Effects of moisture contents and temperature on the thermal properties of some NERICA varieties relevant to its processing

Eze Paul Chukwuka*, Oluka Sylvester Ikechukwu, Eze Chikaodili Nkechi

(Agricultural and Bioresource Engineering, Enugu State University of Science and Technology, ESUT, Enugu, Nigeria)

Abstract: The thermal properties of NERICA (New Rice for Africa) were investigated on differing moisture content levels and temperatures. The NERICA varieties studied includes FARO 44, FARO 52, FARO 57, FARO 60 and FARO 61. The variety samples were later categorized into two; NERICA Raw-Paddy (FAROs 44, 52, 57, 60 and 61) and NERICA Parboiled-Milled (FAROs 44, 52, 57, 60 and 61) samples. The thermal properties studied were thermal conductivity, specific heat, and thermal diffusivity. The thermal conductivity and the specific heat were determined using the thermal conductivity probe method and a digital scanning calorimeter, respectively. The thermal diffusivity was determined from the obtained results of the specific heat and the thermal conductivity. Results indicated that, increase in moisture content and temperature results to increase in the specific heat, thermal conductivity, and thermal diffusivity of NERICA varieties and these ranged from 4.245 to 39.976 kJ kg^{-1} $^{o}C^{-1}$; 0.042 to 1.403 W m^{-1} $^{o}C^{-1}$; and 1.236×10^{-5} to 5.933×10^{-5} m^2 s^{-1} respectively for NERICA Raw-Paddy and 7.033 to 81.657 kJ kg^{-1} $^{o}C^{-1}$; 0.067 to 1.876 W m^{-1} $^{o}C^{-1}$; and 1.413×10^{-5} to 5.219×10^{-5} m^2 s^{-1} respectively for NERICA Parboiled-Milled. Bulk density decreased with an increase in moisture contents and temperature and the obtained results ranged from 760.3 to 698.7 kg m^{-3} for NERICA Raw-Paddy and 720.4 to 652.4 kg m^{-3} for NERICA Parboiled. Regression analyses were carried out on the thermal properties of NERICA varieties and moisture content, and there was positive correlation between the parameters. There were significant effects of moisture content ($p<0.05$) on all the parameters studied.

Keywords: thermal properties, specific heat, thermal conductivity, moisture content, thermal diffusivity, NERICA

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1 Introduction

The word NERICA means "New Rice for Africa", and this is used to represent inborn products developed from the effective crossing of two rice cultivars; the African rice, which is *O. glaberrima steud*, and the Asian rice, which is *O. Sativa L.*, to generate offspring which brings together the first-class qualities of the two parentages (WARDA, 2008). The intensifying cost-effective significance of agricultural food resources, in conjunction with the complications of contemporary technology for their processing, handling, storage and preservation, quality assessment, distribution, marketing and consumption, requires wide-ranging knowledge on engineering properties of these agricultural materials pertinent to their processing, handling, storage, and preservation.

Information on thermal characteristics of agricultural materials is considered necessary in the designing and modification of machines and some parameters utilized during processing, and storage of agricultural products as well as in converting them into food, feed and fiber (Eze and Oluka, 2014).

These properties effect the designing and assessment of rice processing which includes drying, shelling, blanching and shining as well as sorting equipment,

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***Corresponding author: EZE, P. C,** Ph.D., Senior Lecturer, Department of Agricultural and Bioresource Engineering, Enugu State University of Science & Technology, Enugu, Nigeria. Email: paul.eze@esut.edu.ng.

storing and grain handling equipment (Mehdi et al., 2007). To obtain better quality-milled NERICA, packaging and further processing, the knowledge of thermal properties of the grain are essential for modeling of dynamic abrasion in rice molding operations as well as for designing of appropriate polishing systems (Mohapatra and Bal, 2004). It is of particularly important to understand the thermal characteristics of food products since they are needed in multiple phases in food processing and handling of agricultural products. The understanding of the thermal characteristics of food products are particularly important for the effectual and efficient design of the entirely food handling managements that involves transfer of heat. Some of these routine practices that involves the transfer of heat are heating and cooling, freezing and melting, and frying, (Radhakrishnan, 1997). It is also of very significance in the advancement of thermal simulations for producing precise statistical solutions. Heat transfer, as regards to thermal characteristics, plays important roles in appropriate designing of statistical solutions in food processing.

