Research Article

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Effect of microwave-vacuum drying on the physicochemical properties of a functional tomato snack bar

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Abstract

BACKGROUND: Tomato is an indispensable ingredient of the Mediterranean diet. Reformulation of traditional Mediterranean products to increase the adherence of consumers is becoming popular. In this study, a tomato snack bar enriched with olive powder and pea protein was developed by using microwave-vacuum drying. Formulations also included tomato powder (TP) and low-methoxylated pectin (LMP) as a structuring agent.

RESULTS: The moisture content of microwave-vacuum-dried samples varied in the range 13.6–19.8% and water activity (a_w) values were ~0.6. LMP and TP concentrations affected the color of microwave-vacuum-dried samples. However, the color mainly changed in conventionally dried samples due to browning. In microwave-vacuum-dried samples, lycopene content decreased with increasing LMP, but increased with increasing TP. Textural properties of microwave-vacuum-dried snack bars increased with increasing LMP and TP.

CONCLUSION: Both texture and Fourier transform infrared spectroscopy results indicated that there was a network formation due to the contribution of protein and pectin; however, the type of interaction was highly dependent on the drying mechanism. Nuclear magnetic resonance relaxometry data showed that microwave-vacuum-dried samples had a more uniform water distribution. Besides its time and energy efficiency, microwave-vacuum drying improved the color and textural properties of tomato snack bars compared to conventionally dried ones.

Keywords: microwave drying; pectin; tomato powder; snack bar; Mediterranean diet; transverse relaxation

INTRODUCTION

Increasing demands for ready-to-eat and snack foods has changed the eating habits of consumers. Consumption of such foods constitutes a risk factor for the development of cardiovascular diseases and obesity.[1] To decrease the risks, design of a balanced and healthy diet with functional foods is gaining interest. Plant-based components of the Mediterranean diet, such as tomato and olive, are good candidates for designing health-promoting snack foods.[2] Tomato with its ascorbic acid and phenolic content is a highly nutritious Mediterranean product. Olive is another important Mediterranean product containing high amounts of oil and unsaturated fatty acids.

New fruit, vegetable, cereal-based and high-protein snack bars can be seen on the shelves of grocery stores every week. These bars usually contain high amount of sugar and starch, which provide taste and texture.[3] However, a health-promoting snack bar that is low in sugar and starch, but rich in in fiber and protein, is preferable.

Conventional snack bar production often includes molding and baking steps.[4] During production, the use of high temperatures (above 60 °C) for a long time results in the degradation of some functional constituents, such as the phenolics, that show antioxidant activity.[5] Processes with faster heating times are usually preferred for such functional products.

One of these techniques is the microwave-assisted heating system.[6] In microwave heating, water molecules in foods collide

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as they try to align themselves with the oscillating electric field, and thus the heat is generated by these molecular collisions of water molecules.[7,8] This heat generation enhances the moisture loss and creates a pressure gradient within the sample. The high pressure inside the material causes the water molecules to flow from the interior to the surface and increases the rate of drying.[9] Therefore, microwave-assisted drying systems are highly efficient in terms of time and energy. Increasing temperatures of food samples upon microwave application could be detrimental to some heat-sensitive functional components. One technology that avoids high temperatures is the use of vacuum during microwave processing.[10] As water evaporates at a lower temperature under vacuum than under atmospheric conditions, vacuum drying can better preserve heat-sensitive components.[8]

There are many studies on microwave-vacuum drying of fruits and vegetables, such as apple,[11] carrot,[12] banana,[13] tomato slices[14] and berries.[15] These studies reported that microwave-vacuum-dried products had a more porous structure, were softer and had better rehydration properties than conventionally dried ones. Additionally, high-quality products in terms of appearance, color, taste, aroma and texture were obtained by using microwave-vacuum drying.[16]

Although microwave-vacuum drying has been used for several fruits and vegetables in several studies, there is no study on the production of a functional tomato snack bar using this method. In this study, a tomato snack bar containing several functional ingredients, including olive powder and pea protein isolate, was prepared using microwave-vacuum drying. Efficiency of the process and product quality were compared with conventional oven drying using physical, chemical and textural analyses of the tomato snack bars. Fourier transform infrared (FTIR) spectroscopy and time domain NMR relaxometry experiments were also performed for detailed analysis at molecular level.

MATERIALS AND METHODS

Materials

Fresh tomatoes were obtained from Kraft Heinz Food (Balıkesir, Turkey). Fresh tomatoes were cleaned and a hot break procedure (85 °C for 3 min) was applied to inactivate enzymes. Tomato pomace and juice were obtained separately by sieving. Pea protein isolate (PPI) was obtained from Vegrano (Başakşehir, Istanbul, Turkey). Olive powder was prepared by means of a freeze-drying process after the homogenization of green olives.[17] Salt, mint, thyme and red pepper powder were bought from a local market. Low-methoxylated pectin (LMP, 27%) was obtained from Cargill (Balıkesir, Turkey). Acetone, hexane, ethanol, potassium nitrate, sodium bromide, sodium chloride, sodium hydroxide, magnesium chloride and potassium acetate were purchased from Merck (Darmstadt, Germany); ammonium sulfate, potassium sulfate, potassium chloride and potassium carbonate were purchased from IsoLab (Istanbul, Turkey).

Preparation of the tomato snack bar

Tomato snack bar ingredients and their amounts are given in Table 1. Tomato powder (TP) was prepared by drying the tomato skins and seeds at 55 °C for 48 h (with a moisture content (MC) below 8%) and then grinding the dried material using a household grinder. The LMP, PPI and salt were mixed with tomato juice in a beaker using a high-speed mixer (Ultraturrax T25, IKA-Werke, Staufen, Germany) at 14 000 rpm for 2 min. The other ingredients were then added to the beaker and mixed manually until the mixture became homogeneous. The mixture was molded into a bar shape and allowed to set overnight at 4 °C (Fig. 1). Following this, a microwave-vacuum oven (2 kW, 2450 MHz; Plazmatek, Isparta, Turkey) was used to dry the bars. IMPI test showed that the maximum microwave power was 1200 W. Vacuum was performed at 150 torr (0.02 MPa). Water activity (a_w), which was determined as 0.6 with preliminary experiments, was chosen as the main criterion in snack bar preparation.

