ARTICLE

Effect of pretreatment and geometry on the thermophysical properties of raw *ubi* (*Dioscorea alata* L.)

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Ubi (*Dioscorea alata* L.) is a tropical root crop in the Philippines that can be processed into powder for use in manufacturing several food products such as ice cream, *ubi* jam, among others. The thermophysical properties of *ubi* need to be determined and compared to prediction equations to understand and optimize the heat transfer in processing *ubi*. This study was conducted to determine the effect of two pretreatments (sulfite dipping and steaming) and two sample geometries (parallel and perpendicular) on the thermophysical properties (apparent density, specific heat, thermal conductivity, and thermal diffusivity) of raw *ubi* (Hinaligi variety). Apparent density (ρ) was measured by liquid displacement method. Results (944.0 – 1092.5 kg m^{-3}) showed that pretreatment had negligible effect. Specific heat (C_p) was determined using the method of mixtures. C_p values (3.44 – 4.07 kJ kg^{-1} ºC^{-1}) varied minimally with pretreatment and approximated theoretical values. The heated probe method was used to measure thermal conductivity (k). Thermal conductivity of steamed samples (0.426 W m^{-1}°C^{-1}) approximated predictive equations using perpendicular geometry, while that of raw (0.382 W m^{-1}°C^{-1}) and sulfite dipped samples (0.379 W m^{-1}°C^{-1}) correlated better with equations based on parallel geometry. Results of this study can be used to design efficient heat processes for *ubi.*

KEYWORDS

thermophysical properties, yams, heat transfer, density, specific heat, thermal conductivity, thermal diffusivity

INTRODUCTION

Many fresh and processed food products undergo heating and cooling during production. The thermal process consists of the transfer of heat energy of the system to or from the food product. The thermophysical properties of any material are those that control the thermal energy transport and/or storage within it, as well as the transformations undergone by the material under the action of heat (Urbicain and Lozano 1997). These include density, specific heat, and thermal conductivity. Such properties

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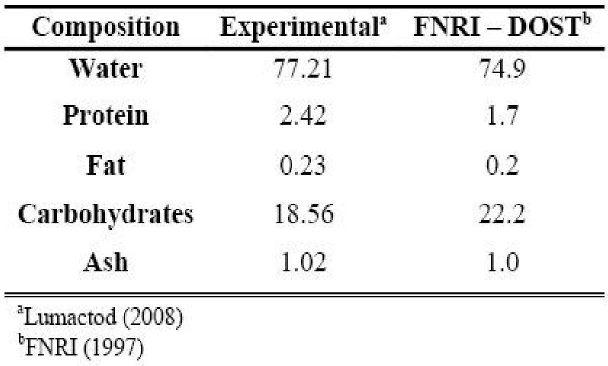
Table 1 Percent composition of *ubi*



Composition	Experimental[a]	FNRI – DOST[b]
Water	77.21	74.9
Protein	2.42	1.7
Fat	0.23	0.2
Carbohydrates	18.56	22.2
Ash	1.02	1.0

[a] Lumactod (2008)
[b] FNRI (1997)

play an important role in determining the rate of heat transfer (Singh and Heldman 2001). Thermal properties are important for modeling processes (microwave heating, extrusion, freezing, etc.), engineering design of processing equipment, calculating energy demand, and developing sterilization and aseptic processes. Besides processing and preservation, thermal properties also affect sensory quality of foods and are used for formulating energy-saving measures (Nwabanne 2009).

Density is usually measured by liquid displacement method (Muzilla et al. 1990), while specific heat can be obtained by the method of mixtures (Rizvi and Mittal 1992, Peralta Rodriguez et al. 1995) or by differential scanning calorimetry. The heated probe method was previously used to evaluate thermal conductivity (Nahor et al. 2003, Flores et al. 2007). Published reports on thermophysical properties have served to increase the database and permit and test the accuracy of prediction equations that depend on composition, temperature, pressure, and fiber orientation, among others (Pham 1996, Saravacos and Kostaropoulos 1996, Carson et al. 2006, Njie et al. 1998). However, experimental studies are still relevant because existing equations prove inadequate in studying prepared foods.

In the Philippines, *ubi* (*Dioscorea alata*) is one of the root crops that are processed into several delicacies, the most famous of which is the *ubi* jam or *halaya*. The average production of *ubi* from 1990 to 2008 was 26 376 metric tons per year, with an average per capita utilization of 0.34 kg per year (http://www.das.bas.gov.ph). Processing of *ubi* into powder is seen as a technique of assuring a constant supply of *ubi* for the whole year. This will also lead to value addition and increased utility for this crop. In this regard, knowledge of the thermophysical properties is fundamentally important in mathematical modelling studies for the design and optimization of food processing operations involving heat and mass transfer, such as food drying.

