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ORIGINAL ARTICLE

The assessment of tomato fruit quality parameters under different sound waves

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Abstract Sound stress is an abiotic stress factor wherein the sound wave form affects the growth and development of plants as an alternative mechanical stress. To explore this, 10-week-old tomato (*Solanum lycopersicum*) plants were used in this experiment. The tomato plants were exposed to three different frequency values consecutively: 600 Hz in the first week, 1240 Hz in the second week and 1600 Hz in the third week. The decibel (dB) value was adjusted to 90 dB in the sound amplifier. At the end of the experiment, lycopene, vitamin C, total sugar, total acid and total phenol levels were analysed and pH and ^{0}Brix were measured in tomato fruits. As a result, it was determined that as the sound frequency intensity level increased, the concentration of fruit parameters also increased: lycopene, vitamin C, total sugar, total acid and total phenol. The total phenol content, lycopene content and ascorbic acid of the tomato plants that were exposed to sound waves at different frequencies increased at a rate of 70%, 20% and 14%, respectively. According to the results of all measured parameters in tomato fruits, 1600 Hz has been determined the best of sound wave frequency value.

Keywords *Solanum lycopersicum* · Vegetable · Abiotic stress · Fruit quality parameters · Frequency (Hz) · Sound waves

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Introduction

In recent years, the benefit of fresh fruit and vegetable consumption to human health has been increasingly investigated. The consumption of fruits and vegetables provides almost 50% of the total proposed daily antioxidant intake to human beings (ca. 3.000–3.600 µmol Trolox equivalent antioxidant capacity, TEAC) (Prior and Cao 2000). Phenolic compounds, antioxidants and vitamins are very important because of their antioxidant properties. These compounds are critical for human health because of their effects on cancer and ageing (Dillard and German 2000). Globally, tomato (*Solanum lycopersicum*) is one of the most consumed vegetables and one of the most produced agricultural products. For this reason, it is considered an important antioxidant source in human nutrition (Lenucci et al. 2006). Compounds with essential antioxidant properties in tomato fruit include phenolics, carotenoids and pigments (Giovanelli et al. 1999). The interest in consuming high quality fresh or processed tomatoes continues to increase. This phenomenon, defined as functional quality, is based on how much protection against disease can be attained by the consumption of a specific food. Tomato fruit is consumed in high quantities all over the world and is regarded as a health-enhancing fruit owing to its vitamin C, vitamin E, lycopene, carotene, lutein and flavonoid contents (Dorais et al. 2008). With an increasing interest in functional foods, tomato has become a focal point in several studies that have investigated factors that affect nutritional quality. It is a well-known fact that useful element levels in tomato vary according to cultivar, ripening level, growth conditions and level of exposure to environmental stress (Dorais et al. 2008; Slimestad and Verheulb 2009).

Since plants are immobile living organisms, they are compulsorily exposed to environmental stress including mechanical stresses (Liu et al. 2007). Plants have the ability of responding to the environmental stimuli like light, heat, gravity and contact (Telewski 2006; Gagliano et al. 2012). Sound is one of these environmental stimuli and is an acoustic energy that spreads in the form of a pressure wave after a vibration. The audible sound is between approximately 20 Hz and 20 kHz frequency. Sound is a wave that travels via the vibration of mass molecules. Sound waves are longitudinal waves that have the same diffusion and vibration direction. Sound waves are mechanical waves; they need material medium to diffuse. One of the most important sound magnitudes is sound pressure. Sound pressure refers to the changes that occur in air pressure during sound diffusion within a specific time. The sound pressure p(t) changes according to time, and vibrations in the form of a sine wave have a magnitude that cannot be characterised directly. In its simplified form, the active sound pressure p is more beneficial. During the time t in which the observation is 86 made, the average value may be computed based on the changing sound pressure as follows:

$$P = \sqrt{\frac{1}{T}\int P^2(t)dt},\ [\mathrm{Pa}]$$

Here, Pa is the Pascal unit $\left[\frac{\mathrm{N}}{\mathrm{m}^2}\right]$.

The basic sound pressure p^0 is 2.10–5 Pa at a 1000 Hz hearing limit. This computation method using digital sound measurement devices is currently used.

Another characteristic magnitude of sound is sound velocity (v(t)), which changes according to time. Similar to sound pressure, sound velocity (v) may be computed as follows: $v = \sqrt{\frac{1}{T}\int_o^T v^2(t)dt}\ \left[\frac{\mathrm{m}}{\mathrm{s}}\right]$

Although sound pressure changes may be computed in an accurate and simple way using a microphone, the computation of sound velocity is extremely difficult in terms of measurement techniques. Sound measurements are made at a distance that is adequately far away from the source (approximately 1 m) to protect the sound pressure and velocity rates from diffusing in open field conditions. In this context, it is possible to write the following equation:

$$v = \frac{p}{c}\ \left[\frac{\mathrm{m}}{\mathrm{s}}\right]$$

Here, p is the density of the medium in which the sound diffuses, v is sound velocity, and c is the sound diffusion velocity. In this way, sound velocity can be determined using sound pressure in an indirect way.

