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Evaluating the efficacy of *Moringa oleifera* leaf extracts prepared using different solvents on growth, yield and quality of tomatoes and peppers

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ABSTRACT

Purpose: The study aimed to explore different extraction methods, extraction solvents, as well as solvent/water mixtures that could potentially yield(s) the best growth-enhancing, yield- and quality-promoting effects of *Moringa oleifera* leaf extracts (MLEs), when applied foliarly to tomatoes and peppers. **Research Method:** This study was laid out following a complete randomized design with three replications. Foliar application of MLEs tested included: control, aqueous (hot water, MLE HW), aqueous (cold water, MLE CW), ethanolic (MLE ETH) and methanolic (MLE METH) extracts. These treatments were repeatedly sprayed onto the leaves of selected plants, from two weeks after transplanting in weekly intervals until fruit set. **Findings:** Foliar application of all MLEs significantly enhanced growth of both pepper and tomato plants compared with the control. MLE HW application positively affected yield parameters, followed by MLE ETH and MLE METH. All MLEs significantly enhanced the colour coordinate a* and TSS, excluding MLE CW. Carotenoids in red peppers were significantly higher, following all MLE treatments, excluding the MLE CW, while in red tomatoes MLEs enhanced lycopene and β-carotene content. The concentration of Vitamin C was also significantly enhanced by MLE application to peppers, while in tomatoes, only MLE METH and MLE ETH positively altered the fruit Vit C concentration. These results generally prove that MLE application could potentially be used to improve crop production and their nutritive value. **Research limitations:** There were no limitations identified. **Originality/Value:** The results obtained in this study highlight the potential MLEs, particularly hot water MLE, to enhance growth, yield and nutritional quality of pepper and tomato, without compromising human health and environmental sustainability.

INTRODUCTION

Consumption of vegetable crops is a very important part of a well-balanced diet, since their intake provides nutrients, fibre, fat and carbohydrates to meet human dietary needs, thereby sustaining a healthy body (Hounsome et al., 2008). Amongst fruit vegetable crops, peppers (*Capsicum annum*) and tomatoes (*Solanum lycopersicum*) are recognised as high value crops with high nutritive value (Friedman, 2013; Salehi et al., 2019; Diouf et al., 2023). These vegetable crops are good sources of health-promoting constituents, such as vitamins, proteins, minerals and various antioxidants. In peppers, the antioxidants capsaicin, capsorubin and capsanthin are present, while in tomato lycopene and β-carotene are important phytonutrients (Topuz and Ozdemir, 2007; Dorais et al., 2008; Bae et al., 2014; Salehi et al., 2019).

To achieve high yields in horticultural commodities, the use of moringa (*Moringa oleifera*) plant extracts, particularly of leaf extracts, is an innovative, promising approach that has been tested by various authors using different agricultural crops, including cereals (Phiri, 2010), legumes (Phiri et al., 2010) tomato (Culver et al., 2012) and potato (Mbuyisa et al., 2023). Moringa leaves have high nutritional value, their extract (MLE) has been found to contain high concentrations of vitamins, minerals and other phytochemicals; the extract is also a good source of growth-regulating hormones, such as cytokinin zeatin, which makes MLE a natural plant growth regulator (Hassanein et al., 2018; Siddhuraju et al., 2003; Sreelatha et al., 2011; Goordeen & Mohammed, 2021).

Extraction from and separation of bioactive components found in plant material varies with the solvent, the extraction conditions and the extraction duration (Hayat et al., 2009). The extraction process also affects the active ingredients present in the extract substantially (Mustafa et al., 2011). In addition, in order to become a technology that is adopted by farmers, the method of extraction should be simple, financially feasible and applicable to both small-scale farmers (based in rural areas with little access to resources) and commercial, large-scale farmers (Pothitirat et al., 2010). Furthermore, it is also crucial to ensure that the selected method of extraction is environmentally friendly and thereby part of the green economy.

Despite MLE being an environmentally sustainable and low-cost approach to modify the efficiency of photosynthesis and assimilate partitioning of crop plants, various authors select chemical-based methods, when extracting moringa leaves. Such an extraction might, however, pose health risks and compromise environmental sustainability of plant production. Keeping in mind the reported positive impacts of MLE on plant growth and development, this study was conducted to compare the efficacy of organic and inorganic solvents, as well as various solvent/ water mixtures, to determine, which extraction method (s) yield (s) the best growth-enhancing effects of MLE, when applied foliarly to tomatoes and peppers.

MATERIALS AND METHODS

Plant material and growing conditions

Two experiments were performed separately in a glasshouse at the University of KwaZulu-Natal, Pietermaritzburg, South Africa (29°37'32.9"S 30°24'18.8"E). Plants of cherry tomato (*Solanum lycopersicum*), cv. ‘Gardener’s Delight’, and pepper (*Capsicum annum*), cv. ‘Revelation’, were established from seed. Seedlings were transplanted, when the second true leaf was fully expanded, into 5 L plastic pots filled with Organic for Africa® (Greytown, South Africa) potting mix. Physical and chemical characteristics of the growing medium used in the study were analysed and amended before transplanting. The environmental conditions in the glasshouse were maintained at 25 ± 2°C, 65% relative humidity during the day and 15 ±

2°C, 72% relative humidity during the night with a light/dark cycle of 13 h/11 h. Plants were pruned and trained when necessary and irrigated with drip irrigation system supplying only water to the plants.

Preparation and analysis of moringa leaf extracts

Moringa leaf powder (MLP) was supplied by a commercial supplier (runKZN, Pietermaritzburg, South Africa). The nutrient composition of the powder (Table 1) was analysed prior to the study. Several extractions were performed using different solvents. Moringa powder was extracted repeatedly until extracts were colourless.

Aqueous moringa leaf extracts (MLE HW, MLE CW)

For preparation of aqueous moringa extracts, the dry MLP was boiled, with continuous stirring, in distilled water (5 g MLP + 450 ml distilled water) for 30 min. For cold water extraction, 35 g MLP was soaked in 1 L distilled water for 48 h with continuous stirring. Each extract was then filtered through muslin cloth to remove any larger particles, before filtration through Whatman No. 1 filter paper and centrifugation at 20 000 g for 15 min. The supernatants were stored at 5°C.

