



ORIGINAL RESEARCH ARTICLE

MOISTURE AND TEMPERATURE INFLUENCE ON THERMAL PROPERTIES
OF WINGED BEAN (*Psophocarpus tetragonolobus*) SEED ACCESSIONS

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ARTICLE
INFORMATION

Submitted 31 January, 2022
Revised 22 June, 2022
Accepted 24 June, 2022

Keywords:

thermal conductivity
thermal diffusivity
specific heat capacity
moisture content
winged bean seed
accessions

ABSTRACT

The thermal properties of three winged bean seed accessions (Entry 4 Tropical *Psophocarpus tetragonolobus* (TPT) 6, Entry II Tropical *Psophocarpus tetragonolobus* (TPT) 30, and Entry 12 Tropical *Psophocarpus tetragonolobus* (TPT) 32) at 5, 10, 15, 20, and 25% moisture contents and 30, 40, and 50 °C temperatures were determined with the KD2 Pro Thermal Analyzer. The results showed that the thermal properties of the seed accessions were moisture-temperature dependent. Entry II TPT 30 had the highest specific heat capacity (1.37-2.59 kJ.kg⁻¹K⁻¹), while Entry 4 TPT 6 had the highest thermal conductivity (0.17-0.60 W.m⁻¹K⁻¹) and thermal diffusivity (0.19-0.77 × 10⁻⁷ m².s⁻¹) as the temperature and moisture increased. A second-order polynomial model described the relationship between the moisture, temperature, and the three thermal properties studied. Respective high correlation coefficients ($R^2 \geq 0.9126$, 0.9872, and 0.9801 for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32 accessions, respectively) indicated their ability to simulate these parameters within the moisture-temperature domain studied. The winged bean seeds' thermal properties will be used to guide design decisions for the creation of agricultural machinery, thermal processes, and equipment required for storage, drying, heating, and cooling.

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1.0 Introduction

Winged bean (*Psophocarpus tetragonolobus* (L.) seeds are tropical crops listed as under-exploited legumes, notwithstanding their high yield potential and nutritional value compared with soybean (Vatanparast et al., 2016; Adegboyega et al., 2019). Winged bean is a crop with several uses; it can be grown as a pulse, root, and tuber crop. Every part of the plant contains distinct nutritional constituents. The leaves and pods are rich sources of vitamins, minerals, and fibre; the seeds are high in protein, while the tubers are rich sources of carbohydrates (Wong et al., 2015; Vatanparast et al., 2016; Adegboyega et al., 2019). The winged bean seed contains high dietary protein due to its amino-acid contents, considerable protein bioavailability, and low anti-nutritional factors (Wan Mohtar et al., 2014). Depending on the accessions and agro-climatic conditions, the seeds have a high range of crude protein (28.43-36.6%), crude fat (13.87-19.01%), ash (4.55-4.98), and carbohydrate (18.43-37.82), as reported by Adegboyega et al. (2019). The seeds also contained a high proportion of phosphorus, calcium, magnesium, zinc, sodium, and copper (Lepcha et al., 2017). Because

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most parts of the plant are edible at all stages of its life cycle, coupled with its exceptional nutritional quality, it was taken as a promising candidate for food and nutrient security in protein-deficient areas of the world (Lepcha *et al.*, 2017).

Notwithstanding the great potential of winged bean seeds, prolonged cooking times significantly limit their utilization. Sambudi and Buckle (1991) reported that the seeds are the essential part; unfortunately, they are the least used product because they are difficult to cook and require a long cooking time for their tenderization. Some winged bean seed accessions have harsh seed coats, making water absorption difficult, while most of them have differing degrees of impermeability to water (Sambudi and Buckle, 1991). Ojo and Ade-Omowaye (2015) also reported certain anti-nutritional compounds such as enzyme inhibitors, hemagglutinins, cyanogens, phytic acid, apart from prolonging cooking time. Oligosaccharides, saponins, and tannins are other factors preventing the efficient utilization of leguminous crops. Thus, the need for intensive heat for cooking wing bean seeds and cracking processes. The thermal properties are essential in various handling and processing operations involving heat and mass transfer (Oriola *et al.*, 2021). Therefore, studying the thermal properties of wing bean seeds is imperative especially for those accessions that have proved promising.

Knowledge of the thermal properties of food and agricultural products is essential for quantifying some unit operations like cooling, heating, drying, pasteurization during post-harvest handling and storage processes and designing processing systems. Thermal properties of agricultural products commonly determined are specific heat, thermal conductivity, and thermal diffusivity. The property needed in the estimation of the amount of energy required to change the temperature of a given mass of product by 1°C is called specific heat, while thermal conductivity and thermal diffusivity are involved in the assessment of the rate of heat transfer for efficient process and equipment design (Yang *et al.*, 2002; Mahapatra *et al.*, 2013). The measure of the ability of a material to conduct heat through it is known as its thermal conductivity. In contrast, the material's inertia, that is, the ability of a material to conduct heat relative to the heat stored per unit volume, is thermal diffusivity. Thermal conductivities are used for modelling thermal processes such as chilling, freezing, and drying, as such models allow for process optimization to improve quality and efficiency (Carson, 2017). On the other hand, the thermal diffusivity explains the heating rate (the heat penetration and temperature distribution) of grains stored in steel silos, mainly in the grain layers closest to the metal sheet, where convective currents of air are responsible for the migration of moisture and heat (Pohndorf *et al.*, 2017).

These thermal properties are important parameters to know in designing equipment or its part and, in a computer simulation, to analyze, optimize, and control the temperature during the elaboration, storage, transportation, and commercialization of foods. Research results have shown that the thermal properties of food and agricultural materials are temperature and moisture dependent (Oriola *et al.*, 2016; Oriola *et al.*, 2021). Also, there is much research on the thermal properties of nuts or seeds such as pumpkin seeds (Kocabiyik *et al.*, 2009), peanut pods (Bitra *et al.*, 2010), Roselle seeds (Bamgboye and Adejumo, 2010), baobab fruits (Adekunle *et al.*, 2013), cowpea flour (Mahapatra *et al.*, 2013), red lentil seeds (Gharibzahedi *et al.*, 2013), cooked locust bean (Oriola *et al.*, 2016), Bambara groundnuts

(Abioye et al., 2016), soybean (Pohndorf et al., 2017), and jack bean seeds (Adeyanju et al., 2019; Oriola et al., 2020).

