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New insights into cooked rice quality by measuring modulus, adhesion and cohesion at the level of an individual rice grain

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ABSTRACT

Causal relationships between physical properties and structure/composition of cooked rice are difficult to quantify when mechanical measurements are performed on bulk samples using large deformations that alter the structure irreversibly. We demonstrate here methods involving small-deformation to characterise the elastic modulus (E), adhesion and cohesion at the individual grain level, and show distinct differences between freshly cooked rice and shelf-stable retorted rice. On average, retorted rice is harder and less adhesive and cohesive than freshly cooked rice, but their distributions in each of these mechanical properties overlap. E is independent of adhesion and weakly correlated with moisture content. In addition, a ring-shear tester is shown to distinguish the bulk cohesion and flowing ability between rice samples. Measuring the inherent physical properties of individual grains has the potential to enable a more sensitive evaluation of new processes and grain varieties, and development of quantitative structure-property-processing relationships for rational design of products to perform optimally at different stages, from manufacturing through to oral processing.

1. Introduction

The desire for processed food to have the character of freshly prepared food is driving manufacturers to explore new processing methods and/or formulations. The distribution of ready-to-eat rice in shelf-stable, chilled, and frozen forms is particularly desirable given its one of the most consumed staple foods in the world. In designing and evaluating innovative new processing methods to achieve this goal, such as high pressure processing (Yu et al., 2017), there is a need for reliable and sensitive measurements of the physical properties of cooked rice and its structure. Specifically, the mechanical and surface properties of cooked rice are anticipated to contribute to their flow behaviour during processing and consumption. Causal structure-property-processing relationships provide a means in which to rationally evaluate and optimise the specific effect of process and formulation variables. To predict the sensory perception of texture, and to assist in the process of designing a particular structure of food, instrumental procedures have been designed to measure texture-relevant physical properties. However, these are usually based on imitative techniques such as texture profile analysis (TPA), which have limited sensitivity and do not measure inherent material properties of cooked rice. In this paper, we aim to demonstrate new approaches to evaluate the material properties of cooked rice grains based on measuring the elastic modulus, adhesion and cohesion at the level of individual rice grains.

For cooked rice, uniaxial compression tests (including those embedded within TPA routines) as well as others such as puncture tests or extrusion tests, have been used to evaluate how the measured mechanical properties of cooked rice relate to the sensory perception of texture (Li et al., 2016; Lyon et al., 2000; Meullenet et al., 1998; Perez et al., 1993). Li et al. (2016) reported that 80% compression in TPA measured on 1 g of rice placed as a single layer can differentiate between sticky and non-sticky rice. An observed correlation between TPA and sensory measure of ‘hardness’ and ‘stickiness’ largely depends on the significant difference in amylose content in waxy (no amylose) and high amylose (*ca.* 30% of the starch content) rices. For rice varieties with an amylose content between 18 and 26%, they observed that the hardness measures no longer correlate while the stickiness correlation becomes weaker. Weak correlations between instrumental TPA-assessment of hardness, adhesiveness and cohesiveness with sensory hardness, adhesiveness and cohesiveness of mass were also reported by Lyon

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et al. (2000) for different rice varieties. The authors highlight the need for more sensitive instrumental mechanical methods to capture the subtle, yet detectable differences in sensory texture between samples (Lyon et al., 2000).

We note in particular that both the extrusion test and the TPA approach commonly measure the mechanical response of cooked rice grains while they are being destroyed during exposure to high compression. In this case, the rice is transformed dramatically, well-beyond its elastic limit, as it is compressed into a 'single' bulk soft material constructed of all components of the grain. This transformed product bears little resemblance to the original rice grains, and so it is perhaps unsurprising that measurements obtained on the rice in this state do not strongly relate to adhesiveness and cohesiveness of rice that we would hypothesise to be closely related to the surface properties of the grain.

Despite the wide utilisation of uniaxial compression tests to evaluate texture-related mechanical properties of cooked rice and other food systems, the sample preparation, sample size and amount, plunger size, compression speed, and degree of compression vary highly between study groups. This renders the results difficult to compare, particularly when the inherent material properties (e.g. modulus) are not extracted from measured data (Champagne et al., 1999; Meullenet et al., 2001; Mossman et al., 1983; Okadome et al., 1999). Due to such variability in parameters combined with the tendency to perform measurements at high compressive strains, where rice is transformed to a new structural state, such mechanical measurements do not necessarily provide information about the inherent physical and surface properties of the rice. This limits the establishment of a unifying structure-property relationship that is relevant to a full spectrum of sensory texture attributes.