Table 1. Chemical composition of dry *Moringa oleifera* leaf powder (average of five analyses).

Property	Value	Unit
N	4.49	%
P	0.36	%
K	1.62	%
C	44.28	%
Ca	2.71	%
Mg	0.51	%
Na	993.7	mg/kg
Zn	24	mg/kg
Cu	8.5	mg/kg
Mn	57	mg/kg
Fe	842	mg/kg
Al	795	mg/kg
B	18	mg/kg

Table 2. Phytochemical profile of different *Moringa oleifera* leaf extracts.

Components	Treatments				
	MLE CW	MLE HW	MLE ETH	MLE MET	Units
N	0.14	0.05	0.07	0.08	%
P	76.40	4.93	0.00	0.40	mg/L
K	436.47	53.07	0.13	5.87	mg/L
Ca	324.40	53.47	9.20	1.73	mg/L
Mg	105.20	15.33	0.40	0.13	mg/L
Na	46.53	41.60	0.80	0.53	mg/L
Mn	1.00	0.00	0.00	0.00	mg/L
Zn	0.00	0.00	0.00	0.00	mg/L
Fe	0.00	0.00	0.00	0.00	mg/L
Al	0.00	0.00	3.67	1.00	mg/L
Ascorbic acid	22.92	121.02	63.16	16.51	mg AAE/g DM
Total phenolics	204.48	216.60	103.46	174.41	mg GAE/g DM
Total flavonoids	215.33	155.64	487.89	472.67	mg QE/g DM
DPPH	14.18	125.16	66.83	5.18	mg AAE/g DM
FRAP	175.35	394.92	239.40	256.32	mg AAE/g DM

Maceration of dry MLP in methanol (MLE METH) and ethanol (MLE ETH)

Preparation of MLE was carried out according to (Vongsak et al., 2013), with slight modifications. Moringa leaf powder (35 g) was macerated in 1 L 80% methanol (MLE METH) or 80% ethanol (MLE ETH) (1:35, w/v) and left to stand for 48 h at room temperature with occasional shaking. The mixture was then filtered through Whatman No. 1 filter paper to obtain precipitate-free extracts. Extractions were carried out on the day of MLE application.

Quantitative analysis of phytochemicals and antioxidant capacity in moringa leaf extracts

Following the preparation of moringa leaf extracts using various solvents, the mineral analysis was performed using inductively coupled plasma mass spectrometry (ICPMS), while the phytochemical analysis for the quantitative detection of total phenolics, flavonoids and vitamin C, as well as total antioxidant activities (using DPPH and FRAP methods) was performed following the protocols described by Wang et al. (2003); Boonkasem et al. (2015); Rocchetti et al. (2019) and the results are presented in Table 2.

Experimental design and foliar application

A completely randomised design (CRD) with three replications was followed in this experiment. Fifteen healthy, similar-sized plants of both the pepper and the tomato cultivars were selected per treatment, with five plants per replicate. There were five applications (treatments); namely, hot water at 100°C used to extract moringa leaf powder (MLE HW), control (water), cold water (10°C) used to extract moringa leaf powder (MLE CW), ethanol (room temperature) used to extract moringa leaf powder (MLE ETH) and methanol (room temperature) used to extract moringa leaf powder (MLE METH). Applying only water (excluding moringa) did not have any effects on tested parameters, as preliminary results and a previous study determined (Ngcobo et al., 2021). The above-mentioned treatments were sprayed directly onto the leaves of selected pepper and tomato plants to run-off using a hand-held pressure sprayer. The first foliar application of MLE was carried out two weeks after transplanting and treatments were repeated weekly until fruit set as described in our previous study (Ngcobo et al., 2021).

Determination of dependent variables

Measurement of vegetative growth parameters

Data on growth parameters (number of leaves, number of branches, plant height) were recorded immediately after application of the initial moringa treatments, in 14 day-intervals, until maturity. Plant height was measured using a tape measure from the base of the stem to the tip of the terminal bud.

Measurement of yield parameters

A once-over harvest of red ripe fruit was performed. Fruit at the red ripe stage were harvested from each plant of the various replicates. Yield was recorded as the number of fruit/plant and the total fruit mass per plant (g).

Measurement of fruit quality parameters

External quality parameters (colour and size) of five fruit per plant from similar positions (75 fruit per treatment) were evaluated at harvest. The same fruit were utilized for destructive measurements.

Fruit colour
A chroma meter CR-400 (Minolta Co. Ltd., Osaka, Japan) was used to evaluate the surface colour of red-mature fruit. The colour parameters L^*, a^*, and b^* were determined, with (L^*) representing lightness (black (0) to white (100)), a^* characterising the green to red colour ranging from green (-) to red (+)), and b^* representing the yellow to blue colour axis (ranging from blue (-) to yellow (+)).

Fruit size
Fruit size (diameter) of all red-mature fruit in each treatment was measured using 150 mm digital callipers.

Carotenoid analysis
The concentration of carotenoids in the tomato fruit pericarp was determined spectrophotometrically according to (Nagata et al., 1992), using exact absorbance readings of the fruit pericarp material extracted in acetone-hexane (2:3). Individual fruit (1 g) were macerated in a 100 mL acetone: hexane (2:3) solution, centrifuged in a table-top centrifuge and the supernatant collected to read its absorbance at 663, 645, 505, 453 nm using a spectrophotometer (IRMECO GmbH, Germany, Model U2020). The following equations were used to calculate lycopene and β-carotene concentrations of the sample solution:

$$\text{Lycopene (mg/g FM)} = -0.0458\,A_{663} + 0.204\,A_{645} + 0.372\,A_{505} - 0.0806\,A_{453} \quad (1)$$

$$\beta\text{-carotene (mg / g FM)} = 0.216\,A_{663} - 1.22\,A_{645} - 0.304\,A_{505} + 0.452\,A_{453} \quad (2)$$

