Thesis Book

Non-destructive methods for determination of quality attributes of bell peppers

Prepared by

Timea Ignat

This work was carried out under the supervision of

Ze'ev Schmilovitch, DSc

Department of Agricultural Engineering, ARO, Israel

and

József Felföldi, CSc

Corvinus University of Budapest, Faculty of Food Science

Department of Physics-Control

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PhD School

Name:	PhD School of Food Science
Field:	Food Science
Head:	Péter Fodor, DSc
	Corvinus University of Budapest
Supervisors:	Ze'ev Schmilovitch, DSc
	Department of Agricultural Engineering
	ARO, Israel
	József Felföldi, CSc
	Department of Physics-Control
	Faculty of Food Science
	Corvinus University of Budapest

The applicant met the requirement of the PhD regulations of the Corvinus University of Budapest and the thesis is accepted for the defence process.

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Signature of Head of School Signatures of Supervisors

1. INTRODUCTION

Export and local market demands high quality sorted fruits and vegetables, which long preserves its fresh condition on the shelves. Additionally, there is an increased demand for fruits and vegetables that are beneficial for healthy life style as well as rich in ingredients that positively influence the prevention of any health malfunction. Since in most of the agricultural products the changes of inner content and outer properties continues after harvesting, therefore it is crucial to determine the optimal harvest time properly. If the time of the harvest is not properly determined than it might negatively influences the quality of the product. It means that some properties either do not reach their optimal level or in the overripe stage the valuable components like vitamin C starts to degrade. Moreover, the shelf life of the fruit is being shortened due to harvest in the overripe or unripe stage. The consequences of being unripe are that the fruit does not get its cultivar specific properties, like colour, taste. The consequence of being overripe is that the produce gets soft faster, gets wrinkled, and tasteless. The quality of the product is determined by the following attributes: colour, shape, size, and being without fault, damage or signs of sickness moreover, taste, texture, firmness, weight, internal composition. Fresh bell pepper is abundant in valuable nutritional values therefore its popularity increases from year to year mainly as freshly consumed vegetable and as ingredient of processed food in the cuisine. Peppers are one of the main export produce of Israel and of Hungary among many other countries. Several bell pepper cultivars are grown in Israel mainly in greenhouses or net-houses, in the southern part of the country. In Hungary the growth of bell pepper is not significant, more popular varieties are the ‘Yellow Wax’, ‘Kapija’, ‘Ho F1’, and ‘HRF’. At the present practise the harvest schedule is based on appearance and subjective experience of the growers. Since the maturity of the harvested pepper affects its final quality therefore there is a great importance in the accurate determination of the proper harvest time. Quality of pepper is a complex feature it includes among other characteristic parameters of colour, firmness, soluble solid, dry matter, and vitamin C content. Routine measurements of these indices are generally destructive, time and labour consuming. Harvested peppers need to be sorted and classified based on the requirements of the specific market where the product will be later on sent. Most of the cases, mechanical and manual sorting lines are based on external appearance, and lacks the ability to examine essential internal quality attributes. After considering the above facts I found it important to examine the changes during pepper fruit growth in order to develop a non-destructive and objective examination system for the evaluation and prediction of quality attributes of bell peppers during maturation. There is an increasing demand by both growers and packers for rapid, non-destructive evaluation methods for the determination of pepper quality change during growth, maturation and in the process of sorting and classification.

2. OBJECTIVES

The objectives of the present work are:

I. To explore the relationship between several non-destructive testing (NDT) methods and the state of maturity, inner composition, textural, and physiological parameters (DT).

II. To develop a rapid reliable non-destructive cost effective system to measure quality index of bell pepper.

The above objectives were realized in the following steps:

A. Examination of internal and external quality changes during growth and maturation for the selected, three different final colour (green, yellow, red) bell pepper cultivars.