It is well known that environmental factors like moisture, light, wind, and heat have physiological effects on plant growth. However, there is less information on the effects of the audible sound on plants. It is possible to claim that sound is a physical signal affecting the growth of a plant in one way or another. However, the exact mechanism of this effect and the stimulus is not clear yet (Gagliano et al. 2012; Gagliano and Renton 2013). In recent years, studies have been conducted in which audible sound waves were used in various physiological stages of plant growth like germination of the seeds, callus growth, endogenous hormones, photosynthesis mechanism, and the transcription of certain genes (Collins and Foreman 2001; Creath and Schwartz 2004; Telewski 2006; Gagliano and Renton 2013). In actual fact, sound waves and ultrasound waves are among the abiotic stress factors on plants. When sound waves or ultrasound waves are applied to a plant, the effects of these waves increase on biological processes as the frequency increases (Telewski 2006; Gagliano and Renton 2013).

Previously, none of previous studies examined the effect of different level Hertz on some fruit parameters of tomato. In stressed conditions, phenolic compounds, ascorbic acid, and lycopene increase in plants to protect themselves. For this reason, it is expected that the nutritional compound concentrations accumulate under stress condition. These compounds are the ones which increase the quality of fruits and vegetables, which is important in human nutrition and health. Normally, biotic or abiotic stress in plants reduces plant growth and yield. In the present study, the purpose was increasing the quality parameters through different sound waves on the tomato which is the most produced vegetable in the world; and we aimed to do this without harming the plant. The aim of this study was to determine the effects of sound stress on Total Soluble Solids (TSS), Titratable Acidity (TAC), pH total phenolic, ascorbic acid and lycopene in tomato fruits.

Materials and methods

Sound frequency

Sound waves are in the shape of sinus waves (Fig. 1). The distance between the two top points is the *wave length*, and the number of wave tops observed in 1 s is the *frequency*. Measuring sound pressure levels depending on the frequency is referred to as frequency analysis, and the result in graphic form is the sound spectrum. Because human perception limits include sound magnitudes that are different and higher than each other, the decibel (dB) is used as the unit of magnitude measurement. The magnitude here

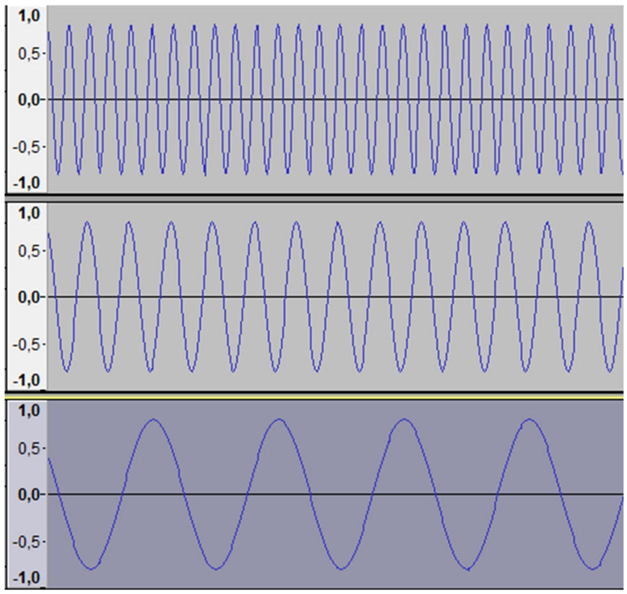

Fig. 1 Diagram of sine waves at different frequencies

is the magnitude of the sound and the amount of sound energy that flows through the sound magnitude unit area.

$$I = \frac{W(\text{watt})}{A(\text{m}^2)}$$

In this definition, if A is the amount of the energy diffusing from the W sound source, this is the field through which the sound energy flows. When a 'sound magnitude level' is mentioned, an understanding of the logarithm of the rate of an energy-physical magnitude to a certain basic value is required. Another meaning of dB is the perceived sound level or the unit of noise level.

The magnitude of the sound is proportional to the square of the sound pressure ($I \sim p^2$). Here, the sound pressure level is calculated by the following equation:

$$L_p = 10 \cdot \log \frac{p^2}{p_0^2} = 20 \cdot \log \frac{p}{p_0} \text{ [dB]}$$

Devices

A sound amplifier with a dB indicator that could be adapted according to regions at various dB values was used in the measurements. To create frequencies at various values (600 Hz, 1240 Hz and 1600 Hz), a signal generator (adjustable frequency oscillator) and three pieces of 4 m^2 chambers were prepared. The four sides of them could be opened. In addition, a sound level metre (noise measurement device) and speakers that were capable of producing 360° sound were used as the sound measurement device. The thickness of the glass used in the chambers was 4 mm, and there was a 10.5 mm space between these glasses (Fig. 2).

Plant material

Tomatoes were planted, and 10-week-old tomato plants were used in the experiments. 13-788 F_1 tomato variety (SFT Agriculture Inc.) was used as a plant material. The plants were placed in 4 L pots with turf and perlite (1:1). During the experiment, tomato plants were given a nutrient solution, which was modified from the study by Dasgan and Ekici (2005) (in 150 ppm): NO_3–N (135–225), NH_4–N (15–25), P (40–50), K (200–400), Ca (150–180), Mg (50–75), Fe (2.8–5.0), Mn (0.8–1.0), Cu (0.3–0.4), Zn (0.3–0.4), B (0.3–0.4) and Mo (0.05–0.1). To determine the effect of the sound stress on the fruits, the plants were placed in the sound chambers at 10-week stages.

