EVALUATION THE PERFORMANCE OF HYPERSPECTRAL REFLECTANCE SENSOR FOR ESTIMATING THE HARDNESS AND BIOCHEMICAL PARAMETERS OF TOMATO FRUITS

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ABSTRACT

Mechanical and biochemical analysis for assessing tomato fruit quality in food processing are the traditional methods, which leads to the destruction of fruits and is time consuming. Similarly, for valuating large quantities of tomato fruits for export, numerous observations are required to characterize them; such methods cannot easily account for rapid changes in these parameters. In this study the performance of hyperspectral passive reflectance sensing at various ripening degrees of tomato fruits was test its relationship to hardness, fruit water content, soluble solids content percentage, titratable acidity and pH via simple linear regression analysis. The results showed that statistically significant relationships between all spectral reflectance indices derived from near infrared (NIR) with measured parameters were found. The spectral index R_{1000}/R_{716}, showed the highest coefficients of determination for the hardness of tomato ($R^2 = 0.85***$), the spectral index R_{970}/R_{964}, showed the highest coefficients of determination for the fruit water content ($R^2 = 0.70***$), soluble solids content ($R^2 = 0.86***$) and titratable acidity ($R^2 = 0.82***$) as well as the spectral index R_{970}/R_{726}, showed the highest coefficients of determination for the titratable acidity ($R^2 = 0.78***$) of tomato fruits. In conclusion, the using of spectral sensing may open an avenue in post-harvest and food processing for fast, high-throughput assessments mechanical and biochemical of tomato fruits.

1. INTRODUCTION

Tomato is one of the most widely consumed vegetable crops in the world, not only because of its volume, but the main supplier of several phytonutrients and providing an important nutritional value to human diet and its important role in human health (Willcox et al. 2003).

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Productive postharvest management and harvest time of tomatoes demand knowledge of the postharvest physiology or biochemical quality parameters to determine the best handling practices to maintain and create high fruit quality during the ripening stage. Ripening is actually part of the natural senescence regarding tomatoes fruits. It is an irreversible process that contributes to organelle disruption and changes in chemical constituents. There are different interesting mechanical and biochemical parameters, such as hardness, fruit water content, soluble solids content (SSC) and titratable acidity (T. Acidity) and pH which can be used as diagnostic indicators of tomato quality. In general, fruits are sorted manually or automatically on the basis of size, color, and surface defects such as bruises. However, dry matter content, total soluble solids content, sugar content, juice acidity and firmness are important internal quality attributes of fruit products. Actual methods for the assessment of tomato fruit quality are generally based on biochemical analysis, which leads to destruction of fruits and is time consuming. Fruit analysis is important for detecting tomato quality; nevertheless, destructive methods are not appropriate. Similarly, for valuating large quantities of tomato fruits for export, numerous observations are required for their characterization; such methods cannot easily account for rapid changes in these parameters arising from changes in environmental conditions. In contrast, high-throughput passive reflectance sensors using spectral reflectance measurements has the potential to provide more information for making better-informed decisions at the tomato scale in real time. Passive sensor systems depend on sunlight as a source of light, which allows hyperspectral information to be obtained in the visible and near-infrared range (Erdle et al., 2011; Mistele et al., 2012; Elsayed et al., 2015a; Nagy et al., 2016). A strong interest for spectrometry (as a non-destructive technique), is that information can be collected on the same fruit, at different times. This means that it gives access, not only to punctual information, but also to the dynamics of the measured characteristics. Regarding tomatoes, nice sets of data have been obtained that allowed to predict color and pigment content with good accuracy, as well as firmness to a lesser extent using the 400 - 1500 nm range (Clément et al., 2008).

Some previous studies assessed the quality parameters of fruits by using spectroscopic measurements (Rutkowski et al., 2008; Deng et al., 2010; Moghimi et al., 2010; Jha et al., 2012). Rutkowski et al. (2008) found that the index of anthocyanin (NAI), calculated as $(R_{780} - R_{570})/(R_{780} + R_{570})$, was significantly correlated with the fruit firmness and titratable acidity in 'Golden Delicious' apples. Partial least square regression (PLSR) based on spectral reflectance from 400-1000 nm, processed with standard normal variate correction (SNV), median filter and 1st derivative, was used to predict the acidity in kiwi fruits (Moghimi et al., 2010). Jha et al. (2012) applied reflectance spectroscopy to measure SSC and pH in seven mango cultivars. The optimal results were obtained by using PLSR models based on 2nd derivative spectra in the 1600-1799 nm range. The reflectance spectrum at 988 nm was significantly correlated with the soluble solids content and vitamin C content of oranges (Deng et al., 2010).

The scientific hypothesis raised in this study investigates whether changes in biochemical quality parameters can be reflected by changes in spectral reflectance measurements based on the change in skin color of tomato fruits from green to red. Therefore, it is very important to develop high throughput sensing methods for assessment water stress in crops, which should be reliable, fast, simple, practical, and economic.

The purpose of this work is to assess whether spectral reflectance indices can estimate the hardness and biochemical parameters of tomato under different ripening levels from green to red.

2. MATERIAL AND METHODS

2.1. Experimental information

The experiments were conducted at the Research Station of Sadat City University in Egypt (Latitude: N 30° 2' 41.185", Longitude: E 31° 14' 8.1625"). The fruit samples of the tomato cultivar (GS-12) were selected at different ripening degrees (Fig. 1) to be assessed via passive reflectance and thereafter used for determining hardness, fruit water content (FWC), soluble solids content (SSC), titratable acidity and pH.

Fig.1. Tomatoes fruits were selected at different ripening degrees

2.2. Hardness, soluble solids content percentage, titratable acidity and pH

Pulp samples were squeezed and the obtained juice was used to determine the percentage of SSC using a hand refractometer according to A.O.A.C. (1980). The titratable acidity was determined in 5 mL of juice samples. For the titration, 0.1 N sodium hydroxide and phenolphthalein as an indicator were used according to A.O.A.C. (1980). The pH was determined by potentiometric measurement made at 20 ^{o}C with pH meter according to A.O.A.C. (1980). The portable durometer (WESTport Rex Model: H1000 Mini-Dial Durometer) were used to estimate the hardness of fruits.