The major limitations of current uniaxial compression methodologies are the poor definition of the contact area, the low likelihood of capturing the true variation of the sample, and the measurement of irrelevant sensory properties. These all need to be overcome in order to predict relevant sensory texture properties accurately. The arrangement of some number of rice grains in a single layer equidistant from each other is a commonly practiced experimental method (Boluda-Aguilar et al., 2013; Li et al., 2016; Meullenet et al., 2001; Patindol et al., 2010). However rice kernels are not flat, so the contact area with the plunger increases as the compression progresses (Tsuji, 1981). This means that it is important for all samples to have the same geometry when submitted to a compression test because stress is defined as the force divided by contact area (Bourne, 2002). A difference in the contact area will lead to a difference in the measured stress, even when the modulus is the same. Shaping each sample into the same geometry is applied to other soft foods such as cheddar cheese. In this case, good predictions of sensory springiness, cohesiveness, cohesiveness of mass, roughness of mass and tooth-pull can be obtained with TPA (Moiny et al., 2002). As well established in material science, differences in forces may be due to differences in contact area and not inherent differences in modulus and fracture properties.

When a layer of rice grains with a distribution of radii are compressed, the plunger makes contact with the rice grain of the largest diameter first, so the reactive force is an ambiguous sum of rice grains at differing levels of compression. This is problematic as a distribution of hard and soft grains under compression can easily lead to measurements that correspond to hard rice grains even when most grains are actually soft. Due to the non-uniformity between grains, a better approach to investigate intrinsic properties relevant to sensory perception, as recommended by Szczesniak and Hall (1975), would be to measure the distribution of hardness by performing measurements on large numbers of individual grains.

There are a number of different terms used to describe stickiness or adhesiveness in the literature; here we define adhesion as the stickiness between the rice grain and the surface, and cohesion as the stickiness between individual rice grains. Adhesion is a measure of force, work or energy required to detach rice grains from a surface but the actual definition of the measurement varies. Typically, a "pull-off" test is performed by confining a sample to a certain extent between two surfaces, and then the surfaces are separated at a set speed. Adhesion is reported as either the maximum negative force required to detach the rice grain from the device surface, or the negative area under the force-distance or force-time curve (Fiszman and DamÁSio, 2000; Okabe, 1979). These differences in definition, as well as choice of extent of confinement and detachment speed, make comparison of literature values difficult. Thus a constant definition and a clear interpretation of how each physical property relates to each sensory property would be beneficial, although it is not well known if the different definitions actually lead to a different conclusion. The physical measurement of adhesion of individual grains to a surface is recommended because Mossman et al. (1983) showed that measuring 40 grains resulted in less variation in adhesion than measuring an individual grain. Such homogeneity may lead to inconclusive results when comparing differences between rices as a function of process variables or rice variety. To evaluate the sensory adhesion of rice to surfaces such as to a spoon, molars or the lips, it is relevant to measure the surface properties of cooked rice grains (Okadome et al., 1999). Large strain deformation tests that are used in many studies will alter the integrity of the rice and the measured adhesion will not necessarily be related to its surface properties.

The purpose of this study is to overcome some of the limitations described above by developing a more sensitive measure of the mechanical and surface properties of cooked rice grains. Individual rice grains of the same rice variety cooked in a rice cooker or retorted are measured in a small strain uniaxial compression test to obtain objective and inherent physical and surface properties of individual grains. The elastic modulus is obtained within the elastic limit of the rice grains. The two common ways of analysing rice adhesion are compared to evaluate which is more suitable to differentiate between the two rice samples when they are in contact with a metal surface. We also seek to evaluate cohesion as a surface property between two individual rice gains, and compare this to 'bulk' values obtained using a ring-shear tester. Whilst the ring-shear tester is normally used to measure flowability and cohesion in powders (Schulze, 2008), including powdered food (Iqbal and Fitzpatrick, 2006), it was recently used to provide insights into these properties in hydrated semi-solid foods (Tobin et al., 2017).

2. Material and methods

2.1. Material

The samples used (variety *Langi*) were grown in the Riverina, NSW, Australia and harvested in 2014. The grains were provided after milling. The retorted rice of the same variety and same batch was kindly provided by SunRice and contained rice, water, 2.5% vegetable oil and 0.5% distilled monoglyceride. The chemical composition of raw rice was provided by SunRice showing a total starch content of 76.9% with 17.8% amylose and a moisture content of 12.1%.

2.2. Sample preparation

For freshly cooked rice, 300 g of milled rice was weighed into a rice cooker bowl and washed three times with 1.5 L of deionised water for 10 s. After each washing step, the rice was drained in a strainer for 10 s. Milled rice was cooked with a water-to-rice ratio of 1.75 in an electric rice cooker (Tefal intelligent rice cooker, Tefal S.A.S, Rumilly, France). The cooking time was 45 min. After cooking, the outer and bottom 1 cm of rice was discarded. The rest was mixed gently with a plastic paddle to distribute the moisture homogenously, then rice was kept warm for another 10 min in the cooker. Before instrumental analysis, retorted rice samples were warmed in the pouch according to the recommendation on the package in a microwave at 900 W for 90 s. All samples were cooled to approximately 40 °C and kept in a water bath