climate, with minimum and maximum temperatures of 18.65 and 25.87°C, respectively, an average relative humidity of 74.4%, and total precipitation of 3 mm during the study period (Fig. 2). The meteorological data were obtained from the Vista Florida Meteorological Station of the

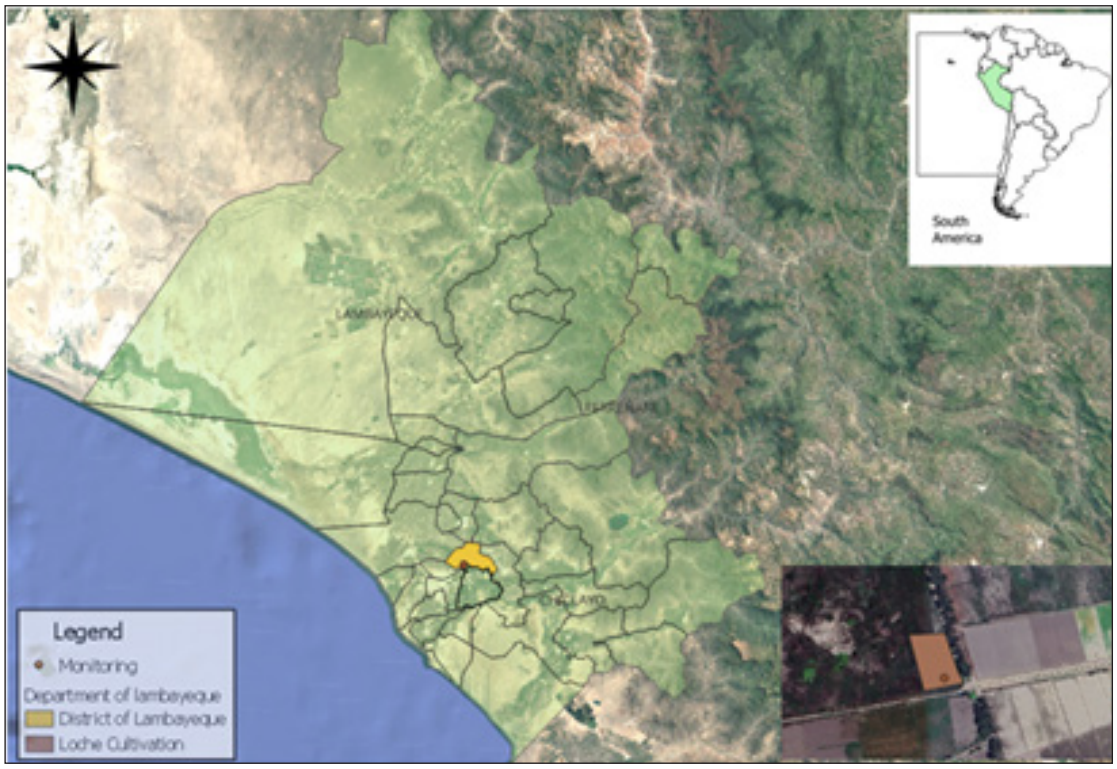

Fig. 1. Location of the study area.

National Meteorology and Hydrology Service of Peru (SENAMHI).

The soil analyses were conducted at the Laboratory of Biotechnology and Agricultural Health of Fruit Crops (LABSAF), Vista Florida Agricultural Experiment Station (EEA-VF), of the National Institute of Agrarian Innovation (INIA), Peru. Soil pH was determined

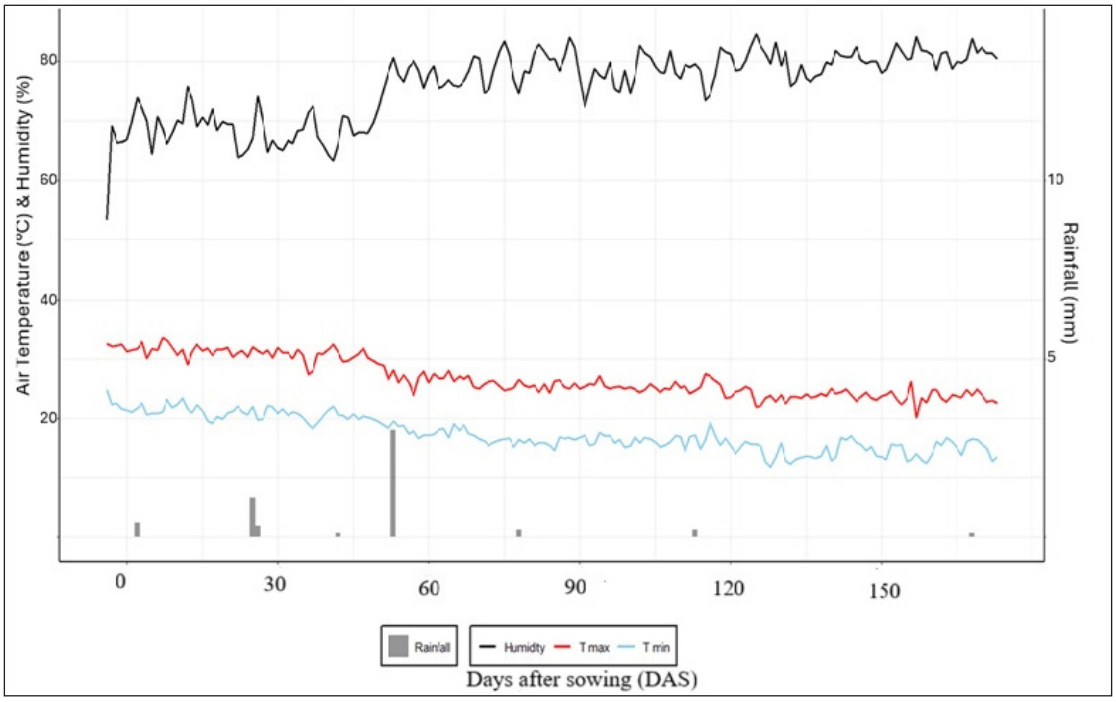

Fig. 2. Climatic data recorded during the crop's vegetative period. It is considered: minimum (T min.) and maximum air temperature (T max.), accumulated rainfall, and relative humidity.

