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Utilizing agricultural waste materials as planting medium for enhancing the vegetative growth, yield and postharvest attributes of sweet peppers (*Capsicum annuum*) under tunnel conditions

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Abstract

The study investigated the potential of composted pineapple agro-waste from Rhodes Food Group (RFG) Eswatini, dry maize stover, and cattle manure as alternative planting medium for sweet peppers under tunnel conditions. Growth parameters (plant height, leaf number, width, and area), yield (fruit number, size, diameter, and length), and post-harvest qualities (fresh weight, TSS, fruit firmness, and decay incidence) were assessed. The trial was set up in a Randomised Complete Block Design (RCBD) with five treatments and four replicates. Significant differences between treatment means were determined using Duncan's New Multiple Range Test (DNMRT) at the level of $P \leq 0.05$. The planting medium containing 60% pineapple agro-waste, 30% cattle manure, and 10% topsoil (T1) and the one with 60% maize stover, 30% cattle manure, and 10% topsoil (T4) produced significantly higher vegetative growth and fruit yield compared to other treatments. Notably, fruit grown in a medium of 70% pineapple agro-waste and 30% topsoil exhibited superior yield parameters, including fruit weight (118.99g), diameter (67.23 mm), and length (71.15 mm). While most post-harvest parameters showed no significant differences, the Brix percentage improved with T1. The study demonstrated that pineapple agro-waste holds potential as an effective alternative planting medium under tunnel conditions.

Keywords: Pineapple Agro-Waste Material; Sweet Peppers (*Capsicum annuum*); Planting Medium; Tunnel Production

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1. Introduction

Intensive horticultural production systems are used broadly to grow high-value horticultural crops such as sweet peppers (*Capsicum annuum*), tomatoes (*Solanum Lycopersicon*) and chili peppers (*Capsicum frutescens*) across the world. These vegetables belong to the family Solanaceae, due to their socioeconomic importance they are cultivated under greenhouse conditions. Nkansah et al. (2017) established that greenhouse production systems can enhance the growth, yield, and marketability of sweet peppers, making them a preferable option for producers aiming for higher quality and consumer satisfaction. Sweet peppers appeal to consumers for their vibrant colour, delightful taste, and nutritional benefits, while farmers find them profitable, breeders value them for their economic potential, and researchers highlight their importance in agricultural systems. In Eswatini, for instance, chili peppers have gained export value, with locally produced organic condiments and sauces finding markets in South Africa, the USA, and Europe (Maritz, 2023). In response to climate change challenges, the Ministry of Agriculture in Eswatini and supporting institutions are advocating for climate-smart production techniques, including the use of technological tunnels for cultivating high-value crops. Greenhouse production systems are becoming popular since they are known to promote vegetative growth and overall productivity. For instance, Nkansah et al. (2017) recorded the highest sweet pepper plant height of 93.7 cm in the greenhouse, while in the open field, the tallest plant was 43.9 cm, six weeks after transplanting. However, conventional tunnel farming practices often rely on mineral fertigation, intensive spraying programs and the use of pine wood shaving as a planting medium, which can have detrimental effects on human health and environmental sustainability.

The research in the use of intensive agricultural systems such as technological tunnels and shade nets has evolved beyond simply enhancing productivity but is now focusing on resource conservation and sustainability (Aznar-Sánchez et al., 2020; Carricondo-Martínez, et al., 2022). Carricondo-Martínez, et al. (2022) investigated the use of agro-waste material to reduce the high dependency of synthetic fertilisers. The use of organic nutrition programs under greenhouse conditions have been questioned because of their low nutrient content, inconsistent supply and quality compared to inorganic fertilisers (Bergstrand, 2021). Organic fertilisers have also been used in caution due to the presence of heavy metals and the inability to control the transformations required to convert the organic forms of N and P into the minerals available to crops (Gos et al., 2013), hence it is recommended to use the right quantity and applied at the right time to reduce the health risks. Whilst the debate about the feasibility of using organic fertilisers has been longstanding, strides to investigate alternative organic nutrition programmes for various crops greenhouse conditions have also been ongoing (Addo et al., 2012; Gos et al., 2013 and Abu-Zahra, 2011).

The adoption of agro-waste fertilizers, derived from crop residues and agro-waste is gaining momentum as a sustainable alternative to traditional fertilizers (Carricondo-Martínez et al., 2022; Berhe et al., 2022 and Çerçioğlu, 2018). Moreover, industries are now becoming more environmentally conscious and are looking into sustainable ways to utilize their agro-waste. For instance, the Rhodes Food Group (RFG), a fruit canning company in the Malkerns area, Eswatini generates volumes of pineapple agro-waste per annum. As a waste management strategy RFG, company has started using its composted pineapple agro-waste material for planting pineapple.

Using agro-waste materials as a growing medium under tunnel conditions is still relatively a new concept. A review by Barret et al. (2016) also gave an evidence-based argument on the need for researchers to identify environmentally friendly planting medium whilst also explaining the parameters that can be used to consistently select new growing medium. The choice of planting media significantly influences the growth, development, and productivity of crops. Traditional planting media often rely on peat-based or synthetic substrates, which may have environmental and sustainability concerns (Barret et al., 2016; Gruda, 2019). In contrast, organic planting medium derived from agro-waste fertilizers offers a viable alternative, with a potential benefit for crop performance. A recent overview by Hazarika et al. (2023) has established the positive effects of organic planting medium on root development nutrient uptake, water retention, and soil structure, leading to improved crop growth and yield. Hence, utilising agro-waste fertilizers as an alternative planting medium for sweet peppers in tunnel farming presents a promising approach to enhance productivity, improve fruit quality, and foster sustainability in vegetable production systems.

