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Influence of Animal Manure Extracts on Physico-Chemical and Nutritional Quality of Tomatoes Grown in Soilless Cultivation

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Abstract: In response to environmental challenges facing the agricultural sector, growers are moving toward innovative and sustainable cultivation methods such as the hydroponic production system. This study evaluated the effect of different sources of manure on the physico-chemical and nutritional qualities of tomatoes (cv. CLX 532) grown under a hydroponic system. The experiment was set up in a completely randomized design with four treatments, which included three types of animal manure-derived hydroponic nutrient extracts, namely, chicken (CHME), cow (CME) and goat (GME), and a commercial fertilizer as a control. Tomato fruit from each treatment were harvested and analysed for macro- and micronutrients, physicochemical attributes such as total soluble solids (TSS), titratable acidity (TA), total soluble solid to titratable acidity ratio (TSS/TA), BrimA, colour index and firmness. The total phenolics and ascorbic acid content were also assessed. The results showed significant differences in physico-chemical and nutritional quality among different treatments. TSS was higher in CHME (6.47 °Brix) compared to other treatments. The TA was higher in both commercial fertilizer and CHME (0.62% and 0.61%) than in GME and CME (0.44% and 0.39%). Both TSS/TA and BrimA were lower in commercial fertilizer and than in animal manure extracts (AME). CHME had a higher colour index (30.32) while GME had higher firmness (316.9 N) than other treatments. The phenolic content was notably higher in GME compared to the commercial fertilizer and AME. Fruit fertigated with commercial fertilizer had more macronutrient content while fruit fertigated with animal manure-based nutrient solutions had high micronutrients. Based on these findings, animal manure extracts, specifically CHME and GME, can be used as a nutrient source in the production of tomatoes as it produces good fruit quality which is comparable to commercial fertilizers.



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1. Introduction

Tomato is one of the most commonly grown horticultural crops, with over 180 million tons produced worldwide per year [1]. Tomatoes are globally popular as they can be consumed raw or processed [2,3]. They are an important component of a healthy human diet because of their high-functioning compounds, such as lycopene and β -carotenes [4]. Several studies have identified tomatoes as being a good source of antioxidants, such as carotenoids, vitamin C, phenolics and flavonoids [3,5]. A high concentration of these antioxidants can help prevent chronic noncommunicable illnesses such as cancer and cardiovascular and neurodegenerative diseases [6,7].

The major factors affecting the yield and quality of tomatoes include drought, extreme temperatures, lack of fertile soil and shortage of high-quality irrigation water [8,9]. With the growing population, there is a need to produce more food in a short period; as a result,

growers currently use fertilizers to boost their production. Using organic fertilizers is not a new phenomenon; it has been practiced for many centuries [10] and involves applying livestock manure, green manure, crop residues, compost and household waste. On the other hand, the use of synthetic fertilizer only started during the Industrial Revolution, and these fertilizers are either mined from mineral deposits or produced industrially through chemical processes [11]. Although these two types of fertilizers supply plants with essential nutrients for enhancing growth and yield, differences in terms of nutritional composition tend to exist [12]. The benefits of synthetic fertilizers over organic fertilizers include high levels of readily available nutrients and rapid and significantly increased plant growth and yield [13]. On the other hand, organic fertilizers, including animal manure, provide varying benefits depending on their nutrient compositions. Goat manure has 0.63–0.95% N, 0.35–0.51% P_2O_5 and 1.0–1.2% K_2O [14], while cattle manure contains 2.06% N, 0.53% P_2O_5 and 1.71% K_2O on average [15,16]. Additionally, chicken manure consists of 4.5–5.0% N, 2.5–2.98% P_2O_5 and 2.04–2.33% K_2O [14]. The application of these organic fertilizers improves the water- and nutrient-holding capacity in a medium, supplies nitrogen in usable form, does not contribute to pollution and is available at little to no cost [11,13,17]. However, the nutrients in organic fertilizers are released slowly over time, which may cause insufficient nutrients in plants at early stages of growth and lower yield than synthetic fertilizers [18].

