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MATHEMATICAL MODELLING OF HEAT TRANSFER DURING OGBONO (Irvingia spp.) SEEDS OPEN-SUN DRYING

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Abstract: Ogbono (Irvingia spp.) kernel is a popular soup condiment in West Africa. Drying is an important step in the processing of Ogbono (Irvingia spp.). This paper is geared towards developing a better understanding of the different factors involved in the heat transfer during the open-sun drying of Ogbono (Irvingia spp.) seeds. For this purpose, a mathematical model was developed for the heat transfer to and out of the seeds. This model served as the framework for factor effects and interaction studies. Ambient temperature, seed size, air velocity and the thermal conductivity of the drying surface showed a direct relationship with the internal temperature of the seeds albeit at varying levels. Moisture content showed an inverse relationship. An analysis of variance showed that ambient temperature, seed size and air velocity were observed to be the most significant factors affecting the heat transport. The interactions between the different factors as it affects heat transport were also elucidated.

Keywords: mathematical model, heat transfer, factors, interaction, Irvingia

1. INTRODUCTION

Irvingia spp. is a semi-wild fruit growing in the tropics of Africa [23]. There are numerous species of the plant which includes Irvingia gabonensis, Irvingia wombolu, Irvingia grandiflora, Irvingia excelsa, Irvingia malayana, Irvingia robur and Irvingia smithii [9]. I. gabonensis and I. wombolu are the two popular species in western Africa. Irvingia spp. is locally referred to as ogbono. The trees are usually large and evergreen and can grow up to 35 meters in height [4]. The tree usually fruits between the months of July and October [1] though efficient storage ensures it availability all year round. The popularity of the plant in the west African area can be attributed to the use of its oil-rich seed cotyledons which are relished as soup condiments [1, 11]. The fruit of I. gabonensis is sweet and edible while I. wombolu is more bitter, sticky and undesirable to eaten raw [22]. I. wombolu kernels is more sought after than those of other species due to its greater sliminess when used as soup condiment [2]. Results from analysis performed on the seed kernels and fruits of Irvingia spp. has revealed numerous nutrients needed for the health of man [1, 10, 15, 17, 19, 24]. The kernel is grounded and utilised as a condiment in the ogbono soup [25] which is eaten with a carbohydrate like cassava or yam [5].

Drying is a key step in the processing of Ogbono (Irvingia spp.) fruit. It first involves the fermentation of the freshly harvested fruits to ease the de-pulping process. The partially fermented and in some cases rotten pulps can then be washed off to obtain the nuts [3]. Subsequently, the nuts are sun-dried and cracked to obtain the kernels. The drying process usually consumes the most time among all the processing stages. This is a major incentive in studying the drying process and gaining a better understanding of it. Research has been conducted over the years on Ogbono (Irvingia spp.) fruit and seed from a horticultural perspective [12, 13, 21, 26]. Mathematical modelling of the thin-layer drying characteristics has been previously undertaken by Aregbosola Ogunsina [3] and the effective moisture diffusivity at different drying temperatures were examined.

This paper has developed a mathematical model of the heat transfer to Ogbono (Irvingia spp.) seeds during open-sun drying and utilising it as a platform to study how certain key factors affect the internal seed temperature during the process. Open-sun drying is still prevalent is western Africa, even in large scale production due to its low cost, non-dependence on electricity, abundance of a high level of solar insolation and availability in remote areas. Drying is a complex chemical engineering unit operation involving transient transfer of heat and, mass along with several rate processes, such as physical or chemical transformations [8], which, in turn may cause changes in product quality and characteristics [20]. A study of the heat transfer will be beneficial to the large scale processing of the fruits as it can help improve the productivity of the process and reduce cost. In addition, the agriculturist can then have a better understanding of the combinatorial effect of some of these drying factors on each other.

2. METHODOLOGY

— Model Formulation

This section encompasses the formulation of a general mathematical model for heat transfer in the open-sun drying of Irvingia spp. For the purpose of studying the factors, prediction of seed constants was made for a specific seed species (I. wombolu). In the development of the model, some simplifying assumptions were employed. They are enumerated below.

- # The shape of the ogbono (Irvingia spp.) seed will be considered as spherical. However, it is practically an oblate spheroid in practical sense.

- # The seed will be analysed as a homogenous isentropic spheroid with the physical, thermal and chemical properties of the seed considered as those of the entire solid.
- # It will be considered that no chemical changes take place within the solid (during the open sun drying process) to significantly affect the physical and thermal properties of the seed.
- # The fruit is static while placed out to dry, and possess no physical velocity component in any direction.
- # Steady state heat transport is assumed.
- # The seeds are dried in a single layer and not heaped on top of each other.
- # There is negligible physical contact between seeds and this does not cause any impingement on air flow to the seeds.
- # It was assumed that all drying surfaces are perfectly smooth.
- # The initial sphericity of the seeds before the commencement of drying will be used for the analysis. It has been shown that sphericity of Irvingia spp can drop by 5 - 10% as moisture content reduces [9].
- # The value of the temperature gradients is typically very small as the ambient air is almost always at thermal equilibrium with the seed surface. It will be assumed that $T_s \leq T_m, \leq T_o$and in increments of about 1 ^{0}C.
- # The heat loss due to the latent heat of evaporation of water is not considered in the convection analysis because in drying operation for Irvingia spp, moisture drop is very slow, gradual and evaporation rate is not significant enough to have an effect on the instantaneous internal temperature of the seeds.

