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Moisture dependent thermal properties of selected vegetables in Akwa Ibom State, Nigeria

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Abstract: The thermal properties of some selected vegetables in Akwa Ibom State, Nigeria were investigated. The specific heat, thermal conductivity and thermal diffusivity for the five selected vegetables (Afang, Nkong, Atama, Editan and Nton) were determined and the moisture content variation was investigated. The specific heat values ranged from 2,348–4,580 $J\cdot kg^{-1}\cdot K^{-1}$, while the thermal conductivity values ranged from 0.00368–0.489 and the thermal diffusivity values ranged from 1.03×10^{-7}–1.99×10^{-7} $m^2\cdot s^{-1}$. Nton had the highest specific heat and thermal conductivity, while Editan had the highest diffusivity. An increase in the moisture content increased the specific heat, thermal conductivity and diffusivity of the vegetables and the relationships were found to be linear. Regression equations for the thermal properties were established as a function of the product's moisture content with the experimental data from this study. The thermal properties of the vegetables varied linearly with the moisture content and there were significant differences in the thermal properties of the selected vegetables.

Keywords: specific heat; thermal conductivity; thermal diffusivity; moisture content; Ibibio

Vegetables are an important part of healthy eating and provide a source of many nutrients. They provide an abundant and inexpensive source of energy, body building nutrients, vitamins and minerals. They are an important part of the world agricultural food production, even though their production volumes are small compared with grains (Ekpunobi et al. 2014). Their consumption provides taste, palatability, increases appetite and provides fibre for digestion among other things. As pivotal as they are in a healthy diet, variety is just as important as quantity. Considering this, five different vegetables that are common among the Ibibio people of Akwa Ibom State, in the South-South region of Nigeria were selected, viz: Afang (*Gnetum africanum*), Nkong (*Telfairia occidentalis*), Atama (*Heinsia crinita*), Editan (*Lasianthera africana*) and Nton (*Ocimum gratissimum*). *G. africanum*, also known as Afang in Ibibio, is a dioecious forest perennial liana up to 10 m long, but sometimes longer with the branches somewhat thickened at the nodes. It is grown as a wild evergreen climbing plant in the rainforest of Nigeria where it is searched for and and has a high price in the regional market. Afang leaves are widely consumed due to its palatability and taste. It is eaten as a vegetable salad when mixed with palm oil and the popularly known Afang soup is sometimes cooked with a water leaf to give the soup a special savoury taste (Ekpo 2007). *T. occidentalis*, also known as Nkong in Ibibio, is a dioecious, perennial and drought-tolerant plant. The young shoots and leaves are the main ingredient of Nigerian Edikang Nkong soup. The herbal preparation of the plant has been employed in the treatment of anaemia, chronic fatigue and diabetes (Kayode, Kayode 2011). *H. crinita*, also known as Atama in Ibibio, is a scrambling