2. Material and methods

2.1. Site description and treatments

The study was conducted in a technological tunnel installed at the Horticulture Department Experimental Farm, Faculty of Agriculture, Luyengo Campus, University of Eswatini (UNESWA). Luyengo is situated at an altitude of 750 meters above sea level with a latitude of 26.534'S and longitude of 31.234'E. The average summer temperature during the trial was 32°C, while the average winter temperature was 15°C. The internal climate of the tunnel was manually controlled.

Ten litre polythene plastic bags were used to plant three different varieties of Sweet Peppers (*Capsicum annuum*) i.e green, red and yellow. These varieties were obtained from Ezigro Nursery, Bhunya. The topsoil for the experiment was collected from Mdutjane farm, near the UNESWA farm. The planting medium, consisting of a mix of pine bark, organic matter, sand, and peat moss, was purchased from a local supplier. Cattle manure was sourced from the University of Eswatini (UNESWA) farm, and maize Stover (SC 701) was harvested from the Horticulture Department Experimental Farm. The maize stover used in the experiment was collected from a dry maize crop and was shredded before being incorporated into the planting medium. The study utilized composted pineapple agro-waste from the Rhodes Food Group (RFG) in Malkerns, Eswatini. The pineapple agro-waste was composted using the composting process in section 2.1.1.

2.1.1. Pineapple agro-waste composting process

The company adhered to a standardized aerobic composting process, which involved collecting pineapple waste and allowing it to decompose over a specified period. In this methodology, pineapple peel, pulp, and other plant residues were systematically mixed with fresh chicken manure and piled to ensure adequate aeration. The pineapple waste was mixed with fresh chicken manure at a ratio of 80:20 to expedite the composting process. During the first three consecutive days, the temperature was measured in the morning hours and maintained at 80°C.

To sustain optimal conditions for decomposition, the compost pile was regularly turned at intervals of seven days using a compost turner, manufactured by Ritlee in Bedfordview, South Africa. This turning process facilitated the infusion of air into the compost, supplying essential oxygen to support the aerobic microorganisms responsible for breaking down the organic material. Moisture levels in the compost pile were meticulously monitored to prevent excessive drying, which could impede the decomposition process. The temperature was also measured weekly, usually a day before turning the compost heap. The temperature was maintained between 30-40°C. If the temperature dropped below expectations, the pile was turned, and if it rose above expectations, water was introduced. The decomposition period generally spans 8 to 12 weeks. Throughout this period, the microbial community within the compost actively decomposed organic matter into a humus-like material, rich in nutrients. The final product was a dark, crumbly, and odorless compost, which was subsequently screened to remove any larger, undecomposed particles before its utilization as planting medium in the experiment.

A Randomised Complete Block Design (RCBD) with five treatments and four replicates per treatment was used. The treatments were as follows:

- Control: Topsoil (50%) + Planting medium (50%)
- T1: Pineapple agro-waste (60%) + Cattle manure (30%) + Topsoil (10%)
- T2: Pineapple agro-waste (70%) + Topsoil (30%)
- T3: Pineapple agro-waste (50%) + Maize Stover (50%)
- T4: Maize Stover residues (60%) + Cattle manure (30%) + Topsoil (10%)

2.2. Soil analysis

The planting medium was tested for its nutrient content, pH, and other soil properties. Prior to planting, two samples of each growing medium were collected and sent for comprehensive soil analysis at the Mhlume Agriculture Laboratory. Soil samples were air-dried to remove moisture and sieved through a 2 mm mesh to eliminate debris and large particles, ensuring homogeneity and accuracy during subsequent analyses. Compost and agro-waste samples underwent similar preparation to ensure representative and reliable results.

The method for determining extractable elements such as copper (ppm), iron (ppm), manganese (ppm), zinc (ppm), calcium (ppm), magnesium (ppm), phosphorus (ppm), and potassium (ppm) involves the use of bicarbonate and EDTA as main extractants, complemented by ammonium hydroxide for pH adjustment. Extraction of the soil samples involves adding 2.5mL of soil to a 100mL Kartell bottle, followed by the addition of 25mL of the Ambic-1 extraction solution. After gently swirling the mixture, it is allowed to stand for 20 minutes before being shaken horizontally at 180 oscillations per minute for 30 minutes. The solution is then filtered through Whatman No. 1 filter paper, ensuring clarity for analysis. Analysis was done using an Induced Coupled Plasma Optical Emission Spectrometer (ICPOES), that was made in Singapore, assembled in Shelton City, Connecticut, USA.

Soil pH was determined using a calibrated pH meter, specifically the Hanna Instruments HI522, manufactured by Hanna Instruments Inc., Woonsocket, Rhode Island, 02895, USA. The pH meter was regularly calibrated with standard buffer solutions to ensure accuracy in measurements. Organic carbon (%) was assessed using the Walkley-Black method. To evaluate physical properties, hydrometer methods were employed to determine clay (%), silt (%), and sand (%) proportions, which helped classify soil texture.

2.3. Soil analysis results

Table 1 illustrates the comprehensive soil analysis (Ambic) results for the control and each treatment group.