Literature search revealed that research on moisture content and temperature effects on the specific heat, thermal conductivity, and diffusivity of winged bean seeds are sparse. The aim of this study was to investigate how temperature and moisture content affected the thermal characteristics of three accessions of winged bean seeds.

2. Materials and Methods

2.1. Samples collection

Mature winged bean seed (Entry 4 Tropical *Psophocarpus tetragonolobus* (TPT) 6, Entry II Tropical *Psophocarpus tetragonolobus* (TPT) 30, and Entry 12 Tropical *Psophocarpus tetragonolobus* (TPT) 32) accessions were obtained from the Genetic Resources Unit of the International Institute of Tropical Agriculture (IITA) Ibadan, Oyo State, Nigeria. The seeds were manually winnowed to remove all the extraneous materials. These have been identified among the ten most promising winged bean seed accessions by the IITA.

2.2. Determination of moisture content

The initial moisture content of the winged bean seed accession was determined as described by AOAC (2010) and adopted by Oriola et al. (2016). Five (5 g) of the sample was weighted with a digital electronic weighing scale (GF-6000AND, Japan) of 0.01 g accuracy. The sample was then dry in an electric oven (DHG9101.ISA, UK) at 103 °C for 48 hours. After drying, the per cent moisture content in the sample was determined using the expression in Equation 1.

$$MC_{wb} = \frac{W_m}{W_w} \times 100 \quad (1)$$

Where;

MC_{wb} = winged bean seed moisture content (% wet basis)

W_m = weight of moisture (g)

W_w = weight of the wet sample (g)

The winged bean seed (100 g each) were also conditioned to five different moisture contents of 5, 10, 15, 20, and 25 % (wet basis) after determining the initial moisture content using an OAHM 60 digital moisture analyzer (MD7822 Model) as described by AOAC (2010) and adopted by Oriola et al. (2016). Next, the moisture content of each sample was increased or decreased to the required moisture contents by using either Equation 1 or 2 as appropriate. After that, the samples were poured into polyethene bags, sealed tightly, and conditioned in a refrigerator for 24 h to equilibrate the moisture contents.

$$Q = \frac{W_i (X_f - X_i)}{100 - X_f} \quad (2)$$

Where:

Q = Mass of water added

W_i = Mass of winged bean seed

X_f = Final moisture content of the winged bean seed

X_i = Initial moisture content of the winged bean seed

2.3. Determination of thermal properties

The Decagon KD2 Pro thermal analyzer that employs the transient line heat source method was used to determine the specific heat capacity (C_p), thermal conductivity (k), and thermal diffusivity (α) simultaneously, as described by Oriola (2014) and Oriola *et al.* (2016). The sample holder was loaded with a known quantity of the already conditioned winged bean seeds, and the SH-1 probe gang was selected and inserted through the lid of the sample holder. The reading time of 2 minutes was set for computing the thermal properties determined at an average room temperature of 30°C at each moisture level. The reading displayed on the screen was taken and recorded at an error value of 0.001. After that, the needle of the SH-1 probe of the thermal analyzer rested for 15 minutes to equilibrate to the surrounding temperature before the next experiment as recommended by the manufacturer. The experiments were replicated five times at each moisture level. A thermostatic water bath (DK-2000-ISL) was used to raise the temperature of the samples to 40 and 50°C, respectively, before the above experimental procedures were then repeated at these temperatures for each winged bean seed accessions.

2.4. Statistical Analysis

The data collected were analyzed with SPSS® version 20 (Statistical Package for Social Sciences, USA). The Duncan's Multiple Range Test was used to determine the significant difference between the means, and the differences were significant at $p < 0.05$. Microsoft Excel spreadsheet software version 2013 was used to do all the experimental calculations. Regression analyses of the experimental data were analyzed with the Stat-Ease Design Expert 11.1.2.0 software.

3. Results and Discussion

3.1. Specific heat capacity (C_p) of the three winged bean seed accessions

Results of the specific heat capacity of the winged bean seed accessions were presented in Table 1. In these seeds moisture ranged, the C_p values were observed to increase steadily with an increase in moisture content of the samples for each of the three winged bean accessions, irrespective of temperature. This increase in the C_p with increasing moisture content could be due to the high specific heat of water compared to the dry material, making the water occupy the void spaces faster at lower moisture contents. The C_p values were lower than those reported for pumpkin seeds (2.53 to 3.13 $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) by Kocabiyik *et al.* (2009) and peanut pod (2.1 to 3.3 $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) by Bitra *et al.* (2010). However, they were slightly higher than cooked locust bean seeds (1.38 to 1.94 $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) and jack bean seeds (1.38 to 1.89 $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) reported by Oriola *et al.* (2016) and Adeyanju *et al.* (2019), respectively. The high C_p values obtained for the three winged bean seed accessions translates to winged bean seed requiring thousands of Joules to increase or lower the heat energy by 1 °C.

