Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Dielectric power spectroscopy as a potential technique for the non-destructive measurement of sugar concentration in sugarcane

Mojtaba Naderi-Boldaji [a,*], *Milad Fazeliyan-Dehkordi* [a], *Seyed Ahmad Mireei* [b], *Mahdi Ghasemi-Varnamkhasti* [a]

[a] *Department of Mechanical Engineering of Biosystems, Faculty of Agriculture, Shahrekord University, Shahrekord 88186 34141, PO. Box 115, Iran*

[b] *Department of Biosystems Engineering, Faculty of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Iran*

ARTICLE INFO

Article history:
Received 15 February 2015
Received in revised form
19 August 2015
Accepted 2 September 2015
Published online 28 September 2015

Keywords:
Sugarcane
Dielectric
Non-destructive test
°Brix
%Pol

One of the existing serious technical challenges in the sugarcane industry is the lack of a low cost technique for the non-destructive measurement of sugar concentration as °Brix (percent soluble solids) or %Pol (percent sucrose) from either standing sugarcane in the field or sugarcane stalk/internode samples in laboratory. This study aimed at investigating the potential of dielectric power spectroscopy as a simple technique for this purpose. A parallel-plate capacitor was developed and supplied with sinusoidal voltage waves swept within a frequency range of 0–10 MHz where the consumed power of the capacitor was monitored as a function of frequency by a spectrum analyser. Seventy five internode samples from four sugarcane cultivars were measured by the dielectric sensor and then analysed for °Brix and %Pol in laboratory. Multiple linear regression (MLR) models were developed for prediction of °Brix and %Pol as functions of dielectric power at the swept frequencies with $R^2 > 0.99$ and $RMSE < 0.31$. The water content of the internode samples was also strongly predicted by the dielectric power spectra with a *RMSE* of 0.17%. It was concluded that dielectric power spectroscopy can be implemented as a potent and simple technique for the non-destructive measurement of °Brix and %Pol of sugarcane.

1. Introduction

Sugarcane with a production of 4.2×10^6 t in 2013 is one of the important agricultural products of Iran. 120,000 ha of land in south of Iran (Khuzestan province) is under sugarcane cultivation with an annual production of 650,000 t sugar (KSRTI, 2013). One of the present technical limitations in the sugarcane industry is the lack of a low cost and reliable technique/sensor for measuring sucrose content from standing sugarcane in the field or sugarcane stalk samples in the laboratory. Such a sensor would be a useful tool for the following applications: (i) the physiological studies and breeding programs

* *Corresponding author*. Tel.: +98 3832320372; fax: +98 3832324428.
E-mail address: m.naderi@ut.ac.ir (M. Naderi-Boldaji).

http://dx.doi.org/10.1016/j.biosystemseng.2015.09.003

Nomenclature

R^2	coefficient of determination
R^2Adj	adjusted coefficient of determination
$RMSE$	root mean squared error
$RMSE_P$	root mean squared error of prediction
$RMSE_C$	root mean squared error of calibration
SD	standard deviation
SDR	standard deviation ratio
OR	degree of optical rotation in a polarimeter
%Pol	light polarisation, the sucrose concentration in a solution
°Brix	light refraction, the soluble solids concentration in a solution
WC	water content
SC	sugar concentration in sugar–water solution
D	the diameter of sugarcane stalk
C	capacitance
A	area of the capacitor plates
D	gap between the capacitor plates
P	power
V	voltage
X_c	capacitor impedance
F	frequency
ε_r	complex relative permittivity
ε_r'	dielectric constant
ε_r''	loss factor

during sugarcane growth when extensive in-field measurements of sugarcane quality may be needed (e.g. Jackson & Morgan, 2003; Purcell, Leonard, O'Shea, & Kokot, 2005), (ii) valuation of the input sugarcane to the sugar factory for a fair payment to the farmers (e.g. Dixon & Johnson, 1988) and (iii) precision agriculture applications and monitoring the within-field variability of sugarcane quality (in addition to quantity) on the harvesters (Johnson & Richard, 2005; Nawi, Chen, & Jensen, 2014). These applications imply the measurements to be performed on either standing sugarcane or sugarcane stalk samples (i and ii) or the continuous input bulk flow of sugarcane to the sugar factory or on the sugarcane harvesters (ii and iii). As for the second application, it is important to mention that defining the quality and final price of the sugarcane in sugar factory is based on testing a juice sample of the input product for determining the sugar concentration. This is sometimes a disputable point, where disagreements between sugarcane growers and industry can occur. That was one of our main motivations to present a fast and reliable technique for the non-destructive measurement of sugarcane quality (from sugarcane stalk samples) because the polarimeter or refractometer sensors widely used for measurement of the sugar concentration from the juice samples need to be periodically re-calibrated to yield an accurate measurement (Alvarenga et al., 2005).