B. Evaluation of textural and internal content prediction ability of several NDT methods such as:

    a. Colour measurement

b. Relaxation test
c. Ultrasonic test
d. Spectral measurements (visible-near infrared and short wave infrared)
e. Hyperspectral imaging.

C. Evaluation of the synergetic effect of the combination of the above NDT methods by fusion.
D. Evaluation of the synergetic effect of the fused DT quality parameters and NDT methods by fusion.

3. MATERIALS AND METHODS

The experiment of the present study based on a preliminary experiment which was carried out during March-May 2009 on fruits taken from 2 greenhouses, examined cultivars were: ‘Vergasa’ (red) and ‘Ever Green’ (green). The preliminary experiment consisted from two parts: the examination of changes during fruit development and the storability of the harvested fruit. Based on the results and experiences of the preliminary experiments the presents studies’ experiment was chosen and established.

3.1. Plant material

The experiments were carried out from December 2009 through February 2010, and involved fruits of three cultivars of different colours, taken from three greenhouses from the same area of En Tamar region, Israel. The particular cultivars were ‘Ever Green’ (green), ‘No. 117’ (yellow), and ‘Celica’ (red). Each cultivar was grown in a separate greenhouse; plants were grown on the soil with drip irrigation. Plants were irrigated 3 times a day, with 5 m^3 solution contains 10 l fertilizer (7 % Nitrogen, 3% Phosphorus, and 7% Potassium). Pepper plants were grown in the ‘Spanish’ system, which means that the plants were supported vertically by ropes.

The peppers chosen for the study were marked during their flowering stage. Fruits were picked nine times at weekly intervals, during the 9-week growing period, from the 34^{th} day after flowering (DAA) until full ripening (88^{th} day). Each picked batch of each variety contained 20 fruits; altogether 180 fruits of each cultivar were collected. Shortly after picking, fruit had been cooled and kept in an air-conditioned laboratory at 23°C. First, each batch of 60 fruits were numbered, weighed and measured their length and diameter at the shoulder of the fruit, then each pepper sample was subjected to NDT measurements than immediately followed by sampling from the same location for destructive tests. All the examinations were carried out on one particular surface of the pepper fruit.

3.2. Experimental setup for non-destructive testing

Colour measurement

Minolta Data Processor DP-301 of Chroma Meter CR-300 series was used for colorimetric measurements. Colour indices were taken at half length and two sides of each pepper fruit. The first measured side is the dedicated side, where all the measurements were conducted, and the second side is the opposite side of the dedicated surface. The two measurements were averaged. The following colour indices were recorded: Lightness (L), Chroma (C) and Hue (h).

Spectral measurement

The experimental arrangement for testing pepper fruits included a USB2000 (Ocean Optics, Dunedin, FL, USA) minispectrometer, with spectral range 340–1014 nm; grating, 600 lines blazed at 750 nm; optical spectral resolution, 1.2 nm at full width at half maximum; spectral sampling interval, 0.5 nm, 2048 data points with bidirectional reflection probe (BIF600-UV-VIS). The instrument uses one fibre to collect radiation reflected toward the spectrometer, and a bundle of six fibres to carry light from the LS-1 Tungsten Halogen Light Source (Ocean Optics, Dunedin, FL, USA). The incident beam, carried via the bidirectional reflection probe fell perpendicularly onto the fruit sample, and the reflected light was collected by the collecting fibre and guided to the slit of the spectrometer. The setup included a cone (25-mm-diameter base, 15 mm in height, with a slope of 450). Due to noise the spectral range was reduced to 477–950 nm.

Spectral measurements also were obtained with a Liga SWIR spectrophotometer (STEAG Micro Parts, Dortmund, Germany) with a single directional fibre-optic connected to a cone attachment. The light source of this instrument is an LS-1 Tungsten Halogen Light Source (Ocean Optics, Dunedin, FL, USA). The detector assembly included a cone that fitted tightly against the pepper surface. The surface area observed through the cone was 30 mm in diameter. The incident beam from the light source was projected perpendicularly onto the fruit sample and radiation reflected at an angle of 45° was collected. Altogether 128 data points were acquired in each scan, covering an 850-1888 nm range interval with optical spectral resolution of 8.1 nm. Both configurations were calibrated with a Spectralon: WS-1-SL standard white ceramic background disc (Ocean Optics, Dunedin, FL, USA).