Table 1. The composition and characteristics of the treatments applied, including fertilization, are outlined below

Treatments	Type of fertilization	Dose (kg · ha^{-1})	Composition summary
T_1	Traditional fertilization (urea, diammonium phosphate, potassium sulfate)	100-100-100	46% N (urea), 18% N + 46% P (phosphate), 50% K + 17% S (sulfate)
T_2	Compost with efficient microorganisms	4000	95% OM (organic matter), 5% EM (effective microorganisms)
T_3	Compost with enzymes	4000	70-90% OM, 1-5% enzymes, 3-10% EM
T_4	Island guano	800	12% N, 12% P, 2.5% K, calcium, magnesium, sulfur

according to EPA Method 9045D (SW-846, Rev. 4, 2004). Electrical conductivity (EC) was measured following ISO 11265:1994 (Soil quality-Determination of the specific electrical conductivity; International Organization for Standardization, Geneva, Switzerland). Organic matter (OM) content was quantified using the Walkley and Black method (AS-07, 2002) established by the National Agricultural Health Service of Peru (SENASA). Available phosphorus (P) and potassium (K) were determined in accordance with NOM-021-RECNAT-2000, using the Olsen method for P and ammonium acetate extraction at pH 7.0 for K. Cation exchange capacity (CEC) was calculated using the ammonium acetate extraction method.

The soil exhibited a pH of 7.4, EC of 1.60 mS cm^{-1}, OM content of 2.1%, available P of 6.8 ppm, available K of 118 ppm, and a CEC of 16.87 meq 100 g^{-1}. The soil texture was classified as loamy, comprising 47% sand, 30% silt, and 23% clay.

The study was conducted using a Completely Randomized Block Design (CRBD) with four treatments and four replicates per treatment. Each experimental unit covered an area of 300 m² and consisted of three furrows, each 20 m in length, spaced 5 m apart. Each furrow was further divided into six plots, with a spacing of 2.5 m between plots (Fig. 3).

The composting process was executed under aerobic conditions, with meticulous regulation of aeration and moisture levels to stimulate microbial activity (Morales-Barron *et al*., 2024; Chinta *et al*., 2021). In treatments T2 (compost + efficient microorganisms) and T3 (compost + enzymes), 200 liters of water per pyramid were applied at the initiation of the process, reaching a moisture level of approximately 35%, which is optimal for microbial decomposition (Medina Lara *et al*., 2018). Sugarcane waste (bagasse) was utilized as the substrate, having been previously chopped into pieces measuring approximately 5 cm. The porous structure of the material was maintained by periodic turning, which was more frequent during the thermophilic phase and reduced in the maturation phase. The synchrony of bio accelerator applications with these turnings was implemented to ensure the maintenance of stable aerobic conditions.

Treatments T2 and T3 entailed the application of distinct microbial formulations to the composting process. Treatment T2 incorporated the bioproduct EM COMPOST®, a biological inoculant designed to enhance the decomposition and fermentation of organic matter by incorporating effective microorganisms such as *Rhodopseudomonas* spp., *Lactobacillus* spp., and *Saccharomyces* spp. (Higa and Parr, 2024). This product has been demonstrated to accelerate the composting process in comparison with conventional methods. It has been shown to enhance compost quality by increasing levels of amino acids, polysaccharides, and other beneficial metabolites. Additionally, it has been observed to significantly reduce odors by controlling fermentation. Consequently, it promotes soil structure, nutrient availability, and plant health. The T3 treatment incorporated cane residues treated with the bioproduct BioDigest® (500 g), which contains a balanced mixture of selected bacteria of the genus Bacillus and Pseudomonas, together with specific enzymes such as amylases, cellulases, and hemicellulases (Morales-Barrón *et al*., 2024). This non-toxic product has been formulated to accelerate the decomposition of organic residues, both from harvest and manure, promoting microbial activity without generating odours. The mechanisms by which this occurs include the elimination of sulphur compounds, the reduction of ammonia, and the decrease of suspended solids. The two treatments utilized

Table 2. The following data represents the values of the compost composition derived from sugarcane residues

Treatments	N (g kg^{-1})	Organic Carbon (g kg^{-1})	C/N Ratio	pH	EC (µS cm^{-1})
Compost with efficient microorganisms	13.31	14.22	10.7	8.35	731.75
Compost with enzymes	15.25	14.83	9.67	8.37	696.62

comparable proportions of organic waste, with 58% of the waste being of animal origin, 34% consisting of cane waste, and 8% comprising other vegetable waste. The initial total mass was marginally higher in T2 (189.9 kilograms) compared to T3 (182.8 kilograms). During the monitoring period, T2 attained a maximum temperature of 54°C between days 4 and 10, while T3 registered a maximum of 49°C, with an average temperature difference of ±5°C. These variations are indicative of differences in microbial activity and the efficiency of the accelerators applied.

