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Comparative 3D simulation on water absorption and hygroscopic swelling in japonica rice grains under various isothermal soaking conditions

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ABSTRACT

Cracking in rice grains caused by moisture absorption is a major concern among food processors because it has a detrimental effect on the texture. This paper aimed to simulate moisture diffusion three dimensionally (3D) using Fick's diffusion equation, compare the results with an empirical model (Peleg's equation), and simulate in 3D the hygroscopic swelling in rice during soaking at 25, 35, 45 and 55 °C. This study intends to provide preparatory information in understanding the cracking mechanism during soaking. The concept was based on finite element analysis to evaluate both the moisture diffusion and hygroscopic expansion coefficients of milled rice using the reconstructed 3D model of rice geometry. The proposed model was satisfactory for describing the moisture absorption kinetics with root mean square error (RMSE), that ranged from 0.66 to 2.52% dry basis. The results of the 3D simulation of hygroscopic swelling were found to be adequate in representing the swelling characteristics of rice. Analysis of 3D simulation enabled both quantitative and qualitative assessment of the changes in the amount, distribution of moisture, and expansion in the geometry of rice grains.

1. Introduction

Soaking is a pre-treatment procedure in the cooking process of rice. This procedure achieves a number of objectives that include improved heat transfer, chemical transformation, and reducing firmness. It also reduces the amount of phytic acid and some enzyme inhibitor which make the rice grain harder to digest and less nutritious. Because soaking is considerably part of the processing operation, information that is useful in the optimization of the soaking process is necessary. Relative information between the soaking process and other factors that are thought to have some effect on the diffusion of moisture like type of cultivar, temperature, moisture content, degree of mill, and soaking condition had been a target of scrutiny among researchers. Over past decades, much extensive research has been conducted to investigate and understand the effect of these factors on the moisture absorption characteristics and their effect on the physical properties of rice (Bakshi & Singh, 1980; Bello, Tolaba, & Suarez, 2004; Kashaninejad, Maghsoudlou, Rafiee, & Khomeiri, 2007; Lin, 1993; Muramatsu, Tagawa, Sakaguchi, & Kasai, 2006; Shittu, Olaniyi, Oyekanmi, & Okeleye, 2009; Thakur & Gupta, 2006). Several researchers have tried to model moisture diffusion in rice grain (Engels, Hendrickx, Samblanx, Gryze, & Tobback, 1986; Muramatsu et al., 2006; Thakur & Gupta, 2006); however, there is still a limitation in the method used because the modeling was only in two dimensions (2D). A number of researchers have tried to adopt newer and more technologically advanced methods to investigate the moisture diffusion characteristics of rice. Takeuchi et al. (1997) used NMR imaging to study moisture changes in rice during boiling. Ishida, Naito, and Kano (2004) and Mohoric et al. (2004) applied MRI imaging to observe moisture loss in newly harvested rice and cooked rice. To extend the understanding of moisture diffusion characteristics and illustrate the relative distribution of moisture in the grain, three-dimensional (3D) modeling is proposed to give a much clearer image.

The development of cracks in rice grains due to wetting and moisture absorption is a common phenomenon and is probably due to the unequal rate of expansion in rice grains during the soaking process. The occurrence of this phenomenon has some detrimental effects on the texture of the grain and eventually on the eating quality of cooked rice. Several researchers have tried to understand the crack formation effect on moisture diffusion (Genkawa, Uchino, Tanaka, & Hamanaka, 2010; Murata, Koide, & Kawano, 1992; Srinivas, 1975).

Since no available reports illustrate 3D modeling on moisture diffusion and hygroscopic swelling of rice grains, a sequentially coupled moisture diffusion and hygroscopic swelling model based on the actual geometry of milled rice was developed to simulate moisture content and hygroscopic expansion during soaking under various isothermal conditions. It can also provide introductory information for understanding the development of cracks in rice grains. This is very important because this is a preliminary step in locating the specific point in the grain with the highest compressive stress that leads to

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Nomenclature

M	moisture content, kg-water/kg-dry matter
D	diffusion coefficient, $m^2 s^{-1}$
E_a	activation energy, kJ mol^{-1}
R	universal gas constant, J K^{-1} mol^{-1}
T	absolute temperature, K
K_1, K_2	Peleg's constants
t	time, sec
$\{\sigma\}$	stress vector
$\{\varepsilon\}$	strain vector
$\{\varepsilon^{hygro}\}$	hygroscopic swelling strain vector
$[d]^{-1}$	compliance matrix
α	coefficient of hygroscopic expansion
E	Young's modulus, Pa
J	diffusion flux
G	shear modulus, Pa
ν	Poisson's ratio
ρ	real density, kg m^{-3}
V	volume, mm^3
V_0	initial volume, mm^3
S	projected area, mm^2
S_0	initial projected area, mm^2
RSME	root mean square error
FEM	finite element method

cracking. The temperature dependency of moisture diffusion and hygroscopic expansion coefficients were also clarified in this study.