Table 1. Comprehensive soil analysis (Ambic)

Parameter	Control	T1	T2	T3	T4.
Copper(ppm)	1.78	2.86	5.41	5.55	1.21
Iron (ppm)	185.22	125.16	407.05	286.69	95.04
Manganese (ppm)	5.28	14.85	19.47	21.29	12.85
Zinc (ppm)	2.26	21.03	27.72	32.62	8.40
Calcium (ppm)	582.47	2377.48	2204.71	2122.21	1719.44
Magnesium (ppm)	160.31	429.66	270.90	306.81	470.03
pH	6.47	8.28	7.95	8.3	8.22
Phosphorus (ppm)	13.23	801.68	449.52	1047.60	560.16
Potassium (ppm)	141.05	2544.71	1557.21	265872	1886.90
Clay %	8	12	14	18	8
Carbon %	1.62	4.74	1.89	4.56	4.68
Organic matter%	2.79	8.15	3.25	7.84	8.05
Silt %	8	10	8	14	4
Sand %	84	78	78	68	88

2.4. Sweet pepper production practices

Uniformly sized and healthy sweet pepper seedlings (green, yellow, red), aged 4 to 6 weeks, were sourced from Ezigro nursery in Bhunya, Eswatini. They were transplanted into tunnel structures that featured appropriate irrigation and climate control systems to maintain ideal growing conditions. Irrigation was conducted twice daily, with the first session occurring at approximately 09:00 and the second at around 14:00. Since tunnel production requires a continuous mineral fertigation program, alternatively a recommended granular fertiliser programme was incorporated during growing season. A granular basal fertilizer with a ratio of 2:3:2 (22) was applied at planting at a rate of 5 grams per planting bag to provide initial nutrients. At 4 weeks and 8 weeks after planting, a granular nitrogen-based fertilizer (L.A.N., Limestone Ammonium Nitrate) was used at the same rate of 5 grams per planting bag to promote vigorous vegetative growth. At the flowering stage, around 12 weeks, a calcium-based fertilizer (Calbomax) was applied as a foliar spray at a concentration of 5 millilitres per 10 litres of water, ensuring full coverage of the plants, to support fruit development and prevent calcium deficiencies.

2.5. Key vegetative and yield parameters

Key parameters, including plant height, leaf area, flower and fruit development, and the number of fruits, were collected at 3, 6, 9, and 12 weeks after planting (WAP). In the technological tunnels where the trial was conducted, the plant height, leaf width and diameter, number of leaves, flowers, and fruits were counted directly on-site. Plant height was measured using a tape measure to record the distance from the base of the plant to its tallest point. Plant diameter was assessed using a Vernier caliper to determine the diameter of the plants at their widest point. The Post-harvest Laboratory at the University of Eswatini, Faculty of Agriculture was used exclusively for analyzing post-harvest parameters, focusing on evaluating the quality and characteristics of the harvested fruits and leaves. This included assessments such as fruit size, weight, and the presence of any defects or variations.

To measure the firmness of fresh peppers, a handheld penetrometer was used. Each pepper was placed on a stable surface, the probe was gently inserted into the flesh, and pressure was applied until the desired depth was reached or a measurement was indicated. The firmness reading was recorded in Newtons and the process was repeated with two peppers to obtain an average value. The probe was cleaned after use to maintain accuracy and hygiene. The Brix %, was measured using the Japan ATAGO PAL-1 (model 3810), a digital handheld pocket refractometer with a range of 0.0-53.0% Brix. This device was used for precise measurement by placing a few drops of liquid on the prism, closing the cover plate, and reading the Brix value on the digital display. The shelf life was collected within 24 hours after harvesting the fruits. A handheld penetrometer was used to measure fruit firmness. The experiment was conducted from 23 February 2023 until 02 June 2023.

2.6. Statistical analysis

All agronomic yield was expressed as means. Agronomic and yield traits data from the different fertilizer sources were pooled and analyzed using one-way ANOVA Analysis of variance was performed by using the ANOVA procedure of the SAS 9.3 (SAS Institute, Cary NC). Significant differences between planting medium treatments means were determined by Duncan’s New Multiple Range Test (DNMRT) at the level of P=0.05

3. Results

3.1. Vegetative parameters

3.1.1. Plant height (cm) of sweet peppers at 3, 6, 9, 12 WAP

The results indicated a notable variation in plant height across different stages of growth (Figure 1). Treatment 4 (T4) consistently demonstrated superior growth with the tallest plants, showcasing steady growth throughout the growth stages (3 to 12 WAP). Treatments with Pineapple agro-waste (60%) + Cattle manure (30%) + Topsoil (10%) also exhibited substantial growth in plant height (51.86 cm and 52.87 cm) at later stages (9 WAP and 12 WAP), indicating the positive influence of the combination of maize stover residue or composted pineapple agro-waste and cattle manure when used as a planting medium.

3.1.2. Number of leaves

T1 exhibited the most significant increase in the number of leaves during the early growth stage (3 – 6 WAP), suggesting that the components of this planting medium are highly effective in promoting early vegetative growth. Treatments with Pineapple agro-waste (60%) + Cattle manure (30%) + Topsoil (10%) consistently outperformed all other treatments, highlighting its superior effectiveness in promoting leaf growth in sweet peppers under tunnel conditions (Figure 2). T4 also demonstrated strong performance, particularly in the later stages, making it a viable alternative.