The overuse of chemical fertilizers is one of the challenges in crop cultivation, as they lead to long-term and short-term consequences that may harm both humans and the environment [19]. This is a great challenge for farmers, as they are expected to produce enough nutritious food while ensuring environmental, social and economic sustainability [20]. Several studies have investigated the effect of organic farming on the yield of different crops, and the results vary. Most studies reported an increase in the yield (number of harvested fruit/ grains per plant and total biomass) of organically grown crops [21–24]; this could be due to the formulation of more solute in the soil, thereby increasing yield [25]. However, Amarante et al. [26] reported that the organic orchard produced fewer ‘Royal Gala’ apples and yielded smaller and lighter ‘Fuji’ apples compared to the orchard that used commercial fertilizer. The authors linked their findings to the limited macronutrients in the organic orchard’s soil. Further research evaluated the quality of organically produced crops; the findings discovered less mass loss [24], high firmness [27], improved titratable acidity [25] and high total soluble solids [21,25,28] of organically grown plants as compared to conventionally grown. Additionally, crops cultivated in organic farms have been shown to possess higher concentrations of ascorbic acid, total phenolics and carotenoids [22,27,29–31].

Despite the extensive body of research on the effect of organic farming on yield and quality, there are still limited studies on the impact of organic fertilizers on quality in soilless cultivation. Recent research efforts have been focused on the potential of liquid manure as an alternative nutrient source for hydroponic production systems. A study by Mowa et al. [28] reported that a hydroponic nutrient solution derived from goat manure results in high tomato fruit quality as compared to fruit from synthetic fertilizers. Furthermore, using aerated cow and turkey manure extract as a hydroponic solution increases growth in kale and lettuce [32]. Based on Charoenpakdee [33], the fresh mass of lettuce produced with bat nutrient solution in a homemade hydroponic system (HHS) was 94%, which indicates that this natural source of nutrients can be used instead of chemical fertilizers for producing lettuce in HHS. However, when using organic fertilizer in a hydroponic system, it is a challenge to obtain plant yield that is comparable to those grown with inorganic fertilizers [34]. This highlights the need for further studies evaluating the impact of animal-derived solutions on tomato quality. It is hypothesized that tomatoes grown with CHME in soilless systems will exhibit higher nutrient contents and better-quality attributes as compared to those grown with GME and CME. Therefore, this study investigated the effects of chicken, cow and goat manure extracts as nutrient sources on the physicochemical quality and nutritional quality of tomatoes grown in a hydroponic system.

2. Materials and Methods

2.1. Plant Material and Environmental Conditions

Four-week-old tomato seedlings of the indeterminate hybrid variety CLX 532 were procured from Sunshine Seedling Services, a vegetable nursery based in Pietermaritzburg, South Africa. This research was conducted at the Controlled Environment Research Unit (CERU) within the University of KwaZulu–Natal, Pietermaritzburg (29°40′05.7″ S; 30°24′20.9″ E), spanning from September 2023 to December 2023. The tomato plants were grown in a 4.8 m × 6 m glasshouse, maintaining an average relative humidity of 32.8% and temperature of 33.7 °C. After harvesting (week 13, Figure 1), the fruit were taken to the Postharvest Laboratory with conditions maintained at 25 °C and 45% relative humidity.



Figure 1. Effects of different sources of animal manure extracts applied through fertigation on the fruit quality of tomatoes (cv. CLX 532) grown in the hydroponic system: CHME: chicken manure extract, CME: cow manure extract and GME: goat manure extracts.

2.2. Manure Collection and Preparation

Dry cow and goat manure samples, approximately 3 months old, were collected from the Cedara Agricultural College Dairy Farm located in Hilton, Pietermaritzburg, KwaZulu–Natal Province (29°32′02.04″ S; 30°16′23.88″ E). One-month-old chicken manure samples were obtained from the chicken house of the Discipline of Animal and Poultry Science at the Ukulinga Research Farm of the University of KwaZulu–Natal, Pietermaritzburg (29°40′05.7″ S 30°24′20.9″ E). The abovementioned sources of manures were chosen specifically due to their nutritional compositions. Chicken manure has high nitrogen and phosphorus contents [35] that support early vegetative growth and root development. Cow manure has a moderate nutrient profile [15], which aids in steady growth without nutrient excess. Finally, goat manure has a lighter load [14], which is suitable for late stages to promote fruiting.