Table 1. Composition of the tomato snack bar

Ingredient	Amount (g)
Tomato juice	100
Pea protein isolate	10
Salt	2
Olive powder	2
Mint	1
Thyme	1
Red pepper powder	1
Low-methoxylated pectin	1/2/3
Tomato powder	8/12/16

In preliminary experiments, the microwave power was changed from 25% to 100% (the set values) with different durations to obtain the a_w of samples close to 0.6. Above this value, microbial growth was observed; however, at this value, at least the growth of pathogenic microorganisms was suppressed. Below this value, the samples became too hard, which created textural problems. Therefore, it was decided to keep a_w of samples at this value based on the preliminary experiments. The time periods for 25%, 50%, 75%, and 100% microwave power were found to be 28, 14, 7, and 5 min, respectively. For microwave-vacuum application, 100% microwave power for 5 min processing conditions were chosen for time and energy efficiency.

A conventional air oven (Alveo, Konya, Tukey) was used at 120 °C for 75 min for the control samples (1% LMP, 8% TP). The duration of drying in a conventional oven was determined in the preliminary experiments to bring the a_w of samples again close to 0.6.

Analysis of tomato snack bars

Color measurements

For color determination CIELAB values were measured using a portable spectrocolorimeter (Serlab SL400, İstanbul, Turkey). Results were obtained from three different points of one sample, and the average values were reported.

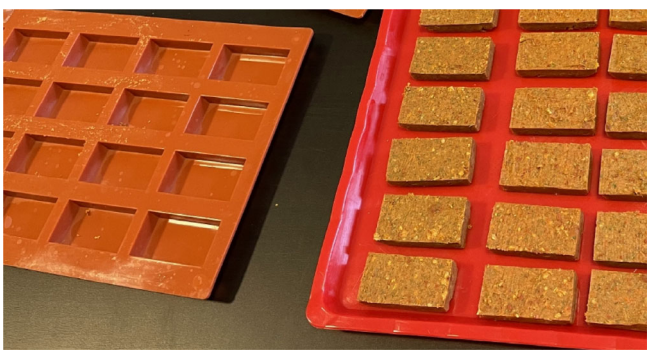

Figure 1. Photo of the molded tomato snack bars before drying.

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Moisture content and water activity

The MC of samples was determined gravimetrically by drying the samples at 105 °C. The a_w was determined by using Aqua Lab 4TE dew point and water activity meter (Decagon Devices Inc., Pullman, WA, USA) at 25 °C.

Sorption isotherm of the snack bars

The sorption isotherm of tomato snack bars was determined using the static method described elsewhere.[18] One type of snack bar formulation (2% LMP, 12% TP) was used for the analysis. The sorption isotherm was obtained by plotting the MC *versus* a_w. Experimental data fitted well the Guggenheim–Anderson–de Boer (GAB) model. The GAB equation is expressed as

$$MC = M_0 CKa_w / [(1 - Ka_w) \times (1 - Ka_w + CKa_w)]$$

where M_0 is the monolayer MC, and C and K are the free sorption constants.[19] The obtained GAB equation is

$$a_w/MC = -0.08\, a_w{}^2 + 0.0792\, a_w + 0.093 \quad (R^2 = 0.992)$$

Lycopene content

Lycopene extraction was performed by conventional solvent extraction.[20] For this purpose, 1 g of snack bar was mixed with 25 mL hexane–acetone–ethanol (2:1:1) mixture. This mixture was mixed by using a digital orbital shaker (Daihan Scientific, Wonju, Korea) at 200 rpm for 1 min, and then kept in a dark place for 1 h. Then, 10 mL distilled water was added and the mixture was kept in the dark for an additional 10 min for the phase separation to take place. The upper hexane phase was diluted appropriately and transferred to a quartz cuvette (10 mm path length), and the absorbance value was determined with a spectrophotometer (Optizen POP UV–visible, Mecasys, Daejeon, Korea) at 503 nm wavelength. Hexane was used as the blank. The amount of lycopene was calculated using the following equation:[21]

Lycopene (mg kg^{-1} fresh weight) = $A_{503} \times 172/W$ *where* W is the weight of the sample (g) and A is the absorbance at 503 nm; 172 L /mmol is the molecular extinction coefficient for lycopene in hexane.[22]

Texture analysis

Texture profile analysis (TPA) was performed with a texture analyzer instrument (CT3 Brookfield, Middleboro, MA, USA) with at least two replicates. Snack bars were compressed with a 12.7 mm diameter cylindrical probe. The samples were deformed at a deformation rate of 25% with a trigger load of 0.1 N. The cross-head moved at a speed of 0.5 mm s^{-1}. Measurements were done at room temperature. Hardness (N), gumminess (N), chewiness (g cm) and cohesiveness data were obtained from the TPA diagram.

Structural analysis by FTIR

The powder forms of individual ingredients and tomato snack bars were examined using an IR Affinity-1 spectrometer equipped with attenuated total reflectance (ATR) attachment (Shimadzu Corporation, Kyoto, Japan). The samples were scanned in the region of 4000–500 cm^{-1} at a resolution of 16 cm^{-1} for 32 scans.

Determination of water distribution using NMR relaxometry

Samples were placed in a 20.34 MHz ^{1}H-NMR system (Spin Track SB4, Resonance Systems GMBH, Kirchheim/Teck, Germany) to measure T_1 and T_2 relaxation times. For T_1 and T_2 measurements, the saturation recovery and Carr–Purcell–Meiboom–Gill sequences were used, respectively. T_1 measurements were made with 600 ms time of observation, 2.5 ms initial step, 16 points, 500 ms repetition delay and eight scans. T_2 measurements were made with a relaxation period (T_R) of 500 ms, 0.5 ms echo time, 1800 echoes and 128 scans. Discrete component analysis of decaying T_2 curves was performed using XPFit software (Softonics Inc., Tel Aviv, Israel).

Statistical analysis

ANOVA was performed using MINITAB 17 (Minitab Inc., State College, PA, USA). The pairwise comparisons were made by using Tukey's test at a significance level of 0.05. Correlations were performed using the Pearson correlation test.