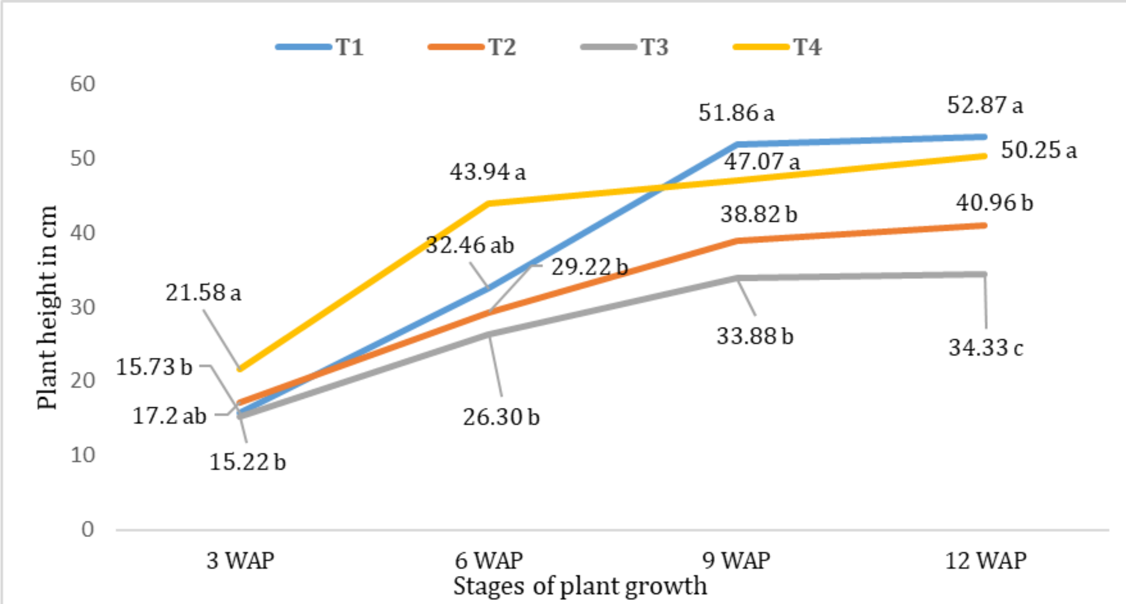

Figure 1. Effect of different plant medium on plant height of sweet peppers at 3,6,9,12 WAP. WAP (weeks after transplanting). Different letters in the same row indicate significant differences between treatments according to the Duncans' Multiple Range Test (DNMRT) test at ($p \leq 0.05$)

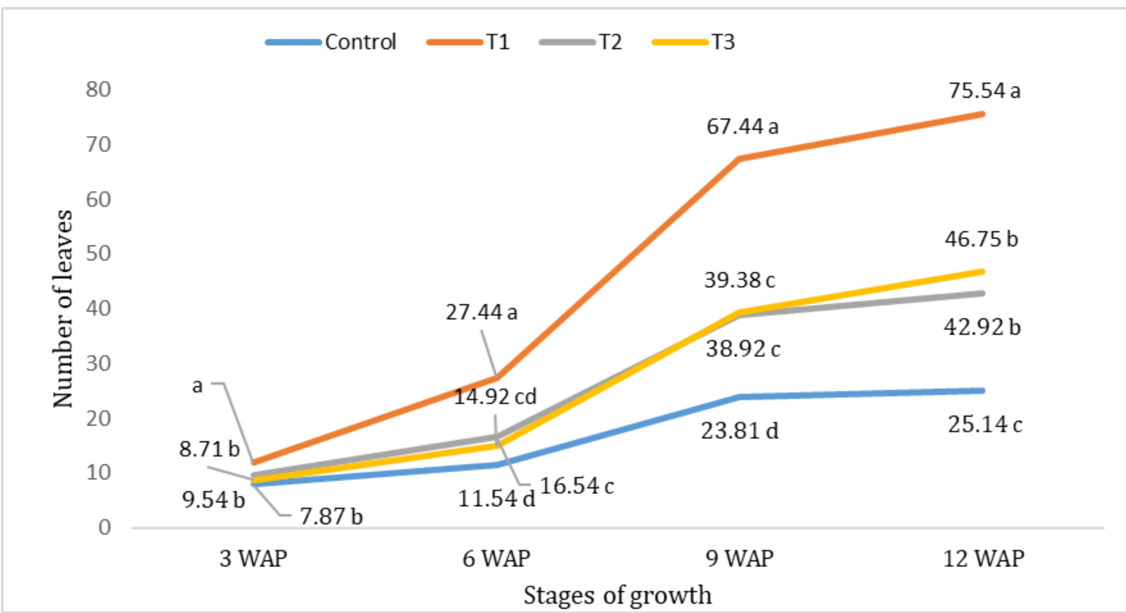

Figure 2. Number of leaves at 3,6,9,12, WAP in response to the application of agro-based planting medium. WAP (weeks after transplanting). Different letters in the same row indicate significant differences between treatments according to the least significant difference (LSD) test ($p \leq 0.05$).

3.1.3. Leaf length and leaf width

The data in Figure 3 reveal variations in leaf length and width across different stages and control treatments. T4 consistently exhibited the longest and widest leaves across all stages. T2 also demonstrated a significant impact, particularly in promoting longer leaves. Despite the similarity in leaf width at 6 WAP across all treatments, T4 and T2 emerged as favourable options for promoting longer and wider leaves, respectively.