2.3. Spectral reflectance measurements:

A passive bi-directional reflectance sensor (tec5, Oberursel, Germany), measuring at wavelengths between 302-1148 nm with a bandwidth of 2 nm, was used. The handheld FieldSpec sensor (Fig.2) consists of two units: one unit is linked with a diffuser and measures the light radiation as a reference signal, while the second unit measures the tomato fruits reflectance with a fiber optic (Elsayed et al., 2015b). The aperture of the optics was 12° and the field of view was 0.1 m^2 from half meter distance. Three spectral measurements were taken for each fruit.   Spectral measurements of eighteen tomato fruits under different ripening degrees were taken within 15 minutes on a sunny period to avoid changes in sun radiation, and the fiber optics were positioned at a height of 0.15 m with a zenith angle of 30° above the tomato fruits to avoid producing a shadow. To guarantee complete reflectance by the tomato fruits, a black sheet was used to prevent spectral reflectance caused by the background. With the

readings from the spectrometer unit, the tomato fruits´ reflectance was calculated and corrected with a calibration factor obtained from a reference gray standard.

Fig.2. A passive bi-directional reflectance sensor measuring wavelengths between 302 – 1148 nm.

2.4. Statistical analysis
2.4.1. Selection of spectral reflectance indices

In Table 1 seven spectral indices from different sources are listed with references. In this study, both known and novel indices were calculated and tested. A contour map analysis for all wavelengths of the hyperspectral passive sensor (from 302 to1148 nm) was used to select some spectral indices, which generally presented more stable and strong relationships with the hardness, fruit water content, soluble solids content, titratable acidity and pH of tomato fruits. All possible dual wavelengths combinations were evaluated based on a contour map analysis for the hyperspectral passive sensor. Contour maps are matrices of the coefficients of determination of all biochemical parameters of tomato fruits with all possible combinations of binary, normalized spectral indices. The R package "lattice" from the software R statistics version 3.0.2 (R foundation for statistical computing 2013) was used to produce the contour maps from the hyperspectral reflectance readings, while eleven wavelengths (716, 726, 740, 780, 940, 950, 960, 964, 970, 992, and 1000 nm) were used to calculate reflectance indices, as indicated in Table 1.

2.4.2. Modeling of measurements

Sigmaplot for Windows v.12 (Systat software Inc., Chicago) and SPSS 22 (SPSS Inc., Chicago, IL, USA) were used for the statistical analysis. Simple linear regressions were calculated to analyze the relationship between the spectral reflectance indices listed in Table 1 and the hardness and biochemical parameters. Coefficients of determination and significance levels were determined; t nominal alpha values of 0.05, 0.01 and 0.001 were used.
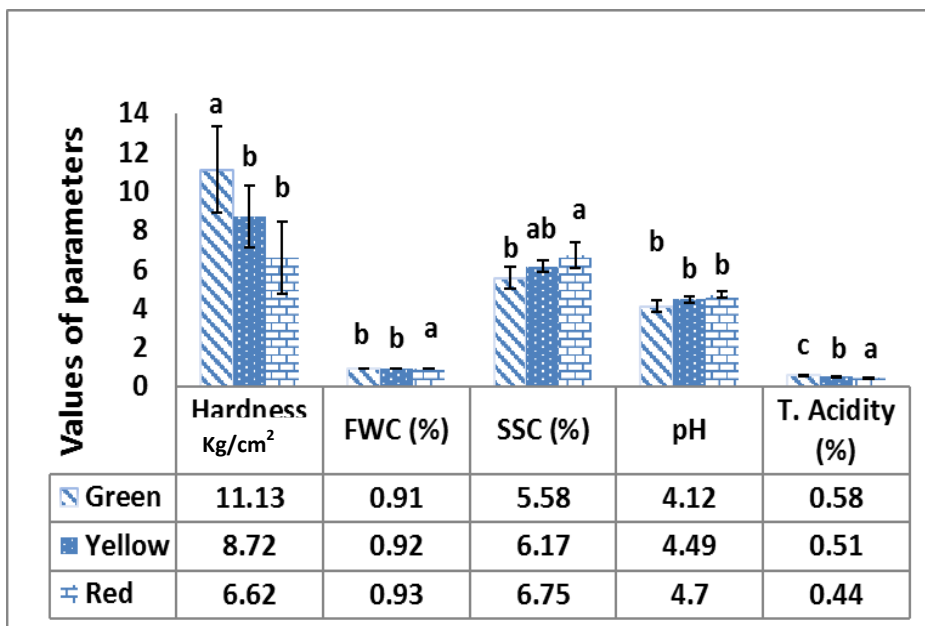
Table 1. Spectral indices, formula and references of different spectral indices used in this study.

Spectral reflectance	Formula	References
R_{970} and R_{950}	R_{970}/R_{950}	Peñuelas et al., 1997
R_{960} and R_{940}	R_{960}/R_{940}	Elsayed et al., 2011
R_{970} and R_{726}	R_{970}/R_{726}	This work
R_{992} and R_{940}	R_{992}/R_{940}	This work
R_{1000} and R_{716}	R_{1000}/R_{716}	This work
R_{970} and R_{964}	R_{970}/R_{964}	This work
R_{780} and R_{740}	R_{780}/R_{740}	Mistele and Schmidhalter. 2008

3. RESULTS AND DISCUSSION

3.1. Variation of hardness and biochemical parameters of tomato fruits

The results indicated that biochemical parameters indices were generally affected by the stage of fruit ripening. There was a wide range between the minimum and maximum values for all studied biochemical parameters (Fig.3). Hardness were varied from 6.62 to 11.13 (kg cm^{-2}), fruit water content from 0.91 to 0.93, soluble solids content from 5.58 to 6.75, pH from 4.12 to 4.7 and titratable acidity from 0.44 to 0.58. The results showed that during fruit ripening hardness and titratable acidity were decreased and the skin color changed from green to red, while the values of fruit water content, pH and soluble solids content were increased.

|	Hardness Kg/cm²	FWC (%)	SSC (%)	pH	T. Acidity (%)
Green	11.13	0.91	5.58	4.12	0.58
Yellow	8.72	0.92	6.17	4.49	0.51
Red	6.62	0.93	6.75	4.7	0.44

Fig. 3. Mean values (green, yellow and red) of hardness, fruit water content (FWC), soluble solids content (SSC), pH and titratable acidity (T. Acidity) of tomato fruits. Values with the same letter are not significantly different (P ≥ 0.05) among cultivars according to Duncan's test. SD indicates standard deviation.