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shrub with persistent and very conspicuous leafy calyx lobes (Keay 1989). The Efiks and Ibibios in Southern Nigeria use the leaves in vegetable soups and also for the treatment of hypertension and abscesses (Ajibesin et al. 2008). The scented leaves are used for treatment of craw and head lice in children. *L. africana*, also known as Editan in Ibibio, is a perennial glabrous shrub of the family Rubiaceae. The plant is widely distributed in the tropical rainforest and can grow up to a height of 1.36 m. The family includes 58 genera and 400 species (Okokon et al. 2009). It comprised of four ethno-varieties namely "Afia" (white variety), "Obubit" (black variety), "Editan akai" (forest variety) and "Editan idim" (riverine variety) which are distinguished by their taste, leaf colour and ecological distribution (Okokon et al. 2009). The black (obubit) variety is the most common. The stem of the *L. africana* plant is used to clean the teeth, and the water extract of the leaf is reportedly used to control stomach ulcers (Akpan et al. 2012). *O. gratissimum*, also known as Nton in Ibibio, commonly referred to as the "scent leaf", is an herbaceous perennial grass. It is pantropical and widely naturalised in many regions (Odoemena, Onyeneke 1998). It is usually seen as a small shrub with many branches and simple oval leaves. It is also a known traditional medicinal plant used in curing different ailments (Onajobi 1986). The leaves are used as food additives for their believed nutritive and medicinal values (Sowofora 1993). It also adds flavour or aroma to the food. It is mainly used as a spice (Grayer et al. 2000). Thermal properties data are required in engineering and process designs, and are useful in modelling the thermal behaviour of agricultural crops during thermal processing operations. Since many stages in the processing and preservation of vegetables involve heat transfer, it is important to understand the thermal properties of the vegetables. The knowledge of thermo-physical characteristics of vegetables is very essential for controlling and evaluating the quality of the foods during their storage and processing (Mykhailyk, Lebovka 2013). The thermal properties of foods are those properties that control the transfer and storage of heat in a particular food (Lozano 2006). Besides processing and preservation, the thermal properties also affect the sensory quality of the foods as well as the energy savings from processing them (Ekpunobi et al. 2014). Mykhailyk and Lebovka (2013) identified the thermal conductivity, thermal diffusivity and specific heat as the main thermo-physical characteristics of agricultural and food materials. The specific heat of a material is the amount of heat needed to increase the temperature of a unit mass by one degree. The thermal conductivity is a measure of a material's ability to transmit heat, while the thermal diffusivity quantifies a material's ability to conduct heat relative to its ability to store it. The thermal properties of most vegetables are significantly influenced by their moisture content, which makes the investigation of their variation with moisture content very important. The knowledge of these properties is very necessary for the modelling, simulation and optimisation of the process operations which involve heat transfer. According to Ekpunobi et al. (2014), the structure and properties of vegetables create the need for the unique consideration of their thermal properties. Considering this, the objective of this research work was to determine the thermal properties of five selected vegetables among the Ibibio people of Akwa Ibom State, in the South-South region of Nigeria. Since these thermal properties are significantly influenced by the moisture content, the moisture content variation was also considered.

MATERIAL AND METHODS

The samples' preparation. The five selected vegetables were purchased at the Use-Offot modern market in Uyo Local Government Area of Akwa-Ibom State. The initial moisture content of the vegetables was determined by the gravimetric (oven-dried) method and the vegetables were conditioned to the desired moisture content levels of 82, 84, 86, 88 and 90% wet basis using the method adopted by Ajav and Fakayode (2011).

Determination of the specific heat. The specific heat was determined using the calorimeter method. The calorimeters were calibrated following the procedure described by Aviara and Haque (2001). The calorimeter contains water of known weight and temperature ranging from 303 to 308°K (30–35°C). The mixture was stirred with a copper stirrer and the temperature was recorded at intervals. At equilibrium, the final temperature was noted and the specific heat calculated using Eq. 1 as adopted by Aviara and Haque (2001). The experiment was replicated five times for the selected vegetables at the five moisture content levels:

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$$c_s = \frac{(m_c c_c + m_w c_w)\left[T_w - \left(T_e + t'R'\right)\right]}{m_s\left[\left(T_e + t'R'\right) - T_s\right]} \quad (1)$$

where: c_s – specific heat of the sample (J·kg^{-1}·K^{-1}); m_c – mass of the calorimeter (kg); c_c – specific heat of the calorimeter (J·kg^{-1}·K^{-1}); m_w – mass of the water (kg); c_w – specific heat of the water (J·kg^{-1}·K^{-1}); T_w – initial temperature of the water (K); T_e – equilibrium temperature of the sample and water mixture (K); t' – time for the sample and water to come to equilibrium (s); R' – rate of the temperature fall of the mixture after equilibrium (K·s^{-1}); m_s – mass of the sample (kg); T_s – initial temperature of the sample (K)

Determination of the thermal conductivity. The thermal conductivity was determined at the five moisture content levels for the selected vegetables. The selected vegetables were ground into fine particles. Deionised water was added to 30 g of each sample to turn it into a form of paste so that the conductivity electrode could be dipped into the paste's solution. The thermal conductivity of the vegetables was determined with the use of a conductivity meter (EC800 Laboratory Benchtop Conductivity Meter) and the readings were obtained and recorded. The experiment was carried out five times for the selected vegetables at the five moisture content levels.