A 350 kg sample of each manure type was composted with three boxes of worms (*Eisenia fatida*) purchased from Wizard Worms situated in Greytown, KwaZulu–Natal. Composting was performed using a woven sack bag with a capacity of 1 ton, and a moisture level of about 40–60% was ensured by daily watering. The compost was routinely monitored and turned regularly after 4 days throughout the composting period (9 months).

2.3. Preparation of Animal Manure Extracts (AME)

The ‘active’ aerobic extraction method by Tikasz [32] was used, with a slight modification by Saba et al. [36]. Briefly, 26 kg of each type of manure was weighed and put into an empty woven sack made from hessian material. Water was measured into a 260 L water tank, and a six-outlet air compressor ACO-400 (Hailea, Chaozhou, China) was plugged in and inserted in the water for aeration for 30 min before the bag full of compost was inserted. This process was repeated for all three types of compost; the tea was left in the glass house for 48 h before transferring it to the 260 L JOJO tanks. This process was repeated every 7 days until the harvest date. Throughout the experiment, the pH of all the AME was kept

between 5.5 and 6.5 and EC at less than $3.5 \text{ mS}\cdot\text{cm}^{-1}$, which is the recommended standard for hydroponic solutions [28].

2.4. Experimental Design, Hydroponic Setup and Crop Establishment

The experiment was laid out in a completely randomized design with four treatments and four replicates per treatment. The four treatments consisted of three animal manure extracts (AME), including goat manure extract (GME), chicken manure extract (CHME), cow manure extract (CME) and a commercial fertilizer. The nutrient concentrations of the AME and commercial fertilizers are shown in Table 1. About 4-week-old ‘CLX 532’ tomato seedlings were transplanted into a 10 L planting bag containing sawdust and inserted into the planting slots of each channel. The AMEs were pumped from 260 L tanks into the planting pots, and a water-soluble inorganic fertilizer mix was pumped separately from a 1000 L tank. The inorganic fertilizer was mixed according to the ratio used by Mngoma et al. [37]: 540 g Omnical (Ca; 190 g/kg, NO_3^- ; 155 g/kg), 100 g Multi-K (P; 380 g/kg, NO_3^- ; 130 g/kg) and 600 g Nutriplex (N; 61.7 g/kg, P; 34 g/kg, K; 262 g/kg, B; 651.9 mg/kg, Fe; 2218 mg/kg, Mg; 17.5 g/kg, Mo; 63 mg/kg, Zn; 645.5 mg/kg, Cu; 86.5 mg/kg, Mn; 508.9 mg/kg and S; 76.7 g/kg) from transplanting to the third flower. From the third flower, it was increased to 600 g Omnical, 400 g Multi-K and 800 g Nutriplex. The continuous application method was used, and the nutrient solution was refilled every 7 days for the animal extract and 3 weeks for the commercial fertilizer. Tomatoes were cultivated for the duration of 12 weeks and harvested during the 13th week. A few healthy tomato fruit were randomly selected at harvest to further analyse the quality parameters. The harvested tomato fruit were washed with distilled water, cut into pieces, freeze-dried in a VirTis benchtop Pro freeze-dryer (SP Scientific Inc, Stone Ridge, NY, USA) and crushed into fine powder with an aromatic coffee grinder (Mellerware, Guangzhou, China). The powder samples were used for nutritional analysis, and some were sent to Cedara Agricultural Analytical Laboratory for mineral analysis; the rest of the tomato harvested tomato fruit were used for physiological quality analysis.

Table 1. Nutrient composition of different sources of animal manure extracts: CHME—chicken manure extract; CME—cow manure extract; GME—goat manure extract.

Nutrient Solution Source	Nutrient Concentration (mg/L)							
	N	P	K	Ca	Mg	Cu	Mn	Zn
CHME	4700	99.1	751.2	30.8	85.8	0.17	0.20	0.45
CME	3400	10.5	205.7	54.3	47.9	0.04	0.77	0.13
GME	2900	36.0	1426.1	25.0	44.9	0.04	0.08	0.05

2.5. Chemical and Reagents

The chemicals used in this experiment included NaOH, Phenolphthalein, metaphosphoric acid, 2,6-Dichlorophenolindophenol, Folin–Ciocalteu reagent, 2,2-Diphenyl-1-picrylhydrazyl antioxidant, ferulic acid, sodium carbonate, methanol and hydrochloric acid, which were all of analytical grade and procured from the Monitoring and Control Laboratories (Durban, South Africa), Prestige Laboratory Supplies CC (Durban, South Africa) and Sigma Aldrich (Johannesburg, South Africa).