In pepper fruit, however, the concentrations of carotenoids were determined according to Hornero-Méndez and Mínguez-Mosquera (2001); briefly, 0.5 g fresh pericarp sample was extracted with 75 mL acetone for 1 h, the extract filtered through Whatman No. 1 filter paper to obtain precipitate-free extracts, transferred to a volumetric flask and made up to 100 mL, before its absorbance was measured spectrophotometrically at 472 and 508 nm. The following equations were used to calculate the red (C^R) and the yellow (C^Y) carotenoid fractions:

$$(CR) = (A508 \times 2144.0 - A472 \times 403.3)\,/\,270.9\ (\mu g\ red/mL) \quad (3)$$

$$(CY) = (A472 \times 1724.3 - A508 \times 2450.1)/\,270.9\ (\mu g\ yellow\ carotenoids/mL) \quad (4)$$

Total soluble solids
A digital refractometer (RFM340+ refractometer, Bellingham and Stanley Ltd, Basingstoke, Hants, UK) was used to determine the percentage of TSS in the fruit juice.

Ascorbic acid
Ascorbic acid was quantitatively determined according to a slightly modified method of (Boonkasem et al., 2015). Briefly, freeze-dried pericarp portions (0.5 g DM) were extracted with 20 mL 3% (w/v) metaphosphoric acid, followed by shaking the sample at 300 rpm for 30 min. The extracts were subsequently centrifuged for 10 min at 2000 g; thereafter, 1 mL sample extract was added to 3 mL 0.2 mM 2, 6-dichlorophenolindophenol (DCPIP) and the solution was measured immediately at 515 nm after mixing for 15 s. The results were expressed in mg ascorbic acid per 100 g dry mass (mg/ 100 g DM).

Statistical analysis

Results obtained were subjected to one-way analysis of variance (ANOVA) using GenStat statistical software (GenStat®, 18th edition, VSN International, UK). Duncan's Multiple Range Tests was used to compare means. Treatments were accepted as significantly different at $P < 0.05$.

RESULTS

Growth and yield parameters

The effects of moringa leaf extracts (MLE) on vegetative growth parameters of tomato and pepper plants are presented in Figure 1. The plant height, number of leaves and number of ranches in pepper plants (Fig. 1a, c, and e) were significantly increased by the application of MLE HW, MLE ETH, MLE METH and MLE CW, while the control (water only) had a lesser and non-significant effect. The response to the MLE application was similar in tomatoes and peppers, as all MLE treatments increased the number of branches and leaves on tomato and pepper plants; similarly, plant height was positively affected (Fig. 1b, d, and f). More notably, MLE HW tended to outperform the organic solvent extracts; however, the difference was not significant. Overall, foliar application of MLE, more so of MLE HW, improved growth of pepper and tomato under greenhouse conditions (Fig. 1).

The effects of various MLEs on pepper and tomato yield parameters is presented in Figure 2 and 3, briefly, a significant increase in fruit diameter, fruit mass and the number of fruits per plant was observed following the foliar application of MLE in both pepper and tomato (Fig. 2 and 3). Treatment with MLE HW affected yield parameters more positively than other treatments (Fig. 2 a-d and Fig. 3a and b), while the MLE ETH and MLE METH treatments were not as effective, but still outperformed the control. On the other hand, even though MLE CW produced yield parameter values lower than other MLEs, it had, however, the potential to improve yield (Fig. 2a, c and d, and Fig. 3a).

Physical and chemical constituents

The application of MLE HW, MLE ETH and MLE METH significantly enhanced fruit colour (a^*, Fig. 4c and d) of red pepper and tomato; this was achieved mostly by treatment with MLE HW. These three extracts had also a significant effect on the lightness (L^*) of fruit, increasing the $L^*$of red pepper and tomato (Fig. 4a and b). The control and MLE CW, however, did not produce notable effects on colour of treated fruit. Similar to colour, TSS in peppers improved following MLE treatment, except for the cold-water treatment (MLE CW, Fig. 5a), whereas in tomatoes all MLEs affected fruit TSS positively (Fig. 5b).

The MLE treatment affected the tomato and pepper fruit carotenoids differently (Table 3). All the MLEs except the MLE CW had a significant effect on the red fraction of peppers while having no significant effect on the yellow fraction. Similar to peppers, all the treatments did not have a significant effect on lycopene and β-carotene, the major carotenoids in tomatoes; however, the MLE HW and MLE ETH had the potential to increase these carotenoids (Table 3). On the other side, the ascorbic acid concentration was significantly enhanced by all the MLEs except the aqueous extracts in tomatoes (Table 3).