2. Materials and methods

2.1. Preparation of samples

Rice samples were taken from a batch of short-grain japonica brown rice. Using a laboratory-type abrasive mill (SKM-5B; Satake Co. Ltd.), the selected samples were polished to 90% milling. Standard procedures were used for triplicate determinations of initial moisture content. A gravimetric method of determining the initial moisture content, specified by the Japanese Society of Agricultural Machinery, was used: a 10 g sample was dried in a laboratory oven for 24 h at 135 °C. The initial moisture content of the samples was about 10.90% wet basis. Broken, cracked and damaged grains were manually separated and discarded.

2.2. Soaking of samples

Before each experiment, the sample containers and distilled water were kept at the desired temperature in a water bath (BO500; Yamato Scientific Co. Ltd.) for several hours to reach equilibrium. About 10 g samples were placed in a specially fabricated metal screen container, which was then placed in a 100 ml beaker containing 100 ml distilled water and soaked at 25, 35, 45 and 55 °C for 90 min. A T-type thermocouple connected to a data logger (MR48Q032; Chino Corporation) was used to monitor the soaking temperature. In addition, a magnetic stirrer was also used so that the heated water was evenly distributed. During soaking, the hydrated samples were periodically removed and superficially dried by placing in a centrifuge, weighed using an electronic balance (AT460 Delta Range; Shimadzu Corporation) and returned to the beaker. The samples were centrifuged at 1500 rpm for 5 min. It was believed that the duration of centrifugation did not have an effect on the hydration characteristics because this value was far less than the 3000 rpm at 15-minute duration specified by Leach, McCowen, and Schoch (1958) in determining the swelling and percentage of leached soluble of starch. Moisture gain in the samples was monitored every 10 min for 90 min. Moisture content of the samples at each time step was calculated based on the increase in sample mass at corresponding times. Dry basis moisture content was used in all calculations and all units.

2.3. Hygroscopic swelling in rice grains

The procedure used in determining the degree of hygroscopic swelling in rice grains was similar to the method used by Yadav and Jindal (2007); however, a different type of software developed by the National Institutes of Health was used to analyze the photographic images. This is available for download at (http://rsbweb.nih.gov/ij/download.html). For a better comparison among samples under all soaking conditions, rice grains were selected carefully so that the initial length was almost of the same size. The initial length of pre-soaked rice grains was determined using a digital caliper (CD-20C; Mitutoyo Corp., Japan). On average, the initial length of the rice samples ranged from 4.81 to 4.87 mm. Prior to each experiment, the sample containers and the distilled water in a glass Petri dish were kept at the desired temperature in a water bath for several hours to reach equilibrium. The levels of distilled water in the water bath and dish were kept at a certain depth, sufficient to partially submerge the Petri dish but to fully submerge the grain. After thermal stability was reached, rice samples were placed in the dish. The samples were heated at various temperatures, 25, 35, 45 and 55 °C, respectively. The temperature of the heated water in both the Petri dish and water bath was monitored using a T-type thermocouple connected to a data logger (MR48Q032; Chino Corporation). A magnetic stirrer was also used to continuously stir the heated water in the water bath but not the dish. A video microscope (VMS-170; Scalar Co. Ltd., Tokyo, Japan) was used to observe changes in the dimensions of the rice grains. Images were captured at 10-minute intervals for 90 min and stored on a personal computer for analysis. The projected area of the rice grain was estimated by determining the boundary of the image of the rice kernel in terms of the number of pixels. The spatial calibration of the ImageJ software (NIH, MD, USA) was used to measure the parameters in mm instead of pixels. The experiment was replicated several times.

2.4. Modeling the moisture absorption of rice grains

A short-grain japonica variety of rice (*Oryza sativa* L. "Hinohikare") was used in the study. The average thickness, breadth and length of the rice grains were 1.88, 2.84 and 4.87 mm, respectively. The 3D geometry was developed using 206 slices of tomography images of the rice geometry. The protein and starchy portions of the grain were visualized by staining. Images of the sectional slices were digitally captured using a CCD camera. More specific details of the imaging procedure were described in the paper by Ogawa et al. (2000). During the reconstruction, the germ part of the sliced tomographic images was removed so as to create a germ-free 3D model. This reconstruction procedure was carried out using AVIZO version 6.1.1 Fire edition (ZIB; Visualization Sciences Group, Berlin Germany). The reconstructed geometry was saved as an STL file and imported into COMSOL Multiphysics 4.0a, a computer simulation package, for further analysis. Fig. 1 shows a 3D replica of the japonica rice geometry used in the analysis. In this paper, coupled analysis of moisture diffusion and hygroscopic swelling was studied. The Finite Element Method (FEM) was used to elucidate the system of coupled analysis. The reconstructed 3D geometry of the rice grain was discretized into numerous tetrahedral elements and Galerkin's weighted residual method was adopted for the solution strategy. The total number of tetrahedral elements developed in the geometry was 33 626 elements. The calculation was set with time steps of 60 s using a backward