2.6. Data Recorded and Plant Materials Used

2.6.1. Colour

The colour was measured on the harvest day using a Konica Minolta Chroma meter CR-300, INC, Tokyo, Japan [38]. Fruit colour measurements included lightness (L^*), green to red (a^*), blue to yellow (b^*) and chroma (C); the results were combined as the tomato Colour Index [39] using Equation (1).

$$\text{Colour index} = \frac{2000a}{LC} \quad (1)$$

2.6.2. Firmness

Fruit firmness was measured on the same day using a method by DeLong et al. [40] with a slight modification, using a handheld firmness tester (Bareiss, Oberdischingen, Germany). Three readings were recorded at the equatorial region of the fruit on a scale of 100 (hard and unripe) to 0 (soft and overripe).

2.6.3. Total Soluble Solids (TSS)

The total soluble solid percentage (TSS) was determined using a method by Ncama et al. [41] with a little modification. Briefly, tomato fruit were blended using a Warring blender (McConnellsburg, PA, USA) and filtered into a 50 mL beaker using a nylon filter (Filcon Filters, Johannesburg, South Africa). The digital refractometer (RFM340+, Bellingham + Stanley Ltd., Tunbridge Wells, UK) was calibrated by cleaning a prism with distilled water, wiping it with a clean paper towel and measuring a zero sample. Subsequently, the tomato juice of each fruit serving as a replicate was then measured by pipetting 2–3 drops of tomato juice into the refractometer prism to determine the TSS. The TSS was expressed in °Brix.

2.6.4. Titratable Acid (TA)

The process of measuring TA involved using a Mettler Toledo compact titrator G20S (Greifensee, Switzerland). In short, the samples were prepared by pipetting 8 mL of juice into a 100 mL beaker. A total of 42 mL of distilled water was added to the juice in the beaker using a separate clean pipette tip and was titrated with 0.1 M NaOH to a pH value of 8.1 using a Mettler Toledo (Columbus, OH, USA). The acid was calculated as a percentage of citric acid using a factor of 0.0064, Equation (2).

$$\text{Percentage acid} = \frac{\text{Titre (mL NaOH)} \times \text{Acid factor} \times 100}{8(\text{mL Juice})} \quad (2)$$

The solid acid ratio and BrimA were calculated using Equations (3) and (4), respectively.

$$\text{Solid acid ratio} = \frac{TSS}{TA} \quad (3)$$

$$\text{BrimA} = TSS - k(TA) \quad (4)$$

The term BrimA (Brix minus acid) is defined as the index employed to assess the equilibrium between Brix and acidity [42,43], where k is a constant that reflects the tongue's higher sensitivity to the TA (titratable acidity) in comparison to the TSS. The k allows the TSS amounts that surpass the TA to make the same numerical changes to BrimA. The equation was adjusted according to the recommendation by Obenland et al. [44], who changed the value of k from 5 to 3 or 4 to omit the negative values of the BrimA of oranges.

2.6.5. Ascorbic Acid (Vitamin C) Concentration

Ascorbic acid was determined using the method by [45] with little modification. Exactly 0.1 g of the freeze-dried samples was extracted using 5 mL of 3% metaphosphoric acid and was vigorously shaken. The mixtures were centrifuged at $12,098 \times g$ for 10 min. The supernatant was collected, and 1 mL was mixed for 15 s with 5 mL 0.05 mM DCPIP. Samples and absorbance were read at 515 nm against blank immediately before 15 sec using the spectrophotometer (UV-1800, Shimadzu Corporation, Kyoto, Japan). The ascorbic acid was calculated using a concentration between 0 and 20 µg/mL of ascorbic acid ($R^2 = 0.987$).