Table 1: Specific heat capacities of three winged bean seed accessions

Temperature (°C)	Moisture Contents (%)	Entry 4 TPT 6 (kJ/kgK)	Entry 11 TPT 30 (kJ/kgK)	Entry 12 TPT 32 (kJ/kgK)
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30	5	1.44 ± 0.16 ^c	1.72 ± 0.03 ^{bcd}	1.67 ± 0.07 ^{cde}
	10	1.65 ± 0.10 ^{bc}	1.93 ± 0.18 ^{bc}	1.84 ± 0.10 ^c
	15	1.73 ± 0.16 ^{bc}	2.09 ± 0.05 ^b	2.26 ± 0.22 ^b
	20	2.40 ± 0.17 ^a	2.48 ± 0.14 ^a	2.37 ± 0.11 ^{ab}
	25	2.42 ± 0.03 ^a	2.59 ± 0.13 ^a	2.63 ± 0.07 ^a
40	5	1.53 ± 0.01 ^c	1.36 ± 0.03 ^e	1.47 ± 0.12 ^e
	10	1.64 ± 0.10 ^{bc}	1.61 ± 0.11 ^{cde}	1.49 ± 0.10 ^{de}
	15	1.76 ± 0.10 ^{bc}	1.67 ± 0.13 ^{bcd}	1.60 ± 0.03 ^{cde}
	20	2.52 ± 0.17 ^a	1.95 ± 0.13 ^{bc}	1.63 ± 0.13 ^{cde}
	25	2.53 ± 0.15 ^a	2.08 ± 0.21 ^b	1.82 ± 0.07 ^{cd}
50	5	1.38 ± 0.02 ^c	1.37 ± 0.28 ^e	1.34 ± 0.09 ^e
	10	1.42 ± 0.16 ^c	1.46 ± 0.10 ^{de}	1.54 ± 0.03 ^{cde}
	15	1.52 ± 0.13 ^c	1.55 ± 0.04 ^{cde}	1.59 ± 0.03 ^{cde}
	20	1.52 ± 0.18 ^c	1.72 ± 0.06 ^{bcd}	1.62 ± 0.03 ^{cde}
	25	2.00 ± 0.18 ^b	1.88 ± 0.14 ^{bcd}	1.66 ± 0.16 ^{cde}

Means within the same column at each temperature with different superscripts are significantly different ($p < 0.05$)

Figure 1 represents the surface plot showing the interactions between the temperature, moisture, and C_p of the winged bean seed accessions. As observed from the plots, the C_p increased linearly as the moisture content increased at a low temperature of 30 °C for the three accessions. The linearly increasing trend in C_p with moisture content correlates with work done by other researchers for other agricultural products such as; Bart-Plange et al. (2012) for cashew kernel, Mahapatra et al. (2013) for cowpea, Isa et al. (2014) for melon seeds, Abioye et al. (2016) for Bambara groundnut, Oriola et al. (2016) for cooked locust bean seeds and Matouk et al. (2018) for faba bean seeds. At a lower temperature (30 °C), the percentage increases of the C_p with moisture increase were higher than those at higher temperatures (50 °C) for the three accessions. This suggests that low heat energy would be needed to change the temperature of the bean seed accessions during heating processes. However, other studies have reported decreasing trends with moisture content, such as; Bamgboye and Adejumo (2010) for roselle seeds and Adeyanju et al. (2019) for jack bean seeds. This shows that the food materials to be processed would determine the type of heat processing it needs to be subjected to. Thus, these results of C_p could help analyze the heat energy required for each stage of the processing and optimization of winged bean seeds. This will, in turn, reduce the heating duration to the barest minimum, which could help in nutrients retention and energy savings.

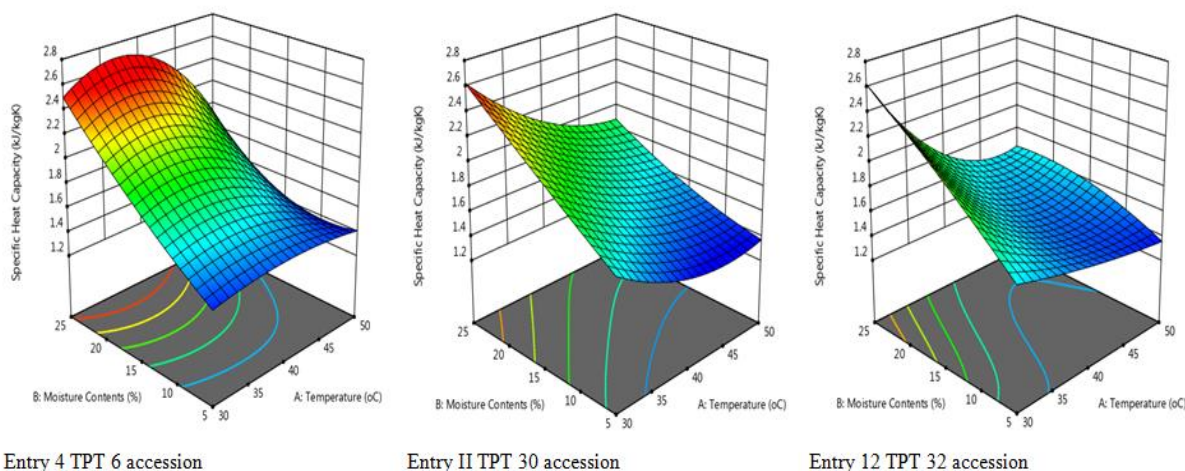


Figure 1: Effects of moisture and temperature on specific heat capacities of winged bean seed accessions

Several regression equations were fitted to determine the model that best describes the relationship between temperature, moisture content, and C_p of the studied winged bean seed accessions. Second-order polynomial models gave the highest coefficient of determination (R^2) value of 0.9126, 0.9877, and 0.9886 for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32, respectively (Table 2). This implies that these 2nd order polynomial equations obtained could best fit the relationships between temperature, moisture, and the C_p of the winged bean seed accessions studied. The model F-values of 10.43, 60.04, and 64.92 for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32, respectively (Table 3), implied that the models were significant. The analysis of variance p-values less than 0.05 indicated that the temperature, moisture contents and the combined temperature and moisture content were significant with the C_p of the Entry II TPT 30 and Entry 12 TPT 32 accessions. However, effects of combined temperature and moisture content were not significant ($p > 0.05$) with the C_p of the Entry 4 TPT 6 accession.