The compost was analysed at the Soil, Water, and Foliar Laboratory (LABSAF) at the EEA-VF of the National Institute of Agrarian Innovation (INIA) in Peru. The pH was measured with a potentiometer suspended in a 1:2.5 soil-water solution (Mclean and Page, 1982), and soil organic matter (SOM) was measured using the RECNAT-200 method (2002). Total nitrogen was analyzed using the Kjeldahl method (Bremmer, 1996), available phosphorus using Olsen *et al*. (1982), and available potassium according to RECNAT-200 (2002).

The planting of Cucurbita moschata cuttings was carried out on March 11, 2024, in an experimental plot with a total area of 6,650 m^2 made up of experimental units of 300 m^2. Prior to the planting process, the plant material underwent a disinfection procedure. The irrigation system utilized was of the gravity-fed variety.

We evaluated plant length and the number of shoots per plant at 46, 63, and 84 days after planting (DAP). Main stem length was measured from the base to the apex using a tape measure following the procedure described by Herrera *et al*. (2019), who employed this technique in their morphological studies of cucurbits.

The number of female flowers per plant was recorded by visual counting at 80, 95, and 107 DAP, identifying only floral structures with a developed gynoecium. The number of fruits per plant was evaluated at 95, 107, 122, and 157 DAP by visual counting. Fruit length measurements were taken prior to harvest at 109 and 123 DAP. This value was obtained using a tape measure and a ruler.

The SPAD index, which is closely associated with chlorophyll concentration and, consequently, with nitrogen content in leaf tissue (Markwell *et al*., 1995; Uddling *et al*., 2007), was evaluated at 59, 81, 95, 107, and 122 DAP using a SPAD DL 502 Plus meter (Konica Minolta), which had been previously calibrated with its chip.

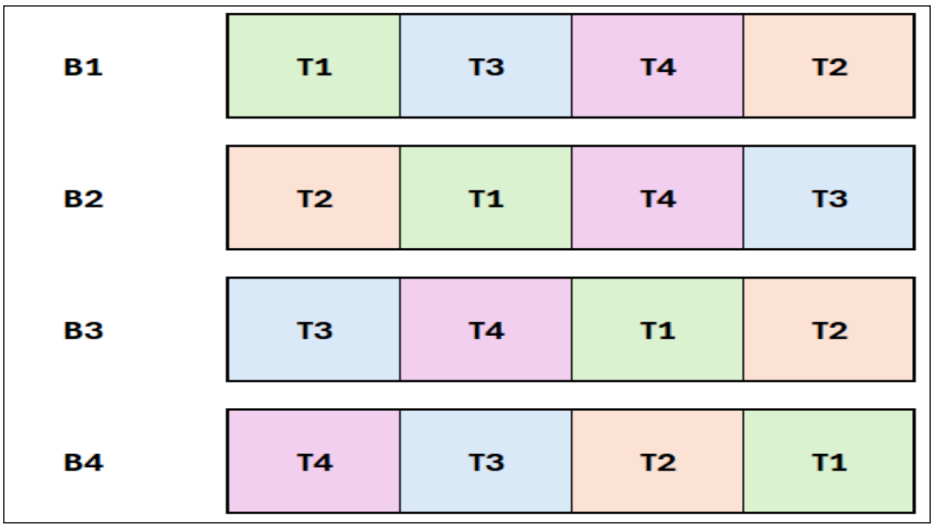

Fig. 3. Experimental area and distribution of blocks and treatments.

Table 3. Morphological characteristics of Cucurbita moschata (Loche) evaluated under mineral (T1) and organic fertilization treatments (T2-T4)

Treatments	SP	NV	LP	NFF	NF	FL
Mineral fertilization (T1)	19.25±1.71	16.12±7.35	385.27±108.7	2.4±0.82 a	6.08±1.46	4.7±0.64
Compost with efficient microorganisms (T2)	19±4.24	14.28±5.09	432.56±34.41	1.75±0.78ab	4.38±2.04	4.92±0.19
Compost with enzymes (T3)	18.75±2.5	13.75±1.91	337.87±125.73	1.7±1.08 ab	4.53±1.91	5±1.32
Island guano (T4)	17±2.16	13.45±7.17	334.46±94.65	0.99±0.36 b	3.26±1.1	5.2±0.71
p-value	0.68	0.72	0.24	0.02	0.21	0.81

Note: SP: Survived plants at the end of the experiment, NV: Number of vines 63 DAP (last evaluation), LP: Length plant 84 DAP (last evaluation), NFF: Number of female flowers, per plant 80 DAP (first evaluation), NF: Number of fruits per plant 157 DAP (prior to harvest), FL: Fruit length 109 DAP (before harvest).

The yield was evaluated by determining the number of commercial fruits harvested per experimental unit (plant) and the total weight of the production obtained, projected in tons per hectare. The classification of fruit for the purpose of yield calculation was conducted in accordance with the criteria outlined in the Cáritas del Perú Loche Manual (2012). Fruit weighing less than 1.15 kg was designated as non-commercial (non-com), while fruit weighing 1.20 kg or more was classified as commercial (com). For the total category, the weight of all fruits, including commercial and non-commercial types, was aggregated. Furthermore, the morphological dimensions of the fruits (length and diameter) were recorded in accordance with the methodology delineated in the section on agro-morphological variables.