Experimental design

The study was conducted in special sound chambers in a plastic greenhouse located at the Research Fields of Cukurova University, Karaisalı Vocational High School (36°59′N, 35°18′E, 20 m above sea level), Adana, Turkey. The experiment was a randomised complete block empirical design with three replicates 10 plants in each; and 4 chambers were used in the experiment, and they were constructed in such a way that only the sound inside the chamber could be heard and no outside sounds could enter. Each chamber was tested before the trial started to ensure sound proofing. The speakers in the chambers could produce 360° sound and were hung in the centre of the chamber 43 cm above the ground. The pots were then placed in these chambers and subjected to different sound waves. Each pot was placed 65 cm away from the speaker. This distance was chosen because the sound measurement was made at an adequate distance from the source (nearly 1 m). For each chamber in which the experiment was conducted, the dB value was adjusted to 90 dB in the sound amplifier. Because exposure to sound waves above 85 dB may be dangerous, 90 dB was used in the trial. Control plants were placed in chambers that had the same properties as the trial chambers but with no sound. In the study, the sound application was continued for 30 days. The tomato plants in each chamber were exposed to sound stress with sound waves at 90 dB and 600 Hz in the first week, 1240 Hz in the second week and 1600 Hz in the third week. The sound waves in the chambers were sent once a day for 1 h in the morning from 10:00 to 11:00. The plants were watered with an equal amount of water during the trial period once every 2 days. Plant analyses were made with fruits that were taken at the end of the first, second and third weeks. Thus, sound stress was applied to

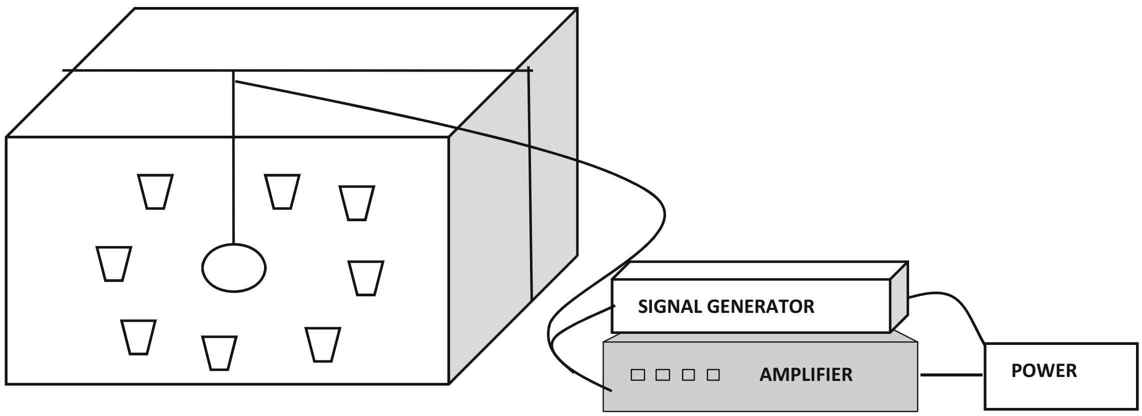

Fig. 2 Schematic of the trial design. Sound-proof room, pots arranged around the sound source and the devices used that (signal generator/frequency oscillator produced by the sound waves of different frequencies, dB value can be adjusted by the amplifier/sound amplifier to be sent to the soundproof rooms)

the plants in a gradually increasing manner, and the fruits collected after the third treatment period had been subjected to previous treatments of 600 Hz and 1240 Hz and a final treatment of 1600 Hz.

Tomato fruit analysis

The experiment started on 21.11.2014 and ended on 21.12.2014. Plant measurements began after 10 days of the exposure to sound stress and then twice again at 10-day intervals. The analyses and measurements were made on fruits that were ripe enough for harvesting, and the fruits were selected randomly. Then, pH, (^{0}Brix), titrable acidity (TAC), vitamin C, lycopene, total sugar (TS), acid and total phenolic contentwere made in the fruits. The harvest was made right at the red ripening stage, liquid nitrogen was applied, and kept at as − 80 °C until the extraction process. For ultra-pure water, the Millipore filter system was used (Millipore Corp., Bedford, MA), and the chromatograph reactive standards and solvents were obtained from the Sigma Chemicals Company.

Determination of TSS, TAC and pH

Among the fruits that were harvested in 3 replicates and 5 fruits were selected from each group and extracted to determine the TSS, TAC and pH. For the TSS, a hand refractometer (ATAGO ATC-1, Tokyo, Japan) was employed. The TAC level was determined according to the acid–base titration method. In this method, 1 ml tomato juice was added to an Erlenmeyer with 50 ml distilled water (conical flask) and was titrated with diluted 0,1 N NaOH until pH 8,1. Total acidic content was determined as the equivalent of citric acid. The pH value, on the other hand, was measured with pH metre (CG 840 Schott Gerate GmbH, Germany) in tomato juice.

TS extraction

Nearly 500 g of a frozen sample was used in a separate manner, and 1 g was then weighed and powdered with liquid nitrogen in a mortar. The powder was then placed in a screw cap Eppendorf tube with 20 ml aqueous ethanol (80%, v/v). The mixture was transferred into an ultrasonic bath, and sonication was applied for 15 min at 80 °C and filtered via regular filter. Extraction was repeated 3 times more. All of the extracts filtered were combined and evaporated to dry on a boiling water bath. After dissolving the residue in 2 ml distilled water and filtering (Whatman nylon syringe filter, 0.45 µm, 13 mm diam.) before high performance liquid chromatography (HPLC) analysis (Kafkas et al. 2007).

