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DETERMINATION OF THE CORRELATION BETWEEN IMAGE PARAMETERS AND CHEMICAL PROPERTIES OF RED SWEET BELL PEPPER DURING FERMENTATION

– Research paper –

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Abstract: The objective of this study was to analyse the image textures and chemical characteristics of red sweet bell pepper samples during the lacto-fermentation process to determine the correlation between these parameters. The raw material of red bell pepper was subjected to spontaneous lacto-fermentation. The imaging by a digital camera and analyses of ascorbic acid, total soluble solids (TSS), acidity, pH, sugars, and carotenoids were performed for raw material and samples after 7, 14, 28, and 56 days of fermentation. The statistically significant decrease in TSS, pH, and the content of L-ascorbic acid, glucose, fructose, total sugars, β-carotene, and total carotenoids of lacto-fermented samples was observed. The strongest relationships with a correlation coefficient (R) of 0.999 were observed for L-ascorbic acid content with image texture bS5SH5DifEntrp and acidity with image texture ZS5SV1InvDfMom of raw and lacto-fermented pepper samples. In the case of carotenoids, the strongest relationship (R=0.999) was observed between image texture XS5SV3DifEntrp and lycopene content. Furthermore, the strong relationships between image textures and the sugar content were obtained reaching R=-0.998 for glucose content and image texture LS4RNLngREmph and R=0.998 for total sugars and BS5SZ5DifEntrp. The results were also used to set the regression equations to estimate chemical properties based on parameters extracted from images.

Key words: red pepper, lacto-fermentation, sugars, carotenoids, image textures, correlation

INTRODUCTION

Red bell pepper (*Capsicum annuum* L.) is a very important vegetable because of its nutritional value, flavour, and colour. It is a source of vitamins C and A, carotenoids, minerals, and phenolic compounds with high antioxidant capacity (Martínez et al., 2005; Silveira Agostini-Costa et al., 2017; Kaur et al., 2020). Due to the presence of flavonoids, phenols, and capsaicinoids, the consumption of pepper can improve immunity and thus prevent the onset of diseases such as tumors, cancers, cardiovascular diseases, Parkinson's, Alzheimer's, and diabetes (Palevitch & Craker, 2012; Blanco-Ríos et al., 2013; Hu et al., 2021). Health-promoting, sensory, and nutritional properties caused pepper as one of the most consumed vegetables worldwide (Di Cagno et al., 2009), however, botanically, red bell pepper is considered a fruit (Janiszewska-Turak et al., 2022a). Red bell pepper contains a high water content. It is sensitive to microbiological activity and spoilage. Furthermore, red bell pepper in a ripe form is susceptible to enzymatic reactions, resulting in the degradation of its quality (Rybak et al., 2020). Therefore, red bell pepper is considered a highly perishable fruit. It can degenerate within a very short time after harvest and losses can be intensified with scarcity of suitable processing techniques, storage space, and marketing. Therefore, the processing is a way to preserve the bell pepper and minimize postharvest losses (Kaur et al., 2020).

The LAB (Lactic Acid Bacteria) fermentation process is one of the oldest methods of food preservation, and fermented plant raw materials are produced and consumed all over the world. The lactic fermentation process has an extremely positive effect on the smell and taste of fermented products, the texture changes, and organic acids are produced, which extend the shelf life of the products. On the other hand, the number of certain nutrients increases, and the amount of anti-

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nutritional, mutagenic, and toxic substances from the raw material is reduced (trypsin inhibitors, cyanide, and aflatoxins) (Bell et al., 2018; de Souza et al., 2023; Siddiqui at al., 2023). According to Bell et al. (2018), the consumption of fermented products promotes the bioavailability of nutrients, mainly dietary fiber, micro- and macroelements, enzymes, lactic acid bacteria, and organic acids. The nutritional value of fermented products is often higher than that of raw materials, which is due to the physiological activity of LAB bacteria, which actively synthesize many nutrients contained in raw materials (Voidarou et al., 2021).

The fermentation process of plant raw materials affects their texture (softening occurs) resulting from the partial enzymatic decomposition of the fiber fraction (mainly cellulose and pectin) into simple sugars. Texture is one of many elements contributing to the quality of products and has a significant impact on consumer decisions about choosing a food product (Kiczorowski et al., 2022; Karwowska and Kaczmarczyk, 2023).

The non-destructive assessment of samples using image processing can provide insight into their quality. The image textures considered as a function of the spatial variation in the brightness of pixel intensity can carry information about the structure of samples. Images can be characterized by the repeated subpatterns of the dispersion and distribution of pixel brightness, which represent the brightness, colour, roughness, smoothness, size, directivity, and granulation of textures. The quantitative analysis of textures from images can provide data on the sample structure quality, considering the numerical description of the image (Szczypiński et al., 2007; Szczypiński et al., 2009; Strzelecki et al., 2013; Armi and Fekri-Ershad, 2019). The available literature reported information about the application of image processing and machine learning to compare the raw pepper material and final product lacto-fermented for six months (Ropelewska et al., 2022) and to monitor the changes in pepper structure with increasing time of lacto-fermentation as 3, 7, 10, 14, 21, 28, and 56 days (Ropelewska et al., 2024). Whereas Ropelewska et al. (2023) studied the impact of the lacto-fermentation periods (1 week and 3 months) on zucchini flesh structure using machine learning models based on image textures. However, there is a lack of literature data on the possibility of using the approach based on image texture parameters for non-destructive estimation of chemical parameters of sweet pepper along with the progress of spontaneous lacto-fermentation. The problem to be solved is related to the selection of specific textures of pepper images that are correlated with individual chemical parameters and that can be used to set models to non-destructively estimate these parameters based on image textures. Therefore, the objective of this study was to select image textures of red bell pepper samples correlated with their chemical characteristics, such as TSS, acidity, pH, L-ascorbic acid, glucose, fructose, total sugars, capsanthin, ß-cryptoxanthin, lycopene, α-carotene, β-carotene, and total carotenoids after specific periods of lacto-fermentation and to set the regression equations to estimate chemical properties using novel approach based on texture parameters selected from a big dataset of 1629 parameters extracted from colour images.