Determination of the thermal diffusivity. The thermal diffusivity was calculated from the experimental values of the specific heat, thermal conductivity and density using Eq. 2. The densities of the vegetables were determined following the procedure described by Ekpunobi et al. (2014):

$$\lambda = \frac{k}{\rho c_s} \quad (2)$$

where: λ – thermal diffusivity (m^2·s^{-1}); k – thermal conductivity (W·m^{-1}·K^{-1}); ρ – density of the vegetable (kg·m^{-3})

Statistical analysis. The data obtained from the experiments were statistically analysed using the Minitab software package (Version 16). The statistical significance was carried out using Tukey's approach at $P < 0.05$.

RESULTS AND DISCUSSION

Specific heat

The average values for the specific heat of the vegetables are presented in Table 1. Nton had the highest specific heat, while Editan had the lowest which implies that Nton has the highest ability to store heat among the selected vegetables. This could be due to the chemical composition and physical structure of the vegetables (Wang, Brennan 1993; Sweat 1995; Ngadi et al. 2003). The vegetables possess a very high specific heat capacity which implies that a lot of energy will be needed to heat or cool the vegetables and when heated or cooled, they have the ability to retain their temperatures for a long duration. This, according to Ekpunobi et al. (2014), is due to their high moisture content. The variation in the specific heat of the vegetables with regards to the moisture content is shown in Fig. 1. It was observed that the specific heat increased linearly with an increase in the moisture content for all the vegetables. This, according to Niesteruk (1996), is due to the way that water is bound in the vegetables which influences their thermal properties. This trend has been reported by Deshpande and Bal (1999), Singh and Goswami (2000), Yang et al. (2002), Subramanian and Viswanathan (2003) and Razavi and Taghizadeh (2005). It was observed that the moisture content had a significant effect on the specific heat as the difference in the moisture content increased; and that there were significant differences in the specific heat of the selected vegetables considered. These are confirmed by the statistical analysis presented in Table 2. The relationship between the specific heat and moisture content for the vegetables can be expressed by the following regression equations [Eqs 3 (Nkong), 4 (Editan), 5 (Nton), 6 (Afang), and 7 (Atama)]:

$$c_s = 168M + 2,951.6 \ \left(R^2 = 0.89\right) \quad (3)$$

where: M – moisture content (% wb)

$$c_s = 277.5M + 2,129.7 \ \left(R^2 = 0.98\right) \quad (4)$$

$$c_s = 351.5M + 2,827.9 \ \left(R^2 = 0.99\right) \quad (5)$$

$$c_s = 31.7M + 3,841.9 \ \left(R^2 = 0.90\right) \quad (6)$$

$$c_s = 75.4M + 3,365.8 \ \left(R^2 = 0.91\right) \quad (7)$$

Thermal conductivity

The average values for the thermal conductivity of the vegetables are presented in Table 1. Nton had

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Table 1. The thermal properties of the selected vegetables at different moisture content (MC) levels

MC (% wb)	Vegetables														
	Nkong			Editan			Nton			Afang			Atama		
	c	*k*	λ	*c*	*k*	λ	*c*	*k*	λ	*c*	*k*	λ	*c*	*k*	λ
82	3,220	0.004	1.03	2,348	0.012	1.69	3,219	0.395	1.39	3,864	0.214	1.24	3,432	0.019	1.34
84	3,232	0.015	1.09	2,783	0.142	1.75	3,439	0.424	1.40	3,928	0.219	1.26	3,548	0.055	1.39
86	3,324	0.017	1.16	2,932	0.154	1.81	3,942	0.453	1.49	3,932	0.280	1.3	3,592	0.215	1.44
88	3,652	0.018	1.21	3,242	0.189	1.94	4,232	0.483	1.52	3,949	0.282	1.48	3,610	0.217	1.46
90	3,850	0.020	1.24	3,506	0.199	1.99	4,580	0.489	1.55	4,012	0.296	1.66	3,778	0.290	1.52

c – specific heat ($J \cdot kg^{-1} \cdot K^{-1}$); *k* – thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$); λ – thermal diffusivity ($m^2 \cdot s^{-1}$)