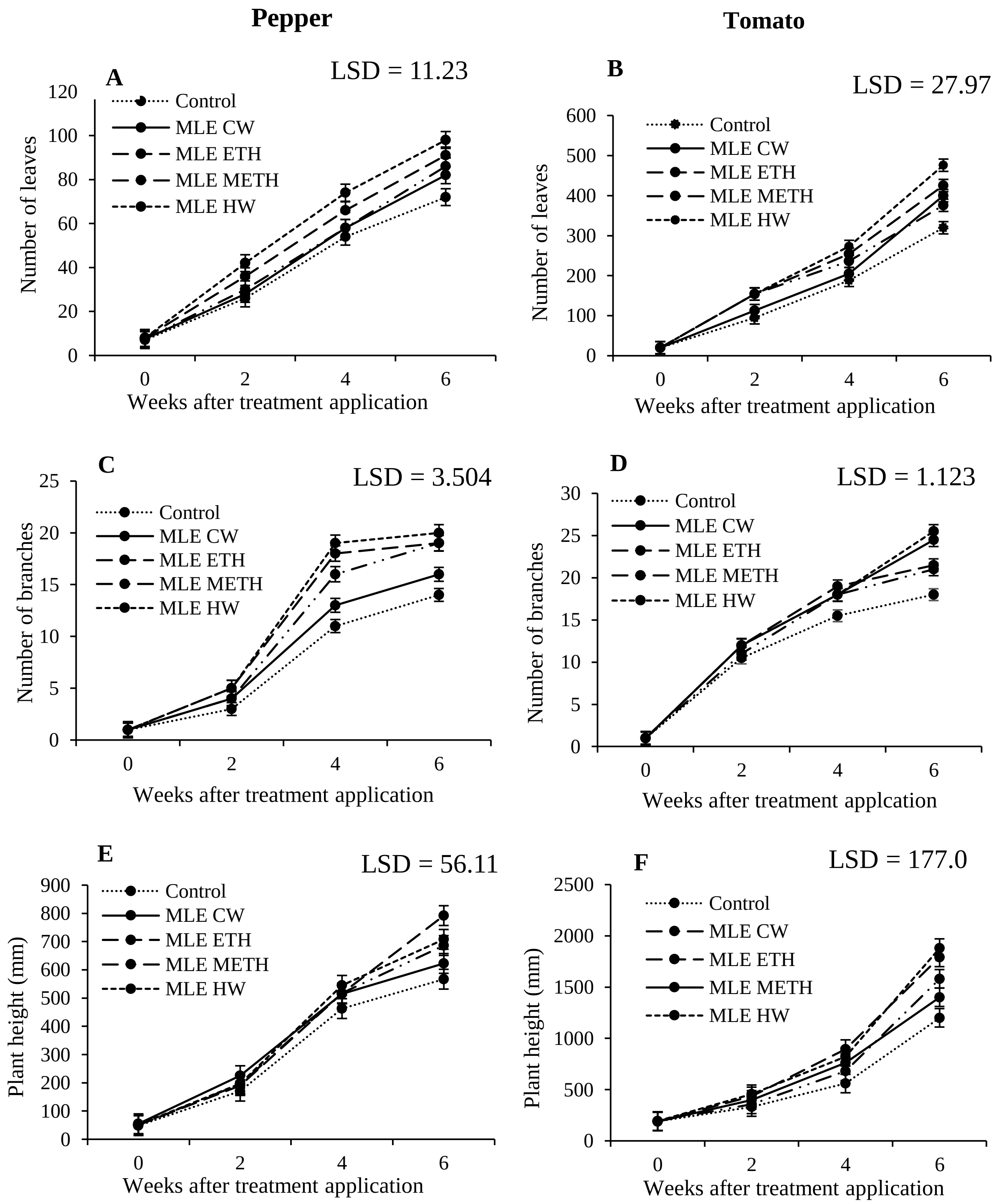

Fig. 1. Effect of foliar application of moringa leaf extract (MLE) prepared using different solvents on vegetative growth parameters of red pepper and tomato. MLE CW = Moringa leaf powder extracted with cold water; MLE HW = Moringa leaf powder extracted with hot water; MLE ETH = Moringa leaf powder extracted with ethanol; MLE METH = Moringa leaf powder extracted with methanol. *(number of leaves and branches are measured per plant). A = pepper number of leaves/plant, B = tomato number of leaves/plant, C = pepper number of branches/plant, D = tomato number of branches/plant, E = pepper plant height, and F = tomato plant height.