MATERIALS AND METHODS

Raw material and preparation of pepper samples for the fermentation

The raw material of red bell pepper ‘California’ cv. was bought from a Polish importer and distributor of fruit and vegetables. The country of origin was Turkey. To ensure the optimal course of the fermentation, fresh pepper fruit samples were subjected to selection, eliminating diseased, soft, and mechanically damaged fruits. Then peppers were washed, cut into pieces, and placed in glass jars with twist-off lids, which were sterilised before the fermentation process. In addition to the chopped peppers, the jars were filled with spices (black pepper, allspice, mustard seeds, bay leaves) and poured with the prepared 3.5% brine consisting of Kłodawska rock salt and tap water. The amount of brine was sufficient to completely cover the surface of the sliced peppers. The jars were then closed tightly and stored at 20 °C to initiate the natural lactic fermentation process which produces lactic acid bacteria. The experiment was prepared in three technological repetitions. The analysis of samples was conducted after 7, 14, 28, and 56 days of lacto-fermentation, and in raw material (0 days). The schematic overview of the experimental design is presented in Figure 1.

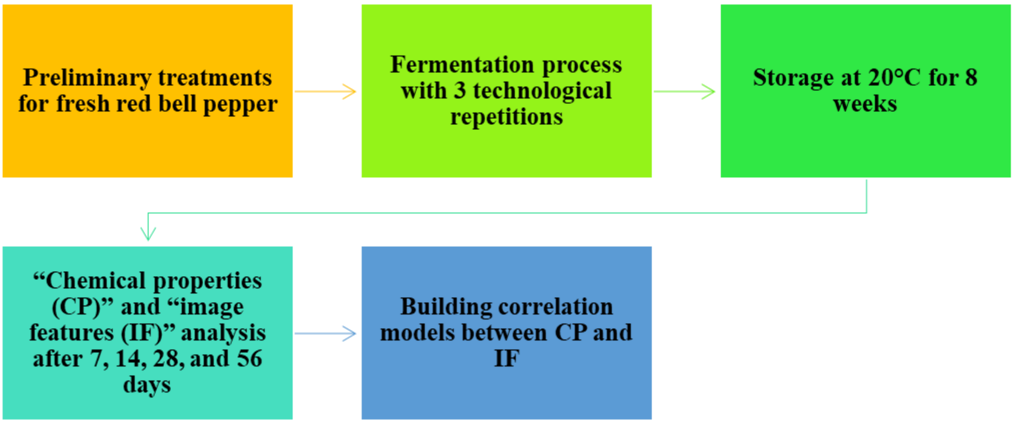

Figure 1. The schematic overview of the steps of the performed experiment.

Chemical properties

The analysis of active acidity (pH) and titratable and total soluble solids (TSS) of the samples was performed immediately after a given fermentation time. For other analysis, pepper samples were quartered, frozen, pulverised in liquid nitrogen, and stored at −20 ◦C until the moment of analysis. All chemical measurements were performed in six repetitions.

Active acidity (pH) and titratable acidity expressed as citric acid were determined according to PN-EN-12147:2000 using a titrator (SI Analytics, TitroLine 7000). The results of titratable acidity were expressed in %.

Total soluble solids (TSS) were using a refractometer (Mettler Toledo, RE50), expressed as °Brix. Sugar content was determined by applying the HPLC method (Agilent 1200 HPLC system, equipped with a differential refractometric detector), using an Aminex HPX-87C column (300 mm x 7.5 mm) with a precolumn. Elution conditions were as follows: flow 0.6 ml min^{-1}, temperature 80 °C, mobile phase – 0.1M aqueous solution of edetate calcium disodium ($CaNa_2$-EDTA). Before HPLC determination, five grams of sample were homogenised in redistilled water and filtered through a Sep-Pak® PLUS C18 filter (Waters) and transferred to HPLC vials. The sugar content was determined on the basis of calibration curves obtained separately for each of the standards analysed: glucose and fructose. The results were expressed in g 100 g^{-1} f.m.

The L-ascorbic acid content was analysed by HPLC method (Agilent 1200 HPLC system with a diode detector),) using Supelcosil LC-18 column (250 mm x 4.6 mm; 5 μm) with a precolumn according to IFU (2005) procedures. Phosphate-buffered solution KH_2PO_4 (1%, pH - 2.5) was used as the mobile phase. The column temperature was maintained at 30°C with a flow rate of 0.8 mL min^{-1}. The detection of L-ascorbic acid was by absorbance at 244 nm. Five grams of a disintegrated frozen pepper sample were homogenised in 6% HPO_3, then filtered and transferred to HPLC vials. The L-ascorbic acid was determined on the basis of the calibration curve for standard. The obtained results were expressed as mg kg^{-1} f.m.

