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Milled industrial beet color kinetics and total soluble solid contents by image analysis

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ABSTRACT

Industrial beets are an emerging feedstock for biofuel and bioproducts industry in the US. Milling of industrial beets is the primary step in front end processing for ethanol production. Milled beets undergo color change during juice extraction. A custom designed computer vision system for measurement of milled beet color kinetics, consisting of a digital camera, custom-designed non-reflective enclosure, and color calibration method was developed in the present study. Beet samples of five different total soluble solids (TSS) contents were prepared by washing with cold water for color kinetics measurement. An artificial neural network model was used for converting the red, green, and blue (RGB) values of the acquired sample images to $L^* a^* b^*$ values. Seven color parameters (L^*, a^*, b^*, hue, chroma, browning index (BI), and total color change (ΔE)) were analyzed. Page, user-defined polynomial, and fractional conversion models gave better fits for the experimental data with color parameters than the zeroth order, first order, exponential, and Peleg kinetic models. Of the color parameters studied, L^* (Page $R^2 > 0.99$, user-defined polynomial $R^2 > 0.97$, and fractional $R^2 > 0.93$) and ΔE (Page $R^2 > 0.98$, user-defined polynomial $R^2 > 0.94$, and fractional $R^2 > 0.85$) gave the best description for the color change kinetics of milled beets. Developed TSS prediction models from the color measurements based on Page model constant, k_p with color parameter, L^* gave good prediction ($R^2 = 0.99$), also did the simple linear model based on direct color values ($R^2 = 0.98$). Measurement and mathematical modeling of milled industrial beets color kinetics will serve as important quality assessment tool in processing the beets for various renewable fuel and products applications.

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1. Introduction

Industrial beets, also known as energy beets, are non-food grade sugar beets specifically bred for production of renewable fuel or bioproducts. Compared to sugar beets suitable for table-sugar production, industrial beets, although relatively less in sugar content, compensate with their higher yield and eventually supply more extractable sugar per unit area than table-sugar beets. Industrial beets can grow well both on wet and drylands, produce high yields (72.6–109.7 Mg ha^{-1}), and are also tolerant to saline soils (Pothula et al., 2014). Beets, unlike cellulosic biomass, provide easy fermentable sugars (Panella, 2010), which don't require the complex hydrolysis stage. These favorable attributes of industrial beets make them a feedstock of choice for the sugar platform conversion pathway and new industry development.

Commercial ethanol and bioproducts production from industrial beets is an emerging industry in the US. In North Dakota, research on commercialization of ethanol production from industrial beet is in progress (NDSU, 2013). With the development of industrial beet production and processing methods, utilizing the whole beet or beet juice for ethanol and bioproducts is increasing. Beet usage as an industrial sugar feedstock is an alternative to molasses—the common raw material and byproduct of the table-sugar beet industry.

Front end processing of beets is the major initial step, which involves hammer milling and multiple pressing of pulverized beets with water addition, for extracting the raw beet juice that forms feedstock for biofuels or bioproducts industries (Pothula et al., 2014). Milled beet changes its color rapidly due to colorants formation possibly due to enzymatic browning in the presence of oxygen. A great deal of pulverization that happens in hammer milling releases the enzymes from the tissue for this browning reaction. It was observed that, milled beet obtained after each press changes its color more rapidly compared to previously pressed milled beets.

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Quantifying the color change of milled beets and modeling its color kinetics are important for quality assessment.

Out of several color spaces used, the International Commission of Illumination $L^* a^* b^*$ color space is the most used color model for measuring the food color, because of the perceptually uniform distribution of colors in the model (Wu and Sun, 2013). Numerous recent studies have been conducted using tristimulus colorimeters $L^* a^* b^*$ on color degradation kinetics of various foods such as dehydrated carrots (Koca et al., 2007); paprika (Topuz, 2008); dried shrimp (Niamnuy et al., 2008); dried bananas (Baini and Langrish, 2009); Urmu mulberry (Kara and Erçelebi, 2013); rocket puree (Ahmed et al., 2013); and seedless grapes (Bai et al., 2013). Girolami et al. (2013) studied the limitations of using a colorimeter for measuring non-homogeneous meat slices and found that computer vision system (CVS) produced true meat color. CVS for measuring the color has added advantage over conventional colorimetry, including high spatial resolution, measurement of non-homogeneous colors regardless of size and shape of the sample, flexible selection of region of interest, and simultaneous inspection of several objects (Balaban and Odabasi, 2006).

In general, CVS mainly consists of an illumination system, digital camera and software for image analysis (Brosnan and Sun, 2004). Illumination is an important prerequisite for image acquisition (Wu and Sun, 2013). Under specified lighting conditions, CVS produce color images in device-dependent RGB color space and must be converted into device independent $L^* a^* b^*$ space by calibrating the CVS against standard color targets. Leon et al. (2006) developed five different models, namely linear, quadratic, gamma, direct, and neural network models for converting RGB to $L^* a^* b^*$; and found quadratic and neural network models were best suitable for conversion. Several researchers used these models as such, or with modifications for color change studies of various foods, such as potato chips (Pedreschi et al., 2006, 2007), fresh cut meat (Quevedo et al., 2013), apple slices (Quevedo et al., 2009); dehydrated shrimp (Mohebbi et al., 2009; Hosseinpour et al., 2013), and pre-sliced hams (Valous et al., 2009). In the present study, neural network model was used in the CVS for converting RGB to $L^* a^* b^*$ for the milled industrial beet samples because of their better fitting performance.