Data obtained from thermal characteristics are needed in the food design processes. Equilibrium energy required for cooling or heating processes, and the temperature constraints inside the food material may possibly not be achieved without the information of the thermal characteristics of such product. Several researchers including Radhakrishnan (1997), Odejobi et al. (2014), Choi and Okos (1986), Sadiku and Bamgboye (2014), Hobani and Al-Askar (2000), Aviara and Haque (2001) and Rahman (1993) have proposed models on thermal properties of agricultural products and highlighted the necessity for thermal properties of food material in general. These properties are significantly influenced by the physical properties of agricultural materials such as shape; size; conditional characteristics, whether chilled or melted; constitutional constraints, such as, content moisture, protein, ash, fiber and fat characterization. Therefore, this research work lays emphasis on the thermal characteristics of selected NERICA varieties, such as the specific heat, the thermal conductivity, the thermal diffusivity, bulk density, the glass transition and enthalpy.

2 Materials and methods

2.1 Sample preparation

The research materials used in this study include five varieties of NERICA, and they are FAROs 44, 52, 57, 60, and 61. These varieties of NERICA were collected from the Ebonyi State Agricultural Development Programme (EBADEP) at storage moisture content of 12.5% (db). Some of the paddy from each variety were parboiled and dehulled using a rice dehulling machine to obtain parboiled-milled samples of the NERICA varieties thereby having ten samples of NERICA; viz: FAROs 44, 52, 57, 60, and Raw-Paddy and FAROs 44, 52, 57, 60, and 61 Parboiled-Milled. The methods used in the parboiling and dehulling were in line with the rice parboiling and dehulling standard. The sample varieties were further hydrated to acquire more three different moisture content levels of 12%, 17%, and 21.5% (db) at which the tests were carried out. A total of 1000 grains were used for the experiments.

2.2 Determination of the specific heat

The specific heat of NERICA varieties was carried out using the differential scanning calorimeter of model DSC 404, NETZSCH, Germany, with maximum temperature of 1500°C. The equipment was regulated for flow of heat, including temperature, using a distinctive pan made of aluminums encompassing a specific number of zincs, calcium and lead in the equipment. Regulation of flow of heat was completed using a standard pan made of aluminum which contains an ascertain indium quantity. But the enthalpy of the samples would be measured at temperatures below the freezing point, a remarkable three-point progression would be carried out using a distinguished classified mercury, acetone and gallium and their respective calibrated melting points are -39.8°C, -95.7°C and -28.9°C. Again, 25 mg of NERICA variety would be enfolded using an aluminum pan and each sample was then scanned at a heating rate of 6°C/min across the ranges of -41°C to 31°C for the measurement of enthalpy parameter, and at a heating rate of 11°C min^{-1} across the ranges of 6°C to 450°C for the measurement of the specific heat. During this experimental process, the reference pan was an empty pan made of aluminum, also, the liquid nitrogen gas was the gas applied as the purgative gas during the experimentation. This method has been utilized by some researchers such as Sweat (1995), Mortaza et al. (2008), and Bart-Plange et al. (2009).

2.3 Measurement of the thermal conductivities of NERICA

The NERICA thermal conductivities were carried out using the line heat source probe approach cantered on non-stable state heat conduction. This approach is accessible, speedy and appropriate for small product samples. For sample food and agricultural materials, this approach has regularly been utilized in current times for the measurement of thermal conductivity (Sweat, 1995; Mortaza *et al*., 2008; Bart-Plange et al., 2009, Mohite *et al.,* 2020). The equipment comprises of an ammeter and voltmeter for the documentation of current and voltage correspondingly. A direct current (DC) power source was applied to supply the heat source. Current and voltage of 0.7 A and 4.5 ±0.5V correspondingly were applied all through the experimentation. In the system, was a regulator that regulates the current in the circuit for the desired current required for the experimentation is achieved. The prepared samples of certain moisture content were permitted to heat up to room temperature. After weighing the sample, it was placed inside the product sample hold container of 2cm diameter, 7±0.5 cm length and 0.2 cm thickness. A heating coil was positioned in the center of the sample and joined outwardly to the power supply. The temperature gauge was implanted inside the product sample hold container and then the switch turned on. Taking of the temperature was carried out immediately after the product sample and sample hold cannister had attained a temperature of 30^{o}C. The current and voltage evaluations were regulated to 0.7 A and 4.5 ± 0.5V, correspondingly and utilized as heat source for the product sample. Temperatures were documented at consistent periods of 30 seconds for 40minutes for each product sample. The experimentation was repeated four times on each moisture content level and documented accordingly. A graph of temperature variance at the intervals took into consideration T_2-T_1 and this resulted to the graph plotting of the average logarithms of the conforming phase ratio $\left(ln\frac{\theta_2}{\theta_1}\right)$. Thus, the graph slope, S, was calculated from the straight-line segment of the graph, which is given as reported by Sahin and Sumnu (2006),

$$S = \frac{Q}{4\pi K} \quad (1)$$

Hence, thermal conductivity is determined as,

2.4Measurement of the thermal diffusivities of NERICA

The thermal diffusivities (α) of NERICA were calculated from the experimentally calculated results of the specific heat, c_p, the thermal conductivity, *k*, and the bulk densities, ρb, of the NERICA sample varieties using the equation as reported by Bart-Plange et al. (2012):

$$\alpha = \frac{K}{\rho_b \, c_{pb}} \quad (2)$$

where α is the thermal diffusivity (m^2 s^{-1}), k is the thermal conductivity (W m^{-1} $^{o}C^{-1}$), C_p is the specific heat (Jkg^{-1} $^{o}C^{-1}$), and ρ is the bulk density (kg m^{-3}).