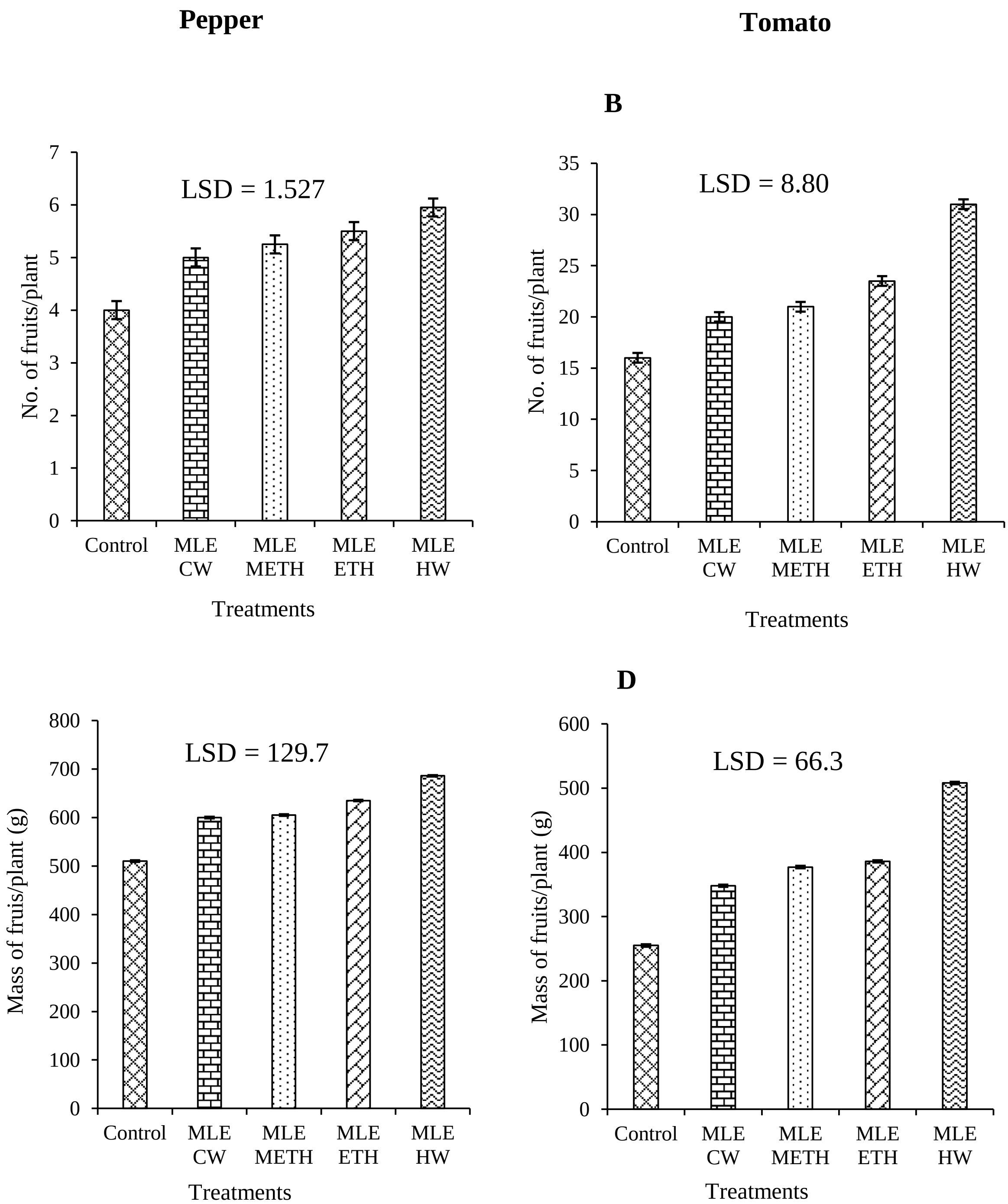

Fig. 2. Effect of foliar application of moringa leaf extract (MLE) prepared using different solvents on yield parameters of red pepper and tomato. MLE CW = Moringa leaf powder extracted with cold water; MLE HW = Moringa leaf powder extracted with hot water; MLE ETH = Moringa leaf powder extracted with ethanol; MLE METH = Moringa leaf powder extracted with methanol. A = Number of pepper fruits/plant, B = Number of tomato fruits/plant, C = Mass of pepper fruits/plant, and D = Mass of tomato fruits/plant.

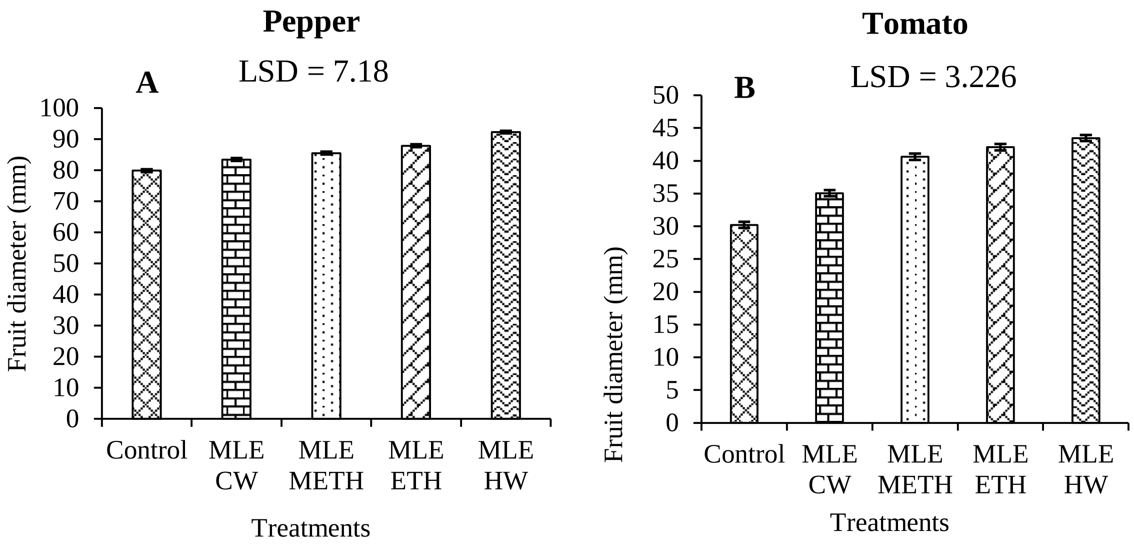

Fig. 3. Effect of foliar application of moringa leaf extract (MLE) prepared using different solvents on fruit diameter of red pepper and tomato. MLE CW = Moringa leaf powder extracted with cold water; MLE HW = Moringa leaf powder extracted with hot water; MLE ETH = Moringa leaf powder extracted with ethanol; MLE METH = Moringa leaf powder extracted with methanol. A = Pepper fruit diameter, B = Tomato fruit diameter.

Table 3. Effect of foliar application of moringa leaf extract (MLE) prepared using different solvents on carotenoid and ascorbic acid concentrations determined in red pepper and tomato fruit.

Treatment	Red pepper		Red tomato	
	Carotenoids (µg. g^{-1} DM)		Carotenoids (mg. g^{-1} FM)	
	Yellow fraction (C^Y)	Red fraction (C^R)	Lycopene	β-carotene
Control	2.434a	4.231a	43.32a	5.956a
MLE CW	2.787a	6.587a	51.68a	6.555a
MLE HW	3.481a	10.914b	52.63a	8.274a
MLE ETH	3.051a	7.812ab	51.25a	10.634a
MLE METH	3.246a	10.876b	42.35a	9.313a
LSD	0.993	3.983	12.84	4.894
CV (%)	21.5	35.8	21.5	19.4

Treatment	Red pepper	Red tomato
	Ascorbic acid (Vitamin C) (mg.100g^{-1} DM)	
Control	400.3a	253.4a
MLE CW	484.1b	262.7a
MLE HW	487.4b	282.4abc
MLE ETH	481b	308.6bc
MLE METH	483.3b	319.6c
LSD	12.89	46.99
CV (%)	2.2	16.6

MLE CW = Moringa leaf powder extracted with cold water; MLE HW = Moringa leaf powder extracted with hot water; MLE ETH = Moringa leaf powder extracted with ethanol; MLE METH = Moringa leaf powder extracted with methanol; C^R = Red carotenoid fraction; C^Y = Yellow carotenoid fraction. *Values followed by different lower-case letters in each column are statistically different at $P \leq 0.05$.