RESULTS AND DISCUSSION

Formulation and visual appearance of the tomato snack bars

The main ingredient of the snack bar was tomato juice. The PPI, TP and LMP had functions in texturizing the bar. PPI is mainly composed of globular proteins, such as legumin and vicillin.[23] These globular proteins underwent heat-induced gelation during drying of the snack bar and formed a network structure. The pH of the snack bar (~4.3) and the presence of salt ions also favored the aggregation of proteins, which enhanced formation of the network. Another techno-functional property of PPI was to provide juiciness to the sample by increasing the water holding capacity.[24] Apart from its texture-giving properties, PPI increased the protein content of the snack bars with a balanced amino acid profile.[25]

Photos of microwave-vacuum-dried tomato snack bars without LMP are shown in Fig. 2 before and after drying. These pictures showed that the amount of TP had an important effect on the structure. The samples in Fig. 1 were the same as with the sample in Fig. 2 at 16% TP before drying. The decreasing concentration of TP resulted in shape deformation, which was mainly because of the decreased dry material content.

The color values of the dried samples should be close to tomato red so that consumers can accept the product easily. Additionally, browning of samples is undesirable due to the production of off-color and off-flavors. In Table 2, color measurement results of dried tomato snack bars are given. The a^* values represent the redness of samples, and the presence of TP increased this value for the microwave-vacuum-dried samples, whereas the presence and different concentrations of LMP did not affect this value. The a^* value mainly changed due to the increasing concentrations of lycopene, which was abundantly present in TP.[26] On the other hand, the lightness (L^*) value of the conventionally dried sample (26.5 ± 0.2) was much lower than the microwave-vacuum-dried one (40.7 ± 2.0), which contained 1% LMP and 8% TP. This was explained by the Maillard reaction that took place between pectin and protein present in the formulation at high temperatures of conventional drying.[27] Browning of the surface of samples is common in conventional heating due to the Maillard reaction, as a result of high temperature accompanied by dehydration. However, in microwave heating, cool ambient temperature inside the oven limits the Maillard browning reactions.[28] The reduced pressure in microwave-vacuum oven lowers the

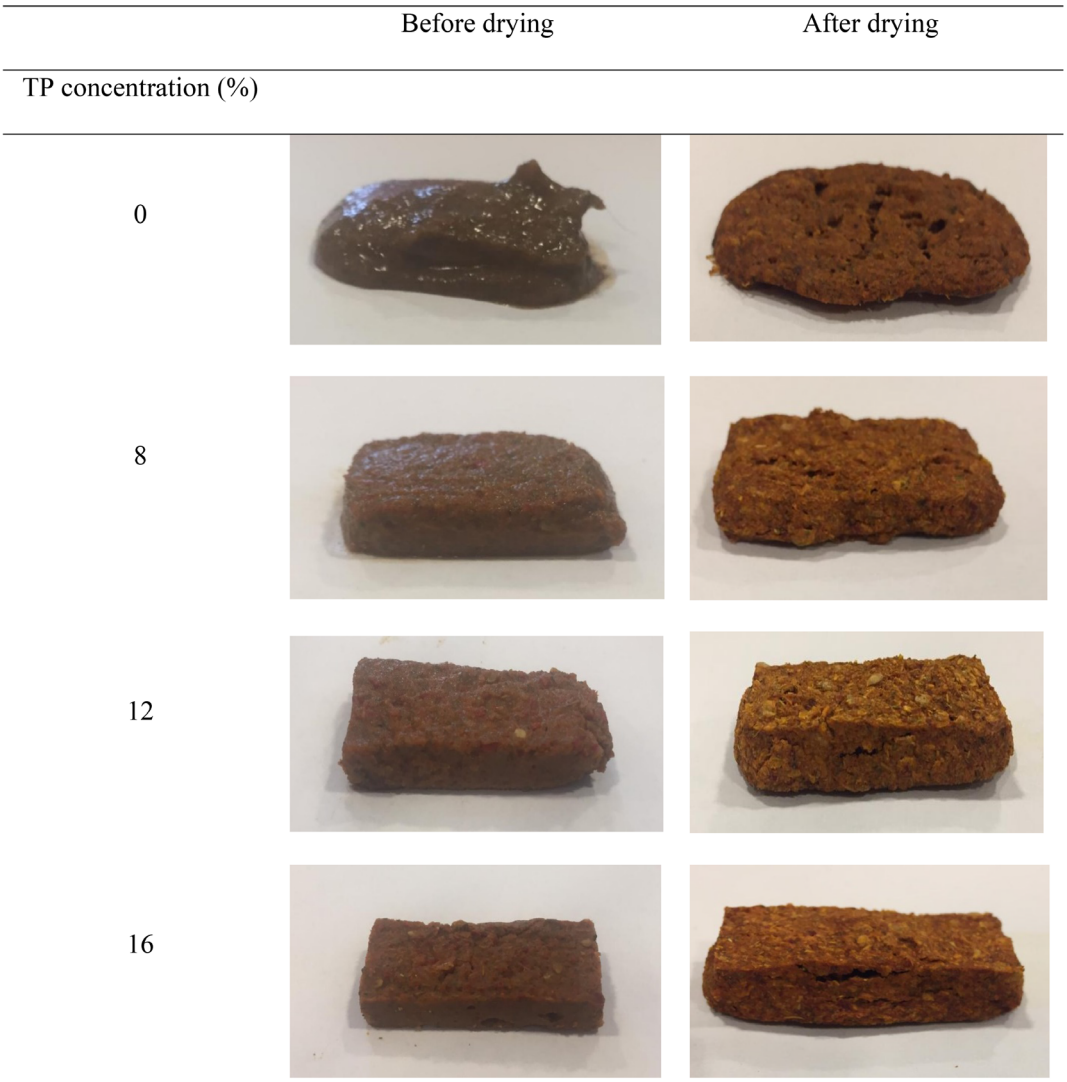

Figure 2. Photos of the tomato snack bars without low-methoxylated pectin at different tomato powder (TP) concentrations before and after microwave-vacuum drying.

temperature and can further slow down the Maillard reaction. Consequently, in tomato snack bar production, color preservation was found to be higher in microwave-vacuum drying compared to conventional drying.

Moisture content and water activity

MC of samples ranged from 13.6% to 19.8% and the average a_w of samples was found to be around 0.6 (Table 3). Almost all samples containing LMP above 2% had an a_w value less than or equal to 0.6. This could be related to the efficient water holding capacity of pectin molecules.[29] On the other hand, samples without LMP and with 1% LMP had a_w values close to or higher than 0.6. This finding showed that LMP held the free water efficiently, and therefore increasing concentrations of LMP decreased the a_w.