2.6.6. Total Phenolic Concentration (TPC)

A method by Ah-Hen et al. [46], with a slight modification, was used to determine the total phenolic concentration. The TPC was determined by the Folin–Ciocalteu photocolorimetric method. Freeze-dried tomato powder (0.2 g) was measured into centrifuge tubes, and 4 mL of 80% ethanol combined with 1% HCL was added. The mixture was then homogenized by shaking it in an orbital shaker at 200 rpm for 2 h at 25 °C. The mixture was centrifuged for 10 min at 700 rpm. The supernatant (100 µL) was combined with 750 µL of the Folin–Ciocalteu reagent and left in the dark for 10 min. Thereafter, 750 µL of sodium carbonate solution was added to the mixture and was left to stand for 90 min at 22 °C. Finally, the absorbance was measured at 765 nm using a UV-3600 spectrophotometer (Shimadzu, Kyoto, Japan) and compared to a standard curve concentration between 0 and 40 µg /100 µL ferulic acid to calculate the actual concentration of the sample extract ($R^2 = 0.994$).

2.7. Statistical Analysis

The data collected was subjected to analysis of variance (ANOVA) using GenStat Version, 23rd Edition (VSN International, Hemel Hempstead, UK). Mean values recorded were separated by LSD (Least Significant Difference) at 5% level of significance.

3. Results

3.1. Nutrient Content of Tomatoes Grown with Manure Extracts

The treatments had a significant effect on P, Ca, K and Mg but had no significant effect on N (Table 2). The commercial fertilizer had significantly high P (3861 mg/kg) as compared to the AME, while the K content was significantly higher in the fruit fertigated with the commercial fertilizer at 4.41 mg/kg, followed by CHME (3.63 mg/kg) and CME (3.47 mg/kg). A similar trend was observed where commercial fertilizers had a significantly higher Ca content (0.116 mg/kg) followed by CME (0.075 mg/kg). On the other hand, the Mg content was found to be higher in the fruit fertigated with CHME (1349 mg/kg) and CME (1338 mg/kg).

Table 2. Effects of the animal manure extracts and the commercial fertilizer on the nutrient contents of tomatoes (cv. CLX 532) grown for 12 weeks in soilless cultivation: CHME—chicken manure extract; CME—cow manure extract; GME—goat manure extract.

Nutrient Solution Source	N	P	K	Nutrient Concentration (mg/kg)			Fe	Mn	Zn
				Ca	Mg	Cu			
Commercial fertilizer	19,270 a	3861 a	44,100 a	1162 a	1180 b	0.18 c	6.68 ab	13.41 b	16.09 b
CHME	21,020 a	3363 b	36,300 ab	440 c	1349 a	0.75 a	8.49 a	11.82 b	18.73 a
CME	20,430 a	1391 d	34,700 ab	705 b	1338 a	0.27 bc	8.11 a	18.40 a	13.56 c
GME	21,720 a	1616 c	33,900 b	458 c	1154 b	0.64 ab	5.53 b	8.81 c	10.98 d
$p < 0.05$	NS	**	*	**	*	*	*	**	**
LSD		160	7000	115.5	162.1	0.27	1.38	1.37	1.49
cv%	7.2	3.2	9.9	8.9	6.9	31.5	10.2	5.5	5.3

Values in the same column sharing the same letter are not statistically different at LSD ($p = 0.005$). Values are the means $\pm$ SE (n = 4). Note: **— $p < 0.001$, *— $p < 0.05$ and NS— $p > 0.05$.

The treatments had a significant effect on the Cu, Fe, Mn and Zn contents. The Cu concentrations were higher in CHME (0.752 mg/kg) and GME (0.271 mg/kg), and a similar trend was observed in Fe concentrations where CHME and CME were significantly higher (8.5 mg/kg and 8.1 mg/kg) than in the commercial and GME fertilizers (6.68 mg/kg and 5.3 mg/kg). The Mn concentration was significantly higher in the CME (18.4 mg/kg) than in the other treatments, while Zn was significantly higher in CHME at 18.73 mg/kg as compared to the other treatments.

3.2. TSS, TA, TSS/TA, BrimA, Colour Index and Firmness

The treatments had a highly significant effect on the TSS, TA, TSS/TA and BrimA (Figure 2A–F). The TSS was significantly higher in CHME (6.47 °Brix) as compared to the

other treatments. A similar trend was observed for the TA, where CHME and the commercial fertilizer had a significantly higher effect (0.62 and 0.61) than GME and CME (0.44 and 0.39).