In normal practice, the sugar concentration of sugarcane juice is determined in terms of either °Brix (soluble solids content determined from the refraction index of the light passed through the sample) or %Pol (the percent sucrose measured using the property of optical activity which causes polarised light to be rotated when is passed along the sample) which are measured in laboratory on sugarcane juice samples (Engelke, 2002). One degree Brix represents 1 g of soluble solids (i.e. different kinds of sugars and non-sugar solids) in 100 g of solution (here sugarcane juice) whilst %Pol represents the weight percent of mainly sucrose in juice which is preferred to °Brix, although they are usually highly correlated. The ratio Pol/Brix is determined as the purity coefficient describing the extractable fraction of sugar from the juice (Engelke, 2002). However, the laboratory methods of measuring °Brix or %Pol of juice samples are time consuming and not easily applicable for in-field measurements, because it is a rather difficult task to prepare enough juice samples in the field. Nawi, Chen, Jensen, and Baillie (2012) and Nawi et al. (2014) reviewed the potential technologies for measuring sugarcane quality in the field. The methods were classified to refractometry, polarimetry, chromatography, biosensor, Brix hydrometer, wet chemical method and spectroscopy. All of the aforementioned methods need raw or clarified juice samples and therefore are not appropriate for in-field measurements other than spectroscopy which has been evaluated in a range of studies (e.g. Berding, Brotherton, & Skinner, 1991; Mehrotra & Siesler, 2003; Nawi, Chen, Jensen, & Abdanan Mehdizadeh, 2013). For instance, the skin scanning of sugarcane using visible and shortwave NIR (350–1100 nm) revealed the possibility of predicting °Brix with R^2 and $RMSE$ of 0.91 and 1.41°, respectively (Nawi et al., 2013). Spectroscopy methods, though accurate, are expensive and delicate and may not be a proper technology for applications in a harsh environment. Furthermore, they need high skilled operators.

Dielectric sensing of the properties of agricultural products has been proven as a simple, reliable, robust and non-destructive sensing technique (Nelson & Bartely, 2000; Venkatesh & Raghavan, 2004, 2005). The dielectric properties of hygroscopic materials such as food and agricultural products depend strongly on the amount of water in the material as well as the frequency of the applied alternating electric field, the temperature of the material, and the density, composition, and structure (Nelson & Trabelsi, 2012). Dielectric spectroscopy determines the dielectric properties of a medium as a function of frequency (Skierucha, Wilczek, & Szypowska, 2012). This frequency dependence has been proven in many previous studies as a result of polarisation, arising from the orientation with the imposed electric field, of molecules which have permanent dipole moments (Nelson, 1973, 1991; Nelson & Datta, 2001 all cited by Nelson and Trabelsi (2012).

The dielectric techniques have been applied in diverse studies regarding the quality of food and agricultural materials e.g. grape juice and wine (García, Torres, De Blas, De Francisco, & Illanes, 2004); milk (Nunes, Bohigas, & Tejada, 2006); aubergine ripening (Wu, Ogawa, & Tagawa, 2008); banana ripening (Soltani, Alimardani, & Omid, 2011); apple ripening (Guo et al., 2011); egg quality (Ragni, Cevoli, & Berardinelli, 2010); meat quality (Castro-Giráldeza, Botella, Toldrá, & Fito, 2010); measurement of sugar and water content of honey (Guo, Zhu, Liu, & Zhuang, 2010); characterisation of sugar content in yogurt (Bohigas, Amigó, & Tejada, 2008), water content of sugarcane (Taghinezhad, Alimardani, & Jafari, 2012) and determination of sucrose in raw sugarcane