One gram of the frozen sample was weighed and grinded as powder with liquid Nitrogen. Then, this powder was transferred into an Eppendorf Tube which had 20 ml diluted ethanol (80%, v/v). This mixture was kept at an ultrasound bath at 80 °C for 15 min (it was sonicated i.e. it was exposed to ultrasound waves) and was filtered with a paper filter. This extraction process was repeated for 3 times, and then the filtered extracts were joined. These extracts were dried in a boiling water bath by vaporizing its water content. This dried sample was dissolved with 2 ml distilled water before the HPLC analysis, and was filtered through 0.45 µm, 13 mm-diameter Whatman nylon syringe filters (Kafkas et al. 2007).

HPLC of sugars

The HPLC Device (Shimadzu LC 10A vp, Kyoto, Japan) used in the study consists of a built-in pump, gas eliminator, and a series of controller photodiode detectors (Shimadzu SPD 10A vp). In addition, a computer that has the Class VP chromatography manager software

(Shimadzu, Japan) and an automatic injector (20 μL injection volume) were employed. The separations were made with the 5 μm, reverse-phase ultra-sphere ODS analytic colon (Beckman, Fullerton, CA) that had an internal diameter of 250 mm * 4.6 mm operated at room temperature with 1 ml min^{-1} (1 ml/min) flow-rate. The results were recorded between 200 and 360 nm wavelength with a full-scale sensitivity at 0,1 absorbance units. The elusion was isocratic with 0.5% diluted meta-phosphoric acid. In order to define those that had specific standards, the components were compared in terms of process times. A 10-min interval was given between the injections for balamnce purposes. At the same HPLC, 150 mm *4.6 mm i.d., 5 μm, reverse-phase Nucleosil as NH2 analitik colon (Shimadzu, Tokyo, Japan) was used to separate the sugar at room temperature at 1 ml min^{-1} flow rate (Kafkas et al. 2007).

Determination of total phenolic content (TPC), ascorbic acid and lycopene in tomato fruits

In this experiment, we used Folin–Ciocalteu method for Total Phenolic Content (TPC) (Spanos and Wrolstad 1992). The samples have been homogenized with T18, IKA Homogeniser, Germany. After then 5 g of tomatoes with 25 ml ethanol was centrifuged at 3500×*g* for 3 min and was filtered. Two millilitres of 10% Folin–Ciocalteu reagent was added to 0.4 ml of the extract and left for 2–3 min. Then, 1.6 ml (7.5%) of Na_2CO_3 was added to the mix and incubated for 1 h in the dark. It was determined at 765 nm in a spectrophotometer (UV-1201, Shimadzu, Kyoto, Japan) against a blank solution (0.4 ml water + 2 ml Folin–Ciocalteu reagent + 1.6 ml Na_2CO_3). The total amount of phenolic compounds was calculated as a mg gallic acid equivalent (GAE), 100 g^{-1} using the gallic acid standard (Kafkas et al. 2007).

Tomatoes were crushed with a blender and 5 g sample was mixed with 45 ml 0.4% oxalic acid and then filtered for ascorbic acid content. One ml filtrate and 9 ml 2,6-Dichlorophenolindophenol sodium salt solution ($C_{12}H_6$-$C_{12}NO_2$-Na) was mixed and then absorbans values was read at 520 nm in a spectrophotometer. Results are expressed as mg 100 g^{-1} (Ozdemir and Dundar 2006).

The lycopene content of tomatoes was measured according to Sharma and Le Maguer (1996) and Rao et al. (1998). Tomato was ground, and 1 g of the homogeneous tissue was combined with 50 ml of hexane–ethanol–acetone (2:1:1, v/v) and shaken for 30 min in a 100 ml flask that was wrapped with aluminium foil. Then, 10 ml distilled water was added, and it was shaken again for 5 min. The solution was placed in a separator funnel and then filtered. The lycopene concentration was measured by absorbance of the solution at 502 nm [a UV–Vis spectrophotometer (UV-1201, Shimadzu, Kyoto, Japan) was used for this purpose]. Results are given as mg kg^{-1} fresh weight (FW) (Kafkas et al. 2007).

Data analysis

SPSS Statistics version 20 (Armonk, NY: IBM Corp.) was used for data analysis. The effect of fruit parameter data was significant ($P \leq 0.05$), and mean values for each parameter were compared by a multiple comparison Duncan test was applied to investigate the grouping (at $P \leq$ 250 0.05).

Results

Total soluble solids (TSS), titratable acidity (TAC) and pH

The results showed no significant changes in pH of tomato fruits based on the application of different frequency sound waves (600, 1240 and 1600 Hz). The pH range was 4.38–4.57. When TSS and TAC results were analysed, a statistically significant difference was observed among the applications. TSS and TAC levels were lower in fruits that had been exposed to sound in a chamber. TSS was 4.92% in control plants and 5.30%, 5.69% and 5.74% in the 600, 1240 and 1600 Hz trial groups, respectively. As the sound frequency increased, so did the TSS and TAC levels, and TAC was also higher at 600 Hz when compared with that in the control group plants. TAC was significantly higher at an exposure level of 1240 and 1600 Hz compared with that in control plants and plants that were exposed to 600 Hz. TAC was 0.64% in the control group, 0.73% at 600 Hz, 0.87% at 1240 Hz and 0.91% at 1600 Hz. TAC levels increased by 30% at the highest sound level (Fig. 3 and Table 1).