Table 2: Polynomial regression model equations for three winged bean seed accessions

Accessions	Equations	R^2
Entry 4 TPT 6	$C_p = 1.930 - 0.221x_1 + 0.576x_2 - 0.137x_1x_2 - 0.256x_1^2 + 0.126x_2^2 - 0.171x_1^2x_2 + 0.081x_1x_2^2 + 0.016x_1^2x_2^2$	0.9126
	$k = 0.330 + 0.136x_1 + 0.068x_2 + 0.040x_1x_2 + 0.010x_1^2 + 0.011x_2^2 + 0.008x_1^2x_2 + 0.011x_1x_2^2$	0.9862
	$\alpha = 0.572 + 0.073x_1 - 0.226x_2 - 0.125x_1x_2 - 0.047x_1^2 - 0.044x_2^2 + 0.255x_1^2x_2 + 0.036x_1x_2^2$	0.9567
Entry II TPT 30	$C_p = 1.740 - 0.297x_1 + 0.356x_2 - 0.101x_1x_2 + 0.124x_1^2 - 0.006x_2^2 + 0.001x_1^2x_2 + 0.027x_1x_2^2 + 0.041x_1^2x_2^2$	0.9877
	$k = 0.409 + 0.131x_1 + 0.152x_2 + 0.007x_1x_2 - 0.095x_1^2 + 0.022x_2^2 - 0.097x_1^2x_2 + 0.007x_1x_2^2$	0.9872
	$\alpha = 0.369 + 0.133x_1 - 0.164x_2 + 0.004x_1x_2 - 0.049x_1^2 + 0.074x_2^2 + 0.098x_1^2x_2 - 0.011x_1x_2^2 -$	0.9880

	$0.049x_1^2x_2^2$	
	$C_p = 1.560 - 0.287x_1 + 0.168x_2 - 0.173x_1x_2 + 0.321x_1^2 + 0.074x_2^2 + 0.149x_1^2x_2 - 0.030x_1x_2^2 - 0.141x_1^2x_2^2$	0.9886
Entry 12 TPT 32	$k = 0.395 + 0.110x_1 + 0.154x_2 + 0.014x_1x_2 - 0.079x_1^2 + 0.007x_2^2 - 0.078x_1^2x_2 - 0.006x_1x_2^2$	0.9801
	$\alpha = 0.322 + 0.227x_1 + 0.054x_2 + 0.085x_1x_2 + 0.101x_1^2 + 0.009x_2^2 + 0.107x_1^2x_2 + 0.024x_1x_2^2 + 0.027x_1^2x_2^2$	0.9959

Where; x_1 = Temperature
 x_2 = Moisture content

Table 3: Analysis of variance for effect of temperature and moisture content on the specific heat capacities of three winged bean seed accessions

Polynomial regression Source	Entry 4 TPT 6 (kJ/kgK)					Entry II TPT 30 (kJ/kgK)					Entry 12 TPT 32 (kJ/kgK)				
	Sum of Squares	Df	Mean Square	F-value	p-value	Sum of Squares	Df	Mean Square	F-value	p-value	Sum of Squares	Df	Mean Square	F-value	p-value
Model	2.33	7	0.333	10.43	0.003*	1.88	10	0.235	60.04	0.0001*	1.86	8	0.232	64.92	0.0001*
A-Temperature	0.201	1	0.201	6.28	0.041*	0.362	1	0.362	92.55	0.0001*	0.339	1	0.339	94.84	0.0001*
B-Moisture Contents	0.829	1	0.829	25.97	0.001*	0.317	1	0.317	80.96	0.0001*	0.071	1	0.071	19.73	0.004*
AB	0.094	1	0.094	2.94	0.130	0.051	1	0.051	13.03	0.011*	0.150	1	0.150	41.84	0.001*
A ²	0.205	1	0.205	6.42	0.039*	0.021	1	0.021	5.42	0.059	0.141	1	0.141	39.48	0.001*
B ²	0.049	1	0.049	1.52	0.257	0.000	1	0.000	0.007	0.935	0.005	1	0.005	1.35	0.289
A ² B	0.049	1	0.049	1.53	0.257	1.67E-06	1	1.67E-06	0.000	0.984	0.037	1	0.037	10.35	0.018*
AB ²	0.012	1	0.012	0.36	0.566	0.001	1	0.001	0.330	0.587	0.002	1	0.002	0.440	0.532
A ² B ²	-	-	-	-	-	0.001	1	0.001	0.256	0.631	0.012		0.012	3.26	0.121
Residual	0.224	7	0.032			0.024	6	0.004			0.022	6	0.004		
Total	2.56	14				1.90	14				1.88	14			

The asterisk (*) values are significant at $p < 0.05$

3.2. Thermal conductivity (κ) of three winged bean seed accessions

Results of the thermal conductivity of the three winged bean seed accessions at different moisture contents and temperatures are as presented in Table 4. Like the C_p , the κ of the three winged bean seed accessions were observed to increase with an increase in the moisture content irrespective of the samples temperature. But, unlike the C_p , the κ was observed to increase with the temperature for the three seed accessions. The values of thermal conductivities obtained in this study were slightly higher than 0.11 to 0.28 $W.m^{-1}K^{-1}$ reported for borage seeds (Yang et al., 2002), 0.113 to 0.135 $W.m^{-1}K^{-1}$ for pumpkin seeds (Kocabiyik et al., 2009), and 0.19 to 0.24 $W.m^{-1}K^{-1}$ for red lentil seeds (Gharibzahedi et al., 2013). However, it falls within the same ranged of 0.57 to 0.61 $W.m^{-1}K^{-1}$ for egusi melon (Isa et al., 2014), 0.25 to 0.31 $W.m^{-1}K^{-1}$ for Bambara groundnut (Abioye et al., 2016), and 0.21 to 0.41 $W.m^{-1}K^{-1}$ for jack bean seeds (Oriola et al., 2020) within the same moisture contents studied. These values obtained are also within the range of 0.02 to 0.62 $W.m^{-1}K^{-1}$ for unfrozen food products, as Carson (2017) reported. The high value of the thermal

conductivity obtained for these winged bean seed accessions indicated better heat conductors.