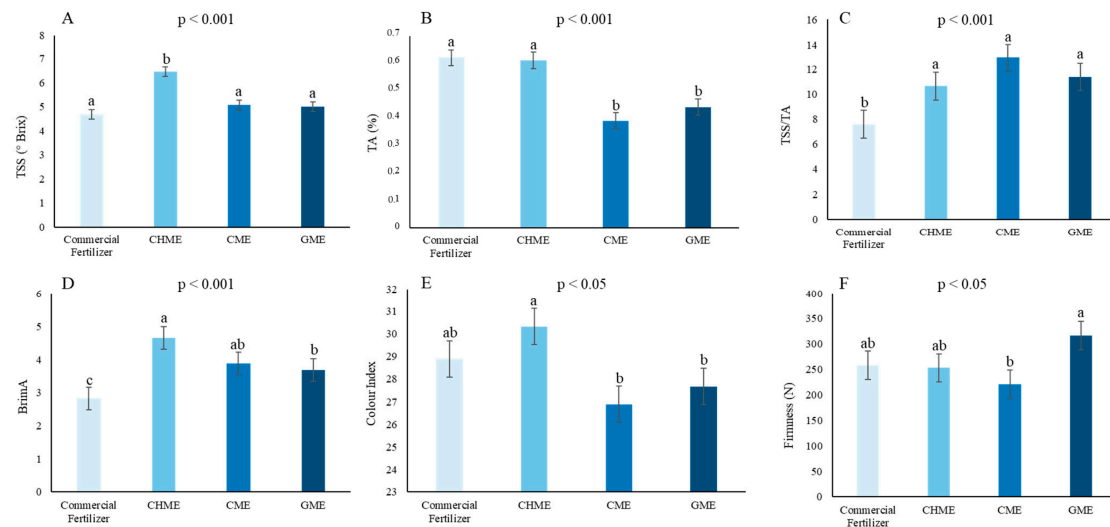


Figure 2. Effects of the animal manure extracts and the commercial fertilizer on the total soluble solids (A), titratable acidity (B), solid acid ratio (C), BrimA (D), colour index (E) and firmness (F) of tomatoes (cv. CLX 532) grown for 12 weeks in soilless cultivation. CHME—chicken manure extract; CME—cow manure extract; GME—goat manure extract. Values are the means $\pm$ SE ($n = 4$). Different lower-case letters within the graph indicate significant differences among different treatments at LSD ($p < 0.05$).

The CME, GME and CHME significantly affected the TSS/TA (12.9, 11.4 and 10.6) (Figure 2C), while BrimA was significantly higher in CHME, recording 4.65 as compared to CME, GME and the commercial fertilizer (3.88, 3.68 and 2.83, respectively) (Figure 2D).

The treatments showed a significant effect on the colour index and firmness (0.014) of the tomatoes (Figure 2E,F). The colour index was significantly higher in plants fertigated with CHME and the commercial fertilizer (30.2 and 28.9, respectively). Additionally, firmness was significantly higher in GME (316.9 N), followed by CHME (253.1 N).

3.3. Phenolic Content and Antioxidant Capacity in Tomatoes

The treatments had a highly significant effect on the total phenolic content and no significant effect on the ascorbic acid of tomatoes (Figure 3A,B). GME had a significantly high effect (2.61 g/kg) on the concentration of the phenolic content, followed by CME (2.25 g/kg), as compared to CHME and the commercial fertilizer (1.86 g/kg and 1.82 g/kg).