Conventionally dried sample, which contained 1% LMP and 8% TP, had an a_w of 0.64 ± 0.08, and its MC was found to be 30.4 ± 0.7. The MC of a conventionally dried snack bar was higher than the sample dried in a microwave-vacuum oven (1% LMP, 8% TP). This was possibly due to the crust formation in a conventional oven and therefore the moisture was retained inside the snack bar. As the heat transfer takes place from the surface to the inside in a conventional oven, the crust is formed on the surface of the snack bar, which resists the evaporation of water. In this case, heat and mass transfer are in the opposite direction. However, in microwave-vacuum drying, as the heat and mass transfers are in the same direction, there is no crust formation and therefore the evaporation of water inside the matrix is easier.[30] This situation makes microwave-oven drying more efficient than the conventional one. Prolonged drying of snack bars in a conventional oven to match the same MC as those dried in a microwave vacuum resulted in burning of the snack bar surface, which prevented the efficient evaporation of bound water. Therefore, microwave-vacuum-dried samples would have a lower moisture content than conventionally dried samples when the a_w, which can be taken as a measure of the free water content, was of the same value.

It is necessary to determine the sorption isotherm for multicomponent products, such as a tomato snack bar, to gain insight into the moisture distribution and migration and also for packaging design. Figure 3 shows the sorption isotherm of tomato snack

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Table 2. Effect of LMP and TP concentration on color values of dried tomato snack bars

LMP (%)	TP (%)	L^*	a^*	b^*
0	0	38.5 ± 2.6^{abc}	13.7 ± 0.8^{d}	23.4 ± 1.9^{f}
0	8	42.3 ± 3.4^{a}	20.2 ± 2.2^{ab}	31.3 ± 2.8^{abc}
0	12	42.5 ± 1.9^{a}	20.7 ± 1.2^{ab}	32.8 ± 2.1^{ab}
0	16	42.5 ± 3.6^{a}	21.7 ± 2.9^{a}	32.9 ± 2.2^{a}
1	0	33.8 ± 5.3^{c}	14.4 ± 0.8^{cd}	20.5 ± 2.9^{g}
1	8	40.7 ± 2.0^{abA}	19.0 ± 1.8^{abA}	28.3 ± 1.5^{cdA}
1	12	37.8 ± 0.9^{abc}	21.3 ± 2.5^{a}	28.2 ± 1.8^{cde}
1	16	42.7 ± 2.3^{a}	22.2 ± 1.2^{a}	33.1 ± 1.3^{a}
2	0	35.5 ± 1.0^{bc}	17.8 ± 1.5^{bc}	23.4 ± 0.9^{f}
2	8	38.9 ± 1.7^{abc}	21.6 ± 1.6^{ab}	29.2 ± 1.4^{abcd}
2	12	39.9 ± 0.9^{ab}	21.0 ± 1.7^{ab}	28.8 ± 2.7^{cde}
2	16	37.4 ± 1.8^{abc}	20.2 ± 2.3^{ab}	28.4 ± 2.0^{de}
3	0	37.3 ± 2.2^{abc}	18.4 ± 2.2^{ab}	25.5 ± 2.5^{ef}
3	8	39.0 ± 3.2^{ab}	20.6 ± 2.9^{ab}	29.9 ± 3.6^{bcd}
3	12	39.0 ± 3.9^{ab}	22.1 ± 1.3^{a}	29.4 ± 3.2^{abcd}
3	16	40.7 ± 1.2^{ab}	19.6 ± 1.9^{ab}	29.3 ± 0.8^{cd}
1[†]	8	26.5 ± 0.15^{B}	13.1 ± 0.8^{A}	15.3 ± 0.5^{B}

Abbreviations: LMP, low-methoxylated pectin; TP, tomato powder.
[†] Represents the conventionally dried sample. Different lower-case letters indicate significant differences ($P < 0.05$) within the microwave-vacuum-dried samples, whereas different upper-case letters indicate significant differences ($P < 0.05$) between conventionally dried and microwave-vacuum-dried samples at the same LMP and TP concentration. Errors are represented as standard deviations.

Table 3. MC and a_w of tomato snack bars

LMP (%)	TP (%)	MC (%)	a_w
0	0	18.0 ± 1.4^{abc}	0.59 ± 0.06^{cd}
0	8	15.5 ± 0.7^{cde}	0.64 ± 0.08^{abc}
0	12	14.3 ± 0.4^{de}	0.64 ± 0.04^{abc}
0	16	18.9 ± 0.1^{ab}	0.73 ± 0.03^{a}
1	0	15.9 ± 1.3^{bcde}	0.69 ± 0.02^{ab}
1	8	15.1 ± 1.6^{cdeB}	0.65 ± 0.03^{abcA}
1	12	18.2 ± 0.4^{abc}	0.58 ± 0.01^{cde}
1	16	17.4 ± 0.3^{abcd}	0.59 ± 0.01^{cd}
2	0	19.8 ± 1.3^{a}	0.60 ± 0.00^{cd}
2	8	17.7 ± 0.5^{abc}	0.59 ± 0.00^{cd}
2	12	16.3 ± 0.3^{bcde}	0.54 ± 0.00^{de}
2	16	15.3 ± 0.3^{cde}	0.50 ± 0.00^{e}
3	0	15.3 ± 0.0^{cde}	0.49 ± 0.02^{e}
3	8	15.0 ± 0.1^{cde}	0.49 ± 0.01^{e}
3	12	13.6 ± 0.8^{e}	0.49 ± 0.01^{e}
3	16	15.4 ± 1.2^{cde}	0.61 ± 0.05^{bcd}
1[†]	8	30.4 ± 0.7^{A}	0.64 ± 0.08^{A}

Abbreviations: LMP, low-methoxylated pectin; TP, tomato powder; MC, moisture content; a_w, water activity.
[†] Represents the conventionally dried sample. Different lower-case letters indicate significant differences ($P < 0.05$) within the microwave-vacuum-dried samples, whereas different upper-case letters indicate significant differences ($P < 0.05$) between conventionally dried and microwave-vacuum-dried samples at the same LMP and TP concentration. Errors are represented as standard deviations.

