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Non-destructive characterisation and quantification of the effect of conventional oven and forced convection continuous tumble (FCCT) roasting on the three-dimensional microstructure of whole wheat kernels using X-ray micro-computed tomography (μCT)

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ABSTRACT

Food microstructure influences the characteristics of end products. X-ray micro-computed tomography (μCT) enables investigating internal structure of food products non-destructively. High-resolution X-ray μCT, in combination with image analysis, was used to visualise and quantify the impact of conventional oven and forced convection continuous tumble (FCCT) roasting (180 °C for 140 s) on the microstructure of whole wheat kernels. After image acquisition, two-dimensional (2D) cross-sectional images were reconstructed into three-dimensional (3D) volumes. Quantitative parameters, i.e. volume, porosity, expansion ratio (ER) and relative density, were calculated. Oven roasting was associated with a significantly ($P < 0.05$) larger increase in kernel volume (4.47%) than FCCT roasting (1.57%). Porosity was higher in the oven-roasted samples (10.33 ± 4.63%), indicating a more destructive impact on the internal structure (FCCT = 8.29 ± 2.29%). Roasting introduced cavities and cracks within the wheat kernels, resulting in a decrease in whole kernel density (oven = 2.76%; FCCT = 0.55%), however the material density remained unaffected during FCCT roasting.

1. Introduction

Worldwide, wheat (*Triticum aestivum* L.) is an important crop, with total annual yields exceeding 700 million tonnes in 2013 (FAOSTAT, 2015). The success of wheat as a raw material can be attributed to its processing properties and its ability to develop cohesive doughs that can be formed into noodles and pasta or baked into bread (Lamacchia et al., 2010). Wheat is a staple food and is used for human consumption in a variety of products, i.e. breads, pastas, noodles, couscous, cakes, biscuits, pastries, breakfast cereals and flour.

Cereal roasting is traditionally practiced in India with the objective of increasing shelf life, enhancing organoleptic properties and to ease integration into breakfast cereals and other ready-to-eat products (Murthy et al., 2008). Most roasters used in India are batch type heated pans, where sand is used as heat transfer medium. This roasting method has various negative aspects since it is unhygienic, tedious to operate, leads to a low productivity, there is a lack of temperature control and the product has non-uniform characteristics (Murthy et al., 2008).

Few investigations focused on the effect of heat treatment on the microstructure of cereal grains; the effect of roasting specifically has been even less investigated. Gun puffing (105–115 °C) strongly influenced the kernel morphology and it led to an increased water holding capacity of the flour (Mariotti et al., 2006). Roasted wheat can be roller milled to obtain flour yields as high as 70–75% when the moisture content is below 10% (Lazar et al., 1974). Flour from roasted wheat can be included in breads, pastas, baked and fried speciality products, gels, batters, instant sauces, snacks, gruels and it can be used as basis for beverage products (Baiano et al., 2008; Lazar et al., 1974; Mossman et al., 1973).

A few studies reported on the use of a forced convection continuous tumble (FCCT) roaster for agricultural products such as marama beans and cowpeas (Kayitesi et al., 2010; Ndungu et al., 2012; Nyembwe et al., 2015). The FCCT roaster is an energy efficient roasting technique that can be used to modify the

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microstructure of cereal grains. This roaster employs the moisture inside the sample to generate superheated steam, leading to faster and even heat transfer. The rotating cylinder enables the sample to be suspended in the heated air, thus all the surfaces are exposed evenly to the heat. Thermal insulation results in less heat loss and efficient energy usage (Flinn, 2012).

In food science, it is common to relate physical behaviour to microstructure in order to gain more comprehensive insights into the product or production process. Food microstructure plays an important role in determining the characteristics (physical, textural and sensory) of the final product (Aguilera, 2005). Structural probing of also cereal grains are of great importance to the food industry, since microstructure effects processing, storage, functionality and the end use of products (Dogan, 2007). For example, the microstructure of wheat for bread making significantly influences its quality and baking properties. Traditionally, microstructural investigations involved light microscopy (LM), scanning electron microscopy (SEM) and confocal laser scanning microscopy (CLSM). These destructive methods however have various drawbacks. It requires sectioning which are likely to disrupt the structure, cause imaging artefacts and is limited to two-dimensional (2D) images (Salvo et al., 2010).

The limitations of 2D, destructive methods have led to the increasing use of a powerful non-destructive and non-invasive high-resolution imaging technique, X-ray micro-computed tomography (μCT), which enables characterisation of three-dimensional (3D) volumes for better understanding of food microstructure (Salvo et al., 2010; Zhu et al., 2012). X-ray μCT makes use of the differences in X-ray attenuation that arises mainly from differences in density within a sample. High density materials will attenuate the beam and areas of high attenuation will appear brighter on the 2D slice images. X-rays are sent around and through the scanned sample, creating projection X-ray images. Consecutive images are accumulated to create 3D volumes that can be manipulated digitally to perform a number of quantitative and qualitative measurements (Ketcham and Carlson, 2001).