Lahoz et al. (2016) investigated the effect of water stress, which is another abiotic stress, on tomato plants, and reported that it had no effect on pH, a result that is similar to that of our study. However, unlike in our study, they also reported that stress had no effect on TSS. However, Saito et al. (2008) reported that the ^{0}Brix value increased in tomatoes under salt stress. TAC of stress-treated fruit was also 1.6 times higher than that of the control, and citrate levels would affect the total acidity of tomato fruit.

Hou and Mooneyham (1999) conducted a study and examined the effects of agri-wave technology on improving the yield and quality in plants. Agri-wave technology is the application of sound waves in intervals by using the sound frequency technology and spraying the fertilizers that have microelements to the leaves of the plants once a week. In other words, sound waves and fertilizer were

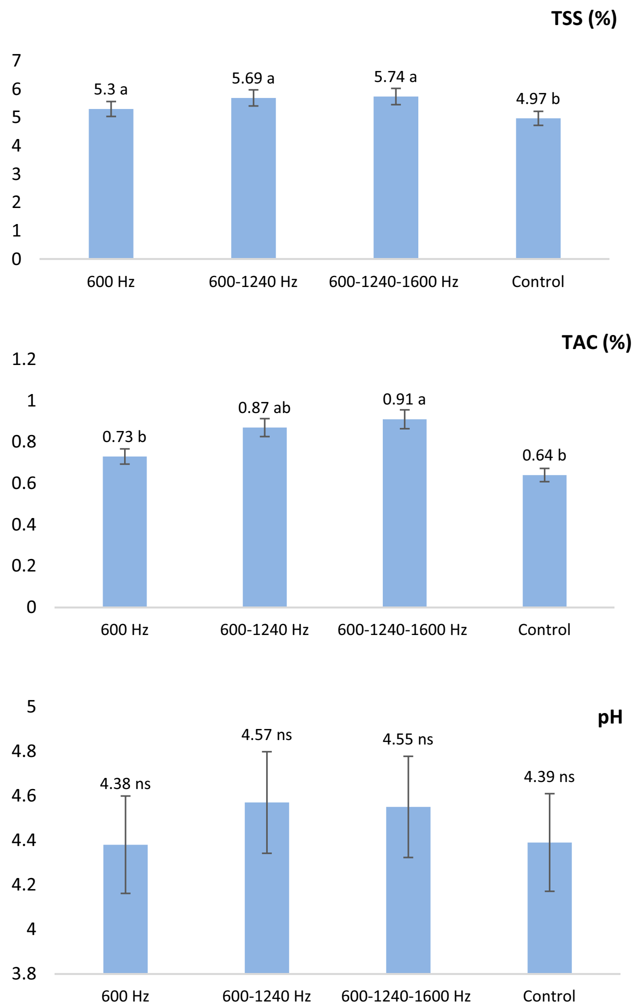

Fig. 3 Effect of different sound wave frequencies on total soluble solids (TSS), titratable acidity (TAC) and pH of tomato fruit. Values in the each graph with different lower-case letters are significantly different at $p < 0.05$

applied to the leaves of the plants together. As a result, this application encouraged the growth (branches, trunk and fresh weight of the leaves) and increased the quality and yield. It was reported that growth rates were found to be higher than the control plants at a rate of 59.5% and the yield was more at a rate of 13.9% ($P < 0.001$). Mitchell et al. (1991) reported that the water soluble solid content increased in tomato plants that were grown in limited water conditions because when water was scarce, the organic soluble dry substance synthesis and accumulation increased.

Total sugars (TS) and total phenolic content (TPC)

When results were analysed, it was seen that there were no significant differences in TS levels between the fruits of the control group and trial group. However, TS in control and 600 Hz application fruits was 2.8% and 2.9%, respectively, and TS increased with increasing Hz frequency to 3.2% at 1240 Hz and 3.9% at 1600 Hz. It is possible to claim that the increase in sound frequency also increased TS in tomato plants. Saito et al. (2008) conducted a study to investigate the effect of salt stress on tomato plants, and they reported that saccharose, which is another type of sugar, increased at a rate of 4.7-fold in plants to which stress was applied, and glucose and fructose were not influenced by stress. Sucrose and citrate are significant elements that affect the taste of tomato fruit; the accumulation of these components will improve its flavour and nutritional status.