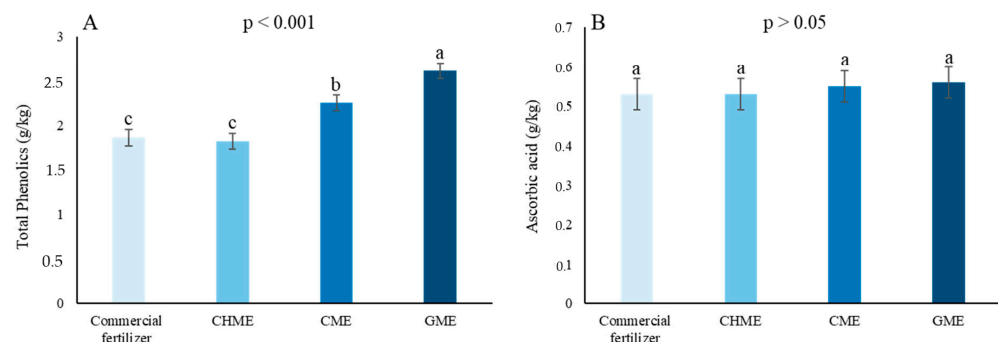


Figure 3. Effects of animal compost extracts and the commercial fertilizer on the phenolics (A) and ascorbic acid (B) of tomato fruit (cv. CLX 532) grown in soilless culture for 12 weeks. CHME—chicken manure extract; CME—cow manure extract; GME—goat manure extract. Values are the means $\pm$ SE ($n = 4$). Different lower-case letters within the graph indicate significant differences among different treatments at LSD ($p < 0.05$).

4. Discussion

The significantly high P, K and Ca in commercial fertilizers could be attributed to their formulation, which is specifically aimed at providing certain nutrients that promote growth and fruit nutritional quality [47]. During the production of chemical fertilizers, the nutrient concentrations are balanced to serve a specific role at different stages of plant production. However, the concentration of these nutrients is often imbalanced in AME. This imbalance of nutrients could result in inadequate levels of macronutrients accessible for plant uptake. The imbalance may also be due to the fact that chemical fertilizers quickly dissolve and release essential nutrients in a form easily absorbable by plants [48].

Various nutrients fulfil different roles during crop production: phosphorus is responsible for root and plant structure development, cell division, photosynthesis and respiration, while potassium is essential for stomatal opening, cell elongation, synthesis of enzymes and sugar and fruit maturation [49,50]. Moreover, calcium helps in the development and maintenance of fruit quality, stabilizes the cell membrane, enhances canopy growth and facilitates root and leaf elongation [49,51]. When these nutrients synergize, they contribute to fruit weight, yield and quality; therefore, regardless of the slow release of the nutrients over time, their impact is evident on the firmness (Figure 2F) produced by AME in comparison to commercial fertilizers.

The high Mg content in fruit fertigated with CHME and CME is in agreement with Kassem and Marzouk's findings [52], who reported high magnesium content in date palm (*Phoenix dactylifera* L.) grown using cow dung as compared to mineral fertilizers. The high magnesium (Mg) content observed in tomato fruit fertigated with CHME and CME could be attributed to the higher Mg concentration in these nutrient solutions compared to GME. When the organic fertilizer is applied, the nutrients are not immediately available to plants [12]; they are released slowly and are made available for root absorption over an extended period, thus accumulating in tomato fruit. In the realm of crop production, magnesium plays an important role in the synthesis of chlorophyll and photosynthesis and contributes to the stabilization of ribosomal particles, which are essential for protein synthesis [49,50,53]. It further supports phosphorus absorption, and this is true for the current study: CHME had the highest concentration of Mg amongst the other types of AME, and tomato fruit fertigated with CHME exhibited higher levels of phosphorus.

Overall, animal manure-derived hydroponic solutions produced fruit with high levels of micronutrients as compared to the commercial fertilizer. This is attributed to the organic fertilizer's ability to supply a range of nutrients [54], which are then slowly released over time [55]. The organic matter then increases the absorbing ability of the root system for nutrient uptake [56]. The application triggers over 100 enzymes; contributes to carbon dioxide emission; enhances the production of proteins, vitamins, sugars and starch; and influences the lignin and phenolic concentrations [57–59].

High TSS content was observed in plants fertigated with CHME, which was an indication of ripeness (Figure 2A). Similar results were observed by Buajaila et al. [60], where high TSS was recorded in fruit treated with composted poultry manure and urea as compared to fruit treated with commercial fertilizer. The similarities are possibly due to the nutrient composition in chicken manure. The high TSS in CHME may be due to the fact that the application of organic fertilizer increases *Ascomycota*, which is a fungi responsible for facilitating root extension, nutrient availability and nutrient absorption by plant roots [61], thereafter increasing starch accumulation through photosynthesis [60].