2.5 Measurement of the bulk density

The bulk density of NERICA varieties was carried out as reported by Mohsen et al. (2013) by filling a container with sample from a height of 150 mm at a constant rate and weighing the contents. The volume of the container was estimated by filling the container with water and measuring it with 80 mL measuring cylinder. Thus, the bulk density is the ratio of the mass of the sample to its total volume.

3 Results and discussion

Data on the influence of moisture contents and temperature on the thermal properties of NERICA varieties are given in Tables 1 to 2 and Figures 1 - 8, (DSC Thermograms). Specific heat of the NERICA varieties increased with increase in moisture contents and temperature in a linear fashion. For NERICA Raw-Paddy, specific heat ranges from 4.245 to 31.616 kJ kg^{-1} $^{o}C^{-1}$ for FARO 44; 5.430 to 37.767 kJ kg^{-1} $^{o}C^{-1}$ for FARO 52; 8.040 to 39.976 kJ kg^{-1} $^{o}C^{-1}$ for FARO 57; 6.584 to 31.227 kJ kg^{-1} $^{o}C^{-1}$ for FARO 60; and 8.487 to 31.794 kJ kg^{-1} $^{o}C^{-1}$ for FARO 61 at 12.5%, 17% and 21.5% moisture content intervals. For NERICA Parboiled-Milled samples, the specific heat ranges from 7.033 to 61.625 kJ kg^{-1} ^{o}C^{-1} for FARO 44; 9.663 to 58.169 kJ kg^{-1} ^{o}C^{-1} for FARO 52; 7.248 to 81.657 kJ kg^{-1} ^{o}C^{-1} for FARO 57; 9.301 to 38.547 kJ kg^{-1} ^{o}C^{-1} for FARO 60; and 6.682 to 87.516 kJ kg^{-1} ^{o}C^{-1} for FARO 61 also at 12.5%, 17% and 21.5% moisture content intervals at temperature range of 50^{o}C to 400^{o}C. This is in conformity to the linear interdependency and results as obtained by Stewart et al. (2000) for SP roots and ASAE (2003) for MA2 milled rice; Singh et al. (2000) for thermal and physicochemical properties of Thailand rice (Indica), Nipponbare (Japonica), and Himenomochi (Japonica waxy) rice grain, flour and starch; Cao et al. (2004) on brown rice; Mohite and Sharma (2018) for drying behaviour and engineering properties of Lima beans. This was also like the trend of specific heat with moisture content observed for timothy hay (Opoku et al., 2004); red lentil seeds (Kara et al., 2012); mung beans (Ravikanth et al, 2012); rice flours (Mahapatra et al., 2006); sheanut kernel (Aviara and Haque, 2001), and so many others. This indicates that processing of NERICA varieties did not affect its ability to store thermal energy. Some variations exist between this work and that of other researchers and this may be due to the method employed, stage of maturity of samples used and the control factors employed to obtain the results.

Table 1 Thermal Properties of NERICA varieties (Raw-Paddy) at different moisture content and at the temperature range of 50^{o}C to 400^{o}C