Post-harvest quality was determined by evaluating the soluble solids content (°Brix) using a digital refractometer (Hanna Instruments, HI96801). The surface temperature of the harvested fruit was also measured using an infrared thermometer.

Analysis of variance (ANOVA) was performed to evaluate agromorphological and physiological characteristics, yield, and post-harvest quality. Box plots were also created to visualize the variability of agronomic characteristics over time using the ggplot2 and gridExtra tools in R. The dplyr and tidyverse libraries were used to group and summarize the data by treatment (T1-T4).

Results and Discussion

Morphological variables of Cucurbita moschata

Statistical analyses for morphophysiological variables, including plant survival (SP), number of vines (NV), plant length (LP), number of fruits per plant before harvest (NF), and fruit length (FL), did not demonstrate significant differences between the treatments applied ($p > 0.05$). However, the number of female flowers per plant (NFF) (Fig. 5) exhibited significant variations ($p = 0.02$), with the highest value recorded in T1 (2.4 ± 0.5). T2 (1.75 ± 0.78) and T3 (1.7 ± 1.08) followed, while T4 (0.99 ± 0.36) displayed the lowest number of flowers. A decreasing trend was observed for NF from T1 to T4, from 6.08 ± 1.46 in T1 to 3.26 ± 1.1 in T4. However, these fluctuations did not reach statistical significance ($p = 0.21$).

The evaluation of plant length was conducted at 31, 46, 63, and 84 days after planting (DAP) in response to mineral fertilization (T1), compost based on sugarcane residues with efficient microorganisms (T2), compost with enzymes (T3), and guano from islands (T4) (Fig. 4). A progressive increase in length was observed in all treatments as the crop cycle progressed. Although all treatments showed a progressive increase as the phenological cycle advanced (Fig. 4), treatment T2 (organic amendment based on sugarcane residues plus beneficial microorganisms) consistently showed positive trends from 63 days after planting (DAP). This behavior suggests that enriched compost promotes greater efficiency in nutrient absorption and availability, in agreement with the findings of Rekaby *et al*. (2024) and Che *et al*. (2023), who observed a similar effect in cucurbit crops treated with enriched compost.

The number of female flowers was evaluated at 80, 95, and 107 days after planting (DAP) (Fig. 5). Statistically significant differences were identified in the evaluation conducted at 95 DAP ($p < 0.05$), necessitating the application of the Tukey test. The corresponding grouping

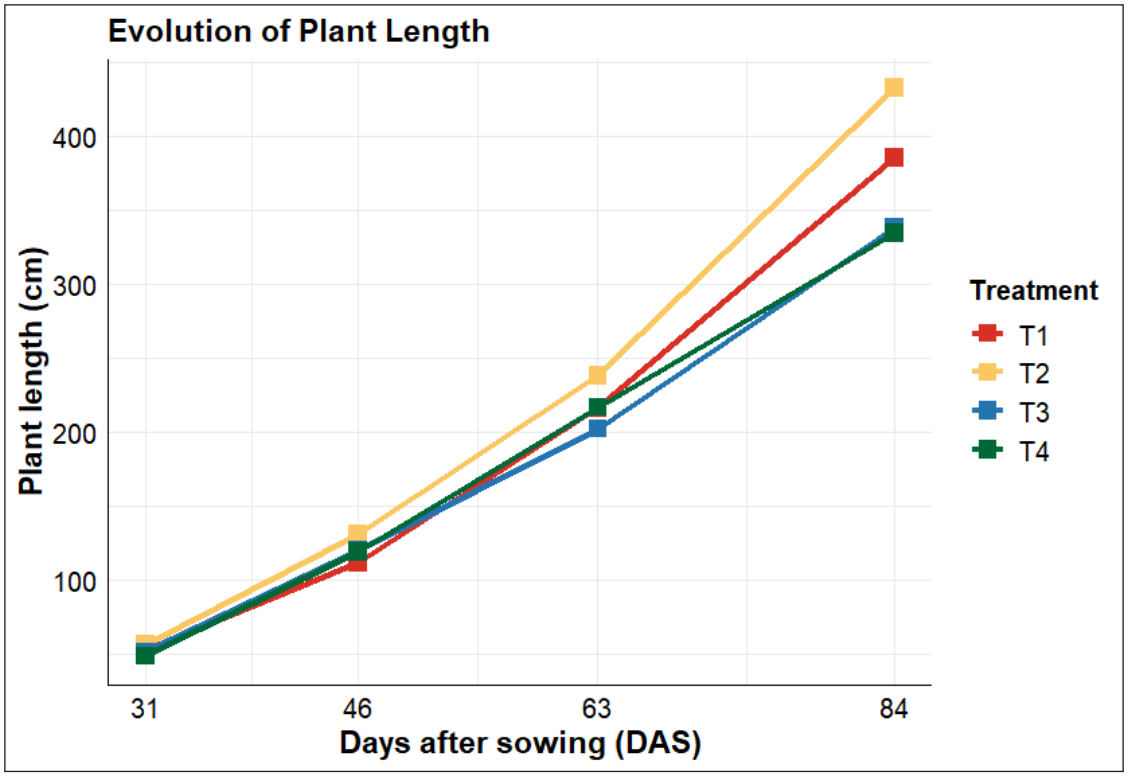

Fig. 4. Plant length dynamics of Cucurbita moschata (loche) at 31, 46, 63, and 84 days after planting (DAP), in response to four fertilization treatments: mineral fertilization (T1), compost from sugarcane residues with effective microorganisms (T2), compost with digestive enzymes (T3), and Island guano (T4). No statistically significant differences were detected among treatments ($p > 0.05$).

letters are depicted in Figure 5. This result aligns with the findings of Shareef *et al*. (2022) and Rekaby *et al*. (2024), who underscored the impact of organic amendments on the flowering of cucurbits. That may be related to a more adequate nutritional balance in treatments combining organic matter and microorganisms (T2 and T3) compared to the exclusive use of island guano (T4). In this sense, T4 could have generated an excess of nitrogen not compensated by other essential nutrients, such as potassium. This imbalance may affect key physiological processes such as flowering, as indicated by Marschner and Marschner (2012) and Luo *et al*. (2023).