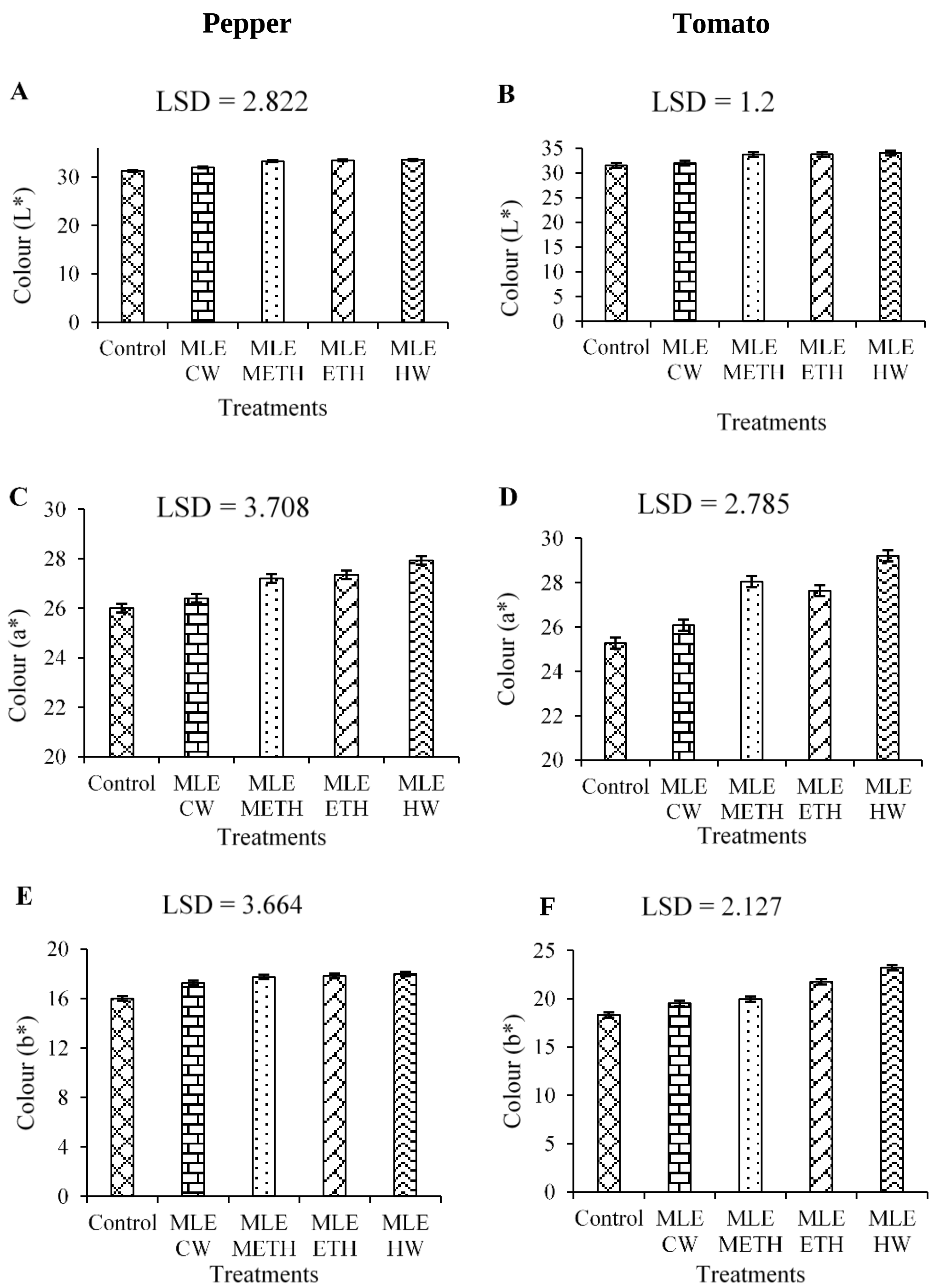

Fig. 4. Effect of foliar application of moringa leaf extract (MLE) prepared using different solvents on colour coordinates (*L**, *a** and *b**) of red pepper and tomato. MLE CW = Moringa leaf powder extracted with cold water; MLE METH = Moringa leaf powder extracted with methanol; MLE ETH = Moringa leaf powder extracted with ethanol; MLE HW = Moringa leaf powder extracted with hot water. . A = pepper colour parameter (L*, lightness), B = tomato colour parameter (L*, lightness), C = pepper colour parameter (a*, green-red axis), D = tomato colour parameter (a*, green-red axis), E = pepper colour parameter (b*, yellow-blue axis), and F = tomato colour parameter (b*, yellow-blue axis).

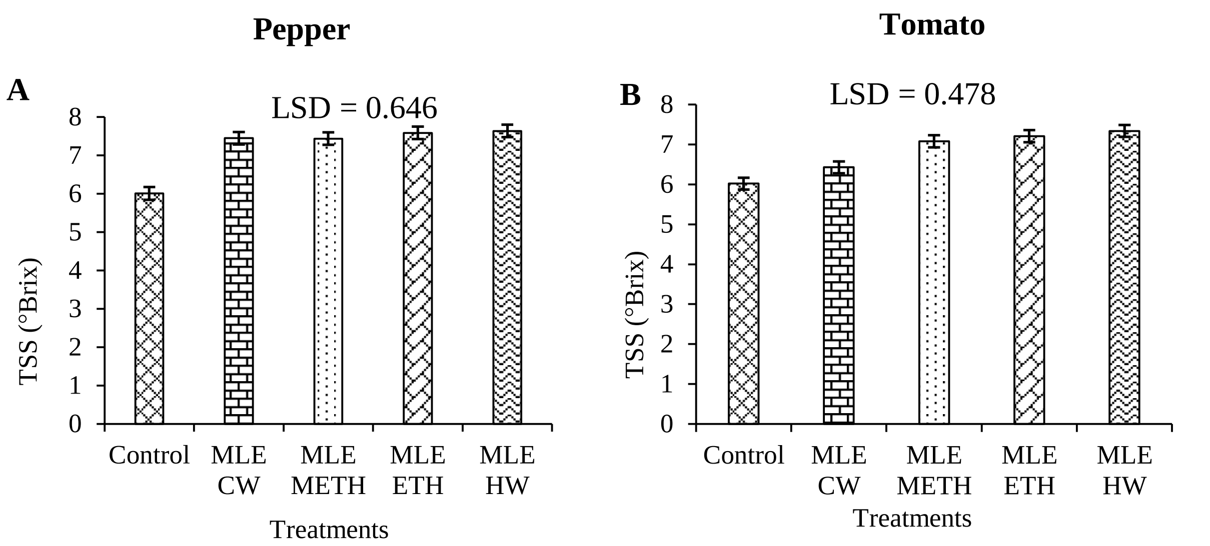

Fig. 5. Effect of foliar application of moringa leaf extract (MLE) prepared using different solvents on total soluble solids (TSS) of red pepper and tomato. MLE CW = Moringa leaf powder extracted with cold water; MLE METH = Moringa leaf powder extracted with methanol; MLE ETH = Moringa leaf powder extracted with ethanol; MLE HW = Moringa leaf powder extracted with hot water. A = Pepper TSS, B = Tomato TSS.