It is well documented that color of the product during processing or storage is one of the important quality attribute and knowledge of color kinetics will help in better design and operation of the process. Of the various studies on color kinetics of food, no published literature was found on the color kinetics of industrial beets. It is expected that milled beets of different total soluble solids (TSS) contents, obtained in multiple pressings during raw juice extraction will have different color kinetics. Therefore, the present study aims to develop a CVS for image capture and analysis to determine industrial beets color using $L^* a^* b^*$, to model color kinetics, and to derive prediction relationships for TSS from color kinetics model and color parameters. Several aspects, such as development of a CVS for color measurement, beets color kinetics modeling using advanced models, and prediction of TSS from beet color constitute novel approaches of this study.

2. Materials and methods

2.1. Sample collection

Industrial beets were collected from the receiving station of American Crystal Sugar Co., ND, USA (geo-coordinates: N47.0050°, W97.2190°, elevation 291 m), harvested in fall of 2012, stored in site as field pile, and transported for experiments in March 2013. These beets were stored frozen in a walk-in freezer (Nor-Lake, Model: Fast-track walk-in; size: 10′ × 10′ × 7′ 7″; outdoor remote refrigeration system, Wisconsin, USA) at −20 °C in plastic storage totes at Northern Great Plains Research Laboratory (NGPRL, USDA-ARS, Mandan, ND, USA). All beets collected were from a single source, and were expected to have uniform TSS. Therefore, to study the color kinetics of beets with varying TSS, we artificially created different TSS samples by washing the milled beets with known quantity of water as described subsequently, for this initial study.

2.2. Sample preparation

To decide the amount of wash water for preparation of different TSS samples, preliminary experiments were conducted. Seven milled beet samples each weighing 150 g were taken from prepared stock in individual glass beakers, and were washed (added, mixed, and drained) with varying volumes of water (0, 50, 100, 200, 300, 400, and 500 mL). Washed samples, which lost proportional quantities of TSS in the drain water, were analyzed for TSS using a digital refractometer. The best fit polynomial relationship (Eq. (1)) among the measured TSS and the amount of added wash water was used for the preparation of varying TSS samples in this study.

$$\text{TSS} = 8 \times 10^{-5} x^2 - 0.0645x + 20.806; \qquad (R^2 = 0.98) \tag{1}$$

where TSS is the total soluble solids (°Brix), and x is the volume of water added (mL). Whole beets central portion, after removing the crown, taproot, and outer skin, was sliced into pieces and ground in a laboratory food processor to prepare the initial milled beets stock. From this stock, five 150 g samples were transfered to five beakers and were added with different volumes of water (0, 40, 90, 150, and 500 mL, respectively). After mixing and draining the water, two 50 g samples were collected in sample cups from each beaker. Immediately after sample preparation, one set of samples was used for color change measurement and the other set of samples for TSS measurement.

2.3. Custom-designed computer vision system (CCVS) for color measurement

The various processes involved from the image acquisition using the CCVS to finally obtaining the $L^* a^* b^*$ for further analysis are described hereunder.

2.3.1. Setting up of CCVS

To provide uniform illumination throughout the experiments in the CCVS, a custom-designed hardboard enclosure (914 mm × 610 mm × 610 mm) was prepared and electrical lights were arranged as shown in Fig. 1A. The enclosure dimensions were designed so that the box encloses a digital camera on tripod and the electrical lights during experiments. The inside walls of the enclosure were painted with non-reflective plain black paint, which reduced the reflected light. Black painted top lid with air relief holes (not shown in figure) was used to cover the enclosure while acquiring the images to prevent the entry of surrounding light. Sample illumination was achieved by using two tabletop fluorescent lights (65W, 4300 lumens, Model L2006, Coleman Cable Inc., Waukegan, IL, USA). Bulbs of the lamps were covered with diffusers (part of the original supply), which produced uniform light intensity. The lamps were set at an angle of 45° from the base and arranged above the samples for better illumination and access for camera. Lamps and camera were switched on 30 min prior to experimentation for stabilization.

A color digital camera (Fig. 1A, Model: Nikon D5100, single-lens reflex, Nikon Corp., Japan) was fitted on a tripod and mounted vertically at a distance of 360 mm from the samples, inside the illuminated hardboard enclosure. Digital camera settings were adjusted to obtain good quality images under the lighting conditions used as follows: exposure mode – manual, aperture – f/5.0, shutter speed – 80, ISO – 250, lens – AF-S NIKKOR 18–55 mm