During the development of the *Cucurbita moschata* crop, the number of fruits plant^{-1} exhibited a progressive increase in all treatments evaluated, being more pronounced in the stages close to harvest (Fig. 6). Treatment T1 (mineral fertilization) achieved the highest cumulative number at the end of the cycle, followed by T2 and T3. Despite the initial advantage of the mineral treatment, the organic treatments (T2 and T3) achieved similar yields with no statistically significant differences. This result suggests that the use of compost enriched with microorganisms can largely compensate for the effect of chemical fertilization on productivity, in agreement with the findings of Shareef *et al*. (2022).

Finally, although there were no significant differences between treatments, fruit length (Fig. 7) showed a slight positive trend for T2 towards day 123 DAP. This observation confirms the positive effect of organic amendments, which are enriched with efficient microorganisms that influence the morphological development of the crop and favor physiological processes related to the formation and growth of reproductive organs. This result is in line with Ahmed *et al*. (2022), who obtained an increase in fruit length of +11-14% compared to the control (mineral fertilization) at harvest stage of *Cucurbita pepo*. They used compost and vermicompost, among other organic amendments. This finding also aligns with the observations reported by Alemán Pérez *et al*. (2017) in a study conducted with local squash (*Cucurbita maxima*), which compared mineral and organic fertilization

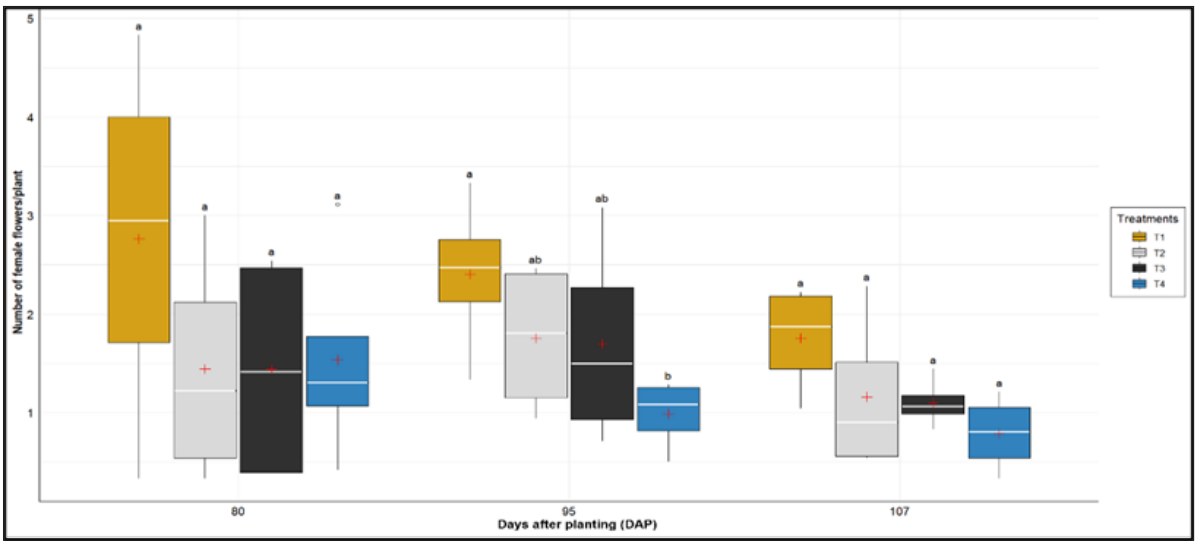

Fig. 5. Number of female flowers produced by Cucurbita moschata (squash) at 80, 95, and 107 days after planting (DAP), in response to mineral fertilization (T1) and organic amendments: sugarcane bagasse compost (T2 and T3) and island guano (T4). Different letters indicate statistically significant differences between treatments according to Tukey's test ($p < 0.05$).

systems. The findings indicated that there was no substantial discrepancy in fruit length between the two systems. However, a modest numerical inclination toward increased fruit length was observed in response to mineral fertilization.