DISCUSSION

The use of biostimulants, as growth and yield enhancers, has recently gained enormous attention. This is due to the ability of such biostimulants to increase plant vigour and yield parameters by modifying plant physiological reactions and increasing plant nutrient acquisition (Zulfiqar et al., 2020). The present study evaluated, hence, the effect of foliar application of MLEs, extracted using different solvents, on pepper and tomato plant growth and development.

The effect of moringa leaf extracts on vegetative growth and yield characteristics

In the present study, foliar application with moringa leaf extracts enhanced the vegetative growth attributes of tomato and pepper plants (Fig. 1). It is not surprising that methanolic and ethanolic extracts enhanced the vegetative growth of the vegetable crops tested in this study since the effect of these extracts has been tested extensively; however, the performance of the aqueous extracts especially the 'MLE HW' tended to outperform the organic solvent extracts; but the difference was not significant. The effectiveness of MLE in enhancing plant height, number of leaves and number of branches in pepper and tomato seedlings (Fig. 1) could be due to the high nutrient concentration in the extracts, as MLEs have been reported to be particularly high in N, K, Ca, Mg, Fe, Zn, Mn, P, these essential nutrients play a pivotal role on growth and development of plants (Table 2; Abd El-Mageed et al., 2017; Gopalakrishnan et al., 2016). In addition to minerals, MLE also contains high concentration of certain plant growth-promoting substance, such as cytokinin zeatin (Rehman et al., 2017), as well as in antioxidant phytonutrients, such as vitamin C, flavonoids and phenolics (Table 2) (Foidl et al., 2001; Siddhuraju et al., 2003; Sreelatha et al., 2011). As a rich source of these compounds, MLE is an ideal natural growth enhancer (Jacob et al., 2011; Makkar et al., 2007); moreover, cytokinin zeatin is a plant hormone, present in high concentrations in moringa leaves

(Yasmeen, 2011). Zeatin plays a crucial role in cell division, resulting in cell multiplication, and general cell enlargement or elongation; leading to growth promotion of greenhouse-grown pepper and tomato plants (Fig. 1a, b, c, d, f) (Anwar et al., 2007; Siddhuraju et al., 2003). In addition, the high concentration of both total phenolics and ascorbic acid (Table 2) from the MLE HW, particularly, compared to other MLEs could be the reason this treatment performed well. The rapid increase in vegetative growth following MLE application is not only accredited to the presence of cytokinins. Besides zeatin, there is also dihydrozeatin, isopentyladenine and high content of crude protein in MLE (Busani et al., 2011). These authors studied the crude protein concentration, and the growth-promoting hormones present in moringa leaves and found that this protein/hormone combination is responsible for growth acceleration. Numerous studies on the response of several crops, such as pear (*Pyrus communis*) (El–Hamied et al., 2015), 'Kinnow' mandarin (*Citrus nobilis x Citrus deliciosa*) (Nasir et al., 2020), sunflower (*Helianthus annuus*) (Iqbal et al., 2020); tomato (Ngcobo et al., 2021) to MLE have been reported; however, there is no study that reported the comparison of hot and cold aqueous moringa leaf powder extracts, or ethanolic and methanolic moringa leaf powder extracts on fruit vegetable crops. It is clear from the analysis presented in table 2 that inorganic solvents (hot and cold water) are also suitable for extracting phytochemicals due unique properties they possess as they are non-carbon-based solvents in nature (Matshediso et al., 2015). Choosing a suitable moringa leaf powder extraction solvent is particularly important, as MLEs can be used in organic food production and the use of water, to extract the moringa leaf powder, is an environmentally friendly method, while organic solvents pose several health problems.

In terms of yield, treatment with MLE HW, again, affected yield parameters more positively than other treatments (Fig. 2a-d and Fig. 3a and b), while the chemical-based treatments were not as effective, but still outperformed the control. It was unsurprising that the application of only cold water (control) to the leaves of tomato and pepper did, in accordance with our recent study (Ngcobo et al., 2021), not produce any effect on yield parameters. The study by Foidl et al. (2001) supports our study, as these authors reported that MLE applied in low concentration showed prominent effects on yield. Similarly, (Cheema et al., 2013) demonstrated that the application of watery moringa extract to wheat (*Triticum aestivum*) improved crop yield considerably. Iqbal et al. (2020) conducted a comparative study using cold, aqueous extract of moringa leaves as well as roots to improve sunflower growth and yield, and reported that moringa extracts, obtained by extraction with cold water, significantly improved growth and yield of sunflower. The high content of vitamin C, total carotenoids and phenolics (Table 2) in aqueous extracts particularly MLE HW could be the possible reason this extract performed well by modifying plant physiological reactions and increasing plant nutrient acquisition. High antioxidant activity in both water extracts potentially resulted in a high photosynthetic rate because antioxidants prevent chlorophyll degradation, protect against oxidative damage, and improve nutrient uptake by the roots (Moyo et al., 2011). There seems, however, no study that investigated the comparison of extraction solvent on the efficacy of fruit yield and quality.

Moringa leaves are a rich source of natural growth-enhancing substances and contain amino acids, minerals, ascorbate and other active ingredients, which are considered "growth supporters" that are likely to enhance yield (Mahmood et al., 2010). These compounds were possibly present on the MLEs, more so on MLEs derived from water solvents. Foliar application of moringa hot water extract, and that of MLEs produced with inorganic solvents, increased the resistance of pepper and tomato plants to pests and diseases and also increased growth parameters (Fig. 1). The number and size of roots was also enhanced by moringa application, seemingly aligned with plants creating more (Fig. 2) and superior fruit (Fig. 3) resulting in increased yield. In addition, an increase in yield may be due to the stimulating effect of MLE, particularly when MLE is produced via a hot water extract, on the vigour of plants and photosynthate accumulation, stimulating pepper and tomato plants to produce larger and more fruit (Abdel-Rahman et al., 2020).