We consider the Figure 1 so as to obtain a better picture of the heat transfer forms and different temperatures of the system.

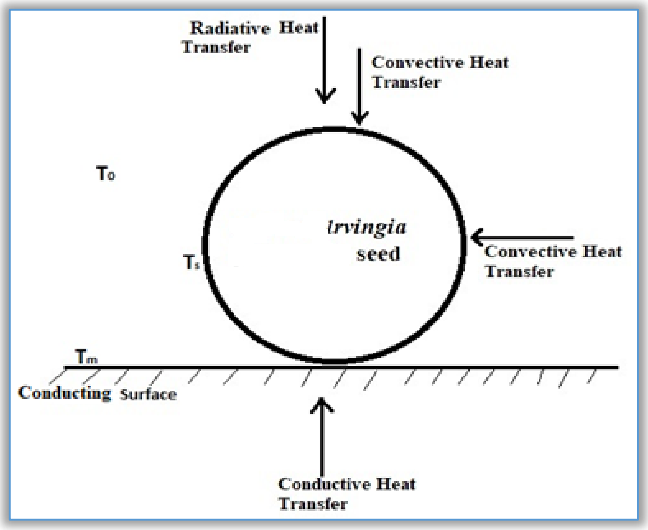


Figure 1: Heat transfer forms and different temperatures of the open sun drying system

Let's consider an elemental shell of the above seed in consideration (of thickness Δr). The diagram below represents this.

Therefore:

Rate of conductive heat flow in at r

$$4\pi r^2 q_r|_r \tag{1}$$

Rate of conductive heat flow out at $r + \Delta r$

$$4\pi r^2 q_r|_{r+\Delta r} \tag{2}$$

Radiative heat transfer from sun to the seed

$$4\pi r^2 \epsilon\sigma(T_s^4 - T_o^4) \tag{3}$$

Convective heat transfer to the seed

$$4\pi r^2 h(T_s - T_o) \tag{4}$$

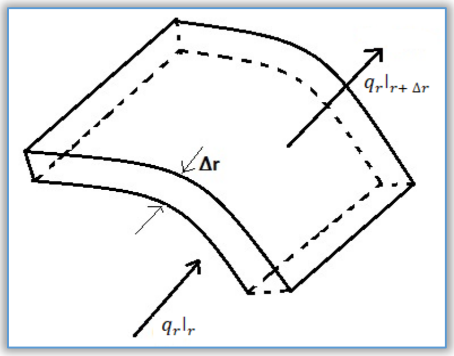


Figure 2: Elemental shell of the Ogbono seed

Taking heat energy balance over the spherical shell of thickness Δr, then we have (5):

$$4\pi r^2 q_r|_r - 4\pi r^2 q_r|_{r+\Delta r} + 4\pi r^2 \epsilon\sigma(T_s^4 - T_o^4) + 4\pi r^2 h(T_s - T_o) = 0 \tag{5}$$

Divide (5) through by $4\pi r^2 \Delta r$ and taking a limit as $\Delta r \to 0$, gives (6):

$$-\frac{dq_r}{dr} - \epsilon\sigma\frac{dT^4}{dr} - h\frac{dT}{dr} = 0 \tag{6}$$

Equation (6) is the general differential expression for the heat flow for the open sun drying of Ogbono seeds. The conductive heat transfer involves the heat flow from the conducting body to the seed surface (m to s) and from the seed surface to the center of the seed (s to c). Both phenomena are in-cooperated into the overall term for convective heat flow as given in (7).

$$q_r = UC_p\nabla T + ή\left(-K_m\frac{dT}{dr}\right)_{m-s} + \left(-K_s\frac{dT}{dr}\right)_{s-c} \tag{7}$$

A coefficient of physical contact (ή) was added because the entirety of the seed surface is not in contact with the conducting surface. This term is the approximate fraction of the total surface area of the seed, in physical contact with the solid support (and the fraction is a small value for a spheroidal particle). U is a physical velocity vector of the drying seeds. Considering that from simplifying assumption (iv) the seeds do not possess any velocity component in any direction and are static while being dried, this term is null. Equation (7) in its reduced form, because of the negligible effects of the first term, is put as (8), while (8), in differential form is (9).

$$q_r = \acute{\eta}\left(-K_m\frac{dT}{dr}\right)_{m-s} + \left(-K_s\frac{dT}{dr}\right)_{s-c} \tag{8}$$

$$\frac{dq_r}{dr} = -\acute{\eta}K_m\frac{d^2T}{dr^2} - K_s\frac{d^2T}{dr^2} \tag{9}$$

Substituting (9) into the general differential expression for the heat flow (6), we obtain (10), which on proper analysis and integration within appropriate limits gives (11). (10) is first integrated between points s and o, then integrated again between points c and s to obtain (11).