Table 4: Thermal conductivities of three winged bean seed accessions

Temperature (°C)	Moisture Contents (%)	Entry 4 TPT 6 (W/mK)	Entry II TPT 30 (W/mK)	Entry 12 TPT 32 (W/mK)
30	5	0.17 ± 0.02 ^g	0.14 ± 0.04 ^h	0.15 ± 0.02 ⁱ
	10	0.18 ± 0.02 ^{fg}	0.17 ± 0.02 ^{gh}	0.18 ± 0.05 ^{hi}
	15	0.21 ± 0.02 ^{fg}	0.19 ± 0.04 ^{gh}	0.21 ± 0.10 ^{ghi}
	20	0.22 ± 0.04 ^{efg}	0.21 ± 0.04 ^{fgh}	0.25 ± 0.02 ^{fgh}
	25	0.24 ± 0.03 ^{def}	0.24 ± 0.02 ^{fg}	0.27 ± 0.05 ^{efg}
40	5	0.28 ± 0.03 ^{cde}	0.28 ± 0.04 ^f	0.26 ± 0.11 ^{efgh}
	10	0.29 ± 0.05 ^{cd}	0.36 ± 0.04 ^e	0.33 ± 0.07 ^{def}
	15	0.32 ± 0.02 ^c	0.39 ± 0.03 ^{de}	0.34 ± 0.02 ^{de}
	20	0.39 ± 0.02 ^b	0.46 ± 0.05 ^{bcd}	0.50 ± 0.04 ^{ab}
	25	0.40 ± 0.02 ^b	0.61 ± 0.06 ^a	0.56 ± 0.07 ^a
50	5	0.39 ± 0.05 ^b	0.41 ± 0.03 ^{de}	0.33 ± 0.08 ^{def}
	10	0.42 ± 0.04 ^b	0.42 ± 0.03 ^{de}	0.38 ± 0.02 ^{cd}
	15	0.45 ± 0.04 ^b	0.44 ± 0.02 ^{cd}	0.44 ± 0.04 ^{bc}
	20	0.58 ± 0.06 ^a	0.51 ± 0.03 ^{bc}	0.47 ± 0.06 ^b
	25	0.60 ± 0.02 ^a	0.52 ± 0.04 ^b	0.51 ± 0.07 ^{ab}

Means within the same column at each temperature with different superscripts are significantly different ($p < 0.05$)

Figure 2 represents the surface plot showing the interactions between the temperature, moisture, and the thermal conductivity of the winged bean seed accessions. The thermal conductivity of the winged bean seed accessions increased with moisture contents in a linear (reduced cubic) positive relationship following a second-order polynomial equation. The increase in the thermal conductivity with moisture content in linear relationship obtained in this study agreed with other researchers such as Singh and Goswami (2000) for cumin seed, Yang *et al.* (2002) for borage seeds, Aviara *et al.* (2008) for shea nut kernel, Kurozawa *et al.* (2008) for cashew nut and apple, Kocabiyik *et al.* (2009) for pumpkin seeds and Gharibzahedi *et al.* (2013) for red lentil seeds. However, a nonlinear relationship was reported by Oriola (2014) for cassava roots and Oriola *et al.* (2020) for jack bean seeds.

These differences in the thermal conductivity may be attributed to the variation in seed size, porosity of sample bulk, and seed chemical compositions of each seed accession (for example, oil and protein contents) (Gharibzahedi et al., 2010).

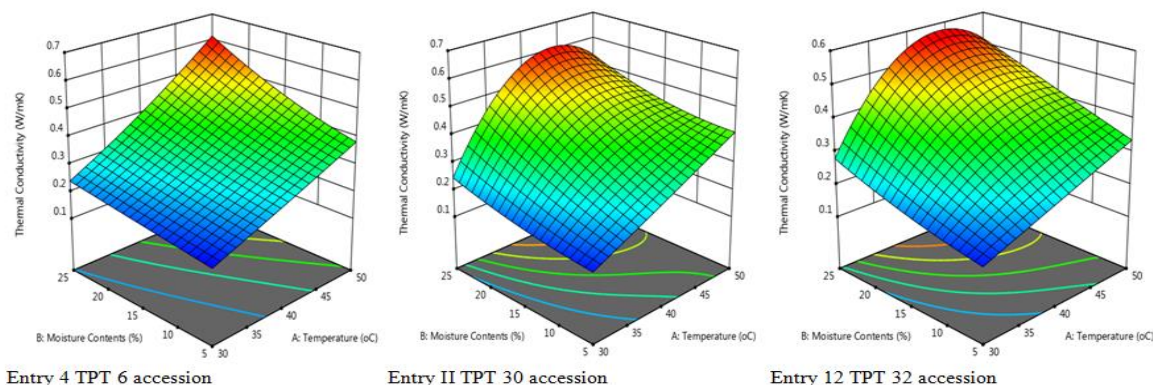


Figure 2: Effects of moisture and temperature on thermal conductivities of winged bean seed accessions

A polynomial function that best described the effects of temperature and moisture content on the thermal conductivity of the three winged bean accessions was investigated. Second-order polynomial models give the best fit resulting in an R^2 value of 0.9862, 0.9872, and 0.9801 was obtained for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32 accessions, respectively (Table 2). This implies that these 2nd order polynomial equations best fit the relationships between temperature, moisture, and the κ of the winged bean seed accessions studied. The model F-values of 71.53, 77.08, and 49.30 for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32, respectively (Table 5), implied that the models were significant. The analysis of variance p-values less than 0.05 indicated that the temperature, moisture contents and the combined temperature and moisture content were significant with the κ of the Entry 4 TPT 6 accession. However, the effects of combined temperature and moisture content were not significant ($p > 0.05$) with the κ of the Entry II TPT 30 and Entry 12 TPT 32 accessions.

Table 5: Analysis of variance for effect of temperature and moisture content on the thermal conductivity of three winged bean seed accessions

Polynomial regression Source	Entry 4 TPT 6 (W/mK)					Entry II TPT 30 (W/mK)					Entry 12 TPT 32 (W/mK)				
	Sum of Squares	Df	Mean Square	F-value	p-value	Sum of Squares	Df	Mean Square	F-value	p-value	Sum of Squares	Df	Mean Square	F-value	p-value
Model	0.2510	7	0.0359	71.53	0.0001*	0.2868	7	0.0410	77.08	0.0001*	0.2246	7	0.0321	49.30	0.0001*
A-Temperature	0.0765	1	0.0765	152.59	0.0001*	0.0711	1	0.0711	133.80	0.0001*	0.0497	1	0.0497	76.35	0.0001*
B-Moisture Contents	0.0116	1	0.0116	23.06	0.0020*	0.0578	1	0.0578	108.65	0.0001*	0.0593	1	0.0593	91.09	0.0001*
AB	0.0080	1	0.0080	15.96	0.0052*	0.0002	1	0.0002	0.4609	0.5190	0.0010	1	0.0010	1.51	0.2595
A ²	0.0003	1	0.0003	0.6650	0.4416	0.0301	1	0.0301	56.59	0.0001*	0.0208	1	0.0208	31.96	0.0008*
B ²	0.0003	1	0.0003	0.6840	0.455	0.0013	1	0.0013	2.37	0.1676	0.0001	1	0.0001	0.1792	0.6847
A ² B	0.0001	1	0.0001	0.2128	0.6586	0.0157	1	0.0157	29.50	0.0010*	0.0101	1	0.0101	15.58	0.0056*
AB ²	0.0002	1	0.0002	0.4560	0.5212	0.0001	1	0.0001	0.1680	0.6942	0.0001	1	0.0001	0.0878	0.7756
Residual	0.0035	7	0.0005			0.0037	7	0.0005			0.0046	7	0.0007		
Total	0.2545	14				0.2905	14				0.2292	14			