The spectral measurement systems were arranged in reflectance mode for receiving the signals from the peel and flesh of the fruit. The sampled pepper was positioned so that the VIS-NIR and SWIR detector assembly sampled a region at one marked site on the circumference of the largest cross-section perpendicular to the stem–blossom axis. Each fruit was scanned 10 times in the sampled region by moving slightly the cone on the surface; the readings were automatically averaged to yield one spectrum signal.

Hyperspectral imaging

Hyperspectral imaging system based on acousto-optic tuneable filter (AOTF): electronically tuned band-pass filter was used in the measurement. The image sampled by the AOTF is captured by a black and white CCD cooled camera (COOL-1300Q/QC, VDS, DE) with a pixel resolution of 1280x1024, and 640x512 with 2x2 binning technology. The lens angle was 12° horizontally and 9° vertically. The control of the AOTF was done by a direct digital synthesizer which sends a radio frequency wave to the AOTF through an amplifier, and thereby changes the filter characteristics.

The measurements were conducted in the wavelength range of 550-850 nm, in step of 5 nm. Custom software was written to control the hyperspectral camera. Under Matlab software a code was written for processing the hyperspectral images and for building the hyperspectral cubes. The code includes: flat filed correction of the images, calculation of the absolute reflectance using the empirical line, exclusion of the saturated pixels, sampling of the hyperspectral cube, and calculation of the averaged spectra, spectral angle map (SAM) and polar quality point (PQS) indices.

Hyperspectral images were acquired of each pepper samples.

Ultrasonic test

A high-power, low-frequency ultrasonic pulse generator-receiver (Krautkramer Model USL33) and a pair of 50-kHz ultrasonic transducers were used to generate the signal; coupled to a microcomputer system for data acquisition and analysis. Exponential-type Plexiglas beam-focusing elements were used to reduce the 55-mm beam diameter of each transducer to the desired area of contact with the fruit. The transducers were mounted with an angle of about 120° between their axes, enabling an ultrasonic signal to be transmitted and received over a short distance between their tips across the peel of the fruit. The ultrasonic measurement was conducted once, on a relatively flat area which was previously chosen on the pepper fruit. The pulse amplitude of the transmitted ultrasonic signal was measured at eight points with 0.25 mm spacing (0.5, 0.75, 1, 1.25, 1.5, 1.75, 2 and 2.25 mm) between the two probes, along the length of the fruit. The attenuation of the ultrasonic signal was calculated.

Stress relaxation of intact fruit

Lloyd LR SK Instrument (Lloyd Instruments Ltd., UK) was used in the test. The general purpose relaxation test was carried out on intact fruit laid on its side on a flat plate and was compressed by a moving plate at a speed of 200 mm/min until a load limit of 20 N was achieved. The hold time was 10 seconds. The results were analyzed by Nexygen 4.1 - Material Test and Data Analysis Software. At the end of the test the rate of relaxation [N/s] and the remaining deformation [mm] was recorded.

3.3. Experimental setup for reference measurements

Rupture test

Compress to Rupture Test was carried out with Lloyd LR SK Instrument (Lloyd Instruments Ltd., UK). Strip (3 cm by 3 cm) was cut from the designated side. The strip was placed, laying on its peel on the lower plate and weighted with the upper plate (1250 g) on the top, to avoid the deflection of the strip during the test. Both plates had a centred 16 mm diameter hole. The speed of the 8 mm diameter penetration probe was 100 mm/min. The tip of the penetration probe was slightly curved. Each strip of pepper was characterized by the coefficient of elasticity ($CE_{Rupture}$, N/mm), calculated from the section before the proportionality limit.