Variety	Moisture Content	Bulk Density (kg m^{-3})	Specific Heat (kJ kg^{-1} ^{o}C^{-1})	Thermal Conductivity (W m^{-1} ^{o}C^{-1})	Thermal Diffusivity (× 10^{-5} m^{2} s^{-1})
FARO 44	12.5%	749.4 (2.46)	4.245 (0.98)	0.042 (0.06)	1.320 (0.87)
	17%	720.6 (2.08)	15.339 (1.08)	0.536 (0.11)	4.849 (1.98)
	21.5%	702.4 (1.99)	31.616 (1.44)	1.317 (0.78)	5.931 (2.87)
	Average	724.1 (2.18)	17.066 (1.17)	0.632 (0.19)	4.033 (1.91)
FARO 52	12.5%	752.6 (2.67)	5.430 (0.56)	0.054 (0.03)	1.321 (0.67)
	17%	732.3 (2.33)	10.264 (0.54)	0.103 (0.10)	1.370 (0.77)
	21.5%	715.8 (1.99)	37.767 (1.21)	1.378 (0.34)	5.097 (1.98)
	Average	733.6 (2.33)	17.820 (0.77)	0.512 (0.16)	2.596 (1.14)
FARO 57	12.5%	734.6 (1.67)	8.040 (1.03)	0.081 (0.02)	1.371 (0.76)
	17%	721.8 (2.08)	9.540 (0.93)	0.851 (0.21)	1.236 (0.98)
	21.5%	701.4 (1.42)	39.976 (1.43)	1.403 (0.43)	5.004 (1.11)
	Average	719.3 (1.72)	19.185 (1.13)	0.778 (0.22)	2.537 (0.95)
FARO 60	12.5%	760.3 (2.32)	6.584 (1.45)	0.066 (0.03)	1.318 (0.76)
	17%	748.4 (2.01)	16.189 (0.99)	0.621 (0.12)	4.890 (1.11)
	21.5%	718.8 (3.02)	31.227 (0.57)	1.313 (0.56)	5.850 (0.94)
	Average	742.5 (2.45)	18.001 (1.03)	0.667 (0.24)	4.019 (0.94)
FARO 61	12.5%	732.4 (3.01)	8.487 (0.34)	0.085 (0.03)	1.367 (0.88)
	17%	720.6 (2.89)	12.498 (1.07)	0.252 (0.12)	2.798 (1.12)
	21.5%	698.7 (1.87)	31.794 (1.83)	1.318 (0.23)	5.933 (0.99)
	Average	717.2 (2.59)	17.593 (1.08)	0.552 (0.13)	3.366 (0.99)

Note: N.B: Numbers in Parenthesis represents the standard deviation.

Table 2 Thermal Properties of NERICA varieties (Parboiled-Milled) at different moisture content and at the temperature range of 50^{o}C to 400^{o}C

Variety	Moisture Content	Bulky Density (kg m^{-3})	Specific Heat (kJ kg^{-1} ^{o}C^{-1})	Thermal Conductivity (W m^{-1} ^{o}C^{-1})	Thermal Diffusivity (x 10^{-5} m^{2} s^{-1})
FARO 44	12.5%	692.6 (2.88)	7.033 (0.43)	0.071 (0.02)	1.458 (0.87)
	17%	677.9 (2.06)	36.636 (1.67)	0.367 (0.10)	1.478 (0.78)
	21.5%	652.4 (2.11)	61.625 (2.01)	1.617 (0.95)	4.022 (1.77)
	Average	674.3 (2.35)	35.098 (1.37)	0.685 (0.36)	2.319 (1.14)
FARO 52	12.5%	710.2 (2.09)	9.663 (0.46)	0.097 (0.04)	1.413 (0.34)
	17%	687.4 (2.67)	36.487 (0.89)	0.365 (0.12)	1.455 (0.45)
	21.5%	679.6 (2.90)	58.169 (1.04)	1.582 (0.32)	4.002 (1.01)

	Average	692.4 (2.55)	34.773 (0.81)	0.681 (0.16)	2.290 (0.60)
	12.5%	690.6 (3.08)	7.248 (0.76)	0.073 (0.03)	1.456 (0.34)
FARO 57	17%	679.6 (2.11)	31.955 (1.22)	0.319 (0.11)	1.469 (0.98)
	21.5%	657.4 (2.05)	81.657 (2.67)	1.818 (0.04)	3.387 (1.51)
	Average	686.4 (2.41)	40.287 (1.55)	0.737 (0.06)	2.104 (0.94)
	12.5%	720.4 (3.81)	9.301 (0.87)	0.093 (0.02)	1.388 (0.23)
FARO 60	17%	708.2 (2.43)	20.064 (1.06)	0.201 (0.01)	1.415 (0.23)
	21.5%	688.9 (2.01)	38.547 (1.34)	1.386 (0.24)	5.219 (1.07)
	Average	705.8 (2.75)	22.637 (1.09)	0.561 (0.09)	2.674 (0.51)
	12.5%	681.2 (2.11)	9.301 (0.56)	0.067 (0.02)	1.472 (0.67)
FARO 61	17%	672.4 (3.03)	20.064 (1.06)	0.296 (0.12)	1.488 (0.54)
	21.5%	663.6 (2.33)	38.547 (0.99)	1.876 (0.14)	3.230 (1.34)
	Average	672.4 (2.49)	22.637 (0.87)	0.746 (0.09)	2.063 (0.85)

Note: N.B: Numbers in Parenthesis represents the standard deviation.