Physiological variables of Cucurbita moschata

The chlorophyll index values (SPAD) were evaluated at six stages of the phenological cycle of *Cucurbita moschata* (43, 59, 81, 95, 107, and 122 days after planting, DAP). The results of this study are presented in Table 4. A general

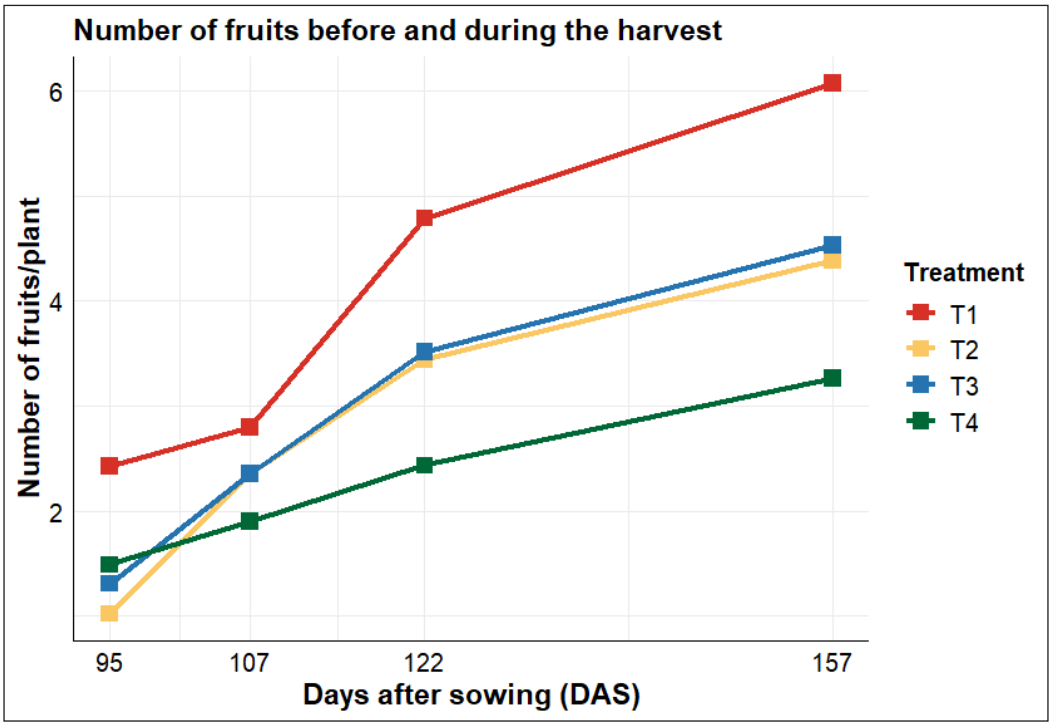

Fig. 6. Fruit number dynamics per plant of Cucurbita moschata (zapallo loche) at 95, 107, 122, and 157 days after planting (DAP), in response to four fertilization treatments: mineral fertilization (T1), compost from sugarcane residues with effective microorganisms (T2), compost with digestive enzymes (T3), and Island guano (T4). No statistically significant differences were detected among treatments ($p > 0.05$).

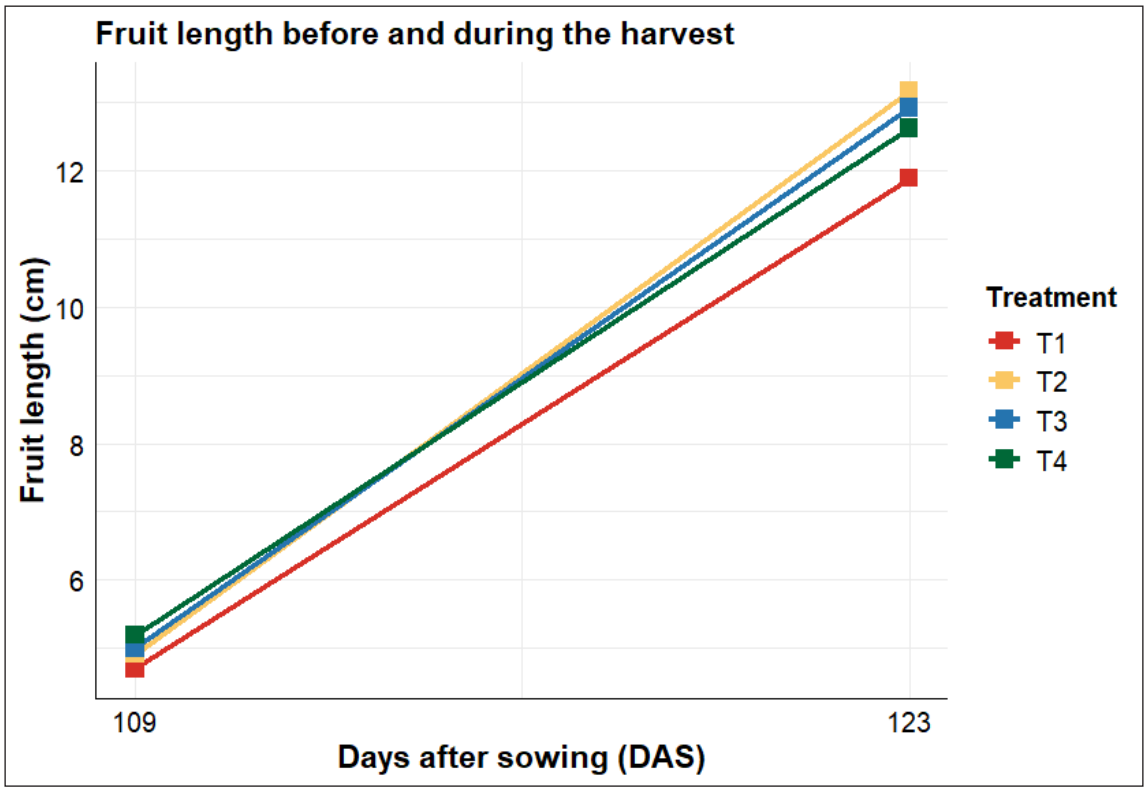

Fig. 7. Fruit length of Cucurbita moschata (loche) evaluated 109 and 123 days after planting (DAP) in response to mineral fertilization treatments (T1), organic compost with sugarcane residues and efficient microorganisms (T2), compost with digestive enzymes (T3), and island guano from the Galápagos Islands (T4). No statistically significant differences were observed between treatments ($p > 0.05$).

observation of the data revealed that, except for day 107 DAP, there were no statistically significant differences ($p > 0.05$) between the treatments on most evaluation dates. However, a significant difference was revealed on day 107 DAP, as determined by analysis of variance ($p = 0.047$).