$$\acute{\eta}K_m\frac{d^2T}{dr^2} + K_s\frac{d^2T}{dr^2} - \epsilon\sigma\frac{dT^4}{dr} - h\frac{dT}{dr} = 0 \tag{10}$$

$$\acute{\eta}K_m\frac{dT}{dr} + K_s\frac{dT}{dr} - \epsilon\sigma(T_s^4 - T_o^4) - h(T_s - T_o) = 0$$

$$\acute{\eta}K_m\frac{dT}{dr} + K_s\frac{dT}{dr} = \epsilon\sigma(T_s^4 - T_o^4) + h(T_s - T_o)$$

$$\acute{\eta}K_m dT + K_s dT = \epsilon\sigma(T_s^4 - T_o^4)dr + h(T_s - T_o)dr$$

$$\int_m^s \acute{\eta}K_m dT + \int_s^c K_s dT = \int_s^c \epsilon\sigma(T_s^4 - T_o^4)dr + \int_s^c h(T_s - T_o)dr \tag{11}$$

The length of the radius at the very centre of the seed is considered to be zero while the length of the radius at the surface is maximum (r); r_s=r and r_c=0. Proper analysis gives equation (12). For the temperature, the entire domain is from c, through s to m. However, the thermal conductivity of the seed material (K_s) is only in-play between c and s (and null beyond that) and the thermal conductivity of the metal surface (K_m) between s and m (and null beyond that). Hence the limits of integration for temperature are set as presented in (11).

$$\acute{\eta}K_m(T_s - T_m) + K_s(T_c - T_s) = -\epsilon\sigma r(T_s^4 - T_o^4) - hr(T_s - T_o)$$

$$K_sT_c - K_sT_s = -\epsilon\sigma r(T_s^4 - T_o^4) - hr(T_s - T_o) - \acute{\eta}K_m(T_s - T_m)$$

$$K_sT_c = K_sT_s - \epsilon\sigma r(T_s^4 - T_o^4) - hr(T_s - T_o) - \acute{\eta}K_m(T_s - T_m)$$

$$T_c = \frac{1}{K_s}\left[K_sT_s - \epsilon\sigma r(T_s^4 - T_o^4) - hr(T_s - T_o) - \acute{\eta}K_m(T_s - T_m)\right] \tag{12}$$

The ambient temperature (T_o), surface temperature (T_m) and temperature of the seed surface (T_s) are measurable. This model can serve as a predictor of the internal temperature of the seed and this is an important indicator of the heat flow into and out of the seed through the different heat mediums. Also, the above model is dimensionally consistent as all addendums possess same units and multiplication with the coefficient/factor gives a final temperature term on the right-hand side (RHS). The dimensional consistency is confirmed and put as (13)

Putting together the units of each term in (12), we have the expression:

$$K\,[=]\,\frac{1}{W/mK}\left[\left(\frac{W}{mK}\right)K - \left(\frac{W}{m^2K^4}\right)(K^4)m - \left(\frac{W}{m^2K}\right)mK - \left(\frac{W}{mK}\right)K\right]$$

$$K\,[=]\,\frac{mK}{W}\left[\left(\frac{W}{m}\right) - \left(\frac{W}{m}\right) - \left(\frac{W}{m}\right) - \left(\frac{W}{m}\right)\right]$$

$$K\,[=]\,K \tag{13}$$

The dimensional consistency of the model is essential in demonstrating the mathematical correctness of the expression.

– Prediction of the Seed (I. wombolu) Constants

For a practical use of the developed model (12), the unknown constants were predicted to give a useable model. The constants predicted included the contact factor ($\acute{\eta}$), thermal conductivity of the seed (K_s), convective heat transfer for open air drying (h) and the emissivity of the seed (ϵ).

The contact factor ($\acute{\eta}$) is the approximate fraction of the total surface area of the seed, in physical contact with the drying surface. This factor depends not only on the sphericity (ϕ) of the seed but the smoothness of the drying surface and seed surface in contact. As stated earlier, it is assumed that all drying surfaces are perfectly smooth. It is important that the contact factor is established as a function of the sphericity of the seed. Equation (14) by McCabe, Smith [16] elucidated the concept.

$$\phi = \frac{6V}{DS} \tag{14}$$

The sphericity is independent of particle size [16]. However, the sphericity reduces as moisture content reduces by about 10% for Irvingia wombolu [9]. However, in-cooperating this assertion by Ikotun [9] will make the model too cumbersome and only relevant for use with softwares. The initial sphericity of the seeds before the commencement of drying will be used for the analysis. The less spherical the seed, the larger the portion of its surface in physical contact with the support (contact factor) and vice-versa; $\acute{\eta} \propto \frac{1}{\phi}$. This gives us a simple relationship represented as (15).

$$\acute{\eta} = \frac{\text{ʒ}}{\phi} \tag{15}$$

ʒ is a value that is unique to each shape and will be subsequently elucidated. In this work, it will be termed as the shape coefficient. It is the product of the sphericity of a shape and the fraction of its surface area in contact with a solid support. The value of ʒ is different for each shapes. The actual approximate shape of ogbono (Irvingia spp.) seed is oblate spheroid. An oblate spheroid has a known sphericity and for seeds of Irvingia wombolu [9, 22] it has been studied and is well understood. The sphericity as earlier mentioned has also be shown to be a function of the moisture content of the seed [9]. This is clearly put as (16).