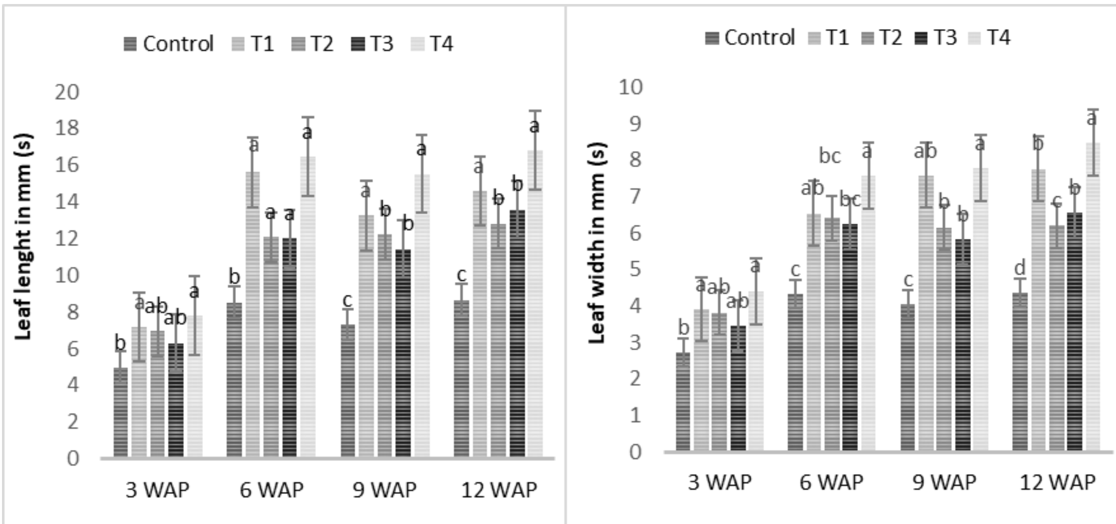

Figure 3. Leaf width and length sweet peppers at 3,6,9,12 WAP in response to the different agro waste-based planting medium. WAP (weeks after transplanting). Bars with the same letters are not significantly different from one another at ($p \leq 0.05$) according to Duncans' Multiple Range Test.

3.1.4. Leaf area

The leaf area (Figure 4) of sweet pepper plants at 3, 6, 9, and 12 WAP showed significant differences in vegetative growth. At 3 WAP, the treatments with 30% cattle manure i.e. Treatment 1 and treatment 2 had larger leaf areas of 20.60 mm^2 and 24.87 mm^2 respectively than all other treatments. At 6 WAP, T4 continued to excel with a leaf area of 80.55 mm^2, closely followed by T1 (72.46 mm^2). At 9 WAP, T4 and T2 had higher leaf areas (85.13 mm^2 and 78.69 mm^2 respectively). At 12 WAP, T4 had the highest leaf area (100.43 mm^2), demonstrating consistent growth benefits throughout the period.

3.2. Reproductive parameters

3.2.1. Number of flowers and fruits at 12 WAP

The data presented in Figure 5 did not show significant differences in the number of flowers and fruits at 12 WAP. However, Treatment 1 with the highest ratio of pineapple agro-waste (60%) combined with 30% cattle manure and 10% topsoil had the highest number of flowers, followed closely by treatments 1 and 2. These treatments also had the highest number of fruits, with T3 showing a relatively high count, and T1 having the lowest. Treatment 4 stands out as particularly effective in fruit production, followed by T2, T3, and then T1.

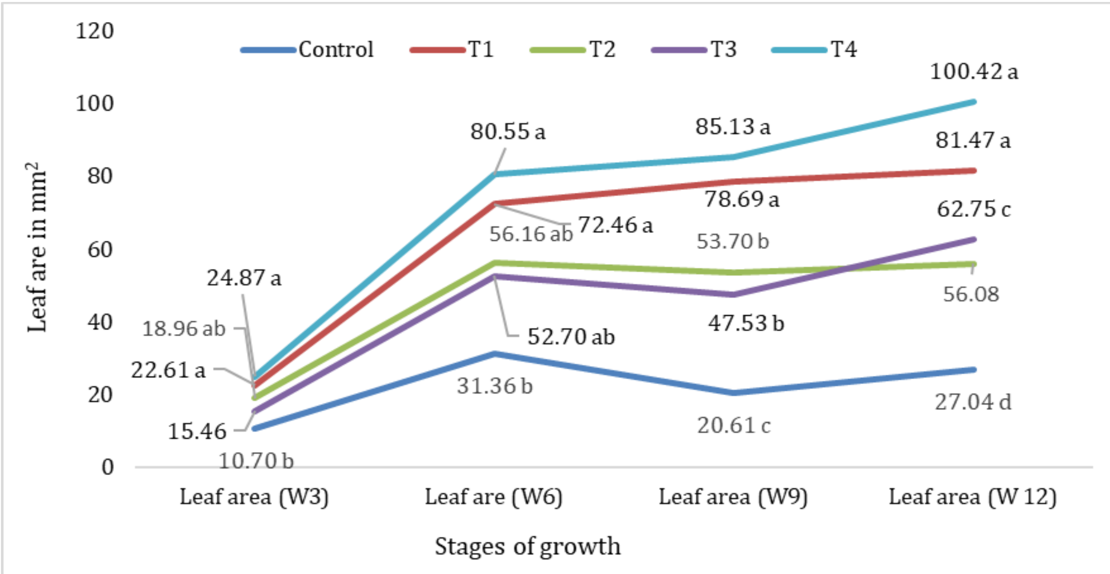

Figure 4. Leaf area of sweet peppers at 3,6,9,12 WAP in response to the different agro waste-based planting medium. WAP (weeks after transplanting). Bars with the same letters are not significantly different from one another at (p ≤ 0.05) according to Duncans' Multiple Range Test.