The asterisk (*) values are significant at $p < 0.05$

3.3. Thermal diffusivity of three winged bean seed accessions

Results of the thermal diffusivity of the three winged bean seed accessions at different moisture contents and temperatures are as presented in Table 6. The Entry 4 TPT 6 accession was observed to have the highest thermal diffusivity values while Entry 12 TPT 32 and Entry II TPT 30 accessions followed, respectively, as the temperature and moisture increased. These values obtained are less than 1.0 and agreed with the thermal diffusivity values published for some other foods in the literature, such as; Cumin seeds by Singh and Goswami (2000), pumpkin seed by Kocabiyik *et al.* (2009), peanut pod and kernel by Bitra *et al.* (2010), doum palm fruits by Aremu and Fadele (2010), soybean grains by Pohndorf *et al.* (2017), and jack bean seeds by Oriola *et al.* (2020).

Table 6: Thermal diffusivities of three winged bean seed accessions

Temperature (°C)	Moisture Contents (%)	Entry 4 TPT 6 (m ² /s) × 10 ⁻⁷	Entry II TPT 30 (m ² /s) × 10 ⁻⁷	Entry 12 TPT 32 (m ² /s) × 10 ⁻⁷
30	5	0.19 ± 0.01 ^c	0.31 ± 0.02 ^{def}	0.13 ± 0.04 ^g
	10	0.41 ± 0.11 ^{abc}	0.20 ± 0.08 ^{fg}	0.16 ± 0.06 ^g
	15	0.45 ± 0.17 ^{abc}	0.19 ± 0.04 ^{fg}	0.21 ± 0.02 ^{fg}
	20	0.46 ± 0.16 ^{abc}	0.19 ± 0.01 ^{fg}	0.22 ± 0.02 ^{fg}
	25	0.55 ± 0.10 ^{abc}	0.14 ± 0.01 ^g	0.29 ± 0.02 ^{ef}
40	5	0.77 ± 0.07 ^a	0.61 ± 0.04 ^a	0.28 ± 0.05 ^{ef}
	10	0.66 ± 0.12 ^{ab}	0.46 ± 0.06 ^{bc}	0.29 ± 0.02 ^{ef}
	15	0.53 ± 0.07 ^{abc}	0.38 ± 0.03 ^{cde}	0.32 ± 0.03 ^{ef}
	20	0.51 ± 0.17 ^{abc}	0.30 ± 0.02 ^{def}	0.36 ± 0.06 ^{de}
	25	0.28 ± 0.09 ^{bc}	0.28 ± 0.03 ^{ef}	0.38 ± 0.04 ^{de}
50	5	0.68 ± 0.16 ^{ab}	0.52 ± 0.05 ^{ab}	0.45 ± 0.03 ^d
	10	0.65 ± 0.10 ^{ab}	0.51 ± 0.05 ^{ab}	0.58 ± 0.04 ^c
	15	0.61 ± 0.10 ^{ab}	0.44 ± 0.03 ^{bc}	0.62 ± 0.02 ^c
	20	0.53 ± 0.14 ^{abc}	0.42 ± 0.06 ^{bcd}	0.79 ± 0.04 ^b
	25	0.50 ± 0.15 ^{abc}	0.41 ± 0.05 ^{bcd}	0.96 ± 0.05 ^a

Means within the same column at each temperature with different superscripts are significantly different (p<0.05)

Figure 3 represents the surface plot showing the interactions between the three winged bean seed accessions' temperature, moisture, and thermal diffusivity. It was observed that the thermal diffusivity of samples of the Entry 4 TPT 6 and Entry 12 TPT 32 generally increased with an increase in moisture content at 30°C while those of Entry II TPT 30 declined with an increase in moisture at the same temperature. Also, at temperatures of 40 and 50°C, the diffusivity of the seed of Entry 4 TPT 6 generally decreased with increased moisture content. The thermal diffusivity of the seeds of the Entry II TPT 30 generally reduced with an increase in moisture content irrespective of the sample temperature. However, seeds of the Entry 12 TPT 32 were observed to increase with both increases in

temperature and moisture. Abioye et al. (2016) reported an increase in the thermal diffusivity with a rise in Bambara groundnut moisture content. In contrast, Adekunle et al. (2013) reported increased in thermal diffusivity with temperature increase for baobab fruit pulp powder.

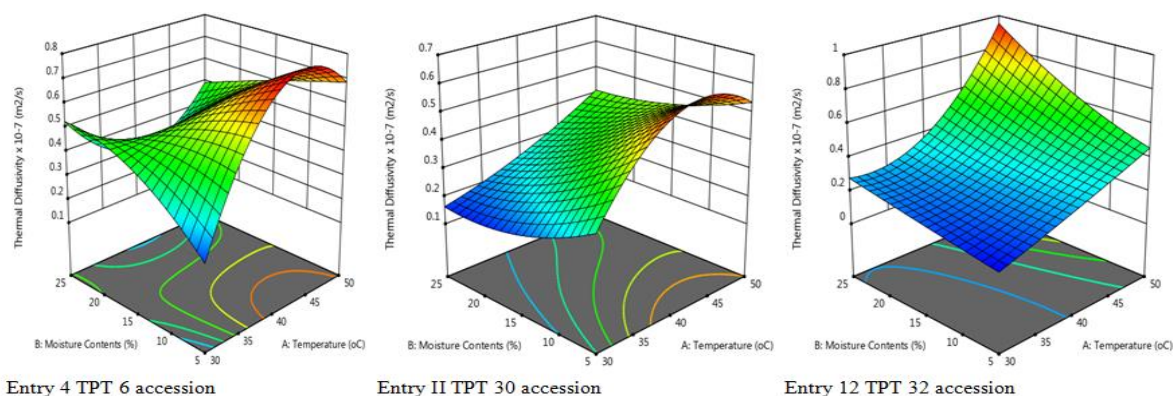


Figure 3: Effects of moisture and temperature dependent on thermal diffusivities of winged bean seed accessions