The measured thermal conductivity values are presented in Tables 1 and 2. As expected for homogenous foods. Thermal conductivity of the NERICA varieties generally increased with increase in moisture content and temperature. For NERICA Raw-Paddy samples, thermal conductivity ranges from 0.042 to 1.317 W m^{-1} ^{o}C^{-1} for FARO 44; 0.054 to 1.378 W m^{-1} ^{o}C^{-1} for FARO 52; 0.081 to 1.403 W m^{-1} ^{o}C^{-1} for FARO 57; 0.066 to 1.313 W m^{-1} ^{o}C^{-1} for FARO 60 and 0.085 to 1.318 W m^{-1} ^{o}C^{-1} for FARO 61 varieties at 12.5%, 17% and 21.5% moisture content intervals at temperature range of 50^{o}C to 400^{o}C. For NERICA Parboiled-Milled samples, the thermal conductivity ranges from 0.071 to 1.617 W m^{-1} ^{o}C^{-1} for FARO 44; 0.097 to 1.582 W m^{-1} ^{o}C^{-1} for FARO 52; 0.073 to 1.818 W m^{-1} ^{o}C^{-1} for FARO 57; 0.093 to 1.386 W m^{-1} ^{o}C^{-1} for FARO 60 and 0.067 to 1.876 W m^{-1} ^{o}C^{-1} for FARO 61 varieties also at 12.5%, 17% and 21.5% moisture content intervals at temperature range of 50^{o}C to 400^{o}C. Similar behavior and trend were observed by Singh et al. (2000) for Thailand rice (Indica), Nipponbare (Japonica), and Himenomochi (Japonica waxy) rice grain, flour and starch; Cao et al. (2004) on brown rice; Azadbakht et al. (2013) for soybean pod and Sadiku et al. (2014) for dates. Therefore, at temperature between 50^{o}C to 400^{o}C, processing did not affect the thermal conductivity of NERICA.

Thermal diffusivity was measured in the same range of moisture content and temperature as that of specific heat and thermal conductivity experiments. The measured thermal diffusivity values are also presented in Tables 1 and 2. Results showed that thermal diffusivity of the NERICA varieties also increased with an increase in moisture content and temperature in a linear fashion at moisture content and temperature range of 12.5%, 17% and 21.5% (db) and 50^{o}C to 400^{o}C, respectively. For NERICA Raw-Paddy, results of thermal diffusivity ranged from 1.320×10^{-5} to 5.931×10^{-5} m^{2} s^{-1} for FARO 44; 1.321×10^{-5} to 5.097×10^{-5} m^{2} s^{-1} for FARO 52; $1.371x\times10^{-5}$ to 5.004×10^{-5} m^{2} s^{-1} for FARO 57; 1.318×10^{-5} to 5.850×10^{-5} m^{2} s^{-1} for FARO 60; and 1.367×10^{-5} to 5.933×10^{-5} m^{2} s^{-1} for FARO 61 varieties. For NERICA Parboiled-Milled samples, results of thermal diffusivity ranged from 1.458×10^{-5} to 4.022×10^{-5} m^{2} s^{-1} for FARO 44; 1.413×10^{-5} to 4.002×10^{-5} m^{2} s^{-1} for FARO 52; 1.458×10^{-5} to 3.387×10^{-5} m^{2} s^{-1} for FARO 57; 1.388×10^{-5} to 5.219×10^{-5} m^{2} s^{-1} for FARO 60; and 1.472×10^{-5} to 3.230×10^{-5} m^{2} s^{-1} for FARO 61 varieties. Similar trend occurred in Azadbakht et al. (2013) for soybean pod and milled rice; Singh et al. (2000) for Thailand rice (Indica), Nipponbare (Japonica), and Himenomochi (Japonica waxy) rice grain, flour and starch; Cao et al. (2004) for brown rice; and Sadiku et al. (2014) for dates.

Results of bulk density tests for each variety of NERICA were also reported. Tables 1 and 2 showed that the density of the NERICA varieties decreased linearly with increase in moisture content of 12.5%, 17% and 21.5% (db). For NERICA Raw-Paddy samples, bulk density decreased from 749.4 - 702.4 kg m^{-3} for FARO 44; 752.6 to 715.8 kg m^{-3} for FARO 52; 734.6 to 701.4 kg m^{-3} for FARO 57; 760.3 to 718.8 kg m^{-3} for FARO 60; and 732.4 to 698.7 kg m^{-3} for FARO 61 varieties. For NERICA Parboiled-Milled samples, bulk density decreased from 692.6 to 652.4 kg m^{-3} for FARO 44;

710.2 to 679.6 kg m^{-3} for FARO 52; 690.6 to 657.4 kg m^{-3} for FARO 57; 720.4 to 688.9 kg m^{-3} for FARO 60; and 681.2 to 663.6 kg m^{-3} for FARO 61 varieties. Similar response has been reported for most food materials (Fasina et al., 2003; AbuDagga and Kolbe, 1997; Urbicain and Lozano, 1997; Aviara and Haque, 2000; Nwigbo et al., 2013). When starch granules are heated in the presence of water, they absorb water and increase in size. It is believed that this is responsible for the reduction in density of NERICA varieties with moisture content.