The effect of moringa leaf extracts on physical and chemical constituents of pepper and tomato

Recently, consumers' attention to the intake of fruit and vegetables with a high phytochemical concentration has increased significantly. Consumers are aware of the health benefits associated with the consumption of nutrient-rich fruit and vegetables, including the prevention of chronic, degenerative disorders. In the present study, the effect of MLE on colour, sugars and carotenoids of two solanaceous crops was evaluated at harvest (Fig. 4, 5; Table 3). Studies of this nature focus mostly on growth and yield attributes, while studies evaluating quality parameters, particularly postharvest, are scarce. This study revealed that MLE HW, MLE ETH and MLE METH significantly enhanced fruit colour (a^*, Fig. 4c and d) of red pepper and tomato; again, treatment with MLE HW outperformed other treatments. These three extracts had also a significant effect on the lightness (L^*) of fruit (Fig. 4a and b). These findings are important for producers and consumers alike, as colour is one of the main characteristics of foodstuffs noted by consumers, relating directly to consumer purchase decisions and fruit market value. Similar to colour, TSS in peppers improved following MLE treatment, except for the MLE CW (Fig. 5a), while in tomatoes all MLEs affected fruit TSS positively (Fig. 5b). The increase in pepper sugars may be due to the high content of zeatin in MLE, a cytokinin involved in the translocation of photo-assimilates towards the fruit (Yasmeen, 2011). On the other hand, carotenoids in red peppers, probably the major pepper pigments capsanthin and capsorubin, were significantly enhanced by MLE treatments, excluding the cold water MLE treatment and the control (Table 3), while MLEs seemingly enhanced lycopene and β-carotene on red tomatoes (Table 3), the activity of antioxidants in the extracts could potentially enhance the concentration of phytochemicals in the treated fruits. These results are in line with those of (Basra et al., 2016), who reported that sugars and carotenoids, particularly lycopene and β-carotene in cherry tomato, were enhanced by foliar application of MLE. Manuscripts assessing postharvest quality of fruit and vegetables after applying preharvest moringa treatment are scarce. Foliar MLE application significantly enhanced vitamin C in peppers, fruit known to be an excellent source of vitamin C (Guil-Guerrero et al., 2006), while the organic-solvent extracts significantly enhanced this parameter compared with the control in tomato fruit; the aqueous extracts, however, only had a potential to do so (Table 3).

The increased carotenoid concentrations in the pericarp and, therefore, colour in pepper and tomato fruit may be attributed to the presence of various secondary metabolites in MLE, such as β-carotene, ascorbate, phenolics and other antioxidants (Table 2; Foidl et al., 2001), as well as zeatin (Yasmeen, 2011). Together with the minerals (Ca, K) found in MLE, zeatin, through its effects on root growth (Atzmon et al., 1993), is likely to have promoted nutrient uptake and photosynthesis, ultimately resulting in an increase in fruit antioxidant concentration or maybe MLE caused a slight stress to plants that contributed to an increase in fruit antioxidant concentration. Carotenoids act as radical scavengers, preventing oxidative damage caused by free radicals (Rao et al., 2007). The carotenoid concentration of fruit, including tomatoes and peppers, determines fruit colour and ultimately also affects the nutritional status of the fruit (Cömert et al., 2020).

The effects of MLE differed with extraction solvent. The use of water as an extraction solvent is slowly gaining popularity due to its high extraction efficiency (Castro-Puyana et al., 2017). Water is obviously the most readily available and environmentally friendly extraction solvent. While the polarity of water does not allow it to dissolve hydrophobic substances which are the most active compounds present in medicinal plants, such as moringa, it has been demonstrated that increasing water temperature improves the extraction efficiency of organic compounds (Castro-Puyana et al., 2017). The ability of water to efficiently extract growth-stimulating compounds presented in Table 1 is linked to the fact that the dielectric constant (polarity) of water can be reduced significantly with increasing temperature (Castro-Puyana et al., 2017; Ong et al., 2006). The polarity of water at 25°C is around 80, indicating that it is an extremely polar solvent (Ong et al., 2006); however, at temperatures higher than 100°C water's polarity is reduced to approximately 27, falling between the polarity of methanol (33) and ethanol (24) at 25°C (Ong et al., 2006). Hot water might, therefore, have been able to extract certain compounds from moringa powder that were not extractable by other solvents. It must, however, be noted that while increasing the water temperature to the boiling point resulted in higher extraction efficiency, the high temperature could also have degraded other compounds (Hawthorne et al., 1994; Miller et al., 1998; van Bavel et al., 1999). Apart from our study, the higher extraction efficiency of hot water was aslo witnessed when antioxidant compounds were extracted from rosemary plants and catechin and epicatechin from tea leaves and grape seeds; these antioxidant compounds could be successfully extracted by hot water at the boiling point, as reviewed by (Ong et al., 2006). A study by (Matshediso et al., 2015) further revealed that extraction of moringa leaf powder with hot water results in a high yield of phytochemicals and this study supports our results.

CONCLUSION

Various solvents used in this study to prepare MLE differ in extraction efficacy. Certain MLEs, particularly hot water MLE (MLE HW) and ethanolic MLE (MLE ETH), were more effective in enhancing vegetative growth parameters, yield and fruit colour of both pepper and tomato plants or fruit. Treatment with MLE HW and MLE METH enhanced the carotenoid concentration in pepper; therefore, MLE application holds the potential to enhance the carotenoid and vitamin C of fruit, thereby improving the nutritive value of these commodities. Results presented in this research are of high significance to both commercial and small-scale pepper, as well as tomato growers, as hot water extracts which is an environmentally friendly, financially feasible and sustainable approach, outperformed other treatments. The positive effect of MLE HW on tomato and pepper, therefore, requires further investigation.

Conflict of interest

The authors declare that they have no conflict of interest

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [BLN], upon reasonable request

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