The results showing high TA in CHME and the commercial fertilizer are in contrast with the findings by Ye et al. [62], who reported lower TA in 'jujube' pear treated with organic fertilizers as compared to the chemical fertilizer. These differences can be attributed to several factors, such as plant species, nutrient profiles and environmental conditions; different plant species may have varying responses to the fertilizers whether organic or inorganic. Each species has specific nutrient requirements that can impact the regulation of organic acids, thus influencing TA. Tomatoes generally have different nutrient requirements at different stages of growth; in the current study, however, AME supplied the same

amounts of nutrients throughout the growing period. Therefore, the increase in both the TSS and TA in tomato fruit fertigated by CHME is likely due to the fact that certain nutrients were not provided according to the plant's requirements, which may have resulted in a higher intake of some nutrients than others.

In the current study, the TSS/TA was notably higher in AME as compared to the commercial fertilizer. These findings corroborate those of Ye et al. [62], who reported a high solid acid ratio of decomposed sheep manure as compared to the control treatment. It can be speculated that, because the nutrients that enhanced the TSS/TA in both of these studies were sourced from livestock waste which had decomposed, the nutrient composition was similar to a certain degree, hence the similar effect.

When the organic fertilizer is applied, it stabilizes as it decomposes [63]. Stabilization decreases microbial activities while slowly releasing essential nutrients for plant uptake. The availability of a sustainable supply of nutrients may contribute to the fruit quality, thus increasing the sugar–acid ratio, BrimA and colour index.

Previous studies have claimed that high nitrogen and low Ca levels delay colour development [26,64]; however, despite the high N and low Ca content on the CHME used in this study, the colour index increased. This may be attributed to the high microbial activities in organic waste-based compost tea [34] which plays an important role in nutrient absorption by plants. This may impact the formation of pigments responsible for tomato colour development. However, these results may warrant further assessment of the impact of CHME on the enzymatic processes that regulate colour development in tomato fruit.

The high firmness in GME and CHME is in contrast with the findings of Kilic et al. [65], who reported that different strawberry cultivars treated with commercial fertilizer and a combination of organic and commercial fertilizers were firmer than strawberries treated with organic fertilizers. Fruit firmness is mostly affected by high Ca content [66]; in this study, however, GME and CHME had more effect on tomato firmness despite their low Ca contents. This may be attributed to the polysaccharide components present in the animals' diets. Similar results were reported by Choi [66], who observed an increase in cherry tomato firmness treated with a starfish nutrient solution (SF), which had lower Ca content.

Similar to Toor, Savage and Heeb [67], who reported high total phenolics in tomatoes grown using organic fertilizers as compared to mineral fertilizers, our results indicated that GME exhibited the highest concentration of phenolics with CME showing the second-highest concentration. Comparably, Amodio et al. [27] also reported high phenolic content in organically kiwi fruit. The authors speculated that the increase in the total phenolics with the organic fertilizer was due to the pathogen pressure on the organically grown kiwi fruit; this pressure arose from the absence of pesticide application that caused biotic and abiotic stresses. The direct impact of organic fertilizers as a nutrient source in the production of the total phenolics is still unclear [68]; however, cultivation methods and environmental factors can impact the phenolic compounds. Nevertheless, the increase in the total phenolics in the current study is not related to the environmental conditions or the cultivation method used because the conditions were uniform in all treatments. However, it may be attributed to the nutrient composition of the nutrient sources used: there might have been a surplus or deficiency in GME and CME over CHME which may have caused plant nutrient stress. When plants encounter stress-inducing conditions, they produce more phenolic compounds as a defence mechanism [28,30].

5. Conclusions

This study showed higher TSS, TA, TSS/TA, BrimA, colour index and firmness in tomatoes treated with chicken manure extract. Similarly, goat manure extract improved the TSS/TA, BrimA, firmness and phenolics concentrations. Fruits fertigated with commercial fertilizer had more macronutrients than fruits fertigated with animal manure-derived hydroponic nutrient solutions. On the other hand, tomato fruit fertigated with animal manure-derived hydroponic nutrient solutions had more micronutrients than fruit fertigated with commercial fertilizer. Based on these findings, goat manure and chicken

manure extract can be used as alternative sources of nutrients, as they produce quality fruit comparable to those grown with commercial fertilizer. Future studies should investigate the effect of the combinational use of chicken and goat manure on quality. The effect of animal manure-based fertilizers on the shelf life of tomatoes should also be investigated.

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Influence of animal manure extracts on physico-chemical and nutritional quality of tomatoes grown in soilless cultivation

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