Statistical analysis was carried out also to study the effect of temperature and moisture content on the specific heat, thermal conductivity, thermal diffusivity, and bulk density of NERICA. Individual regressions, regressing the thermal properties with moisture content and temperature were carried out on each variety. In some cases, temperature proved to be significant and in some it did not. The linear response of these parameters with moisture content and temperature were also like the response that has been reported for most foods, ASAE (2003). The experimentally obtained values were related to moisture content and temperature, Figures 1 to 8, by using the generalized linear model (GLM) regression procedure in statistical software and the means compared by Duncan's test at 5% of significance. All results were expressed as the mean value standard error (SE). Statistical analyses were performed using the statistical package for social sciences (SPSS) for Windows 8.0. Thus, the effect of moisture content and temperature on these thermal parameters were statistically studied and the effects on these parameters are graphically represented in Figures 1 to 8. Regression models were also proposed and tabulated for the thermal properties in Tables 3 to 6.

Table 3 Relationships between Specific Heat calculations of NERICA varieties and moisture content and temperature

NERICA Variety	Equations	
	Raw-Paddy	Parboiled-Milled
FARO 44	$c = 2.74M - 28.59T$, R^2=0.984	$c = 6.07M - 68.03T$, R^2=0.997
FARO 52	$c = 3.59M - 43.26T$, R^2=0.855	$c = 5.39M - 56.85T$, R^2=0.996
FARO 57	$c = 3.55M - 41.14T$, R^2= 0.785	$c = 8.27M - 100.2T$, R^2=0.963
FARO 60	$c = 2.74M - 28.59T$, R^2=0.984	$c = 3.25M - 32.61T$, R^2= 0.977
FARO 61	$c = 2.59M - 26.41T$, R^2=0.874	$c = 3.25M - 32.61T$, R^2=0.977

Note: where; c = specific heat, kJ kg^{-1} $^{o}C^{-1}$; W m^{-1} $^{o}C^{-1}$; M = moisture content, %; T = temperature, ^{o}C.

Table 4 Relationships between Thermal Conductivities calculations of NERICA varieties and moisture content and temperature

NERICA Variety	Equations	
	Raw-Paddy	Parboiled-Milled
FARO 44	$K = 0.141M - 1.78T$, R^2=0.983	$K = 0.171M - 2.245T$, R^2=0.887
FARO 52	$K = 0.147M - 1.99T$, R^2=0.777	$K = 0.165M - 2.123T$, R^2=0.880
FARO 57	$K = 0.146M - 1.72T$, R^2=0.991	$K = 0.193M - 2.559T$, R^2=0.853
FARO 60	$K = 0.138M - 1.69T$, R^2=0.996	$K = 0.143M - 1.887T$, R^2=0.812
FARO 61	$K = 0.137M - 1.78T$, R^2=0.845	$K = 0.201M - 2.676T$, R^2=0.843

Note: where; k = thermal conductivity, W m^{-1} $^{o}C^{-1}$; M = moisture content, %; T = temperature, ^{o}C.

Table 5 Relationships between Thermal Diffusivity calculations of NERICA varieties and moisture content and temperature

NERICA Variety	Equations	
	Raw-Paddy	Parboiled-Milled
FARO 44	$\alpha = 0.512M - 4.67T$, R^2=0.914	$\alpha = 0.282M - 2.49T$, R^2=0.744
FARO 52	$\alpha = 0.512M - 5.83T$, R^2=0.758	$\alpha = 0.283M - 2.52T$, R^2=0.737
FARO 57	$\alpha = 0.403M - 4.25T$, R^2=0.764	$\alpha = 0.213M - 1.52T$, R^2=0.744
FARO 60	$\alpha = 0.503M - 4.54T$, R^2=0.900	$\alpha = 0.422M - 4.511T$, R^2=0.744
FARO 61	$\alpha = 0.506M - 5.25T$, R^2=0.955	$\alpha = 0.193M - 1.23T$, R^2= 0.743

Note: where; α = thermal diffusivity, m^2 s^{-1}; M = moisture content, %; T = Temperature, ^{o}C.

Table 6 Relationships between Bulk Density calculations of NERICA varieties and moisture content and temperature

NERICA Variety	Equations	
	Raw-Paddy	Parboiled-Milled
FARO 44	$\rho = -5.22M + 812.9T$, R^2=0.983	$\rho = -4.47M + 750.2T$, R^2=0.976
FARO 52	$\rho = -4.09M + 803.5T$, R^2=0.996	$\rho = -3.40M + 750.2T$, R^2= 0.925
FARO 57	$\rho = -3.69M + 781.9T$, R^2=0.982	$\rho = -3.67M + 738.5T$, R^2=0.963

FARO 60	ρ = -4.61M + 820.8T, R^2= 0.942	ρ = -3.54M + 765.3T, R^2=0.983
FARO 61	ρ = -2.62M + 765.1T, R^2=0.995	ρ = -1.96M + 705.6T, R^2=0.995

Note: where; ρ = bulky density, kg m^{-3}; M = moisture content, %.