$$\phi = 0.63463 + 0.002379\mathrm{M} \text{ (Irvingia wombolu)} \tag{16}$$

To determine the approximate value of the shape coefficient (ʒ) we will utilize a well understood approximately spherical regular shape. We will consider that for a disdyakis triacontahedron (with 120 faces), only 1 face of the total faces will be in contact with a solid support. The sphericity is a known value of 0.986. This value will suffice as we have earlier assumed that the shape of the seeds will be considered as approximately spherical also, as expressed in

$$1/120 = \frac{\text{ʒ}}{0.986} \tag{17}$$

$$\text{ʒ} = 0.0082$$

$$\acute{\eta} = \frac{0.0082}{\phi}$$

Since we now know the approximate value of ʒ, the expression for the contact factor (as a function of moisture content) is represented in (18).

$$\acute{\eta} = \frac{0.0082}{0.63463+0.002379\mathrm{M}} \text{ (Irvingia wombolu)} \tag{18}$$

The thermal conductivity of the seed ($\mathrm{K_s}$) will also need to be evaluated. Researchers have made great progress in determining the electrical and thermal properties of Irvingia spp. seeds [6, 9, 18]. Thermal conductivity has been shown to vary with temperature and moisture content [6, 9]. The lower the moisture content, the lower the thermal conductivity. Also, data available are only for seed kernels and not for seed. In view of all these, it will be honestly difficult to pin-point a single constant value for the thermal conductivity of ogbono (Irvingia spp.) seeds. For this analysis, the thermal conductivity of the seeds as a function of moisture content will be utilised and are given in (19) [9].

$$\mathrm{K_s} = 0.1462 + 0.0274\mathrm{M} \text{ W/mK (Irvingia wombolu)} \tag{19}$$

The next parameter to be determined is the convective heat transfer coefficient for open air drying (h). This value is highly dependent on the velocity of the flowing air. For air flowing at a velocity over a spherical body and having a forced convection heat interaction, the correlations [7] in (20) and (21) hold:

$$\frac{\mathrm{hr}}{2\mathrm{K_{air}}} = 2 + 0.6\mathrm{N_{RE}^{0.5}N_{PR}^{1/3}} \tag{20}$$

$$\mathrm{N_{RE}} = \frac{\mathrm{r v \rho}}{2\mu} \tag{21}$$

The correlation in (20) stands provided $\mathrm{N_{RE}}$ is between 1 and 70,000 and $\mathrm{N_{PR}}$ is between 0.6 and 400. The fluid properties ($\mathrm{K_{air}},\ \rho,\ \mu,\ \mathrm{N_{PR}}$) were evaluated at the film temperature ($\mathrm{T_f}$) and this is simply $\mathrm{T_f} = \frac{\mathrm{T_o+T_s}}{2}$.

For case by case analysis, a new value of h is always needed to be calculated, but for this work, a convective heat flow coefficient was evaluated at an atmospheric pressure of 1 atm, a film temperature of 25^{0}C, an average seed diameter of 31.83 mm (intermediate diameter for medium size grade by Ogunsina, Koya [21]) and an air velocity of 'v' (in meters per second). It should be noted that the seeds tend to shrink by up to 10% as the moisture content drops [9] so the average diameter of seeds was also determined on a case by case basis. The physical properties of air (interpolated) at 298K [7] are: $\mathrm{N_{PR}}$= 0.709, μ= 1.845×10^{-5} Pa.s, ρ= 1.187 Kg/m^3, $\mathrm{K_{air}}$= 0.026 W/mK, therefore (22) and other auxiliary positions were analysed to give (23):

$$\mathrm{N_{RE}} = \frac{0.0159\times \mathrm{v}\times 1.187}{2\times 1.845\times 10^{-5}} \tag{22}$$

$$\mathrm{N_{RE}} = 511.47\mathrm{v}$$

Substituting this value along with those of other constants into (20)

$$\frac{0.0159\mathrm{h}}{2\times 0.026} = 2 + 0.6\times(511.47\mathrm{v})^{0.5}\times 0.709^{1/3}$$

$$\mathrm{h} = 6.54 + 39.57\mathrm{v}^{0.5}\mathrm{W/m^2K} \tag{23}$$

The final parameter to be determined is the emissivity of the seed (Є). The emittance of a surface is determined by the physical properties and temperature of the surface but independent of the environment of the body [14]. A black body possesses an emittance of one (1) but real bodies have emittance lying between zero (0) and one (1). According to Lienhard and Lienhard [14], for wood and other cellulosic surfaces at 40^{0}C, the emissivity (Є) lies between 0.8 and 0.9. The seed of ogbono (Irvingia spp) is a cellulosic material and will therefore have a value in this range. In this research work, we utilised a value of 0.85 for ogbono (Irvingia spp) seed.

Table 1. Summary of the predicted constants for ogbono seed

Parameter	Irvingia wombolu
Contact factor (ή)	$\frac{0.0082}{0.6346 + 0.0024M}$
Conductive heat transfer coefficient (K_s) [W/mK]	$0.1462 + 0.0274M$
Convective heat transfer coefficient (h) [W/m²K]	$6.54 + 39.57v^{0.5}$
Emissivity of the seed (ϵ)	0.85

– Factor Effect and Interaction Studies

In studying the effects and interactions of the factors involved in the open sun drying, the model was inputted into Microsoft excel 2016 to quicken the mathematical calculations. Response surface methodology (RSM) was used in investigating the factor effects. Design Expert 10.0 did an ANOVA of the calculation results to determine the most significant factors. Significance level was at ≤0.05. Central Composite Design (CCD) was used to design the experiments for the study of factor interactions and effects. In order for more convenient writing, the notations given to the factors/independent variables are presented in Table 2.