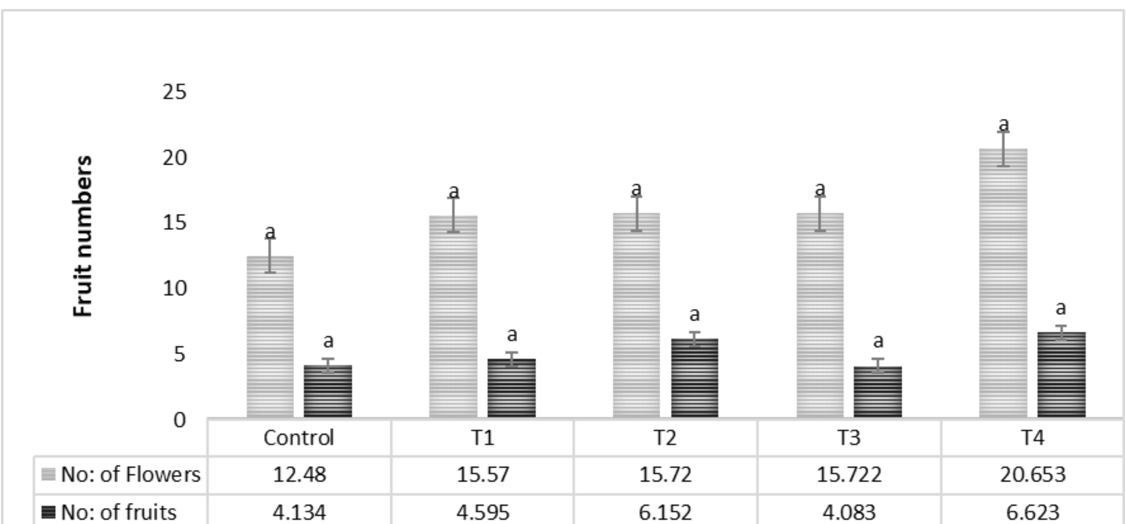

Figure 5. Number of flowers and fruits of sweet peppers at 12 WAP in response to the different agro waste-based planting medium. WAP (weeks after transplanting). Bars with the same letters are not significantly different from one another at (p ≤ 0.05) according to Duncans' Multiple Range Test

3.2.2. Yield components and post-harvest parameters

In general, Treatments 1, 2 and 4 outperformed all other treatments and the control in yield components and post-harvest parameters at harvest as shown in Table 2.

Table 2. Yield Components and post-harvest parameters in response to the different agro-waste based planting media

Trt.	Fruit Number	Fruit Weight (g)	Fruit Diameter (mm)	Fruit Length (mm)	Fruit Firmness (lb)	Fruit Brix (%)	Number of Days to Fruit Decay
Ctrl	3.36±2.06c	46.97±17.5c	48.73± 6.39c	63.73± 7.22b	3.70± 0.61a	3.59± 0.61c	2.00± 0.91c
T1	10.86±5.34a	101.65±27.4ab	65.67±5.57ab	64.31±5.89 b	3.64±0.63 a	5.27± 1.41ab	5.28± 2.78a
T2	6.00±3.51b	118.99±47.7a	67.23±6.45 a	71.15± 8.83a	3.80± 0.88a	4.43±0.87 bc	3.07±2.40bc
T3	6.93±2.60b	82.41±18.4b	61.92±5.59b	63.54± 5.75b	3.83±1.16 a	4.63± 1.95bc	3.60±2.58abc
T4	8.35±3.95ab	90.41±23.3b	65.58±5.22ab	59.77± 6.79b	3.97± 0.96a	5.83±1.99 a	4.86±3.43ab

WAP (weeks after transplanting). Different letters in the same row indicate significant differences between treatments according to the Duncan's Multiple Range Test (DMRT) test at ($p \leq 0.05$).

3.2.3. Number of fruits

In this study, treatment 1 yielded the highest number of fruits, averaging 10.86 per plant. This was greater compared to other treatments. T4 ranked second with an average of 8.35 fruits. T2 and T3 were not significantly different from each other, with T3 yielding 6.93 fruits on average and T2 producing 6.00 fruits. The control treatment exhibited the lowest fruit count, with an average of 3.36 fruits per plant.

3.2.4. Fruit weight

T2 exhibited the highest average fruit weight, measuring 118.99 g. T4 and T3 were not significantly different, with T4 having an average fruit weight of 90.41 g and T3 recording 82.41 g. T1 had an average fruit weight of 101.65 g, making it the second-best treatment. The control treatment had the lowest fruit weight, averaging 46.97 g.