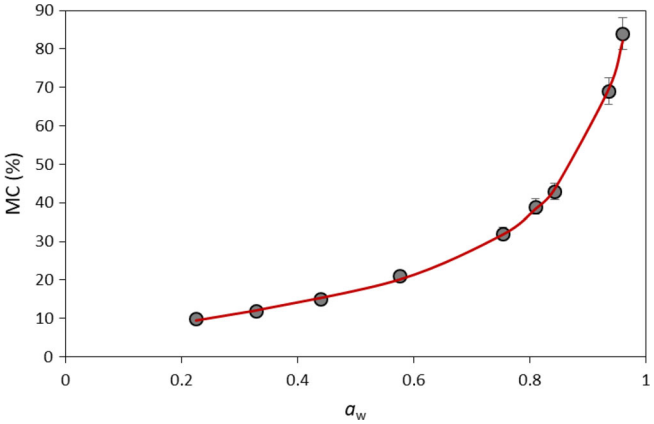

Figure 3. Moisture sorption isotherm of tomato snack bar at 25 °C. The solid line represents the GAB model. MC, moisture content; a_w, water activity.

bar at 25 °C. Experimental data fitted the GAB model well ($R^2 = 0.99$). From linearization of the GAB equation, the estimated constants M_0, K and C were found to be 0.84, 0.60 and 3.42, respectively. As the value of $C > 2$, the model had a sigmoidal shape and a Type 2 curve was obtained according to the Brunauer's classification.[31] Type 2 isotherms are often correlated with high starch composition such as flour, and they are typical for intermediate MC products (a_w between 0.6 and 0.9).[32] Similar to the behavior of the tomato snack bar, freeze-dried vegetable snack bars[33] and fruit cereal bars[34] were previously reported to show Type 2 isotherms. In a Type 2 curve, at low water activities polar and hydrophilic components are saturated with water molecules to form the adsorption monolayer. Additional water molecules at relatively higher water activities then form the multilayer coverage, and water molecules are accumulated in intermolecular free spaces. Particularly protein and pectin inside the tomato snack bar contributed to such sorption behavior.

Water distribution within snack bars

To have better control over the microbial growth and physical stability of a food product, it is desirable that the water distribution be homogeneous within the whole sample. Transverse relaxation behavior of the tomato snack bars was described by a three-component model (Table 4). These values and their corresponding weights represented the state and the distribution of water.[35] In a three-component relaxation model, each proton pool is represented as a peak and its corresponding area (or contribution to the signal). The short T_{21} value indicates a strong interaction of water with the other solid components; thus this transverse relaxation could be attributed to the water in a strongly bound state. Moderate T_{22} indicates weaker interaction of water with the surroundings than that observed for T_{21}. Thus this proton population could be related to the transverse relaxation of the tiny water pools that are entrapped within the gaps of the polymer matrix. On the other hand, the T_{23} value represents the water population that interacts the least with the surrounding polymer structure that is mostly acting as bulk water (but not fully). However, no correlation was found between the a_w and T_{23} values of the snack bars, which was similar to a previous study on confectionery products.[36] This proton population may be associated with distinct and large water populations within the polymer matrix.[37] Changes in peak time and area values suggest that presence/absence and changes in the

Table 4. T_2 values and their corresponding areas of tomato snack bars

LMP (%)	TP (%)	T_{21} (ms)	Area (%)	T_{22} (ms)	Area (%)	T_{23} (ms)	Area (%)
0	0	1.18 ± 0.08^{b}	65.9^{a}	20.06 ± 1.03^{b}	15^{d}	89.13 ± 1.10^{bc}	19.1^{efg}
0	8	0.63 ± 0.01^{b}	56.3^{abc}	20.37 ± 0.31^{b}	16.9^{cd}	96.99 ± 3.20^{abc}	26.9^{cdefg}
0	12	1.00 ± 0.19^{b}	67.5^{a}	19.31 ± 2.72^{b}	15.3^{d}	94.61 ± 11.17^{abc}	17.3^{fg}
0	16	1.17 ± 0.07^{b}	68.7^{a}	20.48 ± 1.79^{b}	16.4^{d}	91.68 ± 8.41^{bc}	14.9^{g}
1	0	0.75 ± 0.07^{b}	59.4^{abc}	19.3 ± 0.83^{b}	17.3^{bcd}	90.26 ± 6.43^{bc}	23.4^{cdefg}
1	8	0.82 ± 0.08^{bB}	$39d^{eB}$	20.78 ± 0.04^{bA}	26.9^{bA}	97.18 ± 2.64^{abcA}	34.1^{abcA}
1	12	0.75 ± 0.1^{b}	56^{abc}	17.3 ± 0.4^{b}	23^{bcd}	78.37 ± 4.07^{c}	21^{defg}
1	16	0.89 ± 0^{b}	61.4^{ab}	22.35 ± 0.93^{b}	19.5^{bcd}	99.19 ± 4.83^{abc}	19.1^{efg}
2	0	1.05 ± 0.07^{b}	64.8^{a}	19.26 ± 0.75^{b}	17.5^{bcd}	86.30 ± 0.34^{bc}	17.8^{fg}
2	8	0.7 ± 0.07^{b}	45^{bcd}	21.97 ± 1.83^{b}	23.7^{bcd}	101.61 ± 9.46^{ab}	31.4^{bcde}
2	12	0.75 ± 0.16^{b}	55.2^{abcd}	20.85 ± 0.21^{b}	20^{bcd}	99.30 ± 0.69^{abc}	24.8^{cdefg}
2	16	0.63 ± 0.05^{b}	44.6^{cd}	18.43 ± 3.41^{b}	22.2^{bcd}	92.93 ± 5.72^{bc}	33.3^{bcd}
3	0	0.87 ± 0.2^{b}	27.1^{ef}	18.86 ± 2.23^{b}	26.2^{bc}	89.16 ± 5.15^{bc}	46.7^{a}
3	8	0.71 ± 0.04^{b}	43.5^{cde}	19.38 ± 0.78^{b}	24.2^{bcd}	91.25 ± 4.39^{bc}	32.4^{bcd}
3	12	3 ± 0.71^{a}	18.7^{f}	29.93 ± 1.29^{a}	39^{a}	116.55 ± 7.85^{a}	42.3^{ab}
3	16	0.45 ± 0.09^{b}	52.4^{abcd}	16.61 ± 0.35^{b}	18.3^{bcd}	92.06 ± 0.21^{bc}	29.4^{cdefg}
1†	8	2.06 ± 0.17^{A}	71.4^{A}	9.8 ± 1.13^{B}	16.2^{B}	81.02 ± 7.60^{A}	12.5^{B}