As illustrated in Table 4, SPAD values ranged approximately from 30 to 55 units during the general crop cycle. In this regard, the SPAD 5 chlorophyll index of treatment T1 exhibited the highest SPAD value (51.39 ± 5.4), which was significantly higher than T3 (44.22 ± 4.62), consistent with studies that establish a correlation between elevated chlorophyll concentrations and augmented nitrogen availability in chemical schemes (Rekaby *et al*., 2024a, b; Shareef *et al*., 2022). T2 and T4 showed intermediate values (45.72 ± 4.25 and 47.00 ± 2.33, respectively), with no statistical difference from the rest according to the Tukey test ($p > 0.05$). This behaviour indicates the potential for a diversified physiological response to the fertilizer sources employed, manifesting in the later stages of the crop cycle. T2 (compost with cane residues and efficient microorganisms) achieved intermediate and stable values, suggesting a gradual and efficient release of nitrogen through progressive mineralization and microbial action. Conversely, T4 (island guano) exhibited the lowest SPAD values, a phenomenon that may be attributed to an imbalance between nitrogen and potassium, which has been demonstrated to diminish the efficiency of chlorophyll synthesis (Marschner, 2012; Luo *et al*., 2023).

Table 5 presents a summary of the mean values and standard deviations of the variables associated with the yield and post-harvest quality of *Cucurbita moschata* fruits. A general observation of the data revealed that no statistically significant differences were identified between the various treatments for the variables under consideration ($p > 0.05$). This finding suggests that the physiological response of the crop to the different fertilization schemes is homogeneous.

Table 4. Mean chlorophyll index values (SPAD) ± standard deviation in Cucurbita moschata under different fertilization treatments, evaluated at six stages of the crop cycle (43 to 122 DAP), with statistical significance by ANOVA

Treatments	SPAD_1	SPAD_2	SPAD_3	SPAD_4	SPAD_5	SPAD_6
Mineral fertilization (T1)	38.03±2.16	40.64±1.97	40.66±1.8	43.67±4.04	51.39±5.4 a	40.04±3.1
Compost with efficient microorganisms (T2)	34.59±2.4	40.94±1.62	34.79±2.72	39.01±1.29	45.72±4.25 ab	42.87±7.34
Compost with enzymes (T3)	36.88±3.66	39.45±1.37	36.02±3.09	40.2±5.43	41.28±4.62 b	36.96±1.98
Island guano (T4)	32.5±10.79	40.65±2.45	38.44±1.7	41.4±1.98	47.4±2.03 ab	38.86±6.46
p-value	0.51	0.74	0.051	0.36	0.047	0.57

Note: SPAD_1: Chlorophyll index at 43 days after planting (DAP), SPAD_2: Chlorophyll index at 59 DAS, SPAD_3: Chlorophyll index at 81 DAP, SPAD_4: Chlorophyll index at 95 DAP, SPAD_5: Chlorophyll index at 107 DAP, SPAD_6: Chlorophyll index at 122 DAP. ANOVA p-value in the last row. Values correspond to mean ± standard deviation. Different letters indicate statistical differences according to Tukey's test ($p < 0.05$).

Specifically, the soluble solids content (°Brix), the average temperature recorded during harvest (MT), and the length (LHF) and diameter (DHF) of the fruit exhibited slight variations between treatments, though without significant statistical impact. Furthermore, commercial yield (CY), non-commercial yield (NCY), and total yield (TY) exhibited numerical variations, with T3 demonstrating a comparatively higher value in TY (1.02 ± 1.34 t ha^{-1}), without significant differences ($p = 0.36$).

The available data suggest that treatments with organic amendments may offer a productive response comparable to conventional mineral fertilization. However, further research is necessary to confirm these observations. Specifically, additional studies with greater replication are required to substantiate these trends.

The range of total soluble solids (°Brix) was from 6.34 to 7.26, with no statistically significant differences observed between treatments ($p > 0.05$). These values are comparable to, and even slightly higher than, those reported by Gío-Trujillo (2024), who recorded contents between 3.6 and 5.0 °Brix for *Cucurbita pepo*, and between 4.3 and 7.3°Brix for *Cucurbita moschata*, reaching a maximum of 7.33°Brix in treatments with mycorrhizae. This finding indicates that the sugar content of fruit is not solely determined by the method of fertilization, but is also influenced by genetic and environmental factors, such as fruit ripeness and nighttime temperatures (Welles, 1988).

Conversely, no substantial disparities were detected in fruit surface temperature (ranging from 23 to 24°C) or morphological dimensions. The length of the specimens ranged from 18.06 to 19.53 cm, while the diameter fluctuated between 8.93 and 10.15 cm. These ranges coincide with those reported by INDECOPI (2010) for Loche squash. This finding suggests that the stability of these characteristics is determined by the genetics of the cultivar (Delgado-Paredes and Rojas-Idrogo, 2014).