The content of carotenoids was analysed by the method reported by Bohoyo-Gil et al. (2012). The sample was homogenised in the extraction solution (hexane:acetone 6:4) with the addition of magnesium carbonate. The solution was filtered through a Büchner funnel under reduced pressure. The extract was transferred to a separatory funnel with water added and shaken. After phase separation, the water-acetone phase was discarded. The acetone rinsing operation was repeated until the lower phase was free of acetone and the upper hexane phase containing carotenoids was filtered into an evaporation flask through a filter paper containing anhydrous sodium sulfate. Hexane was evaporated to dryness in a vacuum evaporator at 40 °C. The dry residue was quantitatively transferred to a flask with a solution of acetonitrile: methanol: ethyl acetate 55:25:20 + 0.1% butylated hydroxytoluene (BHT) + 1 ml triethylamine (TEA) and 4 ml of hexane. The flask extract was filtered with a 0.45 µm PTFE filter into amber vials. Carotenoids were analysed with the use of an Agilent 1200 series HPLC system equipped with a DAD detector. Separation was performed using a Kinetex C-18 column (250 mm x 4.6 mm; 5 µm). The mobile phase was: acetonitrile (solvent A), ethyl acetate (solvent B), methanol containing 0.1 % TEA and 0.1 % BHT (solvent C), and the flow rate was 0.7 ml · min^{-1}. The analysis was conducted with gradient program: 95 % A, 3 % B, 2 % C for 0-3 min.; 95 % A, 3 % B, 2 % C for 3-10 min.; 55 % A, 25 % B, 20 % C for 10-25 min.; 55 % A, 25 % B, 20 % C for 25-35 min.; followed by washing and reconditioning of the column for 5 min. The separation was carried out at a temperature of 28 °C. The absorption wavelength for detection was 450 nm and 472 nm (lycopene). Carotenoids were identified and determined on the basis of the calibration curve for standards of β-carotene and lycopene (Sigma-Aldrich, Germany). The content of carotenoids was expressed in mg 100 g^{-1} f.m.

Image texture parameters

The texture parameters were computed based on images acquired using a digital camera located in a box with black walls and light-emitting diode (LED) illumination. The digital camera was characterised by auto white balance, optical image stabilization, SD (secure digital) card, and F 2.4, 8× digital zoom. The LED illumination included the light sources of 24 LEDs, a related input current of 0.07 A, a related input voltage of AC 110–240 V at 50–60 Hz, and a related output power of 2.2 W.

In the case of lacto-fermented pepper, samples were dried of excess fluid using a paper towel before imaging. All red bell pepper samples were imaged on a black background to facilitate the image processing. The image acquisition was performed in fifty repetitions. The acquired images were uploaded to a computer using a USB cable. Pepper images were saved in a BMP format for performing the image processing. The image processing included image conversion, image segmentation, region of interest determination, and image texture extraction. These steps were carried out using the Mazda software (Łódź University of Technology, Institute of Electronics, Łódź, Poland) (Szczypiński et al., 2007; Szczypiński et al., 2009; Strzelecki et al., 2013). Firstly, the pepper images were converted to colour channels *L*, *a*, *b*, *R*, *G*, *B*, *X*, *Y*, and *Z*. The images were segmented into pepper samples and the black background manually based on the pixel brightness intensity. Each pepper sample was treated as a region of interest (ROI). Then, for each ROI, 1629 texture parameters were extracted from images in each colour channel.

Statistical analysis

The linear correlations between image texture parameters and chemical properties of pepper samples were determined at a significance level of $p < 0.05$.

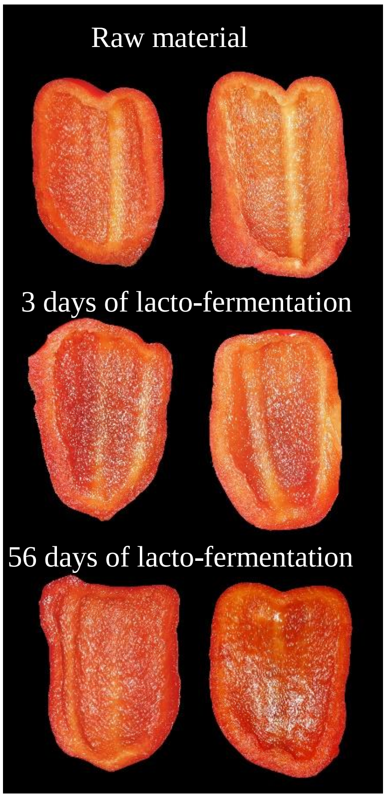

Figure 2. The red pepper samples before and after selected periods of spontaneous lacto-fermentation

The statistical analysis included raw material and samples after 7, 14, 28, and 56 days of lacto-fermentation. The analysis was performed for 1629 image textures, including 181 textures for each colour channel *L*, *a*, *b*, *R*, *G*, *B*, *X*, *Y*, and *Z*, and the content of L-ascorbic acid, glucose, fructose, total sugars, capsanthin, β-cryptoxanthin, lycopene, β-carotene, α-carotene, total carotenoids, as well as TSS, acidity, and pH. Pearson's correlation coefficients (R) were determined. The statistically significant coefficients were selected. The five highest negative and five highest positive coefficients for individual chemical parameters were chosen to present in this paper. For selected parameters, scatter plots were created. The regression equations to estimate the chemical properties based on image parameters, for which the correlation coefficients were the highest, were set.