Compression test

Compress to Limit Test was carried out by Lloyd LR SK Instrument (Lloyd Instruments Ltd., UK). Test disk of 15 mm diameter was cut from the dedicated side of the pepper. The disk was placed on the centre of the lower plate in a way that its peel was laying on the lower plate. The speed of the upper plate was 100 mm/min. The upper plate was compressing the sample until a point when the distance between the probe and the lower plate was 1 mm. Each fruit was characterized by two calculated parameters: the coefficient of elasticity ($CE_{Compression}$, N/mm), calculated from a section of the load-deformation curve before the proportionality limit; and the integral of the area under the load-deformation curve ($Int_{Compression}$). In the later parameter the integral was calculated from the start of deformation until the proportionality limit.

Laboratory measurements

- Dry matter % (DM) determination: a sample was taken from the location at which NDT measurements had been performed. Each sample was weighed and dried at 60˚C in a forced-air oven for 72 h, than it was weighted again and percentage of DM was calculated.
- Total soluble solid (TSS) measurement was done by a digital refractometer (Atago, PR-1).
- Ascorbic acid measurement was carried out based on the AOAC - Official Method of Analysis, 967.21 Ascorbic Acid in Vitamin Preparations and Juices 2,6-Dichloroindophenol Titrimetric Method.
- Chlorophyll and carotenoid measurement: Determination of total chlorophyll and carotenoid content were carried out by extraction in absolute ethanol and spectral determination of absorbance in the wavelength of 470, 648.6 and 664.2 nm.
- Osmotic potential (OP) was measured using a cryoscopic micro-osmometer (µOsmette, Precision Systems, Natick, MA, USA).

3.4. Analysis

Data were analyzed by chemometric procedure of partial least-squares (PLS) regression, principal component regression (PCR), support vector machine (SVM) and the developed Kernel algorithm. All chemometric procedures were run under MATLAB software version R2011a (MathWorks, Natick, MA, USA). Comparisons were made among the regression models built by the reflectance spectra (R), and the pre-processed spectra's such as the first derivative of R (D_1R), the log(1/R), it's first ($D_1\log(1/R)$), and second derivative ($D_2\log(1/R)$).

Residual predictive deviation (RPD) index was determined, to evaluate the goodness of the models; it is calculated as the ratio of performance to deviation.

Standardized weighted sum index (SWS) was developed as a generalized index to compare between models' performance.

$$SWS = \sum_{i=1}^{4}\left(1-\frac{a_i-min_i}{max_i-min_i}\right)*w_i+\sum_{j=1}^{2}\left(\frac{b_j-min_j}{max_j-min_j}\right)*w_j$$

where *SWS* is the standardized weighted sum; *i* is the index of statistical parameter *a*: latent variable (LV), root mean square error of calibration (RMSEC), root mean square error of cross validation (RMSECV), RMSECV/RMSEC; *j* is the index of statistical parameter *b*: r^2, RPD; *min* is the minimum of the range of the particular statistical parameter; *max* is the maximum of the range of the particular statistical parameter; *w* is the weight of the particular statistical parameter. The goodness of the model is evaluated by the SWS values: the higher the SWS, the better the model is.

Sensor fusion was conducted to provide optimal or near-optimal use of the available information for detection, estimation, and decision-making.

Model evaluation was conducted for comparison of a single-sensor system to a multisensor system. In this step SWS index was applied to evaluate the performance of the single and multisensor systems. In this work fusion was realized in three levels:

1. Fusion of the NDT parameters
2. Combination of the cultivars
3. Fusion of the DT parameters

4. RESULTS AND DISCUSSION

The present study examined the changes in the course of growth and maturation of intact bell pepper fruits.

Sigmoid shape trend was found in case of TSS, DM and OP change with the advancement of DAA. The highest TSS, DM and OP contents were achieved by the 'No.117' yellow cultivar at the fully matured stage, whereas 'Ever Green' cultivar accumulated the least of these contents. Whether this observation is related to the final colour of the fruit or not, is a question requires further research.