A polynomial function that shows the simultaneously dependent temperature and moisture content on the thermal diffusivities was investigated to correlate experimental data. The best fit resulting in an R^2 value of 0.9567, 0.9880, and 0.9959 was obtained for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32 accessions, respectively (Table 2). This implies that these 2nd order polynomial equations obtained could best fit the relationships between temperature, moisture, and the thermal diffusivity of the winged bean seed accessions studied. The model F-values of 22.10, 61.87, and 182.61 for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32, respectively (Table 7), implied that the models are significant. The analysis of variance p-values less than 0.05 indicated that the temperature, moisture contents and the combined temperature and moisture content were significant with the thermal diffusivity of the Entry 4 TPT 6 and Entry 12 TPT 32 accessions. However, the effects of combined temperature and moisture content were not significant ($p > 0.05$) with the thermal diffusivity of the Entry II TPT 30 accession.

Table 7: Analysis of variance for effect of temperature and moisture content on the thermal diffusivity of three winged bean seed accessions

Polynomial regression Source	Entry 4 TPT 6 (m ² /s) x 10 ⁻⁷					Entry II TPT 30 (m ² /s) x 10 ⁻⁷					Entry 12 TPT 32 (m ² /s) x 10 ⁻⁷				
	Sum of Squares	Df	Mean Square	F-value	p-value	Sum of Squares	Df	Mean Square	F-value	p-value	Sum of Squares	Df	Mean Square	F-value	p-value
Model	0.3075	7	0.0439	22.10	0.0003*	0.2744	8	0.0343	61.87	0.0001*	0.7916	8	0.0990	182.61	0.0001*
A-Temperature	0.0220	1	0.0220	11.09	0.0126*	0.0725	1	0.0725	130.84	0.0001*	0.2119	1	0.2119	391.05	0.0001*
B-Moisture Contents	0.1277	1	0.1277	64.26	0.0001*	0.0672	1	0.0672	121.31	0.0001*	0.0073	1	0.0073	13.45	0.0105*
AB	0.0781	1	0.0781	39.32	0.0004*	0.0001	1	0.0001	0.1443	0.7171	0.0361	1	0.0361	66.66	0.0002*
A ²	0.0074	1	0.0074	3.71	0.0956	0.0033	1	0.0033	5.88	0.0516	0.0141	1	0.0141	26.06	0.0022*
B ²	0.0050	1	0.0050	2.54	0.1553	0.0048	1	0.0048	8.71	0.0256*	0.0001	1	0.0001	0.1186	0.7423
A*B	0.1084	1	0.1084	54.54	0.0002*	0.0160	1	0.0160	28.88	0.0017*	0.0191	1	0.0191	35.21	0.0010*
AB ²	0.0022	1	0.0022	1.12	0.3244	0.0002	1	0.0002	0.4124	0.5445	0.0010	1	0.0010	1.90	0.2168
A ² B ²	-	-	-	-	-	0.0014	1	0.0014	2.48	0.1662	0.0004	1	0.0004	0.7931	0.4075
Residual	0.0139	7	0.0020			0.0033	6	0.0006			0.0033	6	0.0005		
Total	0.3214	14				0.2777	14				0.7949	14			

The asterisk (*) values are significant at $p < 0.05$

4. Conclusions

The influence of moisture and temperature on the thermal properties of winged bean seed accessions revealed that:

- i. The Cp and thermal conductivity generally increased with increased moisture content for the three winged bean seed accessions. In contrast, the thermal diffusivity decreased with increased moisture content at elevated temperatures (40 and 50 °C).
- ii. Second-order polynomial models best described the relationship between the studied thermal properties and the temperature and moisture content. The regression equations ($R^2 \geq 0.9126$, 0.9872 , and 0.9801 for Entry 4 TPT 6, Entry II TPT 30, and Entry 12 TPT 32 accessions, respectively) obtained in this study provide a reasonable estimate simulating the thermal properties of the winged bean seeds within the moisture-temperature range studied.
- iii. The analysis of variance (ANOVA) showed that moisture and temperature have a significant ($p < 0.05$) effect on the thermal properties of the winged bean seeds.
- iv. These thermal properties of the winged bean seeds examined will help design considerations for the fabrication of agricultural machines, thermal processes, and equipment needed for storage, drying, heating, and cooling.
- v. The recommended use of the winged bean seeds' thermal qualities will enable the development of agricultural machinery, thermal systems, and apparatus for heating, cooling, drying, and storing.

References

- Abioye, AO., Adekunle, AA. and Agbasi-Ebere, V. 2016. Some moisture-dependent physical and thermal properties of bambara groundnut. IOSR Journal of Environmental Science, Toxicology and Food Technology, 10(10): 65-74.
- Adegboyega, TT., Abberton, MT., AbdelGadir, AH., Dianda, M., Maziya-Dixon, B., Oyatomi, OA., Ofodile, S. and Babalola, OO. 2019. Nutrient and antinutrient composition of winged bean (*Psophocarpus tetragonolobus* (L.) DC.) seeds and tubers. Journal of Food Quality, Article ID 3075208. <https://doi.org/10.1155/2019/3075208>.
- Adekunle, AA., Shittu, TA., Abioye, AO., Adeyanju, JA. and Osanaiye, FG. 2013. Physical and thermal properties of baobab fruit pulp powder. International Journal of Engineering Research and Applications, 3(3): 925-928.

Adeyanju, JA., Adekunle, AA., Abioye, AO., Ogunlakin, GO., Olajire, AS. and Fashina, OZ. 2019. Determination of moisture-dependent physical and thermal properties of jack bean (*Canavalia ensiformis*) related to design of processing machines. Nigerian Food Journal, 37(1), 106-116.