RESULTS AND DISCUSSION

The chemical properties of fresh and fermented pepper fruit

The results of chemical analyses of fresh pepper fruit and after fermentation are presented in Tables 1-3. As the fermentation process progressed, an increase in acidity and a simultaneous decrease in pH were observed (Table 1). The acidity of raw red pepper was at the level of 0.40 % f.m, and the pH was 5.05. After 56 days of fermentation, the acidity of pepper stabilised at the level of: 0.79 % f.m, and pH=3.5. This pH level is recommended for LAB fermentation of vegetables (Niakousari et al., 2021).

Table 1. The content of L-ascorbic acid, TSS, acidity, and pH of raw and lacto-fermented red bell pepper.

Days of fermentation	L-ascorbic acid (mg 100 g^{-1} f.m.)	TSS (°Bx)	Acidity (% f.m.) expressed as citric acid	pH
0 days	187.1±3.78a	8.08±0,05a	0.40±0.01a	5.05±0.08a
7 days	110.7±2.42b	6.46±0.22b	0.51±0.01b	3.85±0.11b
14 days	88.6±0.56c	5.70±0.03c	0.54±0.04c	3.33±0.09d
28 days	86.5±1.73c	5.77±0.08c	0.68±0.03d	3.39±0.12cd
56 days	85.4±3.78c	5.76±0.08c	0.79±0.03e	3.50±0.10c

a,b,… - the same letters in the columns mean no statistical differences between samples; values after ± are standard deviations

Acidity and pH are among the most important parameters determining the high quality and storage stability of the product (Zaręba and Ziarno, 2011; Rybak et al., 2020; Ryznar-Luty and Szymański 2020). Kiczorowski et al. (2022) observed a similar pH value (approx. 3.5) in their studies from the 14th day of the pepper fruit fermentation process. This pH value effectively inhibits the multiplication of pathogenic microflora. In the study by Ratajczak et al. (2017), it was reported that with a decrease in pH in the plant material, the content of lactic acid in the product increased. This is due to the presence of live bacteria, that use sugars present in the product to produce lactic acid and other metabolites such as ethanol and acetic acid, which in turn accumulate and increase acidity and lower pH (Janiszewska-Turak et al., 2022b). The type of bacteria conducting the fermentation process depends on the type of vegetable, climatic conditions, harvesting conditions, and preparation method (Monet et al. 2014). It was found that spontaneous fermentation contributes to an increase in the intensity of taste and aroma compared to conducting a controlled process using pure bacterial cultures (Saranraj et al., 2013).

Total soluble solids (TSS) is an important quality parameter. TSS allows to determine the amount of soluble solids in the product. It consists mainly of sugars, which can be monosaccharides, disaccharides, or oligosaccharides such as sucrose, glucose, fructose, etc. It affects the taste as it can indicate the level of sweetness. Total soluble solids (TSS) content was 8.08% (Table 1) in fresh peppers, which is in line with the results of other studies (Buczkowska et al., 2015; Rohini and Lakshmanan, 2017). As fermentation progressed, a decrease in this value was noted, which after 14 days was 5.7% until its completion. The decrease in TSS is related to the decrease in pH during fermentation due to the action of lactic acid bacteria, which use the sugars contained in the product (Abou-Zaid, 2015).

The fermentation also affects changes in the content of vitamins and other bioactive substances. Pepper is a valuable source of L-ascorbic acid, the content of which depends on the variety, climatic conditions, fruit ripeness stage, and harvest date (Navarro et al., 2006). It is an important biological factor taking part in numerous metabolic processes taking place in organisms, i.e. it is involved in maintaining the oxidation-reduction potential in the cell, it transports electrons by penetrating biological membranes, erythrocyte membranes, lipids, and other tissue cells (Wawrzyniak et al., 2011; Waszkiewicz-Robak et al., 2020). L-ascorbic acid is one of the least durable vitamins. Its losses may be caused by technological processes such as drying, salting, steaming, irradiation with ultraviolet rays, and the use of preservatives (Herbig and Renard, 2017, Migut et al., 2018). In our studies, the content of L-ascorbic acid in fresh pepper fruits was 187.1 mg 100 g^{-1} f.m. As the fermentation process progressed, a decrease in its content in the samples was observed, by approximately 50%, which remained at a constant level after 14 days (Table 1). Similar results were obtained by Kiczorowski et al. 2022. Losses in the content of L-ascorbic acid during the fermentation process may depend on the release and activation of the enzyme - ascorbinase from damaged cellular structures and the access to oxygen. Decreasing pH limits enzymatic processes, which means that a significant amount of L-ascorbic acid contained in them is preserved in vegetables undergoing the pickling process, which was also observed in our studies (Franco et al., 2012; Grzelakowska et al., 2013; Gorzelany et al., 2015).

In our studies, the content of reducing sugars in relation to the sugar minimum in pepper fruits met the quality requirements of plant material that can be used for fermentation (Holzapfel and Schillinger, 2002; Breidt et al., 2013). Along with the progressing fermentation process, a decrease in the content of individual sugars was observed, however, not all sugars were used by bacteria during the fermentation of peppers.

The total sugar content in the raw material was equal to 2.99 g·100 g^{-1} f.m. and in the first week of pepper fermentation, a significant decrease in the content of monosaccharides: glucose and fructose by approximately 50% was observed, compared to the initial value.

Table 2. The content (g 100 g^{-1} f.m.) of sugars of raw and lacto-fermented red bell pepper.