The ascorbic acid content showed a different trend in the examined period of growth. The ascorbic acid content had increased and reached a maximum at the 67^{th}-74^{th} DAA, than decreased in case of all three cultivars. The highest AA content was reached by the ‘Ever Green’ variety (74th DAA) while the lowest vitamin C was accumulated by the ‘Celica’ cultivar at the 67th DAA.

Total chlorophyll content in the ‘No.117’ and ‘Celica’ cultivars has a sigmoid decreasing trend and the concentration of total chlorophyll significantly starts to decrease after the 47th DAA and converges to zero. Meanwhile the total chlorophyll content in ‘Ever Green’ cultivar decreases to a certain extent but at the fully ripe stage its total chlorophyll content still higher than the ‘No.117’ and ‘Celica’ cultivars in their unripe green stage.

The carotenoid content of the ‘No.117’ and ‘Celica’ cultivars started to increase after the 60th DAA without stagnation. The same process occurs in case of the ‘Ever Green’ cultivar alike just with 7 days delay. The highest carotenoid concentration was found in the ‘Celica’ cv. followed by the ‘Ever Green’ and least carotenoid was accumulated by the ‘No.117’ cv.

Efficient prediction models were built for the estimation of TSS, DM, OP, AA, total chlorophyll, carotenoid content, coefficient of elasticity of compression, and coefficient of elasticity of rupture destructive parameters by the VIS-NIR, SWIR and hyperspectral imaging.

PLS, PCR, Kernel and SVM regressions resulted with efficient prediction models for TSS, DM, OP, AA, total chlorophyll, carotenoid content, coefficient of elasticity of compression, and coefficient of elasticity of rupture by the fused NDT-s. The fused models were found more efficient than the single sensor models. Comparison of the PLS models of the single and multisensory models were based on the SWS index. PLS regression models by the fused NDT parameters achieved significantly lower RMSECV values than the single sensor models in case of each variety and each DT parameters. Based on the SWS index it was concluded that the PLS and the SVM regression models were most suitable to predict DT parameters from the fused NDT parameters.

PLS, PCR, Kernel and SVM regression models were built for the prediction of the DT parameters by the fused NDT parameters for each cultivar separately and as well as for the combination of cultivars. Based on the comparison of the single and the combined cultivar models that the combined variety models have a higher r^2 and lower ratio of RMSECV to RMSEC, which makes these models to be more robust and suggest the possibility that they can be applicable for DT parameter prediction.

PCR regression needed significantly more PC-s to build the models. Moreover, this method generally had higher RMSECV. Therefore based on the results of this study it is not suggested for analysis of combined varieties and fused NDT dataset for bell pepper evaluation. I found the Kernel and SVM regressions resulted with the most efficient models for the combined cultivars and the fused NDT parameters.

New combined quality index (NCQI) was developed by the fusion of the reference parameters (DT): TSS, DM, OP, AA, total chlorophyll, carotenoid content, and coefficient of elasticity of compression and rupture. NCQI was created in order to establish a way to evaluate the global quality of bell pepper. NCQI is the first principal component of the DT variables.

Prediction models were built for the new combined quality index (NCQI) by the fused NDT parameter for 'Ever Green', 'No.117','Celica' and for the combination of the three cultivars.

Efficient models were achieved with the fused DT and fused NDT models for all three cultivars with high correlation of determination. PLS and SVM method found to be most suitable to work with the combined dataset and build regression models for the fused DT and NDT parameters.

Based on the models built for the prediction of NCQI, it was found that the NCQI has negative values when the pepper fruit is still in the physiological development stage (below 60th DAA in the present study). Below the 60th DAA the pepper fruit did not reach its maximum size and did not accumulate the optimal amount of internal components like: soluble solid, carotenoid or ascorbic acid in case of the three examined bell pepper cultivar. Therefore harvest time is not suggested when the NCQI is taking negative value.