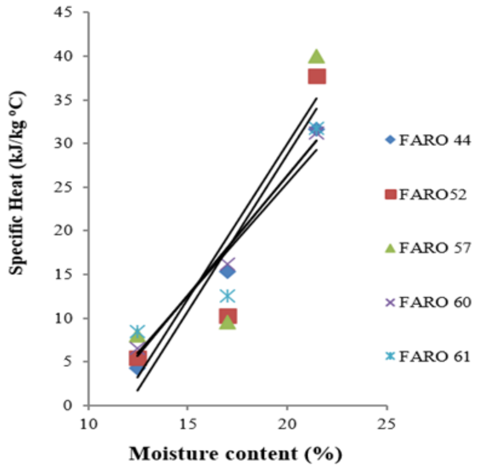

Figure 1 Effect of moisture content on the specific heat of NERICA Raw-Paddy

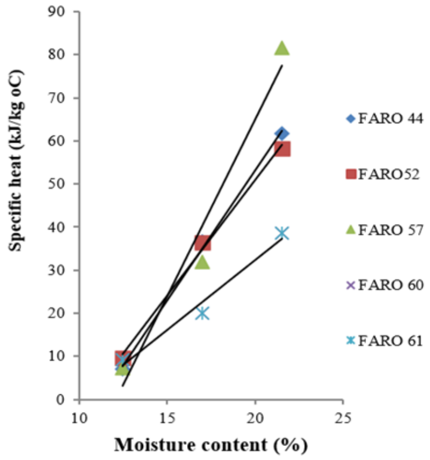

Figure 2 Effect of moisture content on the specific heat of NERICA Parboiled- Milled

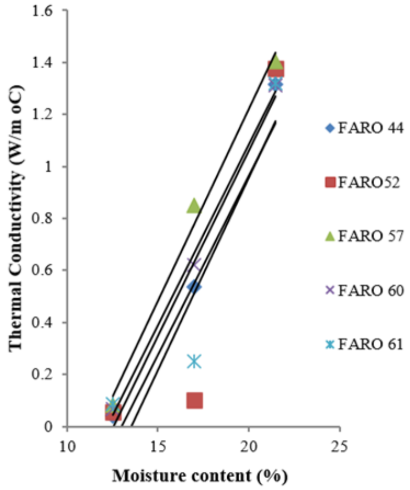

Figure 3 Effect of moisture content on the thermal conductivity of NERICA Raw-Paddy

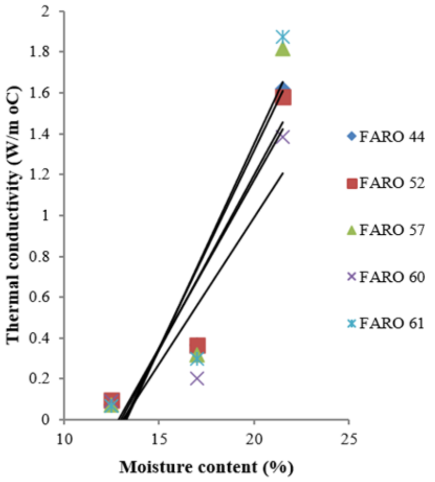

Figure 4 Effect of moisture content on the thermal conductivity of NERICA Parboiled-Milled

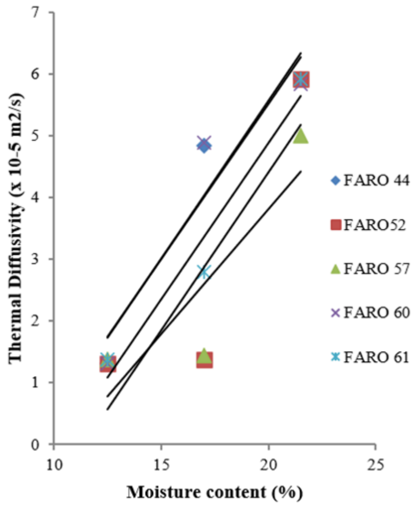

Figure 5 Effect of moisture content on the thermal diffusivity of NERICA Raw-Paddy