Atkinson and Urwin (2012) reported that water stress and nematode stress alone did not affect glucose or fructose concentration in tomato. On the other hand, in case these stresses were applied together, higher concentrations of these two sugars was detected at a significant level in truss five fruits, which resulted in a 23% increase in glucose and a 22% increase in fructose compared with the controls. The TS level was also enhanced in stress-treated tomato fruits. There was an obvious increase in total phenol in fruits exposed to sound waves compared with that in the control group. The total phenol content was 0.48 (mg/100 g GAE) in the control group, and 1.46 at 600 Hz, 1.53 at 1240 Hz and 1.61 at 1600 Hz (mg/100 g GAE). The total phenol content of the tomato plants that were exposed to sound waves at different frequencies increased at a rate of 67%–

Table 1 Effect of different sound wave frequencies on physicochemical quality parameters of tomato fruits

Treatments	pH	TSS (%)	TAC (%)	TS (%)	TPC (mg/100 g gallic acid)	Lycopene (mg kg^{-1})	Ascorbic acid (mg 100 g^{-1})
600 Hz	4.38	5.30 a	0.73 b	2.9	1.46 a	2.81 a	27.87 a
600–1240 Hz	4.57	5.69 a	0.87 ab	3.2	1.53 a	2.97 a	28.65 a
600–1240–1600 Hz	4.55	5.74 a	0.91 a	3.9	1.61 a	3.12 a	29.13 a
Control	4.39	4.97 b	0.64 c	2.8	0.52 b	2.66 b	23.25 b
SD	± 0.0878	± 0.331	± 0.108	± 0.430	± 0.459	± 0.172	± 2.338

The means in the columns followed by different letters are significantly different ($P < 0.05$)

70% when compared with control group plants (Fig. 4 and Table 1).

Oliveira et al. (2013) conducted a study on organic tomato fruits; and reported that oxidative stress increased the water soluble dry substance amount/soluble solid (like sughars and other compounds) concentrations. They also caused that the amounts of the compounds that defined the nutrition value of the fruit like Vitamin C and phenolic compounds increased as well. Atkinson and Urwin (2012) reported that the stress applications affected the levels of the phenolic compounds in plants. They also reported that the levels of the phenolic componuds in tomatoes tat were exposed to nematod stress were higher than the controls at a rate of 56%. Atkinson and Urwin (2012) reported that nematode [3.6 (0.3 mg/100 g)] and water stress alone did not have any effects on the glucose and fructose levels in tomato plants; however, when both were applied [3.3 (0.4 mg/100 g)], the amount of the glycose increased at a rate of 23% and the fructose amount increased at a rate of 22% compared to the control plants [2.3 (0.3 mg/100 g)]. Briefly, the total sugar content increased in stress applications. Atkinson and Urwin (2012) also found that stress treatments influenced the levels of phenolic compounds in truss five tomatoes that were harvested later in the trial.

Ascorbic acid and lycopene in tomato fruits

The ascorbic acid amount was higher in plants exposed to sound compared with the control group. As the sound wave frequency increased, so did the ascorbic acid level. Levels were 23.25 mg/100 gin control plants compared with 29.13 mg/100 gin 1600 Hz, which was the highest