For economical considerations fusion models were evaluated with the exclusion of the hyperspectral imaging on the combined cultivar dataset. By excluding the hyperspectral data SWS index decreased, but the PLS model still predicted the NCQI index with high correlation of determination and low RMSECV (Fig. 1). For the evaluation of the applicability of this model the dataset was divided to calibration and validation sets. As a result efficient validation was achieved with high correlation of determination with low RMSEP (Fig. 2).

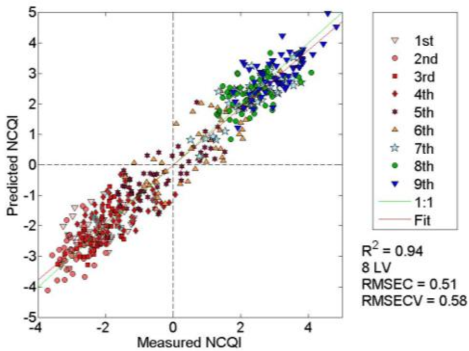

Fig. 1 Scatter plot of NCQI, as predicted by PLS regression model. The PLS model was built with the fused DT and NDT data (without hyperspectral imaging) and combination of cultivars. Data marked by harvest schedule.

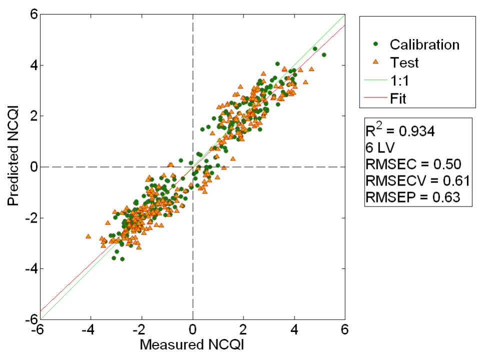

Fig. 2 Scatter plot of NCQI, as predicted by PLS regression model. The PLS model was built with the fused DT and NDT data (without hyperspectral imaging) and combination of cultivars. Data marked by sample participation in calibration or validation set.

5. THESIS'S AND NEW SCIENTIFIC FINDINGS

During my doctorate research I followed and examined the growth and maturation of three cultivars of different final colour bell peppers: 'Ever Green' (green), 'No.117' (yellow) and 'Celica' (red). The bell pepper plants were grown on soil with drip irrigation in Ein Tamar, Israel in protected greenhouses. Plants were irrigated 3 times a day, with 5 m^3 solution contains 10 l fertilizer (7 % Nitrogen, 3% Phosphorus, and 7% Potassium). The changes occurring during maturation was followed by destructive and non-destructive methods and data were analysed by chemometric procedures.

1. I developed the standardized weighted sum index (SWS) for the evaluation and comparison of regression models. SWS index takes into account several parameters from the regression model, such as the latent variables, the correlation coefficient, the RMSEC, RMSECV, the ratio of RMSECV and RMSEC, and the RPD. Therefore it gives a more general and objective evaluation of the regression model about its goodness or robustness.
2. I established non-destructive measurement method of ascorbic acid, total chlorophyll and carotenoid content in the three measured bell pepper cultivars. I built efficient PLS prediction models by means of spectral measurements of VIS-NIR, SWIR spectral data and hyperspectral imaging for the estimation of ascorbic acid, total chlorophyll, carotenoid content for all three studied bell pepper cultivars. I found that VIS-NIR spectral measurement resulted with the best prediction models for ascorbic acid content, while hyperspectral imaging found to be the most efficient for total chlorophyll and carotenoid content estimation. The best model for vitamin C prediction had r^2: 0.78 and RMSECV: 15.1 mg/100g. The best model for prediction of total chlorophyll had r^2: 0.95 and RMSECV: 0.005 mg/g; for carotenoid content r^2 was 0.97 and RMSECV: 0.008 mg/g.

