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Non-destructive characterization and volume estimation of pomegranate fruit external and internal morphological fractions using X-ray computed tomography

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A B S T R A C T

In this study, X-ray computed tomography (CT) was used as a non-destructive technique to characterise and quantify the internal structure of pomegranate fruit (cv. Wonderful). A commercial X-ray system with a radiation source of 245 kW and electron current of 300 μA was used to generate two-dimensional (2D) radioscopic images which were reconstructed into three dimensional (3D) images for the quantification and volume estimation of internal structural components of fruit. Segmentation of the internal fruit components (arils, peel, kernel, juice content, air space) and single arils was achieved using StudioMax volume graphics software. The calculated volume of each fruit fraction were 162.5 ± 16.2, 163.9 ± 21.4, 16.4 ± 1.8, 10.9 ± 2.6 mL for arils, peel, kernel and air space, respectively which accounted for 48.1, 48.3, 4.9 and 4.1% of total fruit volume. Furthermore, the calculated volume of juice content was 146.1 ± 16.3 mL per fruit which was equivalent to an average of 89.8% of total aril weight, while a single aril (0.3 ± 0.04 mL) accounted for only 0.09% of whole fruit volume. Destructive validation measurements of each fruit fraction showed similar results to non-destructive data, with volumes of 163.3 ± 15.2, 161.8 ± 20.6, 15.1 ± 1.6, and 12.3 ± 4.4 mL for arils, peel, kernel, air space, respectively, while volumes of juice and single aril were 142.7 ± 16.4 and 0.3 ± 0.09 mL per fruit, respectively. Furthermore, the results showed that fruit physical attributes such as length, diameter and peel thickness were underestimated by an average of 0.14%, 1.13% and 5.27%, respectively, while fruit radius was overestimated by 1.75%. Nevertheless, no significant differences were observed for length, diameter, radius and peel thickness between X-ray CT predicted values and actual measurements. This work has demonstrated the capability of X-ray CT as a non-destructive technique to suitably estimate the fruit volume and its fractions which could be employed for fruit quality systems.

1. Introduction

Pomegranate (*Punica granatum* L.) is an important tree of the tropical and subtropical regions which is valued for its delicious edible fruit. The fruit has leathery exocarp and the interior is separated by membranous walls and white spongy tissue into compartments (Holland et al., 2009). Each compartment is packed with an edible portion (aril) which is surrounded by a translucent sac containing juice and each aril contains a kernel (woody portion) (Holland et al., 2009; Aindongo et al., 2014). The fruit is a rich source of organic acids, polyphenols, vitamins, polysaccharides, and important minerals compounds (Miguel et al., 2010; Viuda-Martos et al., 2010; Opara et al., 2009; Fawole and Opara, 2012). Scientific studies have linked potent pharmacological activities of

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pomegranates to several groups of phytochemicals found in the fruit (Viuda-Martos et al., 2010; Fawole et al., 2012). Consequently, there has gained renewed global interest in pomegranate fruit consumption in relation to human health due to increased consumer awareness of its medicinal properties and nutritional value. This has consequently spurred a tremendous global growth in pomegranate fruit production, consumption and research (Arendse et al., 2014).

The evaluation of internal and external quality of fresh produce is extremely important in the agricultural industry. The biophysical parameters that are conventionally used for quality determination are flavour, size, shape, colour, appearance, texture and freedom from internal and external defects (Holland et al., 2009; Fawole and Opara, 2013a). Physical properties such as volume of whole fruit, arils and juice content relative to the peel are important in the marketing and processing of pomegranate fruit because these attributes influence industrial processing value as well as consumer preference (Holland et al., 2009; Fawole and Opara, 2013a). However, the proportion of aril content (number of kernels, volume and juice content) relative to the peel fraction varies depending on the variety, maturity and growing region (Al-Said et al., 2009; Fawole and Opara, 2014; Al-Maiman and Ahmad, 2002). Currently, destructive practices are commonly employed to evaluate the internal quality attributes as well as the characteristics and proportion of individual components of fruit including pomegranates. However, these methods are labour intensive, time consuming, require specialized sample preparation and are inapplicable for in-line grading and sorting in commercial pack-houses. Furthermore, both internal and external fruit quality attributes may differ significantly due to variability amongst cultivars, orchard, preharvest management practices, fruit maturity and growing region (Magwaza et al., 2013a; Fawole and Opara, 2014; Mphahlele et al., 2014a,b). Consequently, the high variability in quality attributes amongst cultivars or even the same cultivar has promoted the development of non-destructive techniques for detection, prediction and segmentation of fruit quality for laboratory and grading that can both visualize and quantify internal and external structures.