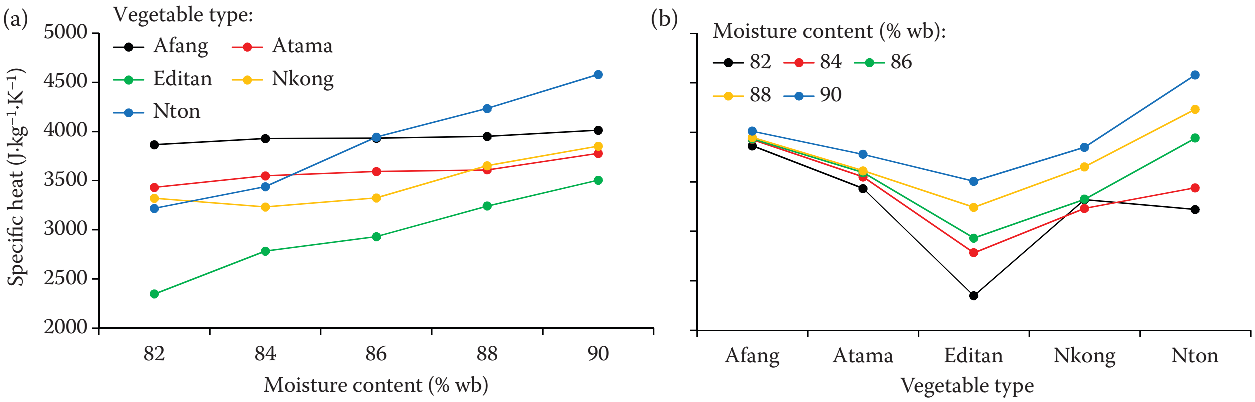

Fig. 1. The interaction plot showing the effects of the moisture content (a) and vegetable type (b) on the specific heat

the highest thermal conductivity, while Nkong had the lowest which implies that Nton has the highest ability to conduct heat among the selected vegetables. This could be due to the chemical composition and physical structure of the vegetables (Wang, Brennan 1993; Sweat 1995; Ngadi et al. 2003) or how the water is bound in the vegetables (Karninski 1972). Comparatively, the thermal conductivities of the vegetables are very low compared to pure water which may be due to the presence of other solids in the vegetable bulk (Ekpunobi et al. 2014). This signifies that they are poor conductors of heat. The heat energy diffusion or transfer through these vegetables during heat processes is likely to be very slow. The variation in the thermal conductivity of the vegetables with regards to the moisture content is shown in Fig. 2. It was observed that the thermal conductivity increased linearly with an increase in the moisture content for all the vegetables. This, as explained by Bart-Plange et al. (2012), can be attributed to the fact that an increase in the moisture content of the sample increases the amount of water molecules available to fill the pores within the sample, which, in turn, increases the ability of the sample to conduct more heat. This trend conforms to earlier reports by Deshpande et al. (1996), Taiwo et al. (1996), Shrivastava and Datta (1999), Yang et al. (2003), and Tansakul and Lumyong (2008). It was observed that the moisture content had a significant effect on the thermal conductivity as the difference in the moisture content increased; and that there were significant differences in the thermal conductivity of the selected vegetables con-

Table 2. The ANOVA for the specific heat ($J \cdot kg^{-1} \cdot K^{-1}$): factors: moisture content (type: fixed, random; level: 5; value: 82, 84, 86, 88, 90%), leafy vegetable (type: fixed, random; level: 5; value: Afang, Atama, Editan, Nkong, Nton)

Source	*df*	SS	MS	*F*-value	*P*-value
Moisture content	4	1,639,902	409,976	8.37	0.001
Leafy vegetable	4	3,075,942	768,986	15.69	< 0.001
Error	16	784,099	49,006		
Total	24	5,499,943			

df – degree of freedom; SS – sum of squares; MS – mean square; $S = 221.37$; $R^2 = 85.74\%$; R^2 (adj) = 78.62%