The thermophysical properties of yam (*Dioscorea dumetorum*) and white yam (*Dioscorea rotundata*) were previously reported (Njie et al. 1998, Oke et al. 2009). To the best of our knowledge, however, no studies on the thermophysical properties of *ubi* (*Dioscorea alata*) have been reported. Thus, this study aimed to determine the effects of pretreatments and sample geometries on the thermophysical properties of *ubi*.

MATERIALS AND METHODS

Sample Preparation

Ubi (Hinaligi variety) was procured from San Pablo, Laguna. The samples were scrubbed to remove adhering soil, washed, peeled, and sliced into 5-cm thick pieces. The composition of *ubi* was previously analyzed vis-à-vis literature values (Table 1). The proximate analysis was then used to calculate the theoretical values of density, specific heat, and thermal conductivity using predictive equations (Table 2).

Samples were divided into three groups. One group was treated with 0.25 % (w/v) sodium metabisulfite (JT Baker Chem. Co., Phillipsburg, NJ, USA) (SMS). Samples were soaked in the solution for 15 minutes. The second group of samples was steamed for six minutes at 93ºC - 99ºC (Rizvi and Mittal 1992). The last group served as control.

Apparent density (ρ) measurement

The density of the *ubi* was measured using the flotation method (Muzilla et al. 1990). Pre-treated samples were allowed to equilibrate for five minutes at room temperature. Samples (approximately 5.0 g) were weighed and put into 100 ml graduated cylinder containing toluene (Mallinckrodt Chemical Works, St. Louis, MO, USA) as flotation liquid. The difference in volume was recorded as equal to the volume occupied by the sample. The procedure was done in five trials. The density was derived from the formula below:

$$\rho = \frac{Mass\ of\ sample\ (kg)}{Volume\ occupied\ by\ the\ sample\ (m^3)} \qquad (1)$$

Theoretical densities were calculated using the proximate analysis of *ubi* and equation (2) from Choi and Okos (1986):

$$\rho = \frac{1}{\sum x_i^w / \rho_i} \qquad (2)$$

where x_i^w and ρ_i are the mass fraction and density of the pure component, respectively

Specific heat (C_p) measurement

The method of mixtures was used (Rizvi and Mittal 1992). The setup consisted of a Dewar flask fitted with type T thermocouple sensors connected to a laptop through an analog-to-digital converter (ADC-1, Remote Measurement Systems, Seattle, WA, USA). The setup was calibrated using cold toluene

(10-12°C). The *ubi* slices were kept at room temperature prior to the test. Approximately 100 mL of cold toluene was weighed and placed in the Dewar flask. The temperature of the toluene and pre-weighed 5-cm thick samples were allowed to equilibrate. Tests were performed in triplicates. Specific heats were calculated using the formula:

$$(mCpT)_s + (mCpT)_w + (mCpT)_{flask} = (m_s\, Cp_s + m_w Cp_w + m_{flask}\, Cp_{flask}) T_{flask} \qquad \textbf{(3)}$$

where the subscripts refer to s=sample; w=liquid (toluene) and flask=Dewar flask, m=mass, C_p=specific heat, T=temperature

Theoretical values for specific heat were calculated using equations (4) and (5):

$$C_p \text{ (Singh and Heldman 2001)} = 1.424m_c + 1.549\, m_p + 1.675m_f + 0.837\, m_a + 4.187m_m \qquad \textbf{(4)}$$

$$C_p \text{ (Earle 1983)} = 4.19\, m_m /100 + 0.84\,(100 - m_m)/\,100 \qquad \textbf{(5)}$$

where:
m_c=mass fraction of carbohydrates
m_p=mass fraction of protein
m_f=mass fraction of fat
m_a=mass fraction of ash
m_m=mass fraction of water

Thermal Conductivity (k) Measurement

Transient methods using the fabricated line heat source probe (Flores et al. 2007) was used in this study (Figure 1). Initially, the probe was calibrated using glycerol (Alysons', Quezon City, Philippines). Samples were cut to obtain a cube with a volume of 1.31×10^{-4} m^3 (8 cubic inches). The probe was inserted through the center, which is the radial axis (Oke et al. 2009) of the sample mass, to prevent any other heat source coming in contact with the sample from the surrounding environment. A current was supplied to the constantan heating wire using a constant DC power source (9V, 0.30 A). The sample in the insulated test container was heated to about 2–3°C below the desired temperature level. During heating, the temperature of the sample was recorded as a function of elapsed time at 5-sec intervals using a Type E thermocouple sensor (Omega, Stanford, CT, USA) connected to a laptop computer through the analog-to-digital converter. This was done in triplicates. The recorded temperature values were then plotted against the natural logarithm (ln) of elapsed time and subsequently the thermal conductivity was calculated using equation (6):

$$k = \frac{Qc}{4\pi M} \qquad \textbf{(6)}$$

where Q is the heat supplied by the probe in Watt- m^{-1}, c is the glycerol constant and M is the slope of a semi-logarithmic time – temperature curve (Shrivastava and Datta 1999).