These results agree with other studies. For example, Medlicott et al. (1986) reported that during fruit ripening, the carotenoid concentration increased. Color changes in fruit are due to the disappearance of chlorophyll and the appearance of other pigments. Chloroplasts are transformed into chloroplasts containing yellow or red pigments (Lizada, 1993). The soluble solids content also increases during ripening because starch and sucrose are converted into glucose, which is the main substrate utilized in respiration (Chan and Kwok, 1975).

3.2. Variation of Spectral Reflectance Curves for tomato fruits under different ripening levels

There are also different between Spectral reflectance curves for tomato fruits under different ripening levels as showed in (Fig.4). Spectral reflectance curves were generally affected by fruit ripening stages.

The spectral reflectance curve of yellow presented higher values compare to the spectral reflectance curve of green and red. The changes were observed in the red edge under fruit ripening stages. There was a clear difference in the water band at 970 nm under fruit ripening stages. Changes in fruit coloration, thus the differences in the spectral properties of tomato skin are demonstrating significant changes in pigment content and their compounds in fruits during ripening process.
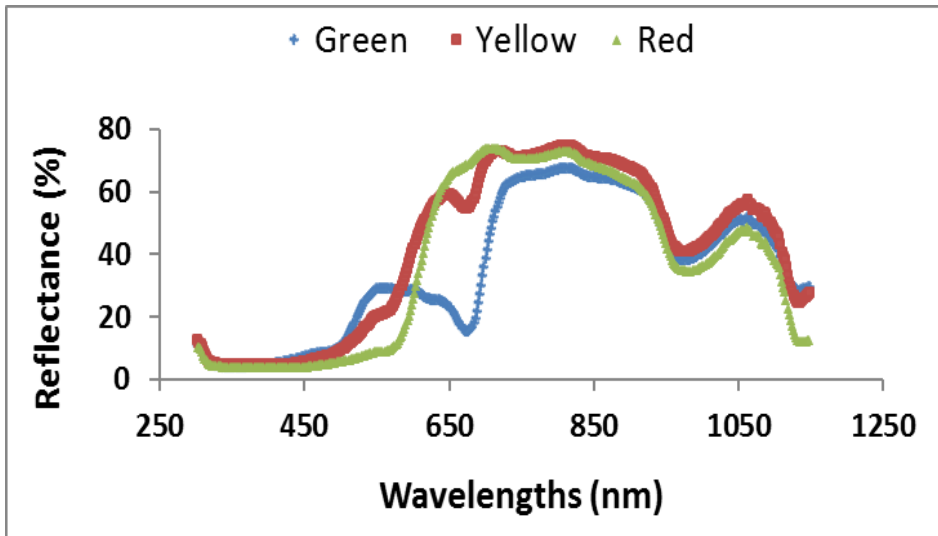
**Fig. 4.** Spectral Reflectance Curves for tomato fruits under different ripening levels.

Low chlorophyll-containing fruits (both in the case of yellow and red fruit varieties) had high reflectance in the range of chlorophyll absorption, between 600 nm and 700 nm, whereas considerable spectral characteristics were not observed in the NIR range with high reflectance values. Decrease in reflectance (also for unripe fruits) was observed in the range of 900-970 wavelength range, which relates to the moisture content.

### 3.3 Contour map analysis of the hyperspectral data
A contour map analysis produced the coefficients of determination (R2) of the measurements for all dual wavelengths combinations from 302 to 1148 nm as spectral index. Contours of the matrices of the hyperspectral

passive sensor presented generally more distinct relationships with all biochemical parameters. The contour map analysis of the relationship between the spectral indices with hardness, fruit water content, pH, soluble solids content and titratable acidity are shown in (Figs. 5a, b, c, d and e). A contour map presented a larger range of indices with similar wavelength contain information relevant for the all biochemical parameters. The contours of the matrices of the spectral passive sensor presented stronger relationships between all biochemical parameters of tomato fruits with near infrared wavelengths and the combination of visible and near infrared wavelengths than visible wavelengths. The averages of the correlation matrices resulting from the measurements, indicated by the coefficients of determination (R2) for all dual wavelengths combinations of 750 - 1000 nm as spectral indices for all fruits measurements, presented higher R2-values compared to all other two wavelength combinations. The reason of that the wavelengths 850 to 1000 nm being more affected by water status.
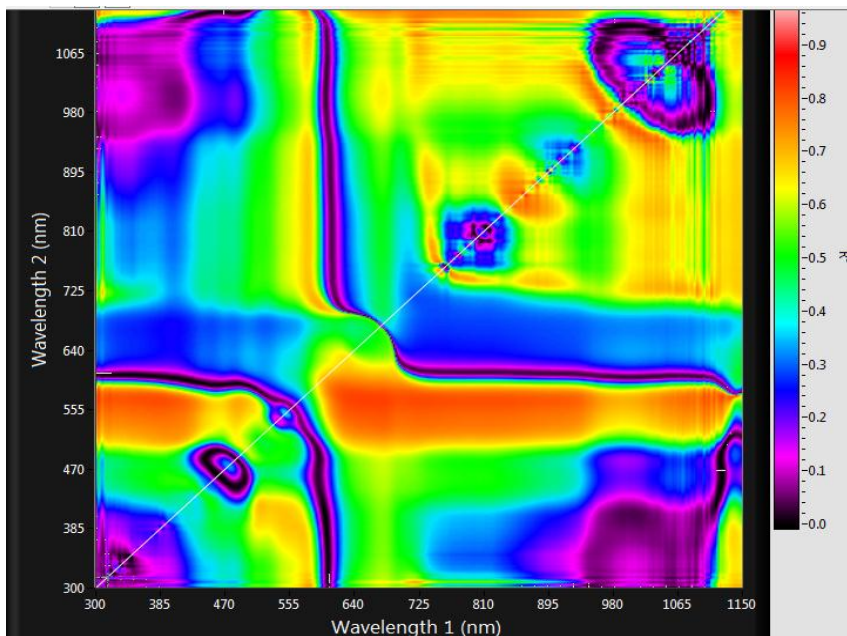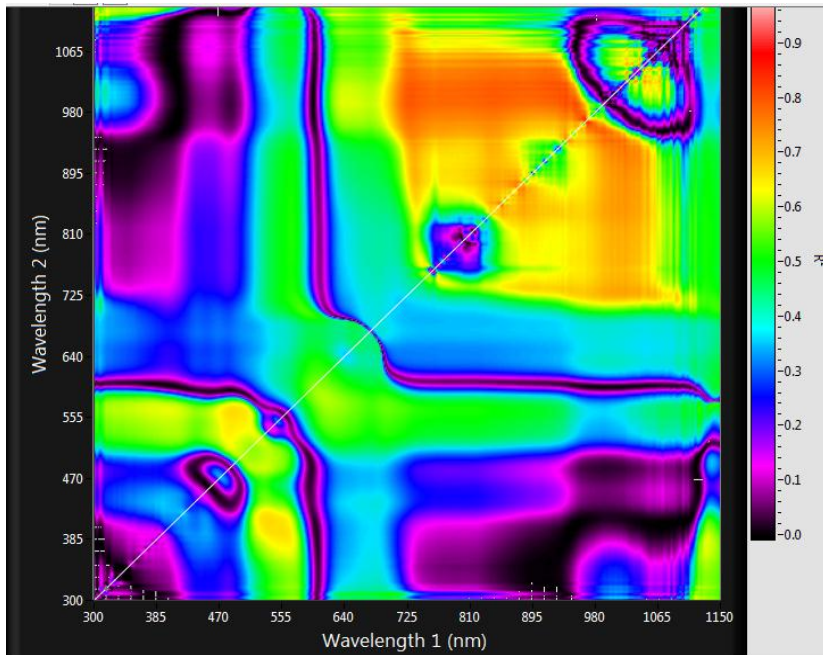

Fig.5a. Correlation matrices (contour maps) showing the coefficients of determination (R^2) for spectral index with hardness.
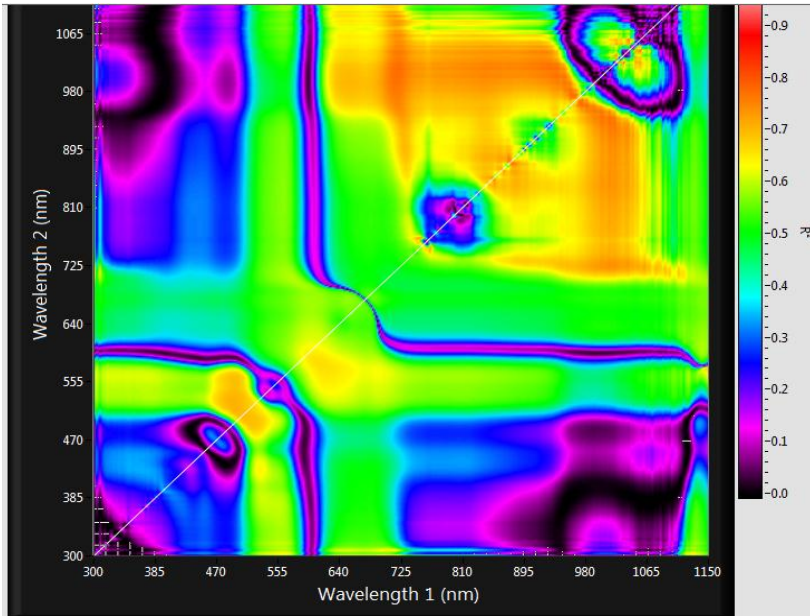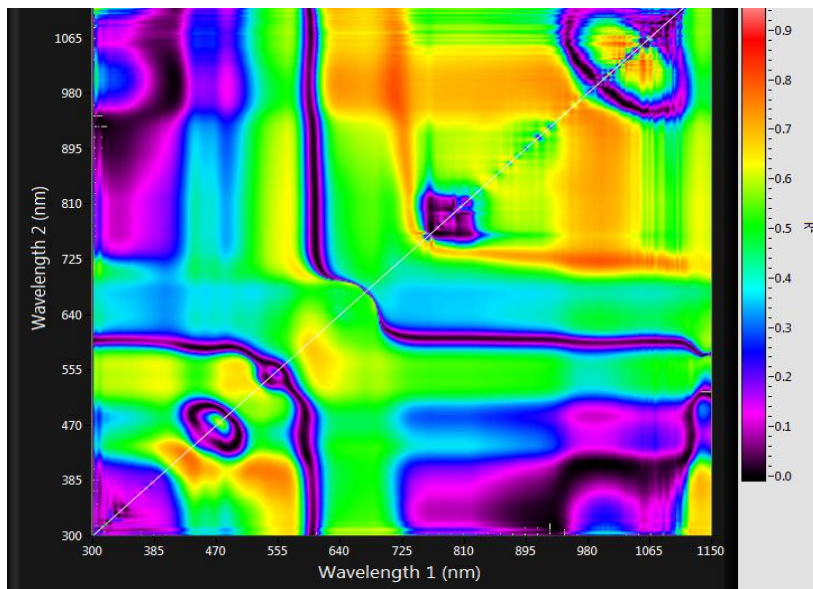
Fig.5b. Correlation matrices (contour maps) showing the coefficients of determination (R^2) for spectral index with Fruit water content (FWC).
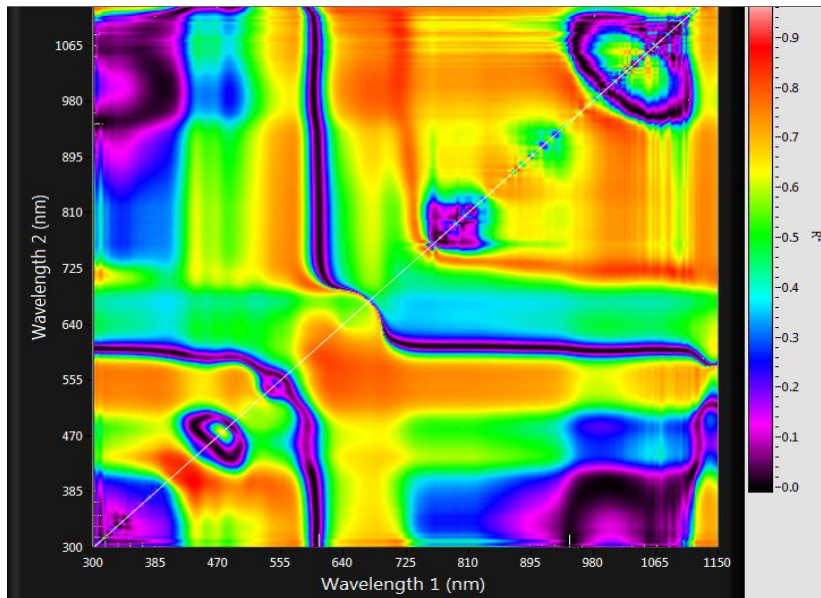
Fig.5C. Correlation matrices (contour maps) showing the coefficients of determination (R2) for spectral index with soluble solids content (SSC).
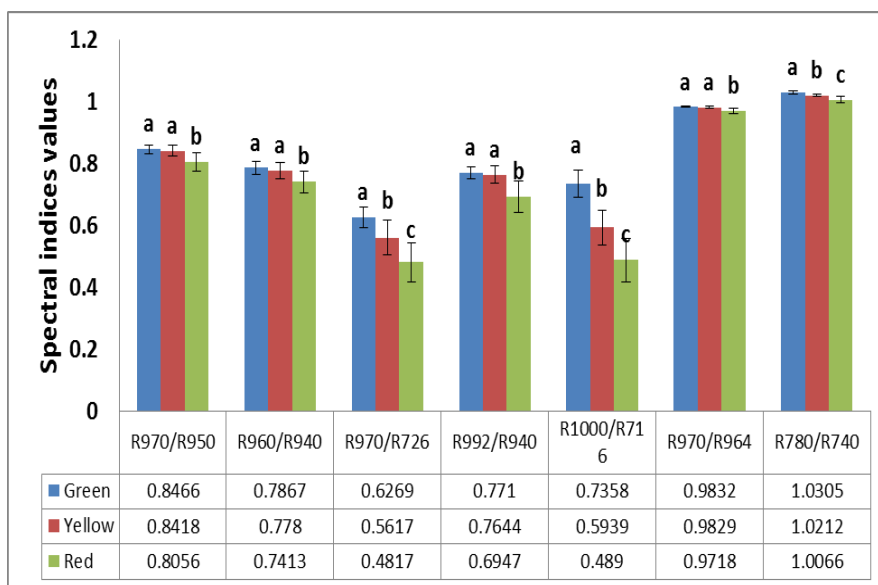
Fig.5d. Correlation matrices (contour maps) showing the coefficients of determination (R^2) for spectral index with Titratable acidity (T. Acidity).

Fig.5e. Correlation matrices (contour maps) showing the coefficients of determination (R^2) for spectral index with pH.

3.4. Variation of spectral reflectance indices s of tomato fruits

In (Fig.6) the results display a wide range between the minimum and maximum values for seven spectral indices for tomato fruits. The spectral index (R_{970}/R_{950}) varied from 0.8056 to 0.8466, the spectral index (R_{960} / R_{950}) varied from 0.7413 to 0.7867, the spectral index (R_{970}/ R_{726}) varied from 0.6269 to 0.4817 and the spectral index (R_{992}/ R_{940}) varied from 0.6947 to 0.7710. Both spectral indices R_{970}/ R_{726}, R_{780}/ R_{740} and R_{992}/ R_{940} presented significant difference under different ripening levels.

	R970/R950	R960/R940	R970/R726	R992/R940	R1000/R716	R970/R964	R780/R740
Green	0.8466	0.7867	0.6269	0.771	0.7358	0.9832	1.0305
Yellow	0.8418	0.778	0.5617	0.7644	0.5939	0.9829	1.0212
Red	0.8056	0.7413	0.4817	0.6947	0.489	0.9718	1.0066

Fig. 6. Mean values (green, yellow and red) values of seven spectral indices of tomato fruits. Values with the same letter are not significantly different (P ≥ 0.05) among cultivars according to Duncan's test. SD indicates standard deviation.

4.5. Relationships between spectral reflectance indices and different biochemical parameters

In Table 2 and Figs. 7, 8 and 9 seven spectral reflectance indices were significantly related to all biochemical parameters. Statistically significant relationships between all spectral reflectance indices derived from the near infrared NIR region were found for the hardness with R^2 values ranging from 0.71*** to 0.85***, fruit water content with R^2 values

ranging from 0.50** to 0.80***, soluble solids content with R^2 values ranging from 0.55*** to 0.86***, titratable acidity with R^2 values ranging from 0.69*** to 0.82*** and pH with R^2 values ranging from 0.52*** to 0.78***. Generally, the spectral index R_{1000}/R_{716}, showed the highest coefficients of determination for the hardness of tomato ($R^2= 0.85$***), the spectral index R_{970}/R_{964}, showed the highest coefficients of determination for the fruit water content ($R^2= 0.70$***), soluble solids content ($R^2=0.86$***) and titratable acidity ($R^2= 0.82$***) as well as the spectral index R_{970}/R_{726}, showed the highest coefficients of determination for the pH ($R^2= 0.78$***) of tomato fruits.

Table 2. Coefficients of determination of linear regressions of five parameters (hardness, fruit water content (FWC), soluble solids content (SSC) and titratable acidity (T. Acidity and pH) with seven spectral indices of the hyperspectral passive sensor of tomatoes.

Fruits parameters	Spectral indices						
	R_{970}/R_{950}	R_{960}/R_{940}	R_{970}/R_{726}	R_{992}/R_{940}	R_{1000}/R_{716}	R_{970}/R_{964}	R_{780}/R_{740}
Hardness (kg/cm²)	0.75***	0.71***	0.82***	0.79***	0.85***	0.77***	0.73***
FWC (%)	0.55***	0.50**	0.60***	0.66***	0.61***	0.70***	0.67***
SSC (%)	0.78***	0.76***	0.81***	0.82***	0.79***	0.86***	0.73***
T.Acidity (%)	0.75***	0.69***	0.77***	0.79***	0.79***	0.82***	0.75***
pH	0.75***	0.72***	0.78***	0.75***	0.77***	0.73***	0.68***

**, ***Statistically significant at $p \leq 0.01$; $p \leq 0.001$

Our assessment of reflectance indices as a method to assess the hardness and biochemical parameters fruits at different ripening degrees demonstrated that the selected seven indices were apparently useful for describing these parameters. Some studies have reported that different biochemical parameters can be assessed remotely and estimated simultaneously in a rapid and nondestructive method if these parameters present a significant relationship with the spectral reflectance indices (Merzlyak et al., 2003; Zude et al., 2006; Rutkowski et al., 2008; Deng et al., 2010).
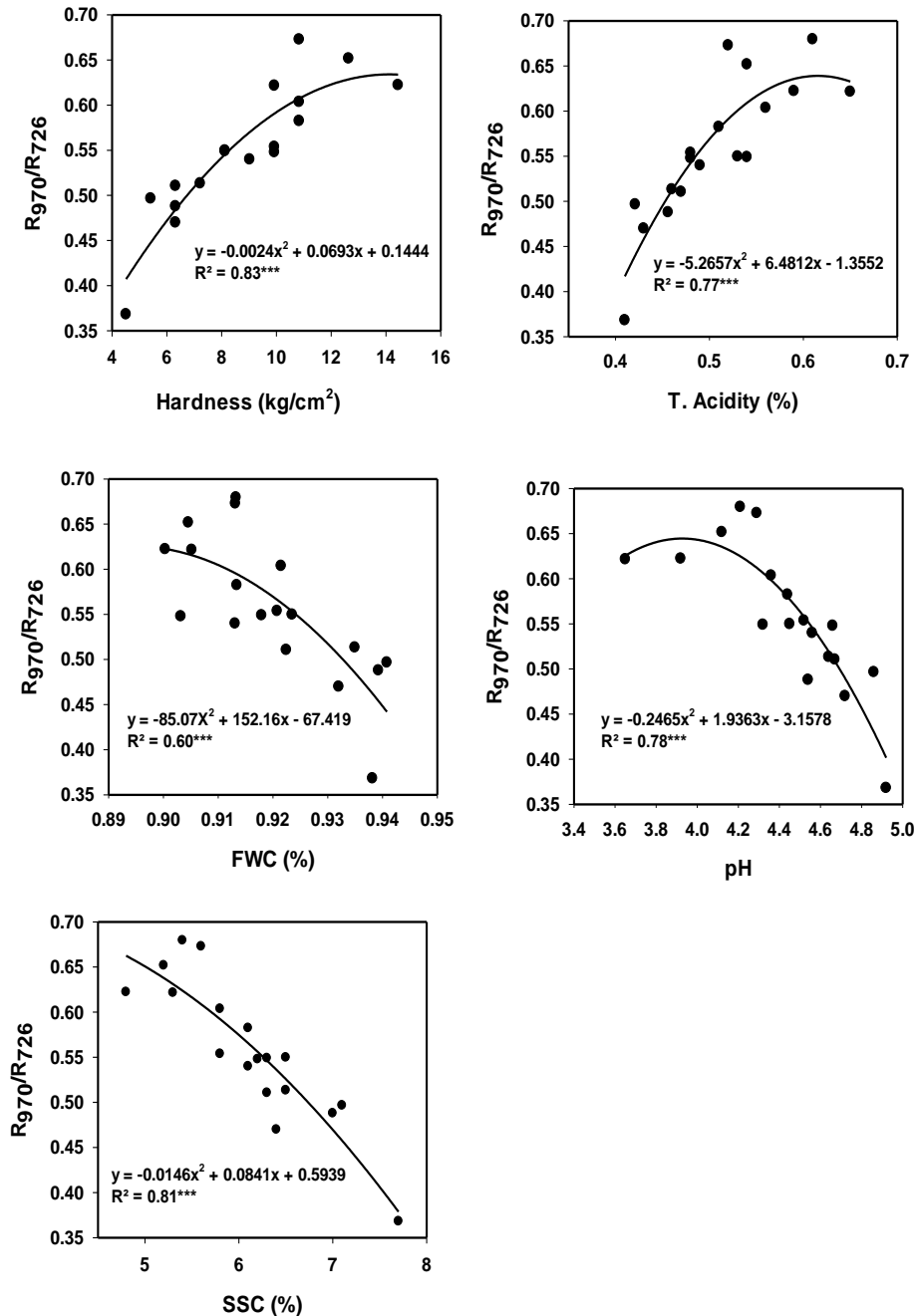
Fig. 7. The relationship between the spectral index (R_{970}/R_{726}) with hardness, fruit water content (FWC), soluble solids content (SSC), titratable acidity (T. Acidity) and pH of tomato fruits.
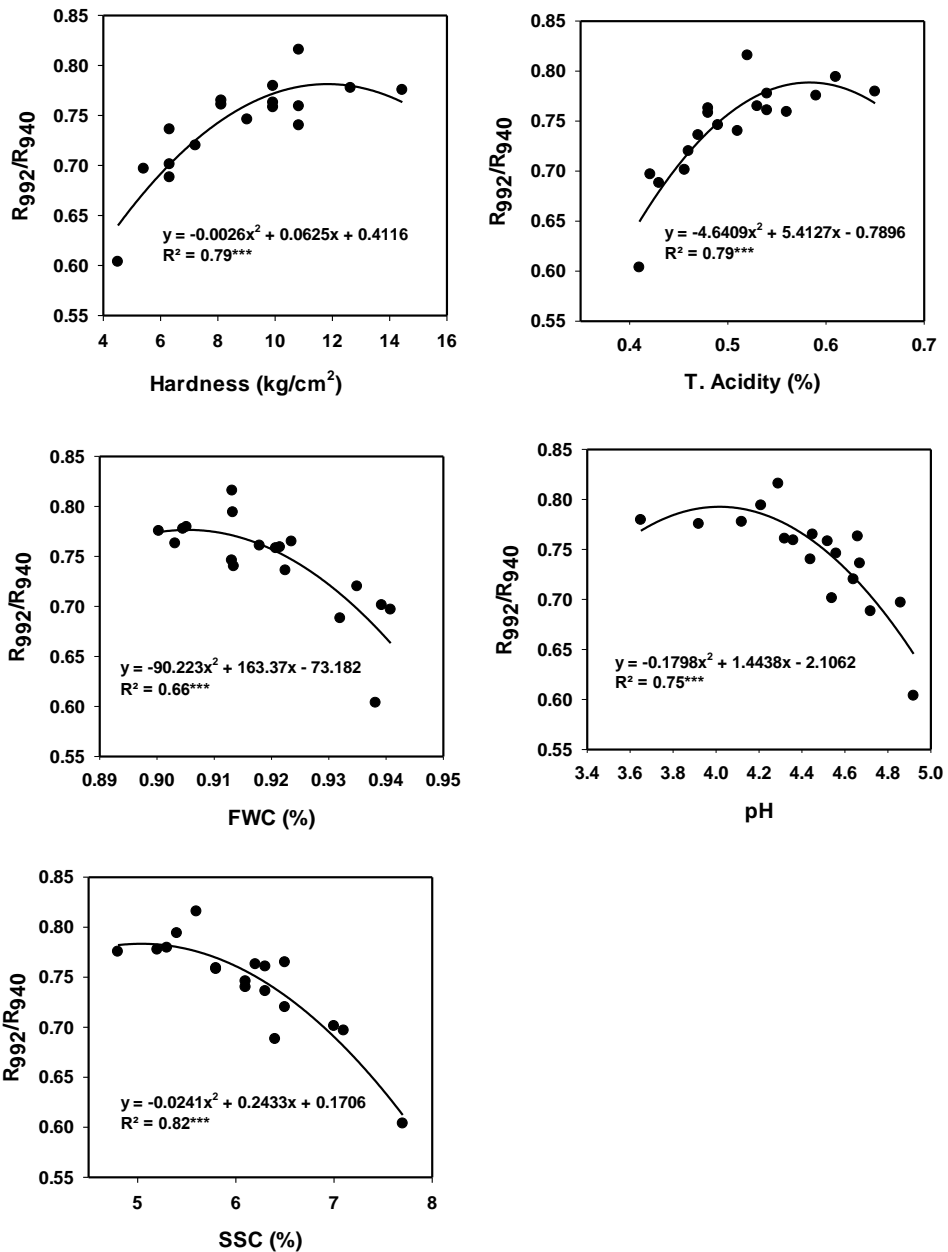
Fig. 8. The relationship between the spectral index (R_{992}/R_{940}) with hardness, fruit water content (FWC), soluble solids content (SSC), titratable acidity (T. Acidity) and pH of tomato fruits.
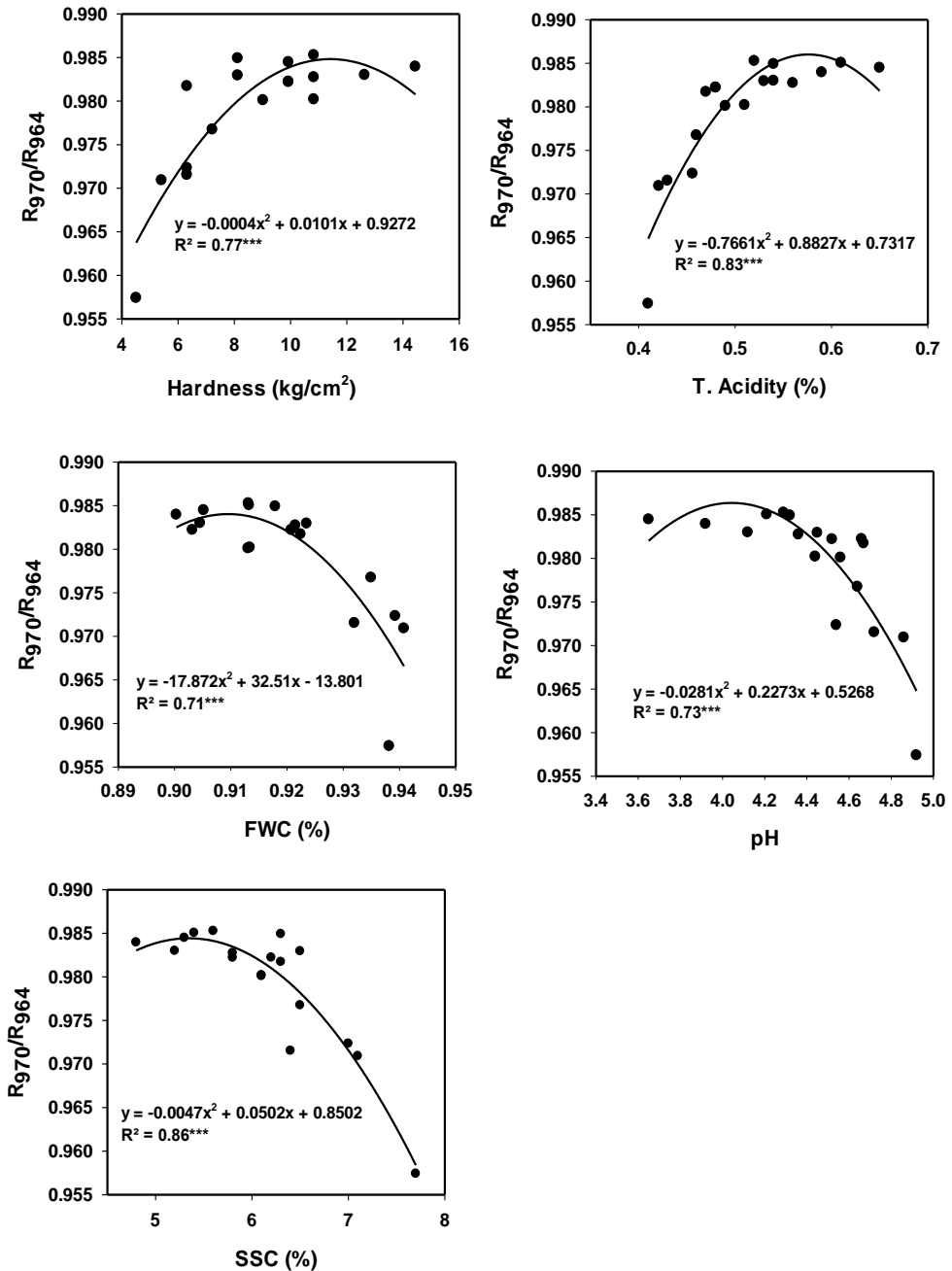
Fig. 9. The relationship between the spectral index (R_{970}/R_{964}) with hardness, fruit water content (FWC), soluble solids content (SSC), titratable acidity (T. Acidity) and pH of tomato fruits.