Abbreviations: LMP, low-methoxylated pectin; TP, tomato powder.
† Represents the conventionally dried sample. Different lower-case letters indicate significant differences ($P < 0.05$) within the microwave-vacuum-dried samples, whereas different upper-case letters indicate significant differences ($P < 0.05$) between conventionally dried and microwave-vacuum-dried samples at the same LMP and TP concentration. Errors are represented as standard deviations.

concentration of LMP and TP affected the water distribution within the microwave-vacuum-dried samples. T_2 values were mostly dependent on the dry material content, to which TP and PPI contributed greatly. In this case, the effect of TP was higher than the effect of LMP on T_2 values. However, the presence of LMP was expected to contribute to the entrapped water, which was represented by the areas of T_{22} values. Increasing the TP concentration from 0% to 8% changed the water distribution within the samples (both in the presence and in absence of LMP) abruptly. This change mainly manifested itself with the decrease in the area values represented by T_{21} and the corresponding increase in the area values associated with T_{22} and T_{23}. Beyond the 8% TP concentration (up to 16%), the same peak areas showed an opposite trend to their initial trend between 0% and 8% TP concentration. At 8%, TP particles could not maintain a continuous interaction with the water molecules. However, the interactions between the TP solids and water became more continuous and homogeneous at higher concentrations, thereby bringing the area values closer to their initial values (0% TP concentration). There was no such trend for the samples prepared with 3% LMP. The reason could be the higher dry material content of these samples.

Conventional heating (for the samples with 1% LMP and 8% TP) resulted in longer relaxation times and higher contributions for the first component and shorter relaxation times and contributions for medium and long components. The longer T_{21} (2.06 ms) and higher peak area (71.4%) of conventionally heated samples suggested that the initial hydration layers around the solid particles were larger than those dried in a microwave-vacuum oven.[38] On the other hand, conventionally heated samples showed shorter T_{23} times and area values: 81.02 ms and 12.5%, respectively. Therefore, this reflected a major difference between the conventional and microwave-vacuum drying methods at the molecular level, since changing the heating type clearly changed the dynamics of polymer–water interactions. There was an interchange between the first and third relaxation peaks. The shorter peak time and area of the conventionally heated samples suggested that the proportion of water that interacted least with the surrounding polymer matrix decreased with respect to that in the microwave-vacuum-dried samples.[39] This result was indeed expected due to the surface-to-interior heating mechanism of conventional drying.[40] In this way, bulk water was removed from the samples to a greater extent by conventional heating, as can be justified by the T_{23} results. On the other hand, microwave-vacuum drying was more successful in removing the proportion of water strongly bound to the solid particles. Consequently, microwave-vacuum-dried samples possessed shorter T_{21} and lower T_{21} peak area than the conventionally dried samples (Table 4).

Table 5. Lycopene concentration (mg g^{-1} dry material) of tomato snack bars at different LMP and TP concentrations

	TP (%)			
LMP (%)	0	8	12	16
0	59.1 ± 3.2^{c}	71.4 ± 4.1^{b}	72.5 ± 1.8^{b}	78.6 ± 3.7^{a}
1	32.2 ± 1.1^{f}	40.4 ± 1.1^{eB}	43.2 ± 6.6^{d}	39.4 ± 2.0^{e}
2	19.5 ± 0.8^{h}	33.0 ± 4.8^{f}	28.2 ± 1.9^{f}	28.5 ± 1.0^{f}
3	9.6 ± 1.2^{i}	15.4 ± 1.6^{hi}	17.1 ± 0.6^{h}	21.7 ± 0.1^{g}
1†		83.4 ± 3.0^{A}		

Abbreviations: LMP, low-methoxylated pectin; TP, tomato powder.
† Represents the conventionally dried sample. Different lower-case letters indicate significant differences ($P < 0.05$) within the microwave-vacuum-dried samples, whereas different upper-case letters indicate significant differences ($P < 0.05$) between conventionally dried and microwave-vacuum-dried samples at the same LMP and TP concentration. Errors are represented as standard deviations.

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Lycopene content

Lycopene content of snack bars is should be as high as possible, so that the antioxidant content of the product would be high and the color would be bright red, as desired. Lycopene contents of microwave-vacuum-dried samples were found to be between 9.6 and 78.6 mg g^{-1} dry material (Table 5). Changing concentrations of both ingredients had a significant effect on the lycopene content of snack bars ($P < 0.05$). The highest lycopene amounts were determined in the absence of LMP, whereas the lowest amounts were determined in the presence of 3% LMP, indicating that LMP showed a detrimental effect on the lycopene content. There could be two possible mechanisms for that effect on the lycopene amount. The first one could be that the increasing amount of pectin created a denser pectin network and the lycopene was entrapped in this network.[41,42] In the snack bar matrix, pectin could form a layer around the lycopene molecules and, as pectin is water soluble, during the extraction of lycopene in its assay only a part of the lycopene could have leached to the hexane. The second mechanism suggested the formation of a pectin–lycopene complex in the presence of an amphiphilic compound, such as protein.[43] In this mechanism, first, lycopene attached to the hydrophobic part of the protein and formed an intermediate product, and then the polar pectin molecules formed a coating around this intermediate product and thereby limited the extraction of lycopene to the hexane.

Lycopene content of the conventionally dried snack bar was found to be 83.4 ± 3.0 mg g^{-1} dry material. This value was higher compared to the lycopene content of microwave-vacuum-dried sample (with 1% LMP and 8% TP). This was expected since the duration of conventional drying was longer and the temperature was higher than the microwave-vacuum application. Lycopene is often found bound to the skin and insoluble fiber in tomatoes, and heat processing enhances the release of lycopene from the cell matrix.[44] In previous studies, the lycopene extraction yield was found to be higher in microwave-assisted techniques, particularly the *trans* isomer of lycopene.[45] Another study reported that the lycopene concentration in fresh tomatoes increased from 2.96 to 25.44 mg 100 g^{-1} dry material after microwave-vacuum drying.[46] They also reported that high microwave power increased the amount of lycopene extracted due to high temperatures. Therefore, the difference in lycopene content for tomato snack bars prepared by two different methods could be due to the temperature difference. Furthermore, the microwave-vacuum oven provided the same amount of lycopene to be obtained in a shorter time than the conventional oven, which was in line with previous studies.[47] Consequently, microwave-vacuum drying demonstrated a higher efficiency in terms of time and energy, as only 5 min of microwave-vacuum drying allowed us to obtain almost 85% of the lycopene that could be obtained from conventional drying.

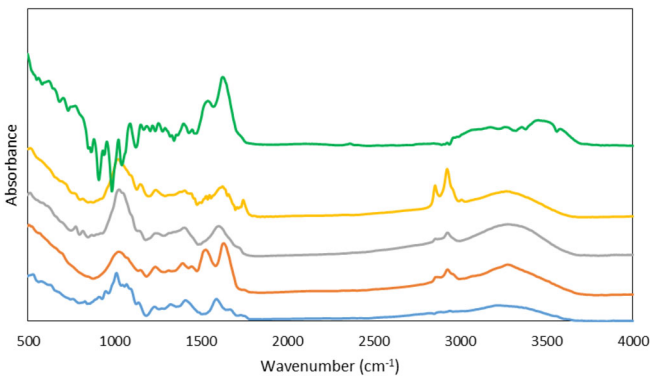

Figure 4. Fourier transform infrared spectra of low-methoxylated pectin (blue), pea protein isolate (orange), tomato powder (grey), microwave-vacuum-dried (yellow) and conventionally dried (green) tomato snack bar.

Investigation of molecular changes by FTIR spectroscopy

FTIR spectra of LMP, PPI, TP and snack bars containing 3% LMP and 16% TP are shown in Fig. 4. Characteristic peaks of the FTIR spectrum observed between 1600 and 1700 cm^{-1} represent the carbonyl (C═O) stretching of the secondary amide (amide I band) of the protein backbone.[48] The peak around 1500 cm^{-1} observed for PPI and snack bars represents the amide II band.[49] The peaks between 3000 and 3500 cm^{-1} were assigned to —OH stretching. On the other hand, the new peak for the tomato snack bar around 2850 cm^{-1} could be an indication of the crosslink between PPI and pectin.[50] Furthermore, the peak at 1590 cm^{-1} of pectin shifted to 1630 cm^{-1} in the snack bar, suggesting the carboxyl groups (—COO—) were crosslinked with Ca^{2+}, which was inherently present in the tomato juice.[50,51]

FTIR spectra of microwave-vacuum-dried and conventionally dried snack bars are different particularly at amide and —OH regions, which correspond to the bonds formed due to the presence of pectin and protein. This suggested the interactions between pectin and protein occurred differently in a microwave-vacuum oven and a conventional oven. The main factor is temperature, as the temperature in the conventional oven was 120 °C, which was higher than that in the microwave-vacuum oven (maximum ~60 °C at 150 torr). With higher temperature and long heating time, proteins were expected to fully denature and more disulfide bonds would have formed.[52] However, at low temperatures and short heating times, denaturation of proteins was not expected to be extensive, and therefore the interaction between pectin and protein should be mainly electrostatic in microwave-vacuum drying.[53] Therefore, the type of interaction between pectin and protein was dependent on the duration and temperature of heating as well as the heating mechanism.

When the amide I and II regions were considered, it was apparent that the conventionally dried snack bar sample demonstrated distinct peaks, whereas the microwave-vacuum-dried sample showed multiple indistinct peaks in these regions (Fig. 4). The peak characteristics of microwave-vacuum-dried sample in the amide region suggested that the secondary structures of the PPI were more disordered.[54] This result indicated that the transitions between the secondary protein structures (α-helix, β-turn, β-sheet) were still ongoing, which was possibly due to insufficient time and temperature in microwave-vacuum drying for a complete PPI denaturation. —OH band regions also showed differences due to drying type. While the microwave-vacuum-dried sample showed a broad and smooth peak, the conventionally dried sample showed a broad but discontinuous peak formed by the merging of many discrete peaks. The broad and smooth —OH peak of the microwave-vacuum-dried sample was the result of the higher number of —OH groups involved in hydrogen bonding.[55] In contrast, the number of free —OH groups that did not take part in hydrogen bonding was higher for the conventionally dried snack bar. These findings demonstrated that the drying mechanism altered the water–polymer interactions at the molecular level.

Table 6. Textural properties of tomato snack bars

LMP (%)	TP (%)	Hardness (N)	Gumminess (N)	Chewiness (g cm)	Cohesiveness
0	8	21.3 ± 3.3^{e}	9.4 ± 0.1^{ef}	142 ± 16.9^{fg}	0.46 ± 0^{b}
0	12	10.6 ± 0.8^{f}	7.0 ± 1.1^{f}	93 ± 2.8^{h}	0.44 ± 0^{b}
0	16	15.1 ± 0.8^{ef}	7.3 ± 0.1^{ef}	129.5 ± 2.1^{g}	0.47 ± 0^{b}
1	8	15.7 ± 0.4^{efB}	9.3 ± 0.2^{efB}	168.5 ± 6.4^{fA}	0.59 ± 0^{aA}
1	12	33.7 ± 0.1^{d}	9.6 ± 1.1^{e}	369 ± 2.8^{e}	0.60 ± 0.01^{a}
1	16	14.2 ± 0.7^{ef}	9.8 ± 0.6^{e}	127.5 ± 2.1^{g}	0.60 ± 0.01^{a}
2	8	47.3 ± 0.3^{c}	26.4 ± 0.5^{c}	489 ± 8.5^{c}	0.56 ± 0^{a}
2	12	74.2 ± 1.0^{b}	38.8 ± 0.9^{a}	675 ± 4.2^{a}	0.57 ± 0.01^{a}
2	16	40.6 ± 3.9^{cd}	20.3 ± 0.8^{d}	441.5 ± 13.4^{d}	0.55 ± 0.01^{a}
3	8	41.6 ± 1.2^{cd}	40.6 ± 0.2^{a}	414 ± 0^{d}	0.57 ± 0.01^{a}
3	12	74.4 ± 4.6^{b}	30.1 ± 0^{b}	606.5 ± 2.1^{b}	0.56 ± 0.05^{a}
3	16	86.6 ± 2.9^{a}	26.9 ± 0.4^{c}	703 ± 11.3^{a}	0.60 ± 0.01^{a}
1[†]	8	28.5 ± 1.9^{A}	13.3 ± 0.9^{A}	195 ± 20^{A}	0.47 ± 0^{B}

Abbreviations: LMP, low-methoxylated pectin; TP, tomato powder.
[†] Represents the conventionally dried sample. Different lower-case letters indicate significant differences ($P < 0.05$) within the microwave-vacuum-dried samples, whereas different upper-case letters indicate significant differences ($P < 0.05$) between conventionally dried and microwave-vacuum-dried samples at the same LMP and TP concentration. Errors are represented as standard deviations.