Days of fermentation	Sucrose	Glucose	Fructose	Total sugars
0 days	0.06±0.01a	1.12±0.33a	1.81±0.21a	2.99±0.53a
7 days	0.00±0.00b	0.52±0.59b	0.88±1.18b	1.40±1.76b
14 days	0.00±0.00b	0.23±0.23c	0.55±0.73c	0.78±0.94c
28 days	0.00±0.00b	0.15±0.03d	0.59±0.27c	0.74±0.27c
56 days	0.00±0.00b	0.11±0.28d	0.58±0.16c	0.69±0.43c

a,b,… - the same letters in the columns mean no statistical differences between samples; values after ± are standard deviations

The presence of sucrose was noted only in the raw material. After the two weeks of fermentation, the content of monosaccharides (glucose, fructose) in the lacto-fermented pepper was approximately 0.7%, g 100 g^{-1} f.m, which corresponded to approximately 80 % of the breakdown of sugars contained in the initial raw material (Table 2). This value did not change significantly in the further part of the experiment. Incomplete breakdown of sugars during the pepper fermentation process may result from the fact that some bacteria prefer pentose sugar over glucose, e.g. *Lactobacillus brevis* (Kim et al., 2010).

There is little research on how the fermentation process can affect changes in the colour of the product. However, the resulting metabolic products of lactic acid bacteria, such as lactic acid production, have led to the creation of a lower pH environment, which affects pigments contained in food. Also during the fermentation process, processes of changes in concentration gradients can occur, which in turn can lead to the exchange of low molecular weight components from tissue to brine and from brine to raw tissue and indirectly affect the bioavailability of pigments, i.e.: carotenoids (Mapelli-Brahm et al., 2020). The carotenoid content results are presented in Table 3. In our research, after the fermentation process, a decrease in the content of total carotenoids in relation to the raw material was observed by approximately 30 %, including β-carotene by approximately 50 % and β-cryptoxanthin ~ 30%. (Table 3). For carotenoids: capsanthin, α-carotene, and lycopene, a slight increase in their content was noted or these changes were not statistically significant (Table 3). Different research results were presented by Kiczorowski et al. (2022), who observed an increase in the content of β-carotene in peppers after 3 weeks of fermentation at 24 °C. In turn, in the research of Chen et al. (2022), a slight increase in carotenoids was observed during 14-21 days of fermentation, and then after the 3rd day of fermentation, a significant decrease in their content by approximately 50% in relation to the raw material. Perhaps the different fermentation conditions in our studies resulted in a reduction in the content of β-carotene and total carotenoids. Kiczorowski et al. (2022) found, that the content of β-carotene during fermentation is very variable and may change depending on the plant material and process conditions. In addition, carotenoids are degraded during vegetable processing and are sensitive to changes in pH (Liu et al. 2020). Studies by Li et al. (2021) and Ponder et al. (2021) found, that the decrease or increase of carotenoids during the fermentation process may also depend on the variety and degree of ripeness of peppers used during the fermentation process. In addition, the increase in carotenoid content in pepper after fermentation may be related to the disruption of tissue cells, inside which these carotenoids may be placed (Janiszewska-Turak et al., 2022a).

Table 3. The content (mg 100 g^{-1} f.m.) of carotenoids of raw and lacto-fermented red bell pepper.

Days of fermentation	Capsanthin	β-cryptoxanthin	Lycopene	α-carotene	β-carotene	Other carotenoids	Total carotenoids
0 days	0.21±0.02ab	0.23±0.02a	0.24±0.02ab	0.07±0.01b	1.21±0.1a	5.10±0.57a	7.06±0.60a
7 days	0.24±0.01a	0.24±0.03a	0.28±0.03a	0.09±0.01ab	0.95±0.04b	4.71±0.38ab	6.50±0.41ab
14 days	0.19±0.01b	0.22±0.02ab	0.22±0.02b	0.10±0.01a	1.05±0.04b	3.96±0.30ab	5.74±0.32bc
28 days	0.19±0.01b	0.19±0.02ab	0.22±0.01b	0.10±0.01a	0.95±0.03b	4.00±0.42ab	5.64±0.43bc
56 days	0.24±0.02a	0.16±0.02b	0.23±0.02ab	0.07±0.01b	0.58±0.02c	3.73±0.59b	5.02±0.56c

a,b,… - the same letters in the columns mean no statistical differences between samples; values after ± are standard deviations

The correlation between image parameters and chemical properties

The correlation between image parameters and the chemical properties of sweet red pepper during fermentation was observed. Correlation coefficients (R) between image texture parameters and the L-ascorbic acid content (mg 100 g^{-1} f.m.), TSS (°Bx), acidity (%), and pH of raw and lacto-fermented red bell pepper are presented in Table 4. Very high positive and negative coefficients were observed for each parameter. In the case of L-ascorbic acid, a strong positive correlation with R reaching 0.999 was obtained for image texture bS5SH5DifEntrp from images in colour channel *b* and a strong negative correlation with R of -0.977 was determined for image texture LS4RNLngREmph from colour channel *L*. The R values for positive and negative correlations for TSS reached 0.994 for BS5SZ5DifEntrp from colour channel *B* and -0.983 for bS5SZ1InvDfMom from colour channel *b*. Acidity was also strongly correlated with image textures with the highest positive coefficient R equal to 0.999 for ZS5SV1InvDfMom from colour channel *Z* and the highest negative coefficient R of -0.963 for ZS5SN1DifEntrp and ZS5SV1DifEntrp from colour channel *Z*. For pH, the positive and negative values of R reached 0.997 for image texture bS5SN3DifEntrp and -0.981 for bS5SZ1InvDfMom, respectively.

