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Energy Indices and Drying Behaviour of Alligator Pepper Pods (*Aframomum Melegueta*) as Influenced by Applied Microwave Power

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Abstract

In the present study, the effect of applied microwave power on the energy indices and drying behaviour of alligator pepper pods (Aframomum melegueta) is reported. Experimental tests were performed at various levels of applied microwave (MW) power levels (120, 230, 380, 540, and 700 W) with a batch size of 60.85 ± 0.5 g of the sample pods. The study objectives were to investigate the impact of different MW-power ratings on the specific energy demand, energy efficiency, energy loss, and drying behaviour of alligator pepper pods. The drying process which occurred in the falling rate phase had its data fitted into 8 commonly used empirical models. Statistical indicators found the Page model most apt in predicting the drying behaviour of the pod samples. Results revealed that the drying time varied between 8.0 - 14.6 mins at MW-powers of 120 and 700 W, respectively. The moisture diffusivity ($\mathbb{D}_{ef}$) which increased with a reduction in moisture content also increased with applied MW-power from $0.473*10^{-9} \pm 0.112$ to $1.207*10^{-9} \pm 0.13$ m^2s^{-1}, and the activation energy was found to be 13.1 Wg^{-1}. The mean specific energy demand, drying energy efficiency, and waste energy differed in the range of $8.39 \leq Q_{sp} \leq 16.21$ $MJkg^{-1}.H_2O$; $29.4 \leq Q_{ef} \leq 41.26\%$; and $5.10 \leq \dot{Q}_{\ell} \leq 11.37$ $MJkg^{-1}.H_2O$, respectively. The study concluded that the microwave system was energy-efficient at 230 W applied MW-power. Future experimental studies were recommended.

1. Introduction

The production of tropical plant-based products like African star apple, alligator pepper, etc. has maintained an increasing trend as a result of their associated sensory qualities and anti-oxidant constituents. Alligator pepper (*Aframomum* Melegueta) also referred to as grain of paradise, belongs to the perennial family of Zingiberaceae (flowering ginger plants). It is a native of the West African coast: Ghana, Nigeria, Liberia, and Togo, with its major import from Ghana and Nigeria. The pods, which resemble a stern fibrous/leather-like husk contains about 60 to 100 seeds concealed in a jelly-like tissue (pulp). The shrill, spicy, and peppery flavour of the seeds is caused by the presence of aromatic ketones contained therein [1]. Alligator pepper has many economic benefits; its striking fragrance and aroma made it apposite to the brewing of beer, wine, and spirits, as well as spicing of vinegar. Its medicinal applications have a large span, which includes handling of gastrointestinal ailments, malaria cure, healing of injuries, anti-microbial, anti-inflammatory, analgesic, dermatological, stimulating, and aphrodisiac attributes. Literature reveals that the presence of phytonutrients and phenolic compounds present in alligator pepper products made it a broad spectrum, and as such protects and constrains microbial attack and growth in the body [2]. It is used in many traditional rites in Nigeria, such as child naming ceremony and traditional wedding present in the Yoruba land, it's served alongside with kola nuts in the Eastern part of Nigeria for hosting of guests. Its application is not limited to the shores of Nigeria but transcends beyond Africa and Europe for culinary and medicinal purposes. Alligator pepper is sold in its pod containing the seeds. It has a high potential for foreign exchange, as a handful of moderately-sized dried pods worth between ₦ 5, 000 – ₦ 7, 000 in the United Arab Emirate.

However, the harvest of alligator pepper is accomplished when the pods are fully matured by indication of red colour, hence prone to deterioration by microbial attack. Loss of viability majorly evolves from poor handling during harvest, inefficient storage and conveyance equipment, deficient technical know-how of food processing preferences. As cooling is not a feasible technique to prolong the shelf life of alligator pepper, an alternative to this end is drying. In this day and age, drying of plant-based materials takes preference to energy demand reduction and provