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Non-Destructive Assessment of Kiwifruit Flesh Firmness by a Contactless Waveguide Device and Multivariate Regression Analyses

Annachiara Berardinelli, Eleonora Iaccheri, Leonardo Franceschelli, Marco Tartagni, *Member, IEEE*, and Luigi Ragni

***Abstract*—Non-destructive and cheap methods to evaluate the slow ripening process with possible on-line applications are highly required by the industry to enhance critical post-harvest management. After a brief review of the literature, we present the potentiality of an electronic contactless device for the non-destructive assessment of the Magness-Taylor flesh firmness (Mtf) of Hayward kiwifruits. The technique combines spectral information acquired in the microwave range by an open-ended aluminum waveguide containing TX and RX antennas, placed above the sample, with the features of the multivariate analysis. The electronic controller comprises a VCO, a low noise amplifier, a gain-phase comparator, and a serial interface governed by an MCU. Partial Least Squares regression analysis (PLS) was used to build predictive models starting from gain and phase waveforms raw data in the 947-1900 MHz frequency range. The main results evidenced that explored spectra variability is related to changes occurring in the fruit during the maturity process and particularly to the cell wall degradation. PLS regression models show, in prediction, R^2 values of 0.726 (RMSE = 5 N) for the estimation of the Mtf starting from gain waveforms. A lower accuracy was observed for the model setup by considering phase waveforms. These results demonstrate that the proposed non-invasive solution combined with the PLS is a grounded starting point for estimating kiwifruit firmness with an acceptable level of accuracy.**

***Index Terms*—Waveguide spectroscopy, contactless device, kiwifruit firmness, Partial Least Square regression (PLS), on-line sorting.**

I. Introduction

POST-HARVEST management is extremely important for slowly ripening and long-term storage of kiwifruit [1]. Kiwifruit ripening involves softening, color, shape, and ethylene modifications traduced into complicated maturity stage prediction [2]. Firmness is one of the critical quality parameters studied for its importance in post-harvest storage, grading and transport operations. The firmness of kiwi has strictly related to cell wall degradation and hydration level; cell boundaries and feeble arrangement produced physical differences [3].

Firmness assessment techniques for quality control can be destructive, non-destructive by contact, or non-destructive contactless. Often, they are non-representative of the whole fruit and differ for on-line implementation suitability [4]. Destructive techniques are generally based on penetrometer devices measuring forces applied to the fruit, with or without permanent deformation measurement.

Non-contact techniques are appealing for the food industry in real time and on-line applications. These techniques are mainly based on the correlations between the destructive firmness parameter of the kiwifruit and mechanical, optical, or dielectric properties [5]. A benchmarking table (Table I) is provided and commented on throughout the text to compare non-destructive methods for fruit firmness estimation.

Regarding non-destructive but contact techniques, piezoelectric sensors were developed and tested on kiwifruits with R^2 up to 0.876 [19]. A non-destructive probe plunger device was used for kiwi firmness evaluation by measuring the compression force within selected deformation limits [20]. A high coefficient of determination ($R^2 = 0.927$) was obtained by using a customized device and a destructive tester to measure firmness for kiwifruits. Furthermore, other authors [2] used a similar theoretical basis exploiting a spherical metal probe to apply a constant load to the kiwi surface.

The induced deformation was recorded and associated with softening determined by the softness meter. Fruit mechanical properties were also predicted by using an impact device equipped with a load cell and multiple regression models; these last were characterized by independent variables related to the mechanical parameters of the impact with R^2 values up to 0.823 [26].

Time-resolved reflectance spectroscopy in the wavelength range from 650 to 1000 nm was also used to assess fruits' chemical and physical properties [27].

Concerning non-destructive approaches, contactless assessments were conducted starting from mechanical or optical

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TABLE I

COMPARISON OF NON-DESTRUCTIVE METHODS FOR FRUIT FIRMNESS EVALUATION

Sample	Range of firmness	Godness of Estimation	Error	Device / Method	Non destructive / contactless	Cost of the device	Author
Mango	Hardness scores: 1, hard; 2, firm (sprung); 3, slightly soft; 4, soft (eating soft); 5, oversoft	$r^2 = 0.95$	N.R.	3 methods: (i) the objective Analogue CSIRO Tomato Firmness Meter (AFM); (ii) the same device modified with a digital displacement gauge (also used by Davie et al. 1996) and a laboratory jack (DFM); and (iii) hand firmness.	Non destructive but with contact	Low cost (500$)	[6]
Tomatoes		$r^2 = 0.93$					
Apple	120-240 N	up to $R^2 = 0.838$	Standard error 10.37 N	Non contact ultrasonic technique (500-kHz non-contact ultrasonic transducer, a pulser/receiver (DPR300, JSR Inc., USA), a digital oscilloscope (TDS5052D, Tektronix Inc, USA), and a jig for holding the ultrasonic transducer)	Non destructive and contactless	Low cost	[7]
Peach	0-60 N	up to $R^2 = 0.922$	Standard error 3.45 N				
Apple	16-100 N	$0.71<R^2< 0.84$ If mostly firm fruit are present $0.2<R^2<0.4$	16.7-35%	Non-destructive method for measuring apple firmness in this study is based on vibrational excitation	Non destructive but with contact	N.R.	[8]
Apple	32-75 N	Golden Delicious and Red Delicious were classified into correct firmness classes with 61.0% and 41.5% success ratio, respectively. 81.0% of Golden Delicious and 69.1% of Red Delicious apples were classified within one firmness class difference among five classes.		A laser beam was used as a light source and output power levels were measured by a digital laser power meter (Coherent Instrument Division, Model LaserMate-Q).	Non destructive and contactless	N.R.	[9]
Peach	Magness Taylor kg/0.5cm^2 : Soft (0.94), half-firm or soft (2.53), half firm (3.92), half-firm or firm (5.00) and firm (5.96).	up to R^2 0.93	19-28%	Three different sensing techniques, namely, sound, impact and micro-deformation devices	Non destructive but with contact	Low cost	[10]
Apple	10-30 N	Not correctly classified		Sensor based on a load cell. The fruit is placed on the cell and struck by a mass of 128 g falling from a height of 1 cm onto the fruit.	Non destructive but with contact	Low cost	[11]
Peach	0.9-33 N	95% were correctly classified (43 correct and 2 erroneous) between soft and the others (firm) fruits .					
Apple	15-30 N	Golden: 59% (10 classes); 97% (3 classes). Starking 54% (10 classes); 100% (3 classes).		Impact test system. 50 g instrumented steel rod with a spherical tip of radius 0.98 cm was dropped from height of 4 cm onto each pears and 3 cm in the case of apples	Non destructive but with contact	Low cost	[12]
Pear	5-40 N	Blanquilla: 76% (5 classes); 97% (3 classes). Decana: 60% (8 classes); 97% (3 classes).					
Peaches	0-100 N	R^2 0.867	N.R.	A low-mass impact sensor for high-speed firmness sensing of fruits that consists of a semi-spherical impacting tip attached to the end of a pivoting arm. A small accelerometer is mounted behind the impacting tip. Impact is done by swinging the impactor to collide with the fruit.	Low damage, with contact	Low cost	[13]
Kiwifruit	0-80 N	R^2 0.924	N.R.				
Apricot	2-93 N	R^2 0.8	mean residual error=8.3 N	Laser "air-puff": this device measures the deformation of fruits subjected to a short but strong jet of air (69 kPa in 100 ms)	Non destructive and contactless	N.R.	[14]
Kiwifruit	2-29 N	R^2 0.8	mean residual error=2.1 N				
Avocados, kiwifruit, peaches, citrus	Avocados 5-35 N, peaches 10-70 N, citrus 15-45 N, kiwi 10-60 N	Avocados R^2 0.70, kiwi R^2 0.69, peaches R^2 0.60, citrus R^2 0.70	N.R.	Sinclair IQ - Firmness Tester. Air pressurised bellows to keep in contact with piezoelectric sensor	Non destructive but with contact	N.R.	[15]
Cherries	3 categories < 3.5 N, 3.5- 6.0 N and >6.0 N	r 0.8	Standard error of prediction 0.55 N	Optical sensor both in VIS (visual) and/or NIR (near infrared) ranges	Non destructive and contactless	High cost	[16]
Apples	N.R.	r 0.9	Standard error of prediction 2.49				[17]
Kiwifruit	5-50 N	R^2 0.66	RMSEP 7.8 N				[3]
Apple, peach, tomato, kiwi, melon	N.R.	correctly classified 76% of apples, 77% of peaches, 81% of tomatoes, 75% of kiwis and 60% of melons		Time resolved diffuse reflectance spectroscopy (TRS) in the VIS and NIR ranges	Non destructive and contactless	High cost	[18]
Kiwifruit	N.R.	R^2 0.876	N.R.	Piezoelectric bending bimorph Q220-A4-303-YB from Piezo Systems based on the acoustic impulse response technique	Non destructive but with contact	N.R.	[19]
Kiwifruit	1-50 N	R^2 0.927	N.R.	HIT-Counter I and the conventional fruit firmness tester (amount of deformation of a certain compressive force can be obtained within the elastic range)	Non destructive but with contact	N.R.	[20]
Kiwifruit	0-70 IFD elasticity units	$r^2 = 0.75$	N.R.	IFD—intelligent firmness detector (applicable also on apple, avocado, mango, pear)	Non destructive but with contact	12,000 €	[21]
Kiwifruit	0.8-87 N	up to R^2 0.777	13 N	NIR sensitive camera and xenon lamp	Non destructive and contactless	High cost	[22]
Kiwifruit	9-62 N	R^2 0.87	RMSECV = 11.9 N	Vis/NIR hyperspectral imaging technology	Non destructive and contactless	High cost	[23]
Kiwifruit	20-60 N	R^2 0.92	RMSE 4.89 N	Dielectric properties (parallel-plate capacitor 40 kHz – 20 MHz)	Non destructive	Low cost	[1]
Kiwifruit	1-65 N	Test set validation R^2 0.831 (1-20 N) R^2 0.797 (20-65 N)	RMSE 2.58 and 8.03 N	Waveguide spectroscopy in the frequency ranges of 2–3 GHz and 15–16 GHz	Non destructive and contactless	High cost	[24]
Kiwifruit Xuxiang and Huayou variety	0.1-70.1 N	74 and 91% accuracy of classification (<3 N Fully matured, soft, 3–7 N Matured, little sour 7–10 N Slight matured, sour >10 N Unmatured, hard even very hard)		Sensor-based grade detector (composed of a control/processing unit, a LEDs and driver unit, a light signal detection and amplifier unit, an input/ output unit and a battery)	Non destructive but with contact	Low cost	[25]

N.R. not reported

properties; furthermore, acoustic and vibrational measures were applied and sometimes combined for error reduction and maximization of firmness estimation.

The non-contact ultrasonic technique was implemented for fruit firmness evaluation [20]. Coefficients of determinations reached 0.824 and 0.922 for apples and peaches, respectively.

The potentiality of machine vision, X-rays, computed tomography, and imaging nuclear magnetic resonance are considered for non-destructively measuring of firmness and chemical properties of fruit [4]. Laser air puff [14] has been studied for many years and is also widely used for fruit quality detection. R^2 values equal to 0.80 and mean residual error of 2.1 N emerged between penetrometer and air-puff measurements for kiwifruit firmness. Among all, VIS-NIR and NIR techniques showed very good results accounting for dry matter, acidity, and solid soluble content, while lower models for firmness estimation were obtained [3].

A prototype based on a NIR sensitive camera and a Xenon lamp capturing an 8-bit greyscale (from 0 = black to 255 = white) image of the radiation that passes through the fruit was also proposed. The count of the pixels with different grey tones was used to set up PLS predictive models to estimate the kiwifruit flesh firmness with R^2 of 0.777 (RMSE = 13 N) in validation [22].

More recently, a Vis/NIR (400–1000 nm) push-broom linear array Hyperspectral Imaging Camera was used to set up predictive models of the Hayward kiwifruit flesh firmness and a value of the R^2 of 0.87 (RMSECV = 11.9 N) in cross-validation was reported [23]. Kiwi firmness detection was also assessed by using a surface acoustic wave (SAW) gas sensor [32].

Today, the assessment of kiwi firmness estimated by non-destructive methods is considered an open challenge for producers and sellers. As cited above, destructive methods are not suitable for on-line process purposes, favoring contactless methods.

Investigation of kiwifruit during storage was also performed using spectroscopy based on dielectric properties as a known non-destructive and rapid way to investigate the physical-chemical behavior of foodstuff and other materials, as previously reported by literature [28]–[30]. A dielectric parallel plate capacitor was developed for dielectric assessment in the frequency range 40 kHz-20MHz. pH, firmness, and soluble content were correlated with dielectric response to predict ripening stages during storage time. ANNs were employed to develop models for quality index prediction [1].

Concerning works focused on kiwifruits, other studies were conducted by using off-line non-destructive techniques. Changes in electrical parameters related to the dielectric properties and influenced by the maturation processes have been evidenced in work conducted by Ragni *et al.* [24]. Soluble fruit solids content (SSC) and Magness–Taylor flesh firmness (MTf) were non-destructively assessed by means of a combination of the waveguide spectroscopy in the range of 2-20 GHz with Partial least squares (PLS) regression analysis. By placing the fruit inside the waveguide (between the receiving and the transmitting antenna), for validation conducted with an external data set (test set validation), PLS models showed R^2 values up to 0.804 (RMSE = 0.98 °Brix) and 0.806 (RMSE = 8.9 N) for the prediction of SSC and MTf, respectively.

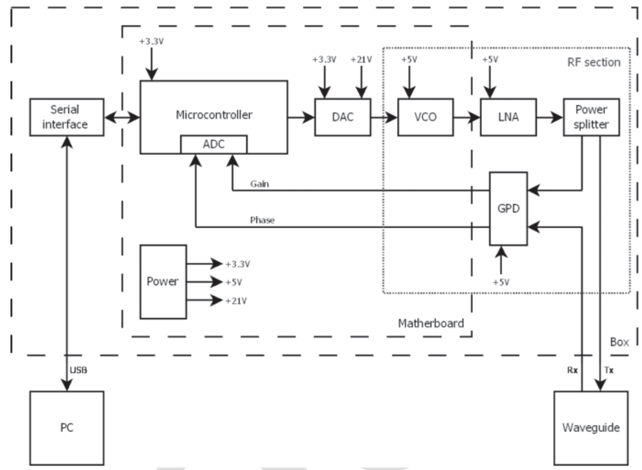


Fig. 1. Schematic of the system architecture. Legend: DAC, Digital to Analog converter; VCO, Voltage Controlled Oscillator; Low Noise Amplifier; GDP, Gain and Phase Comparator; ADC, Analog to Digital Converter (in the microcontroller).

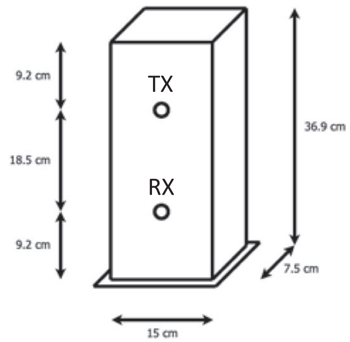
As reported in Table I, several works have been conducted to set up a sensor for kiwifruit firmness determination. However, some techniques imposed to keep the sample in contact or involving in a technique non-applicable for on-line implementation [1], [13], [15], [19]–[21], [24], [25], some others are expensive to become part of a selection line of fruits [3], [18], [21]–[23]. Therefore, the present work proposes a tool characterized by combining the spectroscopic waveguide technique with multivariate data analysis, which will provide a contactless and low-cost solution that can be considered for on-line applications. This tool will be set up to predict the results that could be obtained from the destructive Magness-Taylor technique for the firmness of fresh Haywar kiwifruits. An open-ended aluminum waveguide working in the frequency range of about 950-1900 MHz, placed above the sample, will assess the entire fruit interaction with the electromagnetic wave. “Gain” and “phase” waveforms acquired from kiwifruits samples, characterized by different maturity levels, will be processed by using Partial Least Squares regression analysis (PLS), and correlations between sample physical properties will be discussed.

II. Materials and Methods

A. The Device

The proposed system is composed of three parts: i) an open-ended rectangular aluminum waveguide, ii) a hardware system, and iii) a PC with a graphical user interface (GUI) (Fig. 1). The device works as a vector analyzer returning a complex impedance (“gain” and “phase”) influenced by the sample dielectric properties.

The waveguide dimensions (15 cm × 36.9 cm × 7.5 cm) guarantee a cut-off frequency of the waveguide equal to 1 GHz. A transmitting (TX) and a receiving (RX) antenna are incorporated in the waveguide (Fig. 2). The open-ended



AQ:3 Fig. 2. The layout of the waveguide (the figure is not in scale).

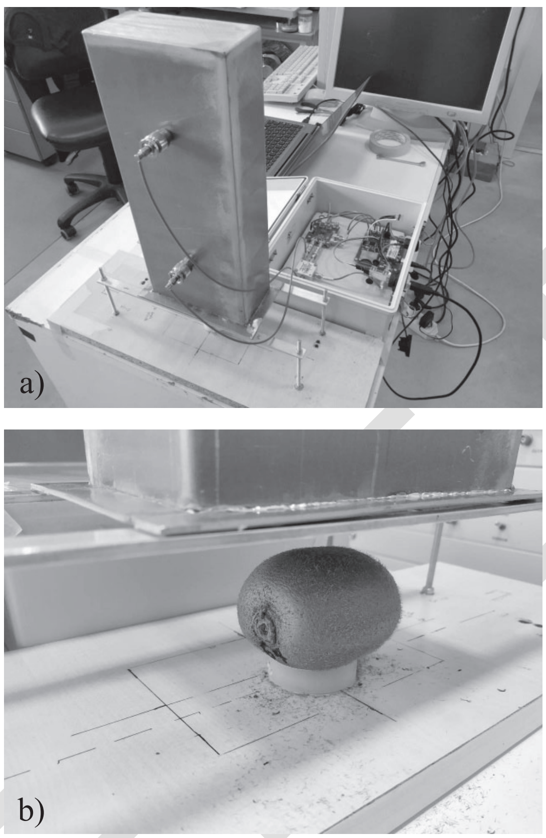


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Fig. 3. Detail of the open-ended waveguide and kiwifruit placement.

waveguide was positioned at 80 mm from a laminated wood sheet (50 × 17.5 × 1.8 cm), where a plastic sample container was fixed under the waveguide center (Fig. 3).

The hardware system is composed of an RF section and a data-control and elaboration system. The following main components characterize the RF section: a Voltage Controlled Oscillator (VCO, MiniCircuits ZX95-2150VW+), an ultra-Low Noise Amplifier (LNA, QORVO TQL9092), a power splitter (MiniCircuits ZFRSC-42+), and a Gain and Phase Detector (GDP, Analog Devices AD8302). VCO generates a sinusoidal wave at a frequency dependent on the input voltage while the LNA amplifies the signal (up to 22 dBm, from 4 dBm to 13 dBm, in the suggested device) with an operating band from 0.6 to 4.2 GHz. The amplified signal is then supplied through the power splitter to the waveguide, and the transmitted and reflected waves are compared by means of the GDP, which provides the measured information to the microcontroller. Gain measurement range is ± 30 dB with a gain sensibility of 30 mV/dB, and 0°÷ 180° with a scale of 10 mV/° for the phase. The gain and phase output voltages vary in a range from 0 V to 1.8 V, and a reference voltage of 1.8 V is provided. The data-control and elaboration system consists of a microcontroller (MICROCHIP PIC24FJ256GB606), a Digital to Analog Converter (Analog Devices AD5761R), and a serial-USB converter (UART/USB converter cable). The microcontroller presents a 32Kbytes (16-bit addresses) SRAM data storage while a resolution of 16-bit characterizes the Analog to Digital Converter. The microcontroller firmware was written in C (IDE MPLAB X di Microchip), and the system is driven and controlled by a Graphical User Interface (GUI) written in a MATLAB platform to perform signal elaboration and to produce and save the gain and phase signals. Both gain and phase signals contain up to 4481 points; each of them is an average of 32 repetitions (3.85 s, time for sweep).

Transmitted (Tx) and reflected (Rx) waves can be described by the following relationships [32]:

$$Tx(t) = A_{Tx} e^{j\varphi Tx} e^{j2\pi f t}$$
$$Rx(t) = H(f) A_{Tx} e^{j\varphi Rx} e^{j2\pi f t} = A_{Rx} e^{j\varphi Rx} e^{j2\pi f t}$$

where A (Tx and Rx) is the wave amplitude, j the imaginary unit, f the frequency, t the time, φ (Tx and Rx) the phase, and H(f) the transfer function between x and y, represented by the tested system impedance.

B. Kiwifruits Samples and Acquisition Procedure

Tests were conducted on 75 Hayward kiwifruits harvested (commercial stage) in October 2018 in the Romagna region (Italy). For each kiwifruit, main dimensional parameters, as minimum equatorial diameter, Dmin (mm), maximum equatorial diameter, Dmax (mm), and maximum length, L (mm), were measured.

Kiwifruits were conditioned in three different ways to obtain different levels of Magness-Taylor flesh firmness (MTf) and solid soluble content (SSC),: i) 25 fruits were kept at 4°C, ii) 25 fruits were left to mature at 22°C in the presence of apples, iii) and the remaining 25 fruits were maintained at 4°C until the day before the test and left for 24 hours at 22 °C (± 1°C).

Similar values characterized each set of 25 fruits in terms of dimensional characteristics.

Acquisitions were conducted in the spectral range of 947-1900 MHz and at a room temperature of about 22°C (± 1°C).

For each fruit, a total of six spectral acquisitions were carried out: three acquisitions on one side and three acquisitions on the other side of the fruit. For each of the three-side process replica, the test was conducted by replacing the fruit under the waveguide.

After spectral acquisitions, MTf (N) and SSC (°Bx) were assessed on two opposite side points of the equatorial region and then averaged. MTf was measured using a compression/traction machine equipped with a load cell and a 7.9 mm diameter probe, interfaced with a PC. The SSC was measured by an IR refractometer (PR-1, ATAGO Co. Ltd., Tokyo, Japan).

C. Multivariate Data Analysis

Partial Least squares regression (PLS) analysis was conducted on both "gain" and "phase" waveforms in order to set up predictive models of the MTf [33]. According to PLS bilinear modeling theory [34], new variables called latent variables, describing the original variability, are extracted taken into consideration a linear relationship between dependent and independent ones.

In detail, a PLS regression algorithm starts from an X matrix of dimensions N × KN × K and a score matrix T of dimension N × AN × A (number of principal components), formed by the X directions with maximum variance. The algorithm then identifies even better directions in the score subspace, called latent variables (LV), maximizing the variance of the output variable Y.

The two sets, respectively for "gain" and "phase," were created by considering the spectral information as independent X variables and the MTf values as dependent Y ones. Each data set was characterized by a 2821 (spectral points, "gain" or "phase") × 450 (number of kiwifruit acquisitions) matrix and by a 450 (number of kiwifruit acquisitions) × 1 (MTf) vector column. A schematic of the PLS model setting up and validation is shown in Figure 4.

An auto-scale pre-processing, consisting of mean centering and scaling of each variable to unit standard deviation, was applied to both independent and dependent variables. The model calculation was performed by using the SIMPLS algorithm working by considering the S0 cross-product of the starting data matrices X0 and Y0 [35]. Cross-validation (method: "Venetian blinds," through a selection of every n^{th} object in the data set, starting at objects numbered 1) was used [36], and the coefficient of determinations (R^2) and the Root Mean Square Error (RMSECV) were calculated.

A function called "choosecomp," operating by reaching a fair equilibrium between generalization and minimization of RMSECV, allows the automatic selection of the optimal number of latent variables; in detail, a good equilibrium between generalization and minimization of the RMSECV value defines the choice of the optimal number of latent variables [37]. To improve the regression parameters, important X variables (able to improve the model) to retain in the model were identified by using a software-implemented algorithm [37].

A prediction was also conducted by dividing each dataset into two portions. 80% of the observations were used for the calibration and cross-validation (360 kiwifruit acquisitions). The remaining 20% (90 kiwifruit acquisitions) was used for the prediction.

The (R^2) and the Root Mean Square Error (RMSE) in prediction were also calculated.

III. RESULTS

A. Characteristics of Kiwifruit Samples

Table II summarizes the mean values of the characteristics of the fruit samples in terms of dimensional parameters, Mtf (N) and SSC (°Bx). For Mtf (N) and SSC (°Bx) quality parameters, the mean values of the two measurements conducted on two opposite side points of the equatorial region were considered.

The variables of Table I are D_{min}, minimum equatorial diameter; Dmax, maximum equatorial diameter; L, maximum length, Mtf, Magness-Taylor flesh firmness; SSC, solid soluble content; SD, Standard Deviation.

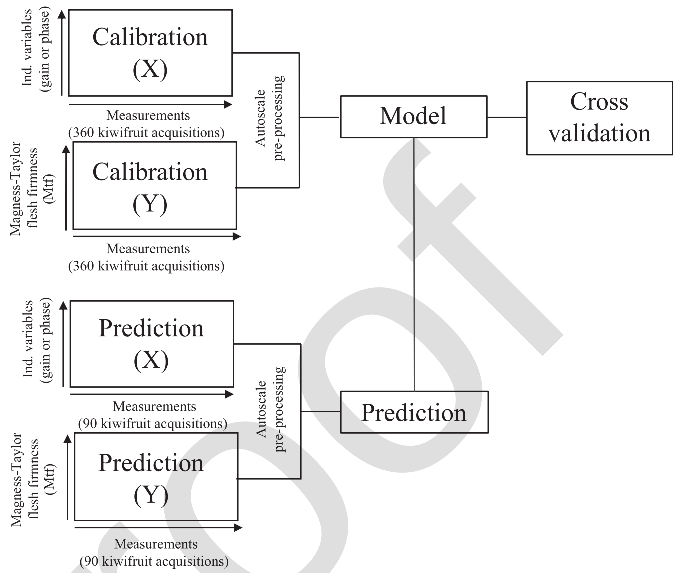

Fig. 4. Schematic of the PLS regression setting up and validation for both "gain" and "phase" waveforms.

TABLE II
MEAN VALUES OF THE DIMENSIONAL AND QUALITY CHARACTERISTICS OF THE KIWIFRUITS USED FOR THE TEST

Parameter	Average	SD
Mass (g)	106	15
Dmin (mm)	49	2
Dmax (mm)	56	4
L (mm)	65	4
SSC (°Brix)	11	2
Mtf (N)	16	12

B. Waveforms Characteristics

Examples of "gain" and "phase" waveforms are reported in Figures 5 and 6 for kiwifruit samples characterized by different values in terms of Mtf (N). Figures showed that a different Mtf level involves changes in both gain and phase spectra. For gain spectra, these changes are appreciated in the entire range of the explored frequencies (947-1900 MHz). Phase spectra variations related to the maturity of kiwifruit are less evident compared to gain spectra.

The firmness decreases during ripening as a consequence of chemical-physical changes. Decomposition of cell wall polysaccharides and consumption of organic acids are the

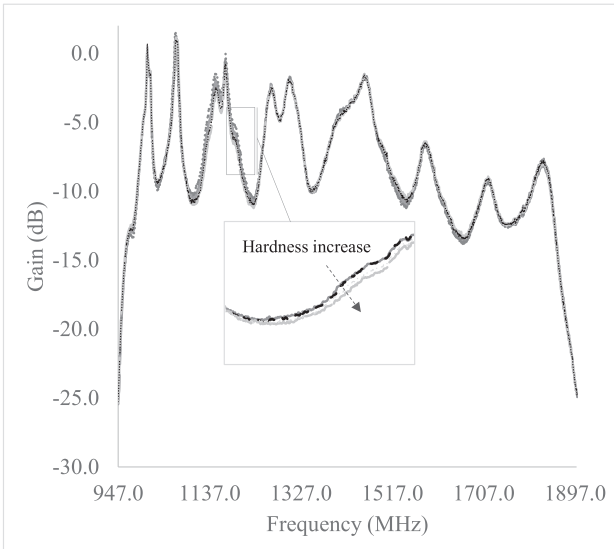

Fig. 5. "Gain" spectra for different fruit Magness-Taylor flesh firmness Mtf (N).

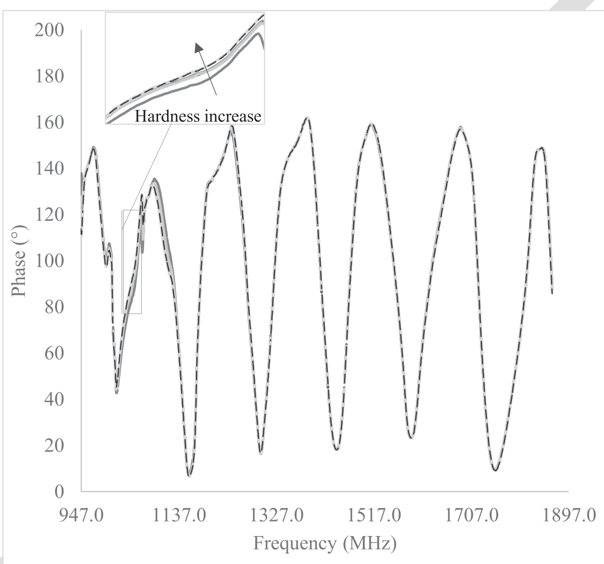

Fig. 6. "Phase" spectra for different fruit Magness-Taylor flesh firmness Mtf (N).

TABLE III

PLS Regressions Models for the Prediction of the Mtf (N) From "gain" and "phase" Waveforms

Waveform	LVs	Calibration		Cross validation		Prediction	
		R^2	RMSC (N)	R^2	RMSCV (N)	R^2	RMSE (N)
Gain	7	0.928	3.2	0.794	5.4	0.726	5.0
Phase	7	0.873	4.2	0.743	6.0	0.663	5.5

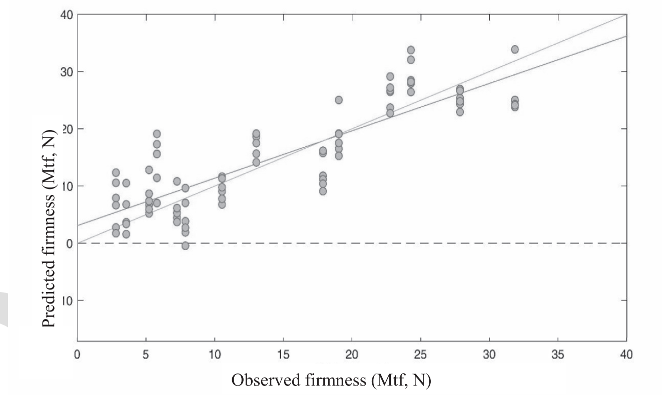

Fig. 7. Predicted versus observed values of the Magness-Taylor flesh firmness Mtf (N) for "gain" spectra (Prediction).

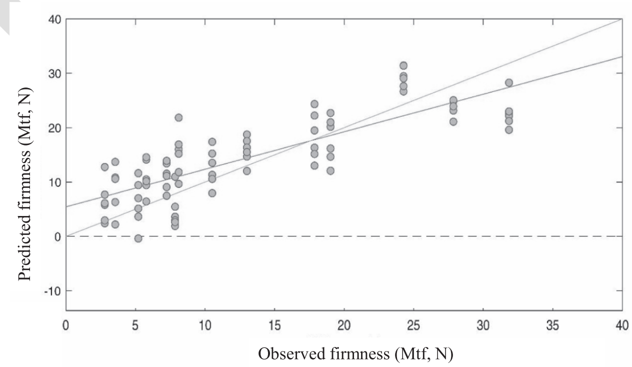

Fig. 8. Predicted versus observed values of the Magness-Taylor flesh firmness Mtf (N) for "phase" spectra (Prediction).

main modifications inducing TSS content and pH increase, respectively [1]. Output voltage loss reported as "gain" and phase shift due to stored charges as "phase" are a complex fingerprint of fruit decomposition. Physical-chemical changes influence the spectral response.

C. PLS Regressions Models

The results of the PLS regression conducted starting from "gain," and "phase" waveforms for the prediction of the moisture content (%) are summarized in Table III. The Table reported R^2 and RMSE values for calibration, segmented cross-validation, and prediction in addition to the optimal numbers of latent variables.

The prediction sets were created with spectral measurements and Mtf values chosen from X and Y calibration sets (and so not included in the model). For every chosen sample, all 6 acquisitions were put in the test set to avoid the presence of the same sample's acquisitions in both data sets to give evidence of the predicted value dispersion for each measurement on a fruit (repetitions). The prediction samples (about 20% of the total) were randomly selected in order to cover all the Mtf range of variability.

The parameters of Table III are LVs, the number of Latent Variables; RMSC, Root Mean Square Error (N) in calibration; RMSCV, Root Mean Square Error (N) in cross-validation; RMSE, Root Mean Square Error (N) in prediction.

As expected, the best results can be observed for the regression model obtained with gain spectra than that of phase waveforms confirming spectral variability evidenced in Figures 5 and 6. In prediction, Mtf can be estimated with an R^2 value of 0.726, and an RMSE of 5 N. A lower accuracy ($R^2 = 0.663$, RMSE = 5.5 N, in prediction) was observed for the phase spectra model. Predicted versus observed Mtf (N) (Prediction) values are shown in Figures 7 and 8 for "gain" and "phase" waveforms, respectively.

As summarized in Table III, the regression model set up and validated from "gain" waveforms seems to produce the highest and the lowest values in terms of R^2 and RMSE. Similar behavior was evidenced by Franceschelli *et al.* (2020) in a work conducted by using a waveguide system for soil moisture content estimation. The waveguide technique is based on the perturbation of electromagnetic field by sample under test. The device provides spectral information related to phase shift (phase) and energy loss (gain) of the electromagnetic wave. At microwaves, the main contribution is energy loss influenced by ion conductivity and dipole polarization, both affected by the density of the tissue and soluble solid content [39]. Accordingly, phase spectra revealed minor variability in terms of spectra shift and resulted in less useful for chemical and physical properties description.

Furthermore, mean values of variability, such as standard deviation, coefficient of variation, and maximum difference, were higher for the phase, both for air and soil acquisitions, than that of "gain."

Kiwi firmness determination is not an easy task considering the contactless needed, as not optimal coefficient of determination of previous works evidenced. In this way, the model presented could be considered in line with the goodness of fitting but introduces a new way to evaluate fruit firmness.

IV. Conclusion

The proposed open-ended waveguide spectroscopy shows a promising technique for contactless and cheap determination of the flesh firmness of kiwifruits. PLS data analysis has provided a predictive models characterized by R^2 of 0.726 and root mean square error of 5 N. The validated model gives a quite good estimation power and low error, coupled with a contactless technique encourages a possible application for selection of fruit machines. Further improvements of the technique can be achieved both for instrumental optimization and implementation of other predictive techniques. Such developments of the system can fit the necessary requirements for an on-line application in kiwifruit sorting machines. Advancements of the system for on-line implementation regards hardware improvement, such as fast sweep, data acquisition, and elaboration as required by industrial production process for reliable firmness evaluation.

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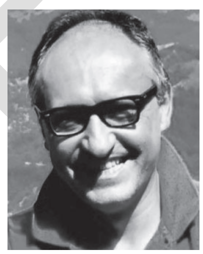

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