Table 2: The factors/independent variables of Open Sun Drying

Notation	Factor	Unit
A	Ambient temperature (T_o)	⁰C
B	Seed size (r)	M
C	Air velocity (v)	m/s
D	Moisture content of the seed (M)	-
E	Thermal conductivity - drying surface (K_m)	W/mK
Y1	Internal temperature (T_c)	⁰C

The lower and upper limits of the independent variables in the experimental plan were fixed as presented in Table 3.

Table 3: The lower and upper limits of the independent variables

S/N	Factor	Lower Limit	Upper Limit
1	A	20	35
2	B	0	0.05
3	C	0	0.2
4	D	0.4	0.5
5	E	0.01	15

The above factor ranges where chosen in the domain of ambient conditions prevalent in the open sun in West Africa. Temperature range is between 20⁰C and 35⁰C, thermal conductivity is between 0.1 to 15 W/mK from insulating to a highly conducting surfaces, maximum seed radius of 50 mm and air velocity ranging between static air and 0.2 m/s air flow. The values of each factor to be used in calculation was according to the design matrix of the factor ranges by Central Composite Design. The calculation results according to the design matrix are presented in the appendix section.

3. RESULTS AND DISCUSSION

There will always tend to be heat exchange between surfaces in contact provided there is a temperature gradient as equilibrium is inherently being pursued. This model is a predictor of the internal temperature of the seed and this is an important indicator of the heat flow into and out of the seed through the different heat mediums. It will be impractical to break every seed being sundried to determine how hot it is inside, just to know what extent heat is getting into it. In this case, this model becomes relevant to farmers and process engineers.

$$T_c = \frac{1}{K_s}[K_sT_s - \epsilon\sigma r(T_s^4 - T_o^4) - hr(T_s - T_o) - \acute{\eta}K_m(T_s - T_m)]$$

We can now substitute the already predicted constants (K_s, h, ϵ, ή) and those constants which are generally known (σ) into the model. This gives us the actual heat transfer model expression for Irvingia wombolu as (24)

$$T_c = \frac{1}{0.1462+0.0274M}\left[\begin{array}{c}(0.1462 + 0.0274M)T_s - 0.85\sigma(T_s^4 - T_o^4)r \\ -(6.54 + 39.57v^{0.5})r(T_s - T_o) - \frac{0.0082K_m(T_s-T_m)}{0.6346+0.0024M}\end{array}\right] \tag{24}$$

For the model in (24), all unknowns on the RHS is essentially a factor. We observe that the key factors affecting the heat transfer to the seed in the drying system are;

i. The size of the seed in terms of the radius (r).
ii. The ambient temperature of the drying system (T_o) which will determine the seed surface and metal surface temperatures (T_s, T_m).
iii. The air velocity (v).

iv. The moisture content of the seed (M).
v. The thermal conductivity of the drying surface $(\mathrm{K_m})$.

The temperature of the drying system $(\mathrm{T_s},\ \mathrm{T_o},\ \mathrm{T_m})$ is dependent on the ambient temperature $(\mathrm{T_o})$. The ambient temperature will inadvertently have significant effects on the seed surface temperature $(\mathrm{T_s})$ and the drying surface temperature $(\mathrm{T_m})$. Theoretical relationship exists between these temperatures but that will require a new mathematical analysis and more models. The value of the temperature gradients $(\mathrm{T_s} - \mathrm{T_o})$ and $(\mathrm{T_s} - \mathrm{T_m})$ are typically very small as the ambient air is almost always at thermal equilibrium with the seed surface. It should be noted that though degrees Celsius is used in this discussion, actual substitution and calculations with the model is done in Kelvin.

– Effect of Factors on seed internal temperature

» Ambient temperature

The Figure 3 represents the relationship between ambient and internal temperature for a seed size of 50 mm, air velocity of 0.1 m/s, 50% moisture content and for a well conducting surface of 15 W/mK. It is observed that at these conditions, the temperature within the seed undergoes a steady rise with ambient temperature. This is valid considering there will be a higher heat transfer driving force with a greater temperature gradient. In the domain of open-sun drying conditions, ambient temperature controls the temperature of the other materials as it inadvertently specifies the largeness of the temperature gradient (and the extent of heat transfer by consequence).