3.2.5. Fruit diameter and length

In terms of fruit diameter, T2 emerged as the clear leader, yielding the largest fruits with an average diameter of 67.23 mm. T1 followed closely with an average diameter of 65.67 mm, while T4 produced slightly smaller fruits at 65.58 mm. T3 recorded the smallest diameter among the treatments at 61.92 mm. The control group produced the smallest fruits overall, with an average diameter of 48.73 mm. Additionally, T2 excelled in fruit length, achieving an average of 71.15 mm. The other treatments—T1, T3, T4, and the control showed no significant differences in their fruit lengths.

3.3. Postharvest attributes

The data on fruit decay incidence revealed varying levels among the treatments. The control treatment exhibited the lowest incidence of fruit decay, with an average of 2.00 counts. In contrast, T1 had the highest fruit decay incidence, averaging 5.28 counts. T2 and T3 showed similar levels of fruit decay incidence, with values ranging from 3.07 to 3.60 counts. T4 demonstrated a favourable balance of attributes, featuring relatively high Brix levels at 5.83 and a lower fruit decay incidence of 4.86 counts compared to other treatments. The control treatment had the lowest Brix levels and a higher fruit decay incidence, suggesting potential issues with both sweetness and post-harvest preservation.

4. Discussion

4.1. Chemical analysis of planting medium used

The soil analysis results revealed distinct variations in nutrient composition and soil properties across the different treatments (Control, T1, T2, T3, T4). Copper, Iron, Manganese, Zinc, and Phosphorus concentrations were significantly higher in T3, with Potassium also highest in T3 at 2658.72 ppm, a considerable increase from the Control's 141.05 ppm. Calcium was most abundant in pineapple agro-waste based planting medium (T1, T2, T3), with T3 showing the highest values of 2377.48 ppm. Magnesium was highest T4 (470.03 ppm). The pH values were alkaline across all treatments compared to the Control (6.47), with T3 exhibiting the highest pH at 8.3. Organic matter (OM) content was highest in T2. Berhe et al. (2022) also observed a higher nutrient level (N P; K; Ca; Mg and organic carbon); higher alkaline content and organic content in coconut pulp vermicompost. It is apparent that organic amendments contribute to a significant improvement of the OM content of the soil, nitrogen, phosphorus and exchangeable potassium levels compared to control.

4.2. Vegetative parameters

This study investigated the use of agro-waste materials as planting medium for sweet peppers grown under tunnel conditions. Previous research has extensively reviewed global trends in sustainable planting medium used under greenhouse conditions (Barrett et al., 2016; Aznar-Sánchez et al., 2020), with some studies exploring organic amendments as an alternative nutrient management approach (Carricondo-Martínez et al., 2020; Khaitov et al., 2019; Turki et al., 2014) and biofertilizer (Zambrano-Mendoza et al., 2021). Recent studies also examined the effect of coconut pulp and coconut coir substrates on sweet pepper yield and nutritional quality (Carricondo-Martínez et al., 2022; Tuckeldoe et al., 2023). Gruda (2019) also reviewed an array of waste materials used for compost, which, in turn, is used as a plant substrate on its own or in a mixture with other materials. To the best of our knowledge, this study is the first to assess the effects of pineapple agro-waste based and maize stover as an alternative planting medium on the vegetative growth, yield, and postharvest attributes of sweet peppers grown under tunnel conditions.

Planting medium comprising agro-waste materials such as pineapple or maize stover (60%), cattle manure (30%), and topsoil (10%) significantly enhanced all measured vegetative parameters. According to Stoleru et al. (2023), the addition of soil to organic materials introduces beneficial microbial activity, including mycorrhizal fungi, nitrogen-fixing bacteria, and plant growth-promoting rhizobacteria (PGPR), known to enhance plant growth and development. While the addition of cattle manures most likely contributed to enhanced leaf growth since cattle manure is a natural source of nitrogen (N) formation process in the soil. Studies have shown that cattle manure returns essential macro elements including N (2.42%), P (1.51%), and K (0.41%), as well as micronutrients such as magnesium, calcium, sulfur, and manganese to the soil while maintaining its fertility (Khaitov et al., 2019). Gruda (2019) also reported that the addition of compost in the planting medium can act as a source of fiber enhancing the rooting medium, as well as an important source of nitrogen (N), phosphorus (P), and potassium (K).

While Tuckeldoe et al. (2023) observed that substrates with higher calcium content significantly promoted vegetative growth, the current study found that although pineapple agro-waste based planting medium had higher calcium levels compared to the control, significant vegetative growth spurts were not observed in T2 (Pineapple agro-waste (70 %) + Topsoil (30%) and T3 (Pineapple agro-waste (50 %) + Maize Stover (50%) despite having high levels of calcium. This study concludes that mixing a higher volume of pineapple agro-waste material (70%) in planting medium does not support vegetative growth and in some instances the vegetative parameters measured were similar to the control. Nonetheless, T1 and T4 consistently facilitated better vegetative growth, highlighting the efficacy of agro-waste materials combined with cattle manure and soils in promoting plant growth under tunnel conditions. This can also be attributed to the alkaline nature of the planting medium. The alkaline nature of Vermicompost was reported to be the key element that enhances root growth and multiplication of microbes, (Nkansah et al., 2017). This underscores the potential of vermicompost as a valuable amendment in agriculture, contributing to both plant growth and soil health. In our study no significant differences in flower and fruit numbers were observed across all treatments at 12 weeks after planting (WAP).