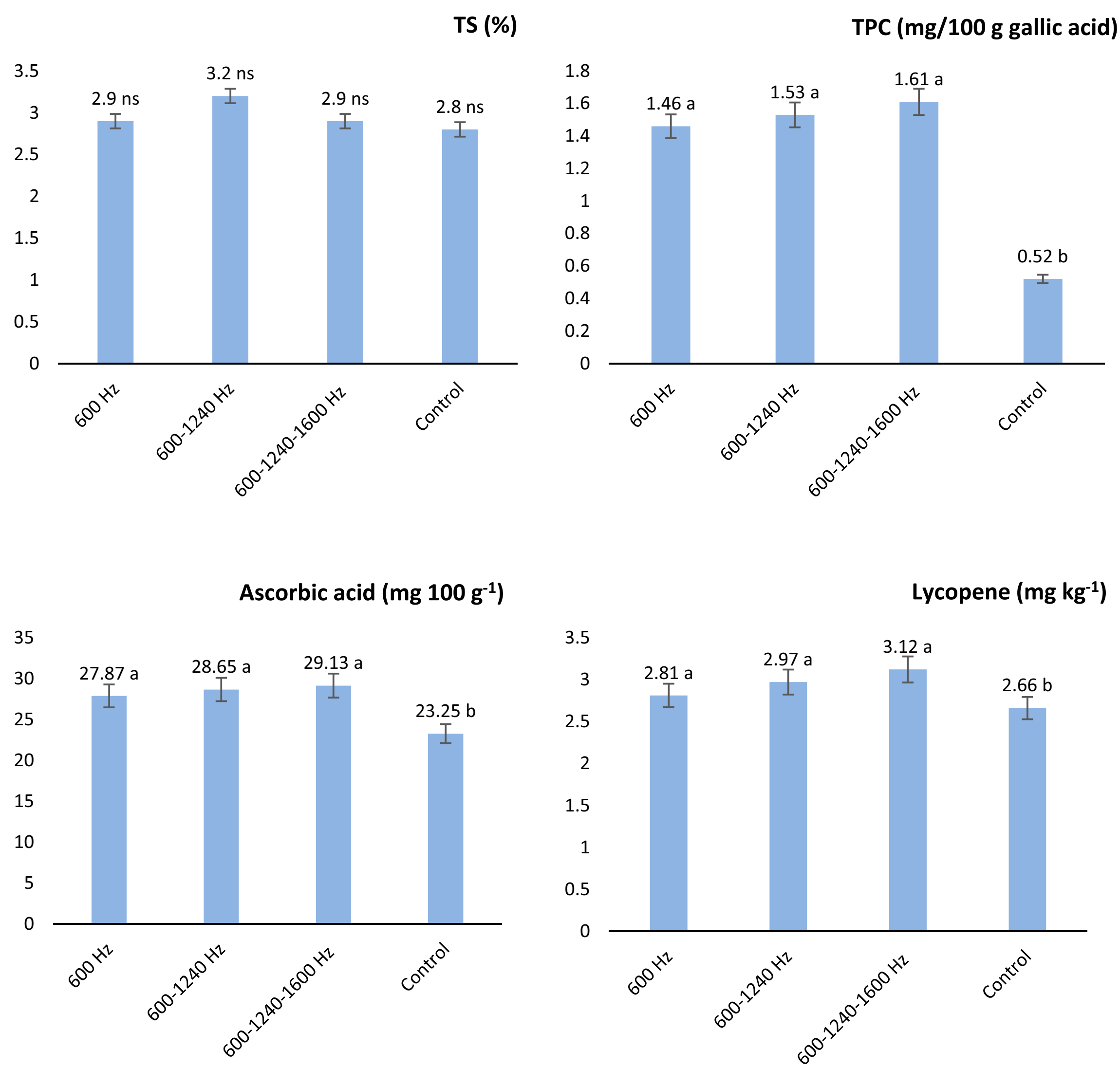

Fig. 4 Effect of different sound wave 32 frequencies on total sugars (TS), total phenolic content (TPC), ascorbic acid and lycopene content of tomato fruits. Values in the each graph with different lower-case letters are significantly different at $p < 0.05$

frequency. This rate corresponds to an increase of 20%. The lycopene content showed similar results to ascorbic acid; as sound frequency increased, so did the lycopene content in the plants. This increase was at a rate of 14% at the highest frequency (1600 Hz) compared with that in the control plants. The lycopene content in the control was 2.66 mg kg^{-1}, 2.81 mg kg^{-1} at 600 Hz, 2.97 mg kg^{-1} at 1240 Hz and 3.12 mg kg^{-1} at 1600 Hz (Fig. 4 and Table 1).

Hou and Mooneyham (1999) spinach (*Spinacia oleacea*) have reported a 22% increase in plant growth and yield with agri-wave technology. In the same study,the sugar content and vitamins of the treated spinach increased by 37-40%. Oliveira et al. (2013) concluded that organik growing tomato fruits under oxidative stress conditions.Under this conditions promote the concentrations of soluble solids like sugars and other compounds to quality (i.e. vitamin C and phenolic compound levels). Favati et al. (2009) reported that limiting water supply (abiotic stress) increased lycopene and carotene content. In the same way, Lahoz et al. (2016) found that deficient irrigation (75% ETc) decreased marketable production by 16.4%. However, the soluble solid (8.4%) and lycopene content was increased but was not significant.

Unlike our results, Atkinson et al. (2011) reported that the stress application decreased the lycopene content in tomato fruits. Limited water stress decreased the lycopene content at a rate of 34% when compared with the control fruits which did not receive any application ($P < 0.01$).

As reported in a recent literature survey, environmental factors can have a strong effect on plants and increase their concentrations of phytochemicals (Poiroux-Gonord et al. 2010). Among all the factors which seem effective in enhancing phytochemical concentrations in fruits and vegetables, the stress factor has come to the forefront as a promising factor. This makes sense when biotic and abiotic stresses are conducive to oxidative stress in plants (Grassmann et al. 2002) and oxidative signalling controls synthesis and the accumulation of secondary metabolites (Fujita et al. 2006). As a defensive mechanism, plants produce phenolic compounds against biotic and abiotic stresses (English-Loeb et al. 1997; Nicholson and Hammerschmidt 1992). Due to the connection between plant antioxidants and human health benefits, it has been suggested that a cultivation system exposing tomato plants to controlled levels of stress could be beneficial to improve the nutritional quality of fruits (Mitchell et al. 1991). The sugar concentration in tomato is frequently considered as an evaluation of nutritional quality because it contributes to flavour and because vitamin C is synthesised from sugars supplied through photosynthesis (Dorais et al. 2008).

Conclusion

In conclusion, sound wave stress in tomato fruit development promoted metabolite accumulation, which resulted in an improvement in fruit quality. Changes in taste, texture and nutritional characteristics will increase the value of tomatoes in the consumer market. Our study clearly demonstrates that different sound wave frequencies applied to tomato fruits increased the concentrations of soluble solids and phytochemicals (like vitamin C and total phenolic compounds). Further studies are necessary to better understand the links between stress and sound wave stress, as well as sound wave stress and secondary metabolism in fruits.