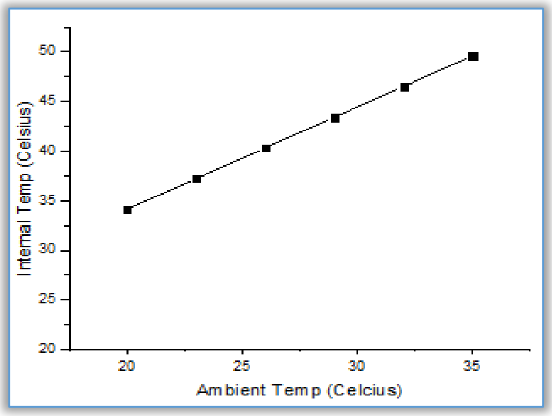


Figure 3: Effects of Ambient Temperature on the Internal Temperature

» Seed size

Figure 4 represents the relationship between seed size and internal temperature for an ambient temperature of 25^{0}C, air velocity of 0.1 m/s, 50% moisture content and for a well conducting surface of 15 W/mK. For the given conditions, larger seeds tend to have a higher temperature within than smaller sized seeds. However, drying is more of a function of moisture content than of internal temperature. The higher temperatures within larger seeds don't necessarily indicate a higher drying rate. Larger seeds will take more time to dry as outward diffusion of moisture from within the seeds also depends on other factors as mass transfer driving force, air humidity and evaporation rate. This figure simply tells us that larger seeds are hotter within than smaller seeds under the same conditions. From the plot it can be theorised that if Irvingia spp were are small as pellets, then for their bio-material, there will exist a far smaller temperature gradient between ambient conditions and the seed internal temperatures (as heat transfer will be more rapid).

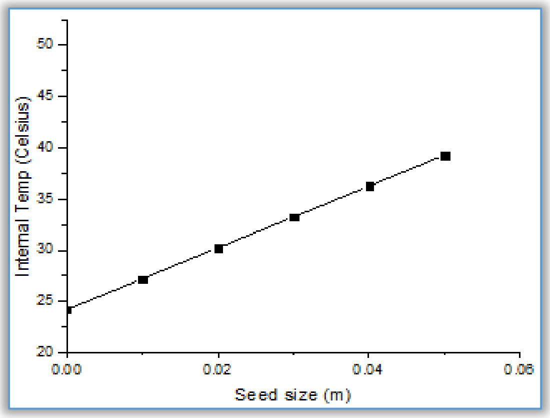


Figure 4: Effects of Seed Size on the Internal Temperature

» Air velocity

The Figure 5 represents the relationship between air velocity and internal temperature for an ambient temperature of 25^{0}C, seed size of 50 mm, 50% moisture content and for a well conducting surface of 15 W/mK. The flow of air around the seeds encourages convective heat flow exchange between the seeds and the surrounding air. At very low air velocities, changes possess significant effect on the heat transfer pattern to the drying seed. However, at high air velocities this effect becomes far less significant on the internal temperatures of the seed.

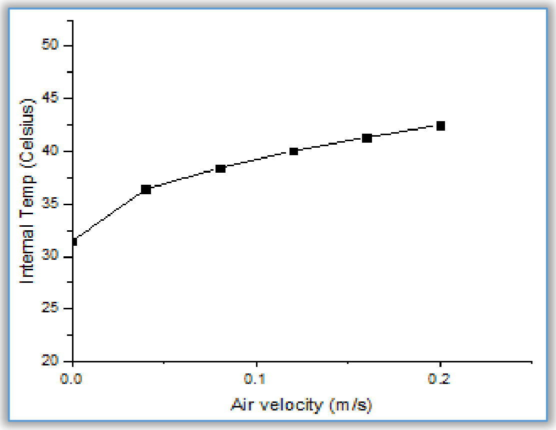


Figure 5: Effects of Air Velocity on the Internal Temperature

» Moisture Content

The Figure 6 represents the relationship between moisture content and internal temperature for an ambient temperature of 25^{0}C, seed size of 50 mm, air velocity of 0.1 m/s and for a well conducting surface of 15 W/mK. There is only a very slight effect of the seed moisture content on the internal temperature of the seed. Though it shows an inverse relationship, in practical terms this is hardly ever noticeable.

» Drying surface thermal conductivity

The Figure 7 represents the relationship between drying surface thermal conductivity and internal temperature for an ambient temperature of 25^{0}C, seed size of 50 mm, air velocity of 0.1 m/s and moisture content of 50%. A highly conductive surface will tend to conduct heat to or from the seed (depending of the temperature gradient). The effect is however not markedly significant on the internal temperature because only a very small fraction of the seed surface is ever in contact with the underlying solid support due to its orientation and shape.

» Significance of Factors

An analysis of variance (ANOVA) was used to determine the significance or non-significance of the factors.

Table 4: Analysis of Variance

Analysis of variance table [Partial sum of squares - Type III]					
Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F
Model	4617.97	20	230.90	21.76	< 0.0001
A (To)	2363.72	1	2363.72	222.74	< 0.0001
B (r)	1492.19	1	1492.19	140.61	< 0.0001
C (v)	256.20	1	256.20	24.14	< 0.0001
D (M)	3.89	1	3.89	0.37	0.5495
E (Km)	3.45	1	3.45	0.32	0.5730
AB	1.07	1	1.07	0.10	0.7532
AC	3.26	1	3.26	0.31	0.5838
AD	2.98	1	2.98	0.28	0.6000
AE	3.00	1	3.00	0.28	0.5993
BC	309.57	1	309.57	29.17	< 0.0001
BD	4.18	1	4.18	0.39	0.5350
BE	3.00	1	3.00	0.28	0.5993
CD	3.76	1	3.76	0.35	0.5563
CE	3.27	1	3.27	0.31	0.5831
DE	2.90	1	2.90	0.27	0.6052
A^2	7.79	1	7.79	0.73	0.3986
B^2	122.73	1	122.73	11.57	0.0020
C^2	0.033	1	0.033	3.120E-003	0.9558
D^2	7.90	1	7.90	0.74	0.3953
E^2	2.92	1	2.92	0.27	0.6041
Residual	307.75	29	10.61		
Lack of Fit			307.75	22	13.99
Pure Error			0.000	7	0.000