3. I found that fused non-destructive measurement data (NDT) with chemometric procedures are capable for the prediction of internal components (TSS, DM, OP, vitamin C, chlorophyll, carotenoid) and texture (coefficient of elasticity of compression and rupture) (DT).

   Comparing the single sensor PLS models to the multisensor PLS models the fused NDT data in each DT prediction resulted with higher SWS indices. I found that fused models are predicting the DT parameters with similar or lower number of latent variables; they have generally higher correlation of determination as well as lower RMSECV. Therefore the fusion of the NDT parameters found to be efficient and beneficial for the prediction of DT quality parameters in the examined three bell pepper cultivars.

   I developed linear and non-linear (PLS, PCR, Kernel, SVM) regression models using fused NDT dataset for the prediction of DT parameters. I found that comparing the different chemometric procedures - based on the SWS index - PLS and SVM models were the most suitable to predict DT quality parameters from the fused NDT measurements in the examined three bell pepper cultivars.
4. Prediction model was developed which combines the three bell pepper cultivars. The linear and non-linear (PLS, PCR, Kernel, SVM) prediction models were built with the fused NDT dataset. I found that Kernel and SVM models resulted with the most efficient models. In case of TSS, AA, OP, and coefficient of elasticity of compression SVM regression gave the highest SWS scores (0.67-0.77). Whereas for DM, total chlorophyll, and carotenoid Kernel method resulted with the highest SWS: 0.64-0.74.
5. I developed a new quality index NCQI in order to establish a way to evaluate the global quality of bell pepper. NCQI was created by the fusion of TSS, DM, OP, AA, total chlorophyll, carotenoid content, coefficient of elasticity of compression, and coefficient of elasticity of rupture variables. NCQI is the first principal component of the DT variables.

6. I developed PLS, PCR, Kernel and SVM regression models for the prediction of NCQI by the fused NDT parameter for ‘Ever Green’, ‘No.117’,’Celica’ and for the total data of the three cultivars. Efficient models were achieved with the fused DT and fused NDT models for all three cultivars with high correlation of determination (0.89-0.97). Based on the SWS scores I found PLS and SVM methods to be most suitable to work with the combined dataset and build regression models for the fused DT and NDT parameters.
7. Harvest time is not suggested when the NCQI is taking negative value. Based on the models built for the prediction of NCQI, it was found that the NCQI has negative values when the pepper fruit is still in the physiological development stage (below 60^{th} DAA in the present study). Below the 60^{th} DAA the pepper fruit did not reach its maximum size and did not accumulate the optimal amount of internal components like: soluble solid, carotenoid or ascorbic acid in case of the three examined bell pepper cultivar.

6. RECOMMENDATION FOR FURTHER RESEARCH

Further research work should be considered as a continuation of the present study.

- For better understanding and evaluation of the physiological changes in the whole pepper fruit during growth and maturation I suggest the in depth examination of the hyperspectral images in the VIS-NIR and SWIR spectral range.
- I suggest the examinations to be conducted in consecutive seasons with higher number of samples in order to validate the established models; make it applicable without depending on the seasons. Moreover, to examine several cultivars with differing shape, colour and growing condition in order to develop more robust regression models.
- I suggest examining the behaviour of the NCQI during storage and shelf life of the product. Moreover, to find the NCQI value

which can indicate the critical condition of the fruit when it cannot be stored longer without quality degradation.

- I suggest including the shape and defect monitoring of the agricultural produce to be integrated to the non-destructive measurement methods and to the fusion.
- I suggest extending the fusion of the NDT and DT parameters for other agricultural products.
- I suggest to examine different combinations of sensors to be fused in order to find the most efficient and economical solution, which can be efficiently integrated into sorting and classification lines.
- For the purpose of proper harvest time estimation for farmers I suggest the development of a portable device for field application.