The strong relationships between image textures and the sugar content of raw and lacto-fermented pepper samples were reflected in very high values of correlation coefficients (Table 5). The highest coefficients are included at the top of the table, regardless of whether they are positive or negative correlations. The values of R reached -0.998 (LS4RNLngREmph) and 0.995 (bS4RZFraction) for glucose, 0.997 (bS5SH5DifEntrp) and -0.974 (bS5SZ1InvDfMom) for fructose, and 0.998 (BS5SZ5DifEntrp) and -0.985 (LS4RNLngREmph) for total sugars.

Correlation coefficients (R) between image texture parameters and the content of carotenoids of raw and lacto-fermented pepper are presented in Table 6. The strongest relationship with the correlation coefficient of 0.999 was observed between image texture XS5SV3DifEntrp extracted from images in colour channel *X* and the content of lycopene. It was a positive correlation. The highest negative correlation (R=-0.998) was found for image textures GS5SV5SumEntrp (colour channel *G*) and RS5SZ1InvDfMom (colour channel *R*) with lycopene content and between image texture bS5SN3InvDfMom (colour channel *b*) and the content of total carotenoids.

Table 4. Correlation coefficients (R) between image texture parameters and L-ascorbic acid, TSS, acidity, and pH of raw and lacto-fermented red bell pepper.

Image texture	Correlation coefficient	Image texture	Correlation coefficient
L-ascorbic acid (mg 100 g^{-1} f.m.)		**TSS (°Bx)**	
bS5SH5DifEntrp	0.999	BS5SZ5DifEntrp	0.994
BS5SZ5DifEntrp	0.994	bS5SN3DifEntrp	0.991
bS5SN3DifEntrp	0.992	BS5SN5DifEntrp	0.987
BS5SN5DifEntrp	0.992	bS4RZFraction	0.982
LS5SN5SumVarnc	0.987	LS5SN5SumVarnc	0.981
LS4RNLngREmph	-0.977	bS5SZ1InvDfMom	-0.983
bS5SN1InvDfMom	-0.975	LS4RNLngREmph	-0.978
bS5SZ1InvDfMom	-0.975	bS5SN1InvDfMom	-0.976
BS4RNLngREmph	-0.971	GS4RNLngREmph	-0.974
GS4RNLngREmph	-0.966	SS5SZ5InvDfMom	-0.969
Acidity (% f.m.)		**pH (-)**	
ZS5SV1InvDfMom	0.999	bS5SN3DifEntrp	0.997
aS4RVLngREmph	0.995	BS5SZ5DifEntrp	0.986
GS5SN5InvDfMom	0.991	LS5SZ5SumVarnc	0.984
aS5SZ1DifVarnc	0.990	LS5SN5SumVarnc	0.984
GS5SZ5InvDfMom	0.990	ZS5SH3Contrast	0.982
ZS5SN1DifEntrp	-0.963	bS5SZ1InvDfMom	-0.981
ZS5SV1DifEntrp	-0.963	bS5SV1InvDfMom	-0.970
VS5SZ1Correlat	-0.962	bS5SN1InvDfMom	-0.969
LS5SH5Entropy	-0.960	LS4RNLngREmph	-0.961
ZS4RHFraction	-0.958	aS5SH1Entropy	-0.957

Table 5. Correlation coefficients (R) between image texture parameters and the content of sugars of raw and lacto-fermented red bell pepper.

Image texture	Correlation coefficient	Image texture	Correlation coefficient	Image texture	Correlation coefficient
Glucose (g 100 g^{-1} f.m.)		**Fructose (g 100 g^{-1} f.m.)**		**Total sugars (g 100 g^{-1} f.m.)**	
LS4RNLngREmph	-0.998	bS5SH5DifEntrp	0.997	BS5SZ5DifEntrp	0.998
SS5SZ5InvDfMom	-0.991	bS5SN3DifEntrp	0.996	bS5SH5DifEntrp	0.994
bS5SN1InvDfMom	-0.988	BS5SZ5DifEntrp	0.994	BS5SN5DifEntrp	0.994
bS5SZ1InvDfMom	-0.983	LS5SN5SumVarnc	0.990	bS5SN3DifEntrp	0.988
SS5SN5InvDfMom	-0.982	LS5SZ5SumVarnc	0.987	bS4RZFraction	0.986
bS4RZFraction	0.995	bS5SZ1InvDfMom	-0.974	LS4RNLngREmph	-0.985
BS5SN5DifEntrp	0.994	LS4RNLngREmph	-0.969	bS5SZ1InvDfMom	-0.981
BS5SZ5DifEntrp	0.991	bS5SN1InvDfMom	-0.968	bS5SN1InvDfMom	-0.981
bS5SH5DifEntrp	0.977	GS4RNLngREmph	-0.967	GS4RNLngREmph	-0.975
bS4RVFraction	0.969	BS4RNLngREmph	-0.956	SS5SZ5InvDfMom	-0.974

Table 6. Correlation coefficients (R) between image texture parameters and the content of carotenoids of raw and lacto-fermented red bell pepper.