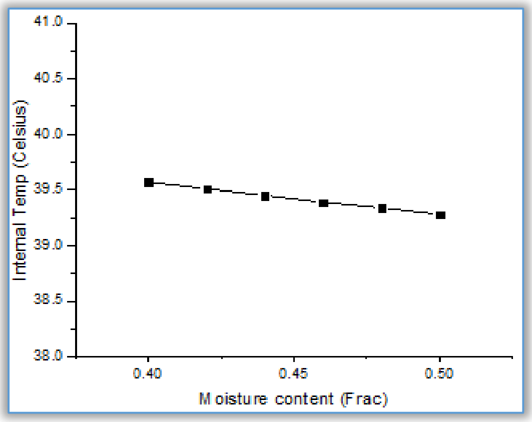


Figure 6: Effects of Moisture Content on the Internal Temperature

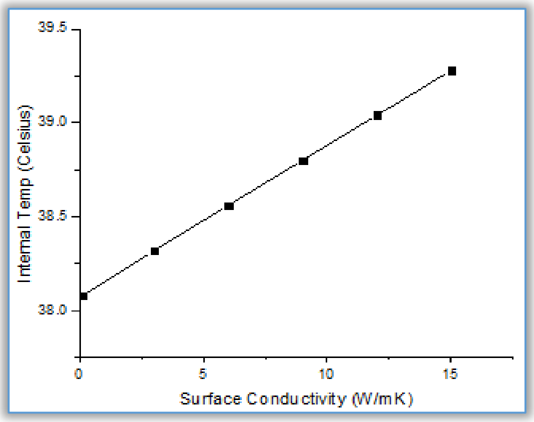
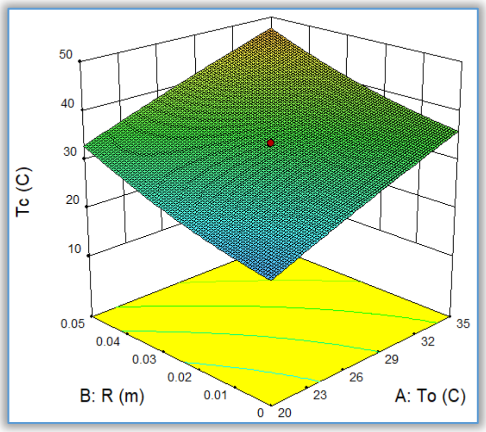


Figure 7: Effects of Surface Conductivity on the Internal Temperature

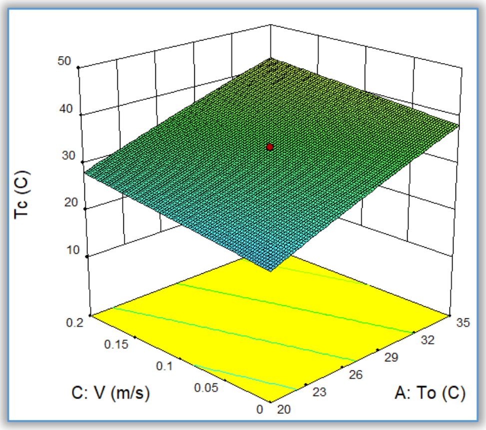
The significance level is 0.05. It can be observed that only ambient temperature, seed size, and air velocity are significant factors affecting the heat transport. Moisture content and drying surface thermal conductivity have less significance on the heat transport. This corresponds with the results obtained in the previous section where. Among the combination of factors, only the combination of seed size and air velocity (BC) was significant.

» Factor interaction studies

This is an examination of the combinatorial relationship between the factors as it affects heat transport. The relationship between one factor and the internal temperature may change markedly for different levels of another factor. Surface plots were used to show the relationship between the factors.



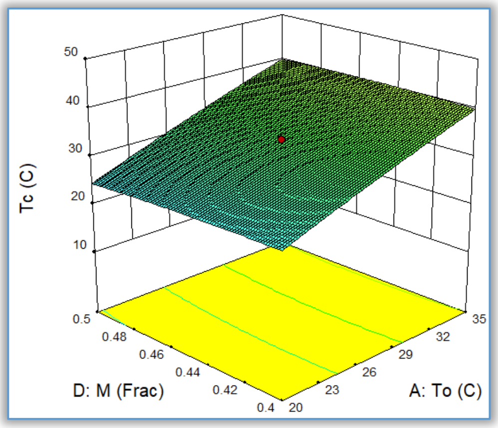
Figures 8: Effect of Seed Size



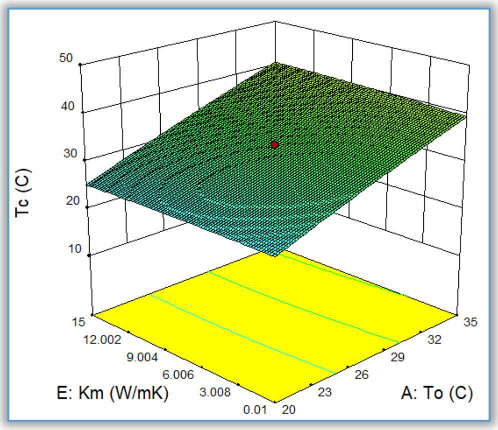
Figures 9: Effect of Velocity

The relationship between seed size, ambient temperature and air velocity is illustrated in Figures 8 and 9. Internal seed temperature increases with increasing ambient temperature. This relationship is same for all seed sizes but with a greater temperature rise for larger seeds. Air velocity does not show any effect on the relationship between ambient temperature and internal seed temperature.