8. PRESENTATIONS AND PUBLICATIONS PUDLISHED IN THE SUBJECT OF DISSERTATION

Reviewed articles published in international literature

- Ignat, T., Schmilovitch, Z., Fefoldi, J., Steiner, B., Alkalai-Tuvia, S. (): Vitamin C content measurement in bell peppers by VIS-NIRand SWIR spectrometry. Postharvest Biology and Technology, (accepted)
- Ignat, T., Schmilovitch, Z., Fefoldi J., Bernstein N., Steiner B., Egozi H., Hoffman A. (): Non-destructive measurement of chlorophyll and carotenoid content in bell peppers by VIS-NIR spectrometry. Biosystem Engineering, (accepted)

Peer-reviewed articles published in international literature

- Ignat, T., Mizrach, A., Schmilovitch, Z., Fefoldi, J., H. Egozi, A. Hoffman (2010): Bell pepper maturity determination by ultrasonic technique. Progress in Agricultural Engineering Sciences, (6) 17–34. p. DOI: 10.1556/Progress.6.2010.2

- Tompos, D., Istella, S., Ignát, T. (2003): Assessment of fruit firmness of pepper using non-destructive physical measurements, in response to different growing and pruning technologies. International Journal of Horticultural Science, 9(1) 71-76. p.
- Felföldi J., T. Ignát (1999): Dynamic method for quick and non-destructive measurement of the surface firmness of fruits and vegetables. Hungarian Agricultural Engineering, (12)29-30. p.

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- Ignát T., Muha V., Gilingerné Pankotai M. (2003): Étkezési paprika tárolási kísérletei, Értékálló Aranykorona III. évfolyam 5,17-18. p.
- Ignat T. (2001): Sajtok állományváltozásának vizsgálata dinamikus módszerrel. *Élelmezési ipar*, 0013-5909, 55(10) 305-308. p.

International conference publications (full paper)

- Ignat, T., Schmilovitch, Z., Mizrach, A., Alchanatis, V., Fefoldi, J., and Fallik, E. (2009): Non-destructive methods for pepper maturity determination. International Conferences in Agricultural Engineering, Synergy and Technical Development 2009, Gödöllő, In: Book of abstracts and CD-ROM full paper version
- Schmilovitch, Z., V. Alchanatis, H. Egozi, A. Hoffman, V. Ostrovsky, T. Ignat, R. Ben Zvi. (2009): Online Sorting of Madjhool Dates According to Total Soluble Solids and Water Content by Near Infrared Spectrometry. Frutic Chile 2009, Information and Technology for Sustainable Fruit and Vegetable Production, Proceeding of the "8th Fruit, Nut, and Vegetable Production Engineering Symposium" Concepción, Chile, 291-300. p.

International conference publications (abstract)

- Ignat T., Schmilovitch Z., Fefoldi J., Bernstein N., Steiner B., Egozi H., Hoffman, A. (2011): Chlorophyll content measurement in bell pepper by VIS-NIR spectrometry, AGRI-SENSING International Symposium on Sensing in Agriculture, Haifa, Israel, Feb. 2011 In: Book of abstract 23. p.

- Schmilovitch Z., V. Alchanatis, H. Egozi , A. Hoffman, V. Ostrovsky, T. Ignat, R. Ben Zvi. (2008): Automatic sorting of Madjhool dates by Near Infrared Spectrometry. Annual conference of ISAE (Israel Society of Agricultral Engineering), Haifa, Israel, Dec 2008 In: Book of abstracts and CD-ROM abstract version
- Pálfi E., Gilinger P. M., Veres Bálint M., Ignát T., Felföldi J. (2004): Storability of Paprika types. CEFOOD - Second Central European Congress on Food, Budapest, 269. p.
- Pálfi E., Gilinger P.M., Veres Bálint M., Ignát T., Felföldi J. (2003): Change in vitamin C content and firmness of sweet pepper types during the storage. 5th European Forum for Dietitians, Budapest, 72-73. p.
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