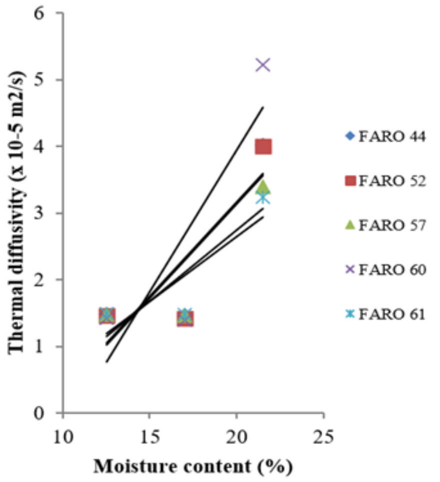

Figure 6 Effect of moisture content on the thermal diffusivity of NERICA Parboiled-Milled

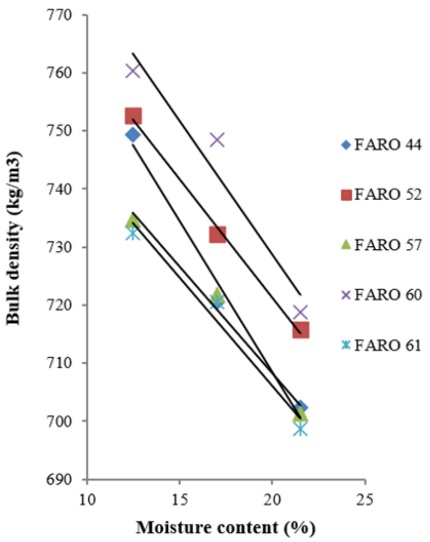

Figure 7 Effect of moisture content on the bulk density of NERICA Raw-Paddy

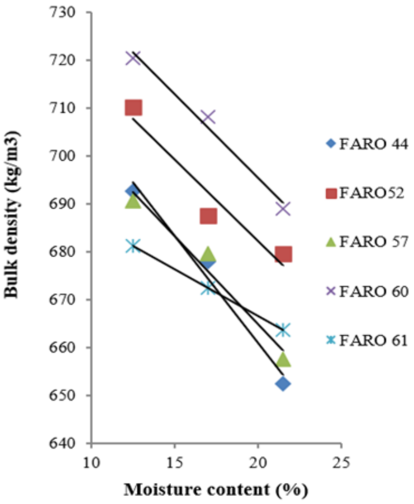

Figure 8 Effect of moisture content on the bulk density of NERICA Parboiled-Milled

5 Conclusion

Owing to the scarcity of information on NERICA and their thermal properties, the present study provides useful information for the food processing industries and for the formulation of new strengthened baking and doughy products from NERICA. Moreover, this research work provides the first report on thermal properties of NERICA. Thus, the following conclusions can be drawn from the study.

1. The thermal properties of NERICA varieties; FAROs 44, 52, 57, 60 and 61 were significantly ($p<0.05$) affected by moisture content (12.5%–21.5%) (db) and temperature (50°C–400°C).

2. Specific heat increased with an increase in moisture content and temperature and the result ranged from 4.245 to 39.976 kJ kg^{-1} $^oC^{-1}$ for NERICA Raw-Paddy and 7.033 to 81.657 kJ kg^{-1} $^oC^{-1}$ for NERICA Parboiled-Milled. Difference in specific heat for NERICA Raw-Paddy and NERICA Parboiled-Milled was because of the morphological arrangement of the varieties.

3. Thermal conductivity also increased with an increase in moisture content and temperature and the result obtained ranged from 0.042 to 1.403 W m^{-1} $^oC^{-1}$ for NERICA Raw-Paddy and 0.067 to 1.876 W m^{-1} $^oC^{-1}$ for NERICA Parboiled-Milled.

4. Thermal diffusivity also increased with an increase in moisture contents and temperature and the result ranged from 1.236×10^{-5} to 5.933×10^{-5} m^2 s^{-1} for NERICA Raw-Paddy and 1.413×10^{-5} to 5.219×10^{-5} m^2 s^{-1} for NERICA Parboiled-Milled.

5. Bulk density decreased with an increase in moisture contents and temperature and the obtained results ranged from 760.3 to 698.7 kg m^{-3} for NERICA Raw-Paddy and 720.4 to 652.4 kg m^{-3} for NERICA Parboiled-Milled.

6. Polynomial equations were used to relate both specific heat, thermal conductivity, thermal diffusivity and bulk densities of the NERICA varieties to moisture contents and temperature and there was positive correlation between the parameters.

7. The results showed that NERICA varieties; FARO 44, FARO 52, FARO 57, FARO 60, and FARO 61 possesses very recommendable qualities in terms of cooking and doughing and these relates with ASAE (2003) report on thermal properties of grain and grain products, though FARO 57 possesses more thermal qualities than others.

8. The thermal properties' results presented in this research work can find utilization in food industry in such processes where heat transport and storage properties of granular agricultural materials are indispensable. They can be applied for instance for the adjustments of drying rate, for the calculations of the economical drying time and for the determination of energetic balances of drying processes.

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