With regard to yield, no statistically significant differences ($p > 0.05$) were observed in the number of commercial, non-commercial, or total fruits among the treatments evaluated. These results are consistent with those obtained

Table 5. Means and standard deviations among treatments for each yield-related postharvest quality variable. The last row shows the ANOVA p-value, as in the previous case

Treatments	BD	MT	LHF	DHF	CY	NCY	TY
	°Brix	°C	cm	cm	t.ha^{-1}	t.ha^{-1}	t.ha^{-1}
Mineral fertilization (T1)	6.34±0.6	23.69±0.2	19.53±1.5	10.15±0.6	0.82±0.7	0.64±0.4	1.47±0.9
Compost with EM (T2)	7.15±1.3	24.31±0.6	18.06±1.4	9.06 0.9	0.12±0.1	0.57±0.4	0.69±0.5
Compost with enzymes (T3)	7.11±0.6	24.8±0.8	18.37±1.5	8.93±0.7	0.43±0.7	0.59±0.7	1.02±1.3
Island guano (T4)	7.26±1.1	24.28±0.8	18.58±1.8	9.85±0.9	0.24±0.1	0.49±0.4	0.74±0.4
p-value	0.57	0.13	0.2	0.22	0.1	0.97	0.36

Note: BD: Brix degrees, indicator of soluble sugar content in the fruit; MT: Average temperature during the harvest period; LHF: Length of harvested fruit; DHF: Diameter of harvested fruit; CY: Commercial yield in tons per hectare; NCY: Non-commercial yield in tons per hectare; TY: Total yield in tons per hectare.

by Shareef *et al*. (2022) in C. pepo and by Vanessa *et al*. (2024) in *C. moschata*, who also reported no significant differences in the number of fruits when comparing organic and mineral fertilization.

Despite the absence of significant differences, trends in yield by category were observed: T1 > T3 > T4 > T2. The results obtained constitute the initial documented experimental evidence on the utilization of compost derived from sugarcane residues for the cultivation of loche squash (*Cucurbita moschata*). Furthermore, the study demonstrates that organic fertilization based on sugarcane residues, enriched with efficient microorganisms or digestive enzymes, is a viable and sustainable alternative to conventional mineral fertilization in the cultivation of *Cucurbita moschata* (loche) under arid conditions on the northern coast of Peru. The absence of significant differences in key parameters such as total fruit yield indicates that these organic amendments can replace up to 100% of synthetic fertilizers without compromising crop productivity. This finding substantiates the agronomic viability of sugarcane compost as a sustainable alternative for the production of loche squash.

Despite the noteworthy disparities observed in certain physiological variables, including the SPAD index (elevated in the mineral fertilization treatment) and the number of female flowers (augmented in the guano treatment), these effects failed to yield substantial agronomic benefits in terms of commercial yield. In contrast, the organic treatments exhibited comparable responses, demonstrating stable physiological and productive performance. The gradual release of nutrients, facilitated by microbial activity, and the enhancement of soil structure would have promoted efficient nutrient absorption, particularly during critical phases of vegetative and reproductive development.

These findings carry significant implications for the design of agroecological strategies that promote the valorization of agro-industrial residues and the transition to sustainable horticultural systems. Specifically, compost enhanced with efficient microorganisms or enzymes, derived from sugarcane residues, presents a cost-effective solution that is readily replicable at the local level and consistent with the tenets of a circular economy.

It is recommended that the adoption of these practices among farmers be encouraged through technical training programs focused on the production and efficient use of bio-inputs made from regional inputs. At the level of agricultural policy, the incorporation of these practices into sustainable management plans would serve to reduce dependence on external inputs and enhance the resilience of production systems to market or climate changes.

It is imperative that further research be conducted to assess the impact of these organic amendments over multiple crop cycles. Additionally, it is essential to investigate their influence on soil microbiota, agroecosystem health, and economic profitability within the country's diverse agroecological contexts.

Conclusions

The findings demonstrate that organic fertilization, (sugarcane residues supplemented with efficient microorganisms or digestive enzymes), constitutes a viable and sustainable alternative to conventional mineral fertilization in the cultivation of *Cucurbita moschata* (loche) under arid conditions on the northern coast of Peru. Non-significant differences in key parameters (total fruit yield) indicate that these organic amendments can replace up to 100% mineral fertilizers without compromising crop productivity. Despite differences in certain physiological traits-such as a higher SPAD index under mineral fertilization and greater female flower production with island guano-these effects did not translate into significant yield advantages. In contrast, organic amendments delivered consistent physiological and productive responses, confirming for the first time in this crop the viability of sugarcane residues as a sustainable bio-input. These results highlight the potential of composts enriched with microorganisms or enzymes from sugarcane residues as a cost-effective, locally replicable solution aligned with circular economy principles. Their adoption should be promoted through farmer training and integration into sustainable management policies to reduce reliance on external inputs and strengthen system resilience to market and climate fluctuations. Further research across multiple crop cycles and agroecological zones

is needed to assess long-term impacts on soil microbiota, ecosystem health, and economic returns.

Author Contributions

MPA: Methodology, Investigation, writing-original draft preparation, Writing-review and editing.

WSC: validation, Investigation, Formal analysis

JPJ: Formal analysis, investigation, data curation, writing-original draft preparation

JR: Formal analysis, investigation, writing-original draft preparation

ECR: Writing-original draft preparation

UAP: Data curation, Software

RSA: Conceptualization, Methodology, Writing-review and editing, Supervision, Project administration

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Data Availability Statement

All data associated with this manuscript are available by request to the corresponding author.

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