4.3. Yield and post-harvest parameters

According to Çerçioğlu (2018), the most effective treatments for improving soil nutritional quality of pepper (Capsicum annuum L.) yield was the direct application of 40 tons of animal manure per hectare combined with mineral fertilizer and 80 tons per hectare of composted tomato residues combined with mineral fertilizer. In our study, T1, which included 60% composted pineapple waste, 30% cattle manure, and 10% soil combined with mineral fertilisers resulted in the highest number of fruits compared to the other treatments and the control. The second-best treatment was T4, which used the same ratio of cattle manure and soil but included composted pineapple agro-waste instead of maize stover. Additionally, while Tuckeldoe et al. (2023) highlighted that both the type of organic manure and the specific plant variety are important for fruit yield, this study did not observe plant variety as a factor.

In the current study, T2, which utilized composted pineapple waste as a planting medium, showed significantly higher fruit weight, diameter, and length. Our findings were consistence with the findings of Lorio and Asis (2021) who observed significantly higher yield parameters in terms of the number of fruits per plant, the weight of fruits per plant, economic yield, and harvest index. Aminifard et al. (2013) demonstrated that applying (15 t ha-1) of compost can enhance the fruit quality parameters of bell peppers including the total soluble solids, and fruit firmness. Hameedi et al (2018) also reported that application of vermicompost 7 t/ha along with Jeevamrut (Drenching @ 5% + Foliar spray @ 3%) significantly influenced growth and yield attributes of bell pepper and recorded (82.4) per cent increase in yield over control. Castellanos et al. (2017) proposed that this is possible because some composting material such as vermicompost can in fact provide the same amount of nutrients that are obtained from nutrient solutions for peppers under greenhouse conditions.

Brix Percentage: The Brix percentage, which measures the sugar content in the fruit, was significantly higher with the use of 70% pineapple agro waste. This indicates an enhancement in fruit sweetness due to the organic medium. Abu-Zahra (2011) noted that adding animal manure increased bell pepper fruit content of soluble solids, ascorbic acid, total phenols, crude fibre, and red colour intensity compared to conventional agriculture. Shahein et al. (2018) reported significant improvements in yield and total soluble solids (TSS) when organic fertilizers were combined with biofertilizers. However, Tuckeldoe et al. (2023) found no significant difference in total soluble sugars content in sweet peppers grown in coconut coir substrates versus loamy soil. Similarly, Carricondo-Martínez et al. (2022) did not observe significant differences in soluble solids content of tomatoes across different fertilization treatments.

Fruit Decay: The number of decayed fruits after 9 days was significantly lower in the control group (2.00) compared to the treated groups. This suggests that the control conditions were more effective in reducing fruit decay. Addo et al. (2012) found that sweet pepper fruits from 6-week-old transplants in unfertilized plots had a longer shelf life of 15.33 days, supporting the idea that different conditions can influence fruit longevity.

5. Conclusion

Several prior studies have meticulously focused on various specific post-harvest parameters, including but not limited to weight loss, shrinkage, decay rates, shelf life, as well as the nutrient and chemical analysis of harvested fruits. This investigation examined a more targeted range of post-harvest parameters, specifically encompassing the number of fruits, fresh weight, fruit diameter, fruit length, fruit firmness, brix percentage, and the incidence of fruit decay observed 9 days post-harvesting. It is evident that further research is imperative to comprehensively understand the impact of employing pineapple agro-waste-based planting medium on these characteristics.

This study underscores the critical importance of utilizing growing medium that furnishes optimal biological and chemical environments to augment nutrient uptake by plant roots. It posits that the selection of planting medium, whether it involves treated or untreated agro-waste, must consider an array of factors including climatic conditions, ecological balance, technological advancements, and economic viability. The utilization of agro-waste fertilizers as planting medium holds considerable promise in substituting traditional substrates such as peat, reducing dependence on fertigation practices, addressing climate change concerns, and being economically advantageous.

Based on empirical findings, it is recommended to adopt the highest-performing planting medium, designated as T1, as a viable alternative to conventional commercial medium used in greenhouse settings. This planting medium, which comprises a judicious combination of composted pineapple agro-waste, cattle manure, and soil, is readily accessible to farmers. Furthermore, it possesses the requisite physical and biological properties conducive to supporting robust plant growth under tunnel cultivation conditions. The adoption of this medium could significantly enhance agricultural sustainability and productivity.

6. Limitations and future research

Post-harvest parameters: The study primarily focused on a few post-harvest parameters, such as fruit firmness and Brix percentage. However, other important post-harvest factors, like fruit weight loss, membrane leakage and nutritional content need to be thoroughly investigated. This suggests a need for future research to explore these additional parameters to gain a more comprehensive understanding of the effects of different planting medium on post-harvest quality.

Effect of pineapple agro waste based planting medium: While the study found that certain mixtures improved vegetative growth and yield, it also noted that not all treatments performed as expected. For instance, higher volumes of pineapple agro waste did not consistently support vegetative growth. This variability suggests that more research is needed to understand the conditions under which these materials are most effective, including potential interactions with other factors such as the climate conditions and the crop variety.

broader application: The findings are based on specific conditions within technological tunnels. Future research could explore the applicability of these results in different agricultural settings such as the use of pineapple agro-waste in the field or with other crops, which would enhance the practicality of the findings. The availability of the pineapple agro-waste material locally and its benefits makes it a viable option for open filed farmers in Eswatini, who want to enhance the productivity of their soils.

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