Traditional computed tomography (CT) and μCT has been applied in various agricultural commodities e.g. traditional medical CT has been used to evaluate undesirable fibrous tissue in carrots (Donis-González et al., 2015) and to assess internal decay in fresh chestnuts (Donis-González et al., 2014), while μCT has been applied for 3D pore space quantification of apple tissue (Mendoza et al., 2007). Synchrotron X-ray CT was used to characterise the 3D gas exchange pathways in pome fruit (Verboven et al., 2008). Lammertyn et al. (2003) performed a comparative study using two non-destructive imaging techniques, X-ray CT and magnetic resonance imaging (MRI), to investigate the spatial distribution of core breakdown in pears.

X-ray μCT (40 kV; 250 μA) was recently investigated for real-time 3D visualisation and quantification of the internal structure of single wheat kernels damaged by sprouting and insect infestation (Suresh & Neethirajan, 2015). Other X-ray μCT cereal grain investigations include the characterisation of rice strains by differences in pore shapes (Zhu et al., 2012) and the effect of heat treatment on rice kernel structure (Mohorič et al., 2009; Witek et al., 2010).

It is not possible to examine expanded starch based products by conventional 2D imaging or scanning methods without destroying the structure. Cutting them also leads to disruption of the pores and breakage due to their brittle texture. To avoid these constraints non-destructive X-ray μCT were applied in a few studies for the characterisation of porous cereal products (Van Dalen et al., 2007), extruded products (Agbisit et al., 2007; Horvat et al., 2014), wheat flour dough (Bellido et al., 2006), bread (Besbes et al., 2013; Demirkesen et al., 2014; Van Dyck et al., 2014; Wang et al., 2011), and to explain airflow resistance in wheat (Neethirajan et al., 2006). Furthermore, X-ray μCT has been used widely to analyse porosity in food products, e.g. banana chips (Léonard et al., 2008) and meringues (Licciardello et al., 2012). Kelkar et al. (2015) recently described a method to determine the density of foods using X-ray μCT.

Andrejko et al. (2011) made use of X-ray radiographic examination to illustrate structural changes in wheat after infrared treatment (exceeding 150 °C and 90 s). High temperature roasting of coffee beans led to an increased volume and porosity and a decreased density with increase in roasting time (Frisullo et al., 2012). The ability to accurately analyse pores makes X-ray μCT an effective technique to study the microstructure of roasted products.

Quality changes occurring during thermal processing include sensory (flavour, odour and taste), optical (colour and appearance), structural (density, volume and porosity), textural, nutritional (proteins and vitamins) and rehydration properties (Vadivambal and Jayas, 2007). Roasting is a time-temperature dependant process that leads to chemical reactions, moisture loss and major changes in volume, shape and density (Hernández et al., 2008).

Wheat endosperm texture influences the energy requirement for milling. Porosity and density are closely related properties (Dobraszczyk et al., 2002) affecting endosperm texture and thus milling yield (Chang, 1988). More dense endosperm ground to larger particles which flows more easily and are easy to handle, whereas more porous endosperm mill to flours that are very fine and results in the blocking of mill sieves (Dobraszczyk et al., 2002). Ideally heat processing or roasting of wheat should have minimum effect on endosperm texture in terms of microstructural changes (porosity, volume and density). Decrease in material density would thus be undesirable. A roasting method resulting in adverse structural changes, i.e. larger cracks, large increase in porosity and loss in material density would be considered destructive.

Wheat kernel microstructural changes occurring during roasting have not been thoroughly studied in the pursuit of understanding the roasting phenomenon. The gap in understanding the mechanism that governs the behaviour of roasted grain microstructure is attributed to the lack of techniques capable of visualising the microstructure non-destructively. The need for 3D characterisation and quantification of microstructure, is now addressed with X-ray μCT which provides datasets that can be analysed for various structural parameters (Chevallier et al., 2014).

This study hypothesises that X-ray μCT is a feasible technique to determine the impact of roasting on wheat kernels. As verification this study presents the application of X-ray μCT in combination with image analysis to non-destructively investigate the impact of conventional oven and FCCT roasting on the microstructure of whole wheat kernels. Qualitatively the internal microstructure and porosity distribution were analysed using X-ray μCT 2D slice images and 3D volume renderings. Quantitative measurements, obtained from 3D volumes, included volume, porosity, expansion ratio (ER) and relative density.

2. Material and methods

2.1. Wheat samples

Eighteen whole wheat kernels were randomly selected from a wheat sample, kindly provided by PANNAR Seeds (Greytown, South Africa). The same kernels were imaged with X-ray μCT before (control) and after roasting to have a direct comparison. Nine kernels were subjected to oven roasting and nine to FCCT roasting. The kernels were weighed before and after roasting to determine the percentage weight loss. The samples were kept in sealed jars at ambient temperature until used.