Texture analysis

Each individual ingredient in the tomato snack bar had the ability to modify the texture. For instance, water acts as a plasticizer and helps maintain softness and flexibility. The presence of fiber and hydrocolloids improves water binding and often minimize water migration throughout the proteins or starch in the structure. However, a higher than necessary concentration of such ingredients yields a very hard product that is not preferred. In a snack bar, hardness, gumminess and chewiness are the most important textural parameters. Therefore, the textural properties of tomato snack bars (hardness, gumminess, chewiness and cohesiveness) at different concentrations of LMP and TP were determined and are shown in Table 6. The TPA of samples without any TP could not be measured; therefore, only the results of the samples including TP are presented. The hardness values of microwave-vacuum-dried snack bars were found to be between 10.6 and 86.6 N. Increasing concentration of LMP had a significant effect on hardness of samples at the same TP concentration ($P < 0.05$). This situation was more prominent in the samples with 2% and 3% LMP, as their hardness values were higher than the samples with 0% and 1% LMP. At high LMP concentration, a more rigid gel network was formed.[56] Additionally, increasing LMP concentration decreased the a_w of samples (Table 3). As there was less free water at low a_w, the hardness of samples became higher. On the other hand, the TP did not show a similar trend with LMP. Hardness values fluctuated with increasing concentrations of TP, which could be due to the interaction of water with different polymers in the matrix.

Gumminess of foods is often related to the swallowing action and is mostly dependent on the presence of polysaccharides and proteins.[57] In microwave-vacuum-dried tomato snack bars, LMP was found to affect gumminess significantly ($P < 0.05$). The strength of interaction between LMP and PPI, which was mainly electrostatic, affected the gumminess.[58] Therefore, in the presence of sufficient PPI, increasing LMP concentrations increased the gumminess of samples.

Chewiness of a sample could be taken as the energy required to masticate a solid food to prepare for swallowing.[48] The lowest chewiness value for the microwave-vacuum-dried snack bars was found to be 93 g cm when there was no LMP, and the highest value was found to be 703 g cm when there was 3% LMP in the formulation. LMP significantly increased the chewiness of tomato snack bars ($P < 0.05$). The amount of TP also affected the chewiness, possible due to increasing the dry material content; however, the effect of LMP was more dominant.

Cohesiveness physically defines the internal resistance of a food material, formed by the internal bonds in the food matrix.[59] It expresses how much the product can resist a second deformation relative to the first one.[60] In microwave-vacuum-dried tomato snack bars, cohesiveness was affected significantly by the presence of LMP ($P < 0.05$); however, TP addition did not affect cohesiveness significantly. The presence of pectin was reported to increase cohesiveness in different studies.[56,61]

Conventionally dried sample had higher hardness, gumminess and chewiness, but lower cohesiveness, compared to the microwave-vacuum-dried sample with the same formulation (1% LMP and 8% TP). The higher gumminess and chewiness results may be due to the higher MC of the conventionally dried sample. However, the MC cannot explain the higher hardness of conventionally dried sample, as a snack bar sample with higher MC would be expected to have lower hardness value. This seemingly contradictory result could be an indication of the uneven heating provided by the conventional oven. Faster drying of the surface of the snack bars yielded a crust formation, which increased the hardness of samples. In addition, the lower cohesiveness value of the conventionally dried snack bar may have indicated the formation of different types of bonds in the structure. Microwave-vacuum heating increased the porous structure of the samples due to the volumetric heating.[62] In this case, as the evaporation of water took place from the inside to the surface, snack bars expanded more uniformly, which resulted in uniform and softer textural properties. Crosslinking of pectin and protein was also expected to be different with microwave heating and conventional heating.[63] In a previous study, the texture of conventional-dried and microwave-vacuum-dried squid shreds were compared and the latter was found to be softer.[64] This result was attributed to the puffing effect of the microwave-vacuum heating system. The microwave-vacuum-dried snack bars had a porous structure, resulting in lower force and deformation values during the compression test compared to the conventionally dried samples.

CONCLUSIONS

This study reported the preparation of a health-promoting tomato snack bar and the effect of different ingredients and drying methods on its physical, chemical and textural properties. Snack bars were produced with a minimal number of ingredients using microwave-vacuum drying, which is an energy- and time-efficient process. The microwave-vacuum process shortened the drying time by 93% and saved energy by 88%.

For color preservation, microwave-vacuum drying was superior to the conventional oven. Textural properties, including hardness, gumminess, chewiness and cohesiveness, were also affected by the type of drying, and the microwave-vacuum drying created higher-quality snack bars. Additionally, the microwave-vacuum

process achieved a more homogeneous drying compared to conventional drying. Another important finding of this study was that the increasing LMP amounts reduced the lycopene availability. Interactions between the main structural ingredients have also been demonstrated at the molecular level. Time domain NMR relaxometry results indicated that the differences between the conventional and microwave-vacuum drying mechanisms could be tracked by transverse relaxation parameters. Changes in T_2 peak times and relative peak areas suggested that the dynamics of polymer–water interactions were affected by the heating type. For instance, microwave-vacuum drying was more successful than conventional drying in terms of removing the strongly bound water fraction. Moreover, LMP and TP can be used to alter the textural properties of snack bars. Chewier or harder snack bars can be formulated for general consumption; however, softer snack bars may be preferred for toddlers and elderly people having difficulty in chewing. Overall, the results of this study showed the possibility of health-promoting snack bar production in an economically feasible way.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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