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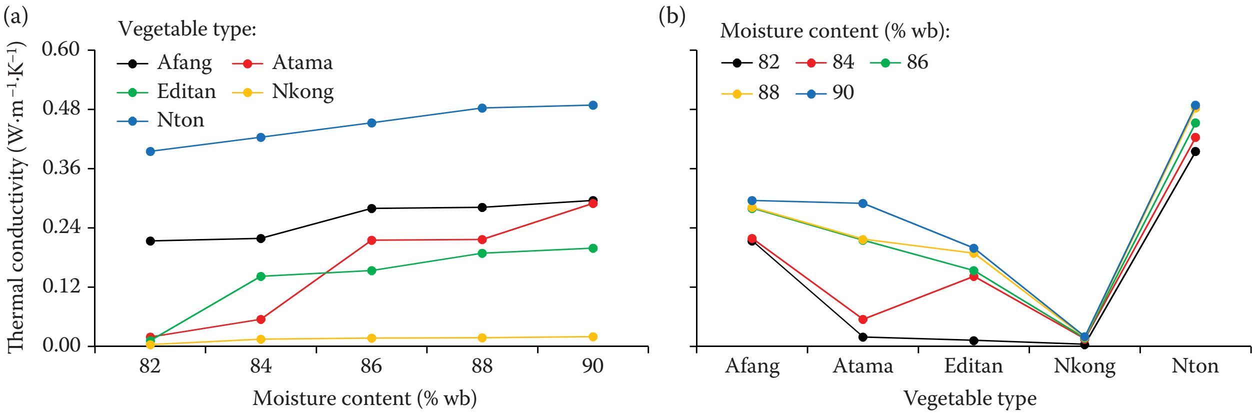

Fig. 2. The interaction plot showing the effects of the moisture content (a) and vegetable type (b) on the thermal conductivity

sidered. These are confirmed by the statistical analysis presented in Table 3. The relationship between the thermal conductivity and the moisture content for the vegetables can be expressed by the following regression equations [Eqs 8 (Nkong), 9 (Editan), 10 (Nton), 11 (Afang), and 12 (Atama)]:

$$k = 0.0036M + 0.0039 \left(R^2 = 0.78\right) \tag{8}$$

$$k = 0.0421M + 0.0128 \left(R^2 = 0.79\right) \tag{9}$$

$$k = 0.0247M + 0.3747 \left(R^2 = 0.97\right) \tag{10}$$

$$k = 0.0227M + 0.1901 \left(R^2 = 0.86\right) \tag{11}$$

$$k = 0.0704M + 0.0521 \left(R^2 = 0.92\right) \tag{12}$$

Table 3. The ANOVA for the thermal conductivity ($W·m^{-1}·K^{-1}$): factors: moisture content (type: fixed, random; level: 5; value: 82, 84, 86, 88, 90%), leafy vegetable (type: fixed, random; level: 5; value: Afang, Atama, Editan, Nkong, Nton)

Source	*df*	SS	MS	*F*-value	*P*-value
Moisture content	4	0.06	0.01	6.93	0.002
Leafy vegetable	4	0.52	0.13	64.37	< 0.001
Error	16	0.03	0.01		
Total	24	0.61			

df – degree of freedom; SS – sum of squares; MS – mean square; S = 0.045; R^2 = 94.69%; R^2 (adj) = 92.03%

Thermal diffusivity

The average values for the thermal diffusivity of the vegetables are presented in Table 1. Editan had the highest thermal diffusivity, while Nkong had the lowest which implies that Editan has the highest ability to conduct heat relative to its ability to store it amongst the selected vegetables. This could be due to the chemical composition and physical structure of the vegetables (Wang, Brennan 1993; Sweat 1995; Ngadi et al. 2003). The variation in the thermal diffusivity of the vegetables with regards to the moisture content is shown in Fig. 3. It was observed that the thermal diffusivity increased linearly with an increase in the moisture content for all the vegetables. This, according to Niesteruk (1996), is due to the way water is bound in the vegetables which influences their thermal properties. This trend conforms to earlier reports by previous researchers (Niesteruk 1996; Aviara, Haque 2001; Farinu, Oon-Doo Baik 2007). It was observed that the moisture content had a significant effect on the thermal diffusivity as the difference in the moisture content increased; and that there were significant differences in the thermal diffusivity of the selected vegetables considered. These are confirmed by the statistical analysis presented in Table 4. The relationship between the thermal diffusivity and the moisture content for the vegetables can be expressed by the following regression equations [Eqs 13 (Nkong), 14 (Editan), 15 (Nton), 16 (Afang), and 17 (Atama)]:

$$\lambda = 0.054M + 0.984 \times 10^{-7} \left(R^2 = 0.98\right) \tag{13}$$

$$\lambda = 0.079M + 1.599 \times 10^{-7} \left(R^2 = 0.98\right) \tag{14}$$

$$\lambda = 0.044M + 1.338 \times 10^{-7} \left(R^2 = 0.94\right) \tag{15}$$

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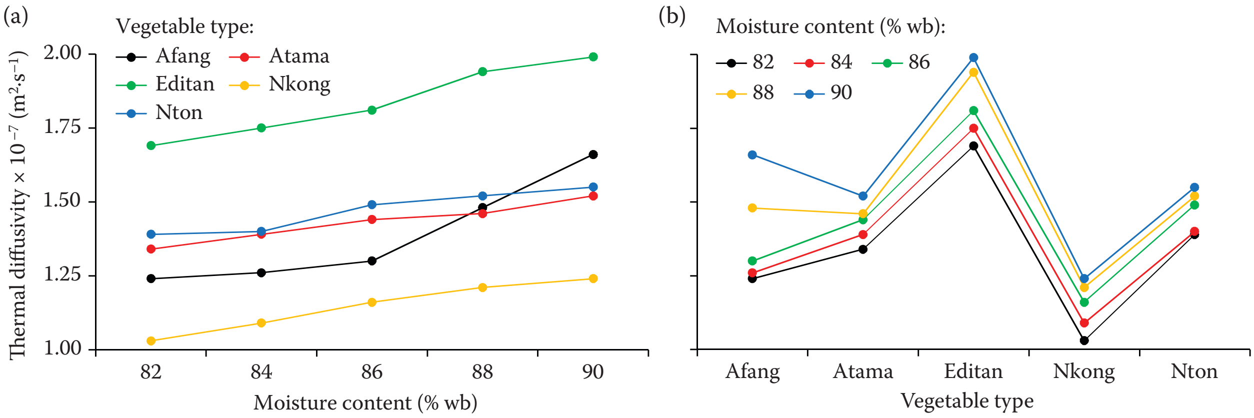

Fig. 3. The interaction plot showing the effects of the moisture content (a) and vegetable type (b) on the thermal diffusivity

Table 4. The ANOVA for the thermal diffusivity ($m^2 \cdot s^{-1}$): factors: moisture content (type: fixed, random; level: 5; value: 82, 84, 86, 88, 90%), leafy vegetable (type: fixed, random; level: 5; value: Afang, Atama, Editan, Nkong, Nton)

Source	*df*	SS	MS	*F*-value	*P*-value
Moisture content	4	0.22	0.05	18.72	< 0.001
Leafy vegetable	4	1.23	0.31	106.85	< 0.001
Error	16	0.05	0.01		
Total	24	1.49			

df – degree of freedom; SS – sum of squares; MS – mean square; S = 0.054; R^2 = 96.91%; R^2 (adj) = 95.37%

$$\lambda = 0.106M + 1.070 \times 10^{-7} \left(R^2 = 0.87\right) \quad (16)$$

$$\lambda = 0.043M + 1.301 \times 10^{-7} \left(R^2 = 0.98\right) \quad (17)$$

CONCLUSION

Amongst the vegetables considered, it was established that Nton had the highest specific heat, while Editan had the lowest; Nton had the highest thermal conductivity, while Nkong had the lowest; and Editan had the highest thermal diffusivity, while Nkong had the lowest. The significant differences in the thermal properties of the vegetables are due to the way that water is bound in them. The thermal properties of the vegetables varied with the moisture content and the variations were found to be linear. Prediction equations for approximate calculations were developed relating the thermal properties with the moisture content. The high coefficient of determination obtained showed excellent correlations between the variables.

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