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References

Atkinson NJ, Urwin PE (2012) The interaction of plant biotic and abiotic stresses: from genes to the field. J Exp Bot. https://doi.org/10.1093/jxb/ers100

Atkinson NJ, Dew TP, Orfila C, Urwin PE (2011) Influence of combined biotic and abiotic stress on nutritional quality parameters in tomato (*Solanum lycopersicum*). J Agric Food Chem 59:9673–9682. https://doi.org/10.1021/jf202081t

Collins ME, Foreman EK (2001) The effect of sound on the growth of plants. Can Acous 29:3–8

Creath K, Schwartz GE (2004) Measuring effects of music, noise, and healing energy using a seed germination bioassay. J Altern Complement Med 10:113–122

Dasgan HY, Ekici B (2005) Comparison of open and recycling systems for ion accumulation of substrate, nutrient uptake and water use of tomato plants. Acta Hortic 697:399–408

Dillard CJ, German JB (2000) Phytochemicals: nutraceuticals and human health. J Sci Food Agric 80:1744–1756

Dorais M, Ehret DL, Papadopoulos AP (2008) Tomato (*Solanum lycopersicum*) health components: from the seed to the consumer. Phytochem Rev 2:231–250

English-Loeb G, Stout MJ, Duffey SS (1997) Drought stress in tomatoes: changes in plant chemistry and potential nonlinear consequences for insect herbivores. Oikos 79:456–468

Favati F, Lovelli S, Galgano F, Miccolis V, Di Tommaso T, Candido V (2009) Processing tomato quality as affected by irrigation scheduling. Sci Hortic (Amsterdam) 122:562–571

Fujita M, Fujita Y, Noutoshi Y, Takahashi F, Narusaka Y, Yamaguchi-Shinozaki K, Shinozaki K (2006) Crosstalk between abiotic and biotic stress responses: a current view from the points of convergence in the stress signaling networks. Curr Opin Plant Biol 4:436–442

Gagliano M, Renton M (2013) Love thy neighbour: facilitation through an alternative signalling modality in plants. BMC Ecol 13:1–6

Gagliano M, Mancuso S, Robert D (2012) Towards understanding plant bioacoustics. Trends Plant Sci 6:323–352

Giovanelli G, Lavelli V, Peri C, Nobili S (1999) Variation in antioxidant components of tomato during vine and post-harvest ripening. J Sci Food Agric 79:1583–1588

Grassmann J, Hippeli S, Elstner EF (2002) Plant's defence and its benefits for animals and medicine: role of phenolics and terpenoids in avoiding oxygen stress. Plant Physiol Biochem 40:471–478

Hou TZ, Mooneyham RE (1999) Applied studies of the plant meridian system: II. Agri-wave technology increases the yield and quality of spinach and lettuce and enhances the disease resistant properties of spinach. Am J Chin Med 27:131–141

Kafkas E, Koşar M, Paydaş S, Kafkas S, Başer KHC (2007) Quality characteristics of strawberry genotypes at different maturation stages. Food Chem 100(3):1229–1236

Lahoz I, Pérez-de-Castro A, Valcárcel M, Macua JI, Beltrán J, Roselló S, Cebolla-Cornejo J (2016) Effect of water deficit on the agronomical performance and quality of processing tomato. Sci Hortic (Amsterdam) 200:55–65

Lenucci MS, Cadinu D, Taurino M, Piro G, Dalessandro G (2006) Antioxidant composition in cherry and high-pigment tomato cultivars. J Agric Food Chem 54:2606–2613

Liu JH, Kitashiba H, Wang J, Ban Y, Moriguchi T (2007) Polyamines and their ability to provide environmental stress tolerance to plants. Plant Biotechnol 24:117–126

Mitchell JP, Shennan C, Grattan SR, May DM (1991) Tomato fruit yields and quality under water deficit and salinity. J Am Soc Hortic Sci 116:215–221

Nicholson RL, Hammerschmidt R (1992) Phenolic compounds and their role in disease resistance. Annu Rev Phytopathol 30(1):369–389

Oliveira AB, Moura CFH, Gomes-Filho E, Marco CA, Urban L, Miranda MRA (2013) The impact of organic farming on quality of tomatoes is associated to increased oxidative stress during fruit development. PLoS ONE 8:e56354

Ozdemir AE, Dundar O (2006) The effects of fungicide and hot water treatments on the internal quality parameters of Valencia oranges. Asian J Plant Sci 5(1):142–146

Poiroux-Gonord F, Bidel LPR, Fanciullino AL, Gautier H, Lauri-Lopez F, Urban L (2010) Health benefits of vitamins and secondary metabolites of fruits and vegetables and prospects to increase their concentrations by agronomic approaches. J Agric Food Chem 58:12065–12082

Prior RL, Cao G (2000) Antioxidant phytochemicals in fruits and vegetables: diet and health implications. Hortic Sci 35:588–592

Rao AV, Waseem Z, Agarwal S (1998) Lycopene content of tomatoes and tomato products and their contribution to dietary lycopene. Food Res Int 31:737–741

Saito T, Matsukura C, Ban Y, Shoji K, Sugiyama M, Fukuda N, Nishimura S (2008) Salinity stress affects assimilate metabolism at the gene-expression level during fruit development and improves fruit quality in tomato (*Solanum lycopersicum* L.). J Jpn Soc Hortic Sci 77:61–68

Sharma SK, Le Maguer M (1996) Kinetics of lycopene degradation in tomato pulp solids under different processing and storage conditions. Food Res Int 29:309–315

Slimestad R, Verheulb M (2009) Review of flavonoids and other phenolics from fruits of different tomato (*Lycopersicon esculentum* mill.) cultivars. J Sci Food Agric 89:1255–1270

Spanos GA, Wrolstad RE (1992) Phenolics of apple, pear, and white grape juices and their changes with processing and storage. A review. J Agric Food Chem 40(9):1478–1487

Telewski FW (2006) A unified hypothesis of mechanoperception in plants. Am J Bot 93:1466–1476