Predictive equations based on composition are given by equations (7) and (8):

$$k \text{ (Sweat 1986)} = m_c + 0.155m_p + 0.16\, m_f + 0.135\, m_a + 0.58m_m \qquad \textbf{(7)}$$

$$k \text{ (Earle 1983)} = 0.55m_m /100 + 0.26(100 - m_m)\ 100\ \ J^{-1}\, s^{-1}\, {}^\circ C^{-1} \text{ above freezing} \qquad \textbf{(8)}$$

STATEXT™ was used to analyze analysis of variance (ANOVA).

Thermal diffusivity (α) Calculation

Thermal diffusivity was calculated by dividing the thermal conductivity with the product of the specific heat and mass density (Sweat 1986).

$$\alpha = \frac{k}{(\rho\, C_p)} \qquad \textbf{(9)}$$

where k is the thermal conductivity in W m^{-1}-$°C^{-1}$, ρ is density in kg m^{-3} and C_p is specific heat in kJ kg^{-1}-$°C^{-1}$.

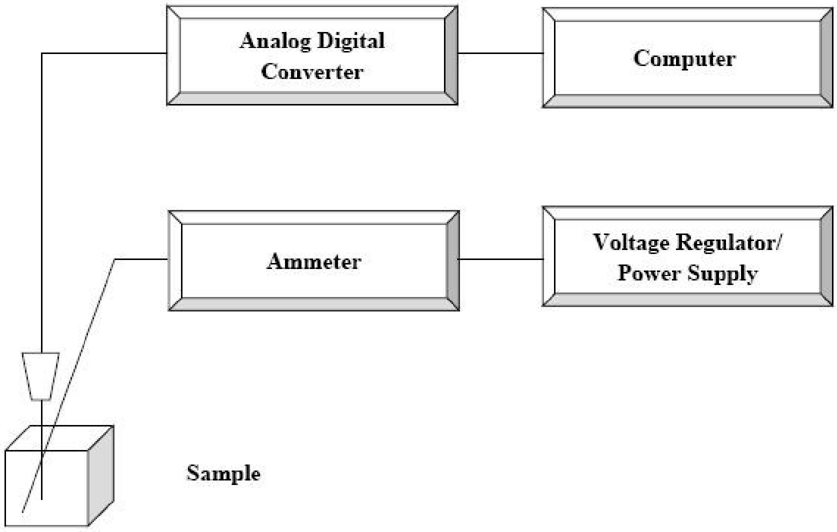


Figure 1. Thermal conductivity setup

RESULTS AND DISCUSSION

Density

The densities of the samples ranged from 944.0 to 1092.5 kg m^{-3} (Table 3) and were all lower than composition-based theoretical models. Samples dipped in sodium metabisulfite may have had absorbed residual amounts of the solute, thus leading to higher values than either the control or the steamed samples and least deviation from theoretical models. The lower values of density for steamed samples were due to starch gelatinization at the surface, which promoted water uptake and yielded densities closer to that of water. Comparison with the previous experiment (Oke et al. 2009) showed a consistent decrease in sample density when subjected to high temperature.

Table 2. Thermophysical properties of food components (Choi and Okos 1986)

Component	ρ (kg m^{-3})	Cp (kJ kg^{-1}-°C^{-1})	TC (W m^{-1}-°C^{-1})	TD (m^2 s^{-1})
Water	997.18	4.1762	0.57109	0.13168
Fat	925.59	1.9842	0.18071	0.098777
Ash	2423.8	1.0926	0.32962	0.12461
Protein	1329.9	2.0082	0.17881	0.068714

Table 3. Densities (kg m^{-3}) of *ubi* samples subjected to different pre-treatments

Pretreatment	Experimental[a]	Theoretical Choi and Okos (1986)	% Error
Raw	1047.14 ± 14.14	1251.29	16.32
With 0.25 % SMS	1063.75 ± 40.65		14.99
Steamed	980.625 ± 61.28		21.63

[a] Mean of five trials

Table 4. Specific heat (kJ kg^{-1}°C^{-1}) of *ubi* subjected to different pre-treatments

Pretreatment	Experimental[a]	Theoretical			
		Singh and Heldman (2001)	% Error	Earle (1983)	% Error
Raw	4.009± 0.080	3.547	13.03	3.349	19.70
With 0.25 % SMS	3.830 ± 0.056		7.98		14.36
Steamed	3.483 ± 0.040		1.80		4.00

[a] Mean of three trials

Specific Heat

The specific heat of the samples used in this experiment ranged from 3.44 to 4.07 kJ kg^{-1}-ºC^{-1} in various treatments (Table 4) and were comparable to results by Peralta Rodriguez et al. (1995). The calorimeter constant C_fW_f obtained in the experiment was 306.325 kJ °C^{-1}. Compared to the experiment done by Oke et al. (2009), there were higher C_p values obtained in this study. In both studies, there was a reduction in specific heat with an increase in temperature. Among the pretreatments, C_p of control samples had the highest deviation from theoretical models. This could be attributed to two causes. First, water has the highest value of specific heat, and an increase in moisture content during dipping and steaming could have led to erroneous results. Second, experimental C_p values agreed with the findings of Rapusas and Driscoll (1995), which reported that composition-based C_p predicts lower values than experimental.