Several non-destructive techniques have been used for the assessment of internal and external quality attributes of fresh produce. These include visible to near infrared spectroscopy (VIS/NIRS, Nicolaï et al., 2007), Vis/NIRS-based systems such as hyperspectral imaging (Zhang et al., 2014) and optical coherence tomography (OCT, Magwaza et al., 2013b), magnetic resonance imaging (MRI, Lammertyn et al., 2003a) and X-ray computed tomography (X-ray CT, Donis-González et al., 2014a). The use of X-ray CT as a non-destructive technique for studying the external and internal morphological characteristics and defects of horticultural products is well documented (Cantre et al., 2014; Donis-González et al., 2014b; Magwaza and Opara, 2014; Kotwaliwale et al., 2014). X-ray CT measures variation in material density of the sample and is based on the attenuation of X-ray that depends on the density of the irradiated object. Jha et al. (2010) reported the potential of X-ray CT to measure the external (size, shape) and internal (pulp, moisture) morphological characteristics of mango (*Mangifera indica*). Using high resolution CT, Mendoza et al. (2007) successfully measured the pore space within apples (*Malus domestica*). Lammertyn et al. (2003a,b) applied X-ray CT to study the development of core breakdown in 'Conference' pears (*Pyrus communis*) and found that X-ray CT were able to differentiate between unaffected tissue, brown tissue and cavities. Shahin et al. (2002) reported that bruising was detectable in 'Golden Delicious' apples using X-ray CT imaging. The use of X-ray CT imagery for inspection of horticultural produce offers considerable advantages including its large field of view, which allows scanning the entire sample without preparation (Léonard et al., 2008). Secondly, the internal structure of an object can be reconstructed into three-dimensional (3D) images from stacked series of 2D images allowing for characterization of physical and physiological structures.

Recently, a preliminary study by Magwaza and Opara (2014) investigated the feasibility of X-ray CT imaging as a non-destructive technique for the quantification of internal structures of pomegranate fruit cv. Shani-Yonay. These authors successfully demonstrated the potential of X-ray CT with image analysis as a non-destructive technique to study the quantity and distribution of edible (arils) and non-edible (albedo) portions of pomegranates. Significantly ($p < 0.001$) high accuracy was obtained using linear regression models to predict destructively measured volumes of albedo (external skin plus internal soft tissue) and arils, with R^2 values of 0.83 and 0.89, respectively. However, the authors did not quantify several key parameters such as juice content and kernel size which are of considerable economic importance in the food and beverage industry.

Pomegranate cultivar Wonderful is the most widely grown and consumed pomegranate cultivar globally (Holland et al., 2009) and during the past ten years, South Africa has seen tremendous increase in commercial production, accounting for over 1000 ha of total planted area and 56% of total production (Pomegranate Association of South Africa (2012)). Therefore, non-destructive estimation of different components for Wonderful cultivar would be immense importance and understanding there relative contribution of these different components to total mass is relevant to consumers, growers and processors. In the food and beverage industry, pomegranates cultivars are commonly selected on the basis of juice content, fruit size, colour, aril yield, and taste (Holland et al., 2009). Juice is produced industrially by either crushing whole pomegranate fruit or extracted arils. The by-products of the fresh aril and juice industries are the remnants of the fruit skin (peel), membranes, and kernels. The fruit skin is rich in elagitannins, which have been reported to possess a wide array of health-promoting bioactivities while the kernel oil has a rare combination of unsaturated fatty acids and sterols, the extracts of which have commercial health importance for humans (Viuda-Martos et al., 2010; Seeram et al., 2006). Therefore, the quantification of pomegranate fruit components, including seeds and juice content, is of considerable economic important for breeders, growers, and food process technologists. The objective of this study were to validate the use of X-ray CT to quantify volumes of key parts of pomegranate fruit cv. Wonderful relevant to the food and beverage industry.

2. Materials and methods

2.1. Fruit sampling

A sample of twenty three pomegranate fruit (*Punica granatum* L. cv. Wonderful) without any external defects selected for analysis were obtained from Sonlia Pack-house (33°34′851″S, 19°00′360″E) in Western Cape, South Africa. Fruit were packed inside Xtend® bags and carton boxes with the following dimensions: width 0.3 m, length 0.4 m, height 0.133 m and a total of 22 perforations and transported to the Postharvest Technology Research Laboratory, Stellenbosch University.

2.2. X-ray computed tomography scanning

X-ray CT images of whole pomegranate fruit were obtained using a commercial X-ray computed tomography system (V|Tome|X L240, General Electric Sensing & Inspection Technologies GmbH, Phoenix, Wun-storf, Germany) situated in the Central Analytical