Due to the fact that moisture content (Figure 10) and surface thermal conductivity (Figure 11) are insignificant factors, they do not show any marked effect on the relationship between ambient and internal seed temperature. The relationship is still that of direct proportionality in all regimes of the moisture content and surface thermal conductivity.

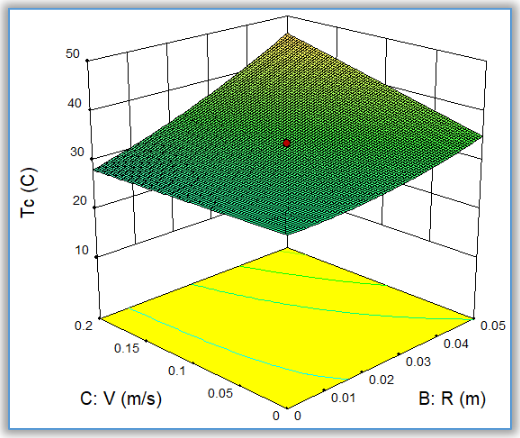


Figures 10: Effect of Moisture Content

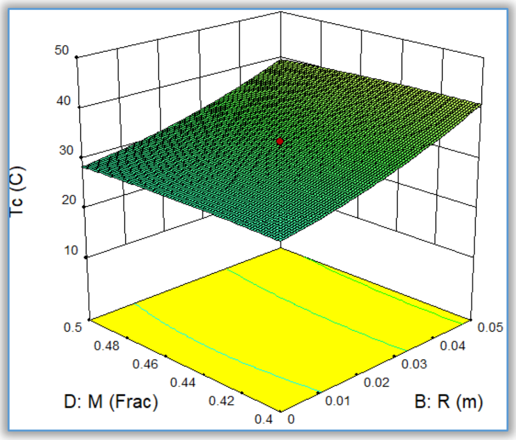


Figures 11: Effect of Thermal Conductivity

At low air velocities, (Figure 12) the internal temperature is almost same for all seed sizes and variation is low. However, at higher air velocities there is a steep rise in the temperature variation with seed size. Moisture content (Figure 13) has no significant effect in the relationship between the seed size and internal seed temperature. For the combinations involving the other less significant factors, there isn't any marked effect on the internal seed temperature during the drying process.



Figures 12: Effects of Air Velocity



Figures 13: Effects of moisture Content

4. CONCLUSION

This paper is geared towards developing a better understanding of the different factors involved in the heat transfer during the open-sun drying of Ogbono (Irvingia spp.) seeds. For this purpose, a mathematical model was developed and utilised as the platform to study how certain key factors affect the process. Open-sun drying is still prevalent is western Africa, even in large scale production due to its low cost, non-dependence on electricity, abundance of a high level of solar insolation and availability in remote areas. Studying the heat transfer process is relevant as beneficial as it furnishes stakeholders with key information about how these factors affect heat transfer to the seeds. Ambient temperature, seed size, air velocity and the thermal conductivity of the drying surface showed a direct relationship with the internal temperature of the seeds albeit at varying levels. Moisture content showed an inverse relationship. An analysis of variance showed that ambient temperature, seed size and air velocity were observed to be the most significant factors affecting the heat transport. The interactions between the different factors as it affects heat transport were also elucidated. Internal seed temperature increases with increasing ambient temperature and is same for all seed sizes but with a greater temperature rise for larger seeds.

Notations

T_f = Film Temperature (^{0}C)
T_s = Temperature of the seed surface (^{0}C)

T_o = Ambient temperature (^{0}C)
T_m = Temperature of the surface (^{0}C)
T_c = Internal Temperature of the seed (^{0}C).
σ = The Stefan-Boltzmann constant [5.6704×10^{-8} W/m^{2}K^4]
ϵ = emissivity
h = convective heat transfer coefficient of seed (W/m^{2}K)
r = radius of the seed (m)
C_p= specific heat at constant pressure
K_m = Thermal conductivity of drying surface (W/mK)
K_s = Thermal conductivity of the seed kernel (W/mK)
K_{air} = Thermal conductivity of air (W/mK)
U = Velocity vector
∇ = Gradient operator
$\acute{\eta}$ = Physical contact factor
V = volume of the seed (m^3)
D = seed diameter (m)
S = total surface area of the seed (m^2)
ϕ = sphericity
M = fractional moisture content (dry basis)
N_{RE}= Reynolds number
N_{PR}= Prandtl number
μ = air viscosity (Pa.s)
ρ = air density (Kg/m^3)
v = air velocity (m/s)
ʓ = Seed shape coefficient

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