Image texture	Correlation coefficient	Image texture	Correlation coefficient	Image texture	Correlation coefficient
Capsanthin (mg 100 g^{-1} f.m.)		**ß-cryptoxanthin (mg 100 g^{-1} f.m.)**		**Lycopene (mg 100 g^{-1} f.m.)**	
VHSkewness	-0.990	ZS5SZ1InvDfMom	-0.993	XS5SV3DifEntrp	0.999
YS5SH3Correlat	-0.984	GS5SN5InvDfMom	-0.990	RS4RVShrtREmp	0.996
aS5SH1SumOfSqs	-0.978	ZS5SN1InvDfMom	-0.986	RS4RHShrtREmp	0.996
aS5SV1SumOfSqs	-0.976	aS4RVLngREmph	-0.985	RS5SN1DifEntrp	0.996
aS5SH3SumOfSqs	-0.973	UHVariance	-0.978	RS4RZShrtREmp	0.994
UATeta1	0.968	ZS5SH3DifEntrp	0.985	GS5SV5SumEntrp	-0.998
VHMaxm01	0.967	ZS4RHFraction	0.979	RS5SZ1InvDfMom	-0.998
ZS4RVShrtREmp	0.962	UHMaxm10	0.963	GS5SN5SumEntrp	-0.996
YS5SH3Contrast	0.962	ZS4RVFraction	0.962	GS5SZ5SumEntrp	-0.996
YS4RVShrtREmp	0.961	ZS4RZFraction	0.960	RS5SV1InvDfMom	-0.996
α-carotene (mg 100 g^{-1} f.m.)		**β-carotene (mg 100 g^{-1} f.m.)**		**Total carotenoids (mg 100 g^{-1} f.m.)**	
LS5SN5AngScMom	-0.996	SS5SZ3AngScMom	-0.994	bS5SN3InvDfMom	-0.998
LS5SZ5AngScMom	-0.996	SS5SH5AngScMom	-0.993	bS5SZ3InvDfMom	-0.996
ZHMaxm10	-0.993	SS5SH3AngScMom	-0.991	aS5SN1Contrast	-0.996
LS5SZ3AngScMom	-0.983	SS5SN3AngScMom	-0.989	bS5SH5InvDfMom	-0.994
RSGNonZeros	-0.979	ZS4RVLngREmph	-0.988	bS4RHLngREmph	-0.991
ZS5SZ3Correlat	0.992	SS5SH3Entropy	0.984	bS5SZ1Entropy	0.997
ZS5SZ1Correlat	0.974	SS5SH1Entropy	0.983	bS5SN1Entropy	0.994
ZS5SH1Correlat	0.962	SS5SN3Entropy	0.981	bS5SV1Entropy	0.990
ZS5SH3Correlat	0.957	SS5SH5Entropy	0.980	SS5SV1Entropy	0.986
RHMaxm01	0.948	BS5SV3Entropy	0.978	ZS5SH5Contrast	0.982

The scatter plots presenting the strongest relationships for image textures and chemical properties are shown in Figure 1. Graphs confirmed linear correlations between selected properties, such as L-ascorbic acid, TSS, acidity, pH, total carotenoids, and total sugars with texture features extracted from images in different colour channels. The lines of best fit on scatter plots were observed for L-ascorbic acid content and acidity, for which the highest correlation coefficient (R) of 0.999 was determined.

Based on selected image textures, for which the correlation coefficients were the highest, the regression equations were determined (Equations 1 to 13). Equations were set for the relationships between texture parameters and chemical properties. The determined regression equations can be used to estimate the ascorbic acid content, TSS, acidity, pH, and the content of sugars, and carotenoids.