AOAC. 2010. Official Methods of Analysis of Association of Official Analytical Chemists (18th ed.). Washington D.C

Aremu, AK. and Fadele, OK. 2010. Moisture dependence thermal properties of doum palm fruit (*Hyphaene thebaica*). Journal of Emerging Trends in Engineering and Applied Sciences, 1(2): 199–204.

Aviara, NA., Haque, MA. and Ogunjimi, LAO. 2008. Thermal properties of guna seeds. International Agrophysics, 22: 291-297.

Bamgboye, AI. and Adejumo, O.I. 2010. Thermal properties of roselle seed. International Agrophysics, 24: 85-87.

Bart-Plange, A., Addo, A., Kumi, F. and Piegu, AK. 2012. Some moisture dependent thermal properties of cashew kernel (*Anacardium occidentale* L.) Australian Journal of Agricultural Engineering, 3(2): 65-69.

Bitra, VSP., Banu, S., Ramkrishna, P., Narender, G. and Womac, AR. 2010. Moisture dependent thermal properties of peanut pods, kernels and shell. Journal of Food Engineering, 106: 503-512.

Carson, JK. 2017. Use of Simple Thermal conductivity models to assess the reliability of measured thermal conductivity data. International Journal of Refrigeration, 74: 458-464.

Gharibzahedi, SMT., Etemad, V., Mirarab-Razi, J. and Foshat, M. 2010. Study on some engineering attributes of pine nut (*Pinus pinea*) to the design of processing equipment. Research in Agricultural Engineering, 56(3): 99-106.

Gharibzahedi, SMT., Ghahderijani, M. and Lajevardi, ZS. 2013. Specific heat, thermal conductivity and thermal diffusivity of red lentil seed as a function of moisture content. Journal of Food Processing and Preservation, 38(4): 1807-1811.

Isa, J., Oladele, SO. and Akinlade, ES. 2014. The effect of moisture content on thermal properties of some selected species of egusi melon (*Colocynthis citrillus* L.). International Journal of Emerging Technology and Advanced Engineering, 4(4): 580-586.

Kocabiyik, H., Kayisoglu, B. and Tezer, D. 2009. Effect of moisture content on thermal properties of pumpkin seed. International Journal of Food Properties, 12(2): 277-285.

Kurozawa, LW., Park, KJ. and Azonbel, PM. 2008. Thermal conductivity and thermal diffusivity of papaya (*Carica papaya* L.) and cashew apple (*Anacardium occidentale* L.). Brazilian Journal of Food Technology, 11: 78-85.

Lepcha, P., Egan, AN., Doyle, JJ. and Sathyanarayana, N. 2017. A review on current status and future prospects of winged bean (*Psophocarpus tetragonolobus*) in tropical agriculture. Plant Foods for Human Nutrition, 17: 225-235.

Mahapatra, AK., Melton, SL. and Isang, EM. 2013. Effect of moisture content on thermal properties of cowpea flours. Agricultural Engineering International: CIGR Journal, 15(2): 251-255.

Matouk, AM., EL-Kholy, MM., Tharwat, A. and Shamala, SF. 2018. Thermal properties of some legume seeds. *Journal of Soil Sciences and Agricultural Engineering*, 9(7): 261-267.

Ojo, MA. and Ade-Omowaye, BIO. 2015. Some functional and physical properties of selected underutilised hard-to-cook legumes in Nigeria. *American Journal of Food Science and Nutrition*, 2(5): 73-81.

Oriola, KO. (2014). Effects of ageing and moisture content on thermal properties of cassava roots using response surface methodology. *International Journal of Applied Agricultural and Apicultural Research*, 10(1&2): 54-63.

Oriola, KO., Hussein, JB., Oke, MO. and Ajetunmobi, A. 2020. Description and evaluation of physical and moisture dependent thermal properties of jack bean seeds (*Canavalia ensiformis*) *Journal of Food Processing and Preservation*, e15166. <https://doi.org/10.1111/JFPP.15166>.

Oriola, KO., Hussein, JB., Oke, MO. and Ajetunmobi, A. 2021. Influence of moisture and temperature on the thermal properties of jack bean seeds (*Canavalia ensiformis*). *Food and Feed Research*, 48(2): 165-174.

Oriola, KO., Oke, MO., Hussein, JB. and Adebisin, KT. 2016. Thermal properties of cooked locust bean (*Parkia biglobosa*) seeds as affected by temperature-moisture interactions. *Nigerian Journal of Horticultural Science*, 21(2016): 48-56.

Pohndorf, RS., Rocha, JC., Lindemann, I., Peres, WB., Oliveira, M. and Elias, MC. 2017. Physical properties and effective thermal diffusivity of soybean grains as a function of moisture content and broken kernels. *Journal of Food Process and Engineering*, e12626. <https://doi.org/10.1111/jfpe.12626>.

Sambudi, H. and Buckle, KA. 1991. Characteristics of winged bean (*Psophocarpus tetragonolobus*) seeds during soaking and boiling. *Journal of the Science Food and Agriculture*, 57(4): 585-595.

Singh, KK. and Goswami, TK. 2000. Thermal properties of cumin seed. *Journal of Food Engineering*, 45: 181-187.

Vatanparast, M., Shetty, P., Chopra, R., Doyle, JJ., Sathyanarayana, N. and Egan, AN. 2016. Transcriptome sequencing and marker development in winged bean (*Psophocarpus tetragonolobus* L.). *Scientific Reports*, 6(1) <https://doi.org/10.1038/srep29070>.

Wan Mohtar, WA., Hamid, AA., Abd-Aziz, S., Muhamad, SK. and Saari, N. 2014. Preparation of bioactive peptides with high angiotensin converting enzyme inhibitory activity from winged bean [*Psophocarpus tetragonolobus* (L.) DC.] seed. *Journal of Food Science and Technology*, 51(12): 3658-3668.

Wong, QN., Massawe, F. and Mayes, S. 2015. Improving winged bean (*Psophocarpus tetragonolobus*) productivity: an analysis of the determinants of productivity. *Acta Horticulturae*, 1102: 83-88.

Yang, W., Sokhansanj, S., Tang, J. and Winter, P. 2002. Determination of thermal conductivity, specific heat, and thermal diffusivity of borage seeds. *Biosystems Engineering*, 82(2):169-176.