Thermal Conductivity

The values of thermal conductivity of the *ubi* samples prepared for different pre-treatments ranged from 0.287 – 0.418 Wm^{-1}°C^{-1} for parallel and 0.240 – 0.432 Wm^{-1}°C^{-1} for perpendicular geometries (Table 5). The glycerol constant computed was 1.39 (The mean theoretical value of the thermal conductivity of glycerol is 0.28 Wm^{-1}°C^{-1}). The set value of 0.29 - 0.30 A was found to be sufficient for the experiment while the power level was obtained as 12.72 Wm^{-1}. Uniform current was observed during the experiment.

There was no significant difference among k values for parallel geometry at 5% level of significance. Conversely, there was significant difference among k values measured in the perpendicular orientation. Overall, there was no significant difference between the thermal conductivity values obtained in parallel and perpendicular orientation of the sample. This showed that the rate of heat transfer in *ubi* slices was independent of fiber orientation.

Published reports on the effect of fiber orientation on thermal conductivity gave divergent results. Our results agree with the previous finding that parallel-geometry k values were higher than those for perpendicular geometry (Sweat 1986) except for the steamed sample. However, contrary to previous studies, parallel-geometry k values (again, with the exception of steamed samples) were more accurate than that of perpendicular-geometry. Deviations could be due to changes in apparent density and porosity during heat treatment.

Table 5. Thermal conductivity (W m^{-1}°C^{-1}) of *ubi* sampes having different treatments.

Pretreatment	Experimental[a]		Theoretical					
			Sweat (1986)	% Error		Earle (1983)	% Error	
	Parallel	Perpendicular	0.499714	Parallel	Perpendicular	0.47721	Parallel	Perpendicular
Raw	0.382± 0.038	0.294 ± 0.006		23.56	41.17		19.95	38.39
With 0.25 % SMS	0.379 ± 0.015	0.357 ± 0.022		24.16	28.56		20.58	25.19
steamed	0.374 ± 0.011	0.426 ± 0.009		25.16	14.75		21.63	10.7

[a]Mean of three trials

Thermal Diffusivity

Thermal diffusivity were computed using the density, specific heat and thermal conductivity (Table 6). The average mean of the experimental values of thermal diffusivity of *ubi* samples was 9.78x 10^{-5} m^{2}s^{-1} for parallel and 9.41x 10^{-5} m^{2}s^{-1} for perpendicular geometries.

Table 6. Measured and computed thermophysical properties of yam

Pretreatment	ρ (kg m^{-3})	C_p (kJ kg^{-1}°C^{-1})	k (W m^{-1}°C^{-1})		α x 10^{-5} (m^2 s^{-1})	
			Parallel	Perpendicular	Parallel	Perpendicular
Raw	1047.143 ± 14.142	4.009± 0.080	0.382 ±0.038	0.294 ±0.006	9.08946	6.99299
With 0.25 % SMS	1063.75 ± 40.656	3.830 ± 0.056	0.379 ±0.015	0.357 ± 0.022	9.31037	8.7595
Steamed	980.625 ± 61.284	3.483 ± 0.040	0.365 ±0.017	0.401 ± 0.044	10.9399	12.4741

CONCLUSION AND RECOMMENDATIONS

In this study, we quantified the density, specific heat, and thermal conductivity of *ubi* and compared them to existing equations. Between sulfite and steam pretreatments, steaming had a more pronounced effect on thermophysical properties, with the results differing in accuracy compared to theoretical models. This could be attributed to water uptake and the concomitant changes in starch structure during gelatinization. Since steam treatment comprises the preliminary step in processing *ubi* into powder, more investigations on the variations in thermophysical properties during cooking will be conducted, including changes in composition and possible effect of porosity development. Carson et al. (2006) reviewed several models for estimating the effect of porosity and temperature on thermal conductivity. This is the subject of future research in the modeling of thermal conductivity of *ubi*.

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CONTRIBUTIONS OF INDIVIDUAL AUTHORS

This study represents a portion of the undergraduate special problem of Ms. Noche. Mr. Cantre served as a panelist while Mr. Flores supervised the conduct of the research.

CONFLICT OF INTEREST

None

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