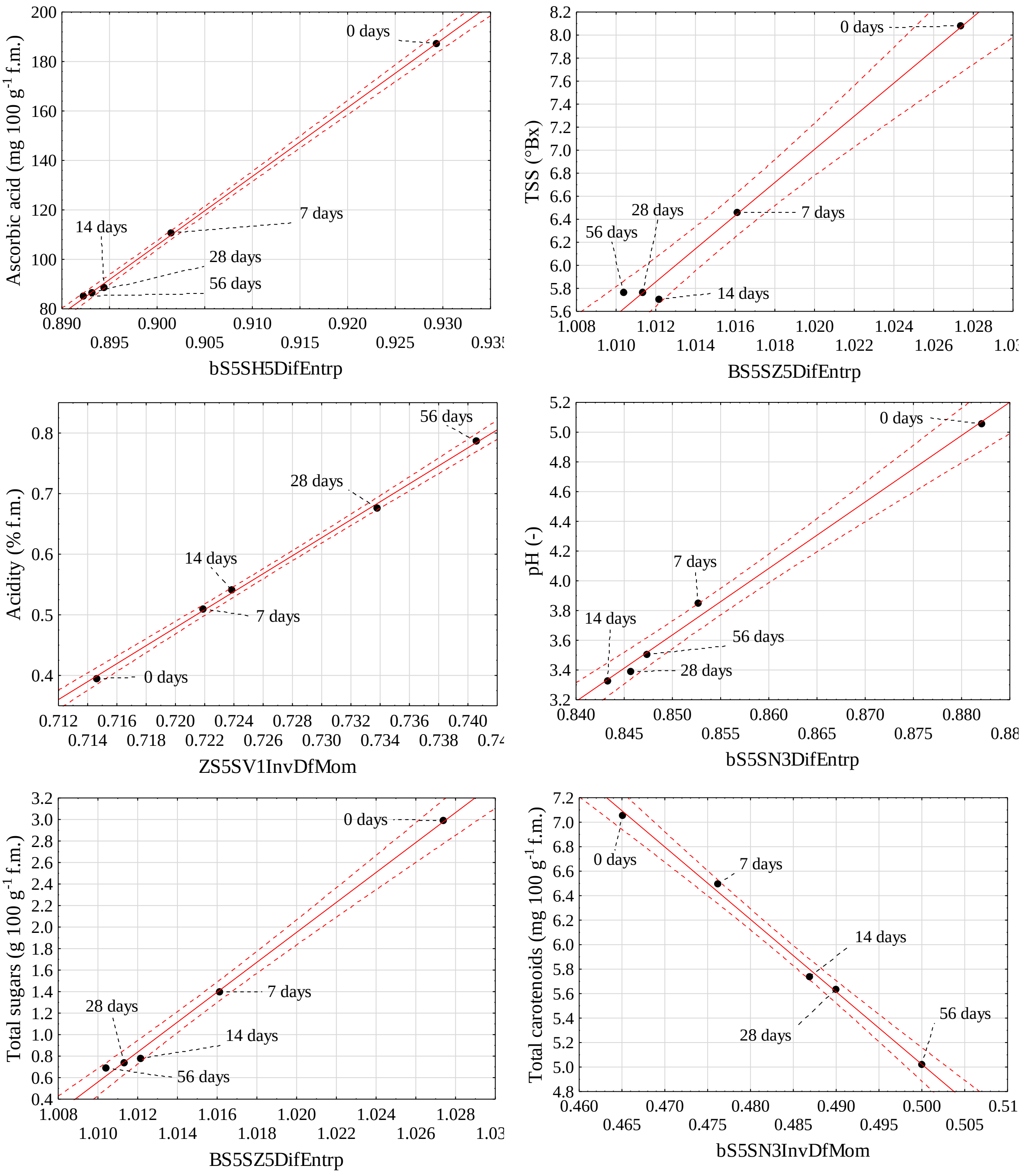

Figure 1. Scatter plots for selected image textures and chemical properties.

Regression equations are:

L-ascorbic acid (mg 100 g^{-1} f.m.) = -2396. + 2780.2 * bS5SH5DifEntrp [1]

TSS (°Bx) = -139.8 + 143.94 * BS5SZ5DifEntrp [2]

Acidity (% f.m.) = -10.08 + 14.673 * ZS5SV1InvDfMom [3]

pH (-) = -34.38 + 44.720 * bS5SN3DifEntrp [4]

Glucose (g 100 g^{-1} f.m.) = 5.2051 - 0.5875 * LS4RNLngREmph [5]

Fructose (g 100 g^{-1} f.m.) = -29.86 + 34.077 * bS5SH5DifEntrp [6]

Total sugars (g 100 g^{-1} f.m.) = -140.0 + 139.14 * BS5SZ5DifEntrp [7]

Capsanthin (mg 100 g^{-1} f.m.) = -0.0941 - 0.2517 * VHSkewness [8]

ß-cryptoxanthin (mg 100 g^{-1} f.m.) = 1.8091 - 2.453 * ZS5SZ1InvDfMom [9]

Lycopene (mg 100 g^{-1} f.m.) = -1.134 + 1.4851 * XS5SV3DifEntrp [10]

α-carotene (mg 100 g^{-1} f.m.) = .56069 - 63.27 * LS5SN5AngScMom [11]

ß-carotene (mg 100 g^{-1} f.m.) = 3.7874 - 136.7 * SS5SZ3AngScMom [12]

Total carotenoids (mg 100 g^{-1} f.m.) = 34.615 - 59.19 * bS5SN3InvDfMom [13]

The obtained results confirmed the strong relationship between texture parameters extracted from colour images and the chemical properties of fresh and lacto-fermented red sweet pepper. Therefore, imaging proved to be useful to estimate changes in the chemical characteristics of pepper during fermentation. In the previous studies, various imaging techniques were also used to predict the quality properties of the fruit. For example, the chemical properties, including firmness, moisture content, total soluble solids, pH, and colour of the pineapple during storage were predicted using infrared thermal image parameters (Mohd Ali et al., 2022). The ripening of papaya fruit was predicted with digital imaging (Santos Pereira et al., 2018). Hyperspectral imaging was used for the prediction mapping of chemical properties, such as firmness, total soluble solids (TSS), and titratable acidity (TA) in mango (Rungpichayapichet et al., 2017). Whereas multispectral imaging was applied to predict the bioactive compound content in intact tomato fruit (Liu et al., 2015). Thus, both the above-mentioned literature data and our own research indicated that image features can be appropriate predictors of the chemical properties of fruit quality. Further research can be performed to investigate the relationship between image parameters and the chemical quality of other fruit and vegetable species during fermentation and other preservation processes.

CONCLUSIONS

The strong relationships between image texture features and the chemical characteristics of fresh and lacto-fermented for 7, 14, 28, and 56 days for red sweet bell pepper samples were confirmed. The correlation coefficient (R) reached 0.999 for the relationship between L-ascorbic acid content with image texture bS5SH5DifEntrp, acidity with image texture ZS5SV1InvDfMom, and lycopene content with image texture XS5SV3DifEntrp. The regression equations for the relationships between image textures and chemical properties were determined. Therefore, the obtained results are added value in sweet bell pepper processing and can be used in practice to estimate chemical properties of lacto-fermented pepper samples based on image parameters. This study set a new direction in lacto-fermented pepper quality assessment and contributed to expanding knowledge on the possibility of using the approach based on image textures for non-destructive estimation of chemical parameters of food products. In view of the promising results obtained, further research can be performed to determine the correlation between image parameters and the chemical quality of sweet bell pepper cultivars with other colours of fruit and various cultivars of hot pepper during preservation using various techniques and to develop predictive models to predict changes in the quality of samples during preservation based on image features.

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