For example, Zude et al. (2006) found relations between the peak absorbance of chlorophyll *a* at 680 nm and the soluble solids content (R^2 = 0.21) in apple fruits. Rutkowski et al. (2008) found that the index of anthocyanin (NAI), calculated as $(R_{780} - R_{570})/(R_{780} + R_{570})$, was significantly related to titratable acid (R^2= 0.66) in 'Golden Delicious' apples. Deng et al. (2010) found that the reflectance spectrum at 988 nm was significantly related to the soluble solids content (R^2 = 0.15) in orange fruits. Our results for spectral reflectance indices presented stronger relationships with hardness and biochemical parameters of tomato fruits compared to the above indices.

5. CONCLUSIONS

The results show that changes in mechanical and biochemical parameters of tomato fruits at various ripening degrees can reliably be detected using spectral reflectance indices. We have further work to establish active and passive sensor platform based on the best indicators of spectral indices for assessment the fruit ripeness.

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الملخص العربي

تقييم مجس الاستشعار الطيفي في تحديد الصلابة والخواص البيوكيميائية لثمار الطماطم

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الطرق المعملية التي تسخدم في تحديد جودة ثمار الطماطم تعتمد علي الطرق الميكانيكية و التحليل الكيمائي الأمر الذي يؤدي إلى تدمير الثمار المستخدمة في التحليل و إستغراق وقتا طويلا في إجراء عملية التحليل و زيادة التكلفة و كذلك عدم السرعة في إتخاذ القرار لتحديد جودة الثمار سواء في الحقل أو ما بعد عملية الحصاد.

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وبالمثل، لتحديد جودة كميات كبيرة من ثمار الطماطم المعدة للتصدير هذا يتطلب العديد من االعينات للحكم علي جودة الثمار. مثل هذه الأساليب لا يمكن أن تنعكس بسهولة عن التغيرات السريعة في الثمار تحت الظروف الجوية أو ظروف التخزين المتغيرة. علي العكس باستخدام طرق الإستشعار المختلفة في معاملات ما بعد الحصاد في مجال هندسة التصنيع قد يؤدي الي سرعة إتخاذ القرار في تحديد درجة نضج الثمار وسهولة التدريج مما يؤدي الي تقليل الفقد و التكلفة.

تهدف هذة الدراسة إلي دراسة كفاءة مجس الإستشعار الطيفي في تحديد جودة الثمار تحت ظروف النضج المختلفة مثل الصلابة ، المحتوي المائي للثمرة ، محتوي السكر و الحموضة . تم إستخدام مجس الإستشعار الطيفي ذو الأطوال الموجية من ٣٠٢ حتي ١١٤٨ نانوميتر حيث تشمل الإنعكاس الطيفي في منطقة الضوء المرئي من ٤٠٠ إلي ٧٠٠ نانوميتر و الضوء غير المرئي من ٧٠٠ حتي ١١٤٨ نانوميتر. تم حساب البصمة الطيفية بالأعتماد علي الأطياف المنعكسة في منطقة الضوء غير المرئي ذلك للحصول علي أفضل مؤشر طيفي كمدلول علي صفات الجودة تحت الدراسة. تم إجراء ثلاث قياسات لتقدير

الأنعكاسات الطيفية لكل ثمرة تحت مراحل نضج مختلفه مع وضع الثمار علي جسم أسود لضمان أن يكون الأنعكاس ممثل كامل للثمرة و لا يوجد تأثير جانبي. أظهرت النتائج أن المؤشر الطيفي R_{1000}/R_{716} ذو ارتباط قوي و معنوي مع الصلابة وكان معامل الإرتباط هو ٠.٨٥ . وأن المؤشر الطيفي R_{970}/R_{964} ذو ارتباط قوي و معنوي مع محتوي المائي للثمار ٠.٧٠ و مع نسبة السكريات الذائبة وكان معامل الإرتباط هو ٠.٨٦ و كذلك مع الحموضة titratable acidity وكان معامل الإرتباط هو ٠.٨٢ . و كذلك أظهرت النتائج أن المؤشر الطيفي R_{970}/R_{726} ذو ارتباط قوي و معنوي مع الحموضه pH وكان معامل الإرتباط هو ٠.٨٥ . وبذلك فانه يمكن باستخدام طرق الإستشعار المختلفة في مراحل ما قبل وبعد الحصاد تحديد درجة النضج وجودة الثمار مما يساعد على سرعة إتخاذ القرار و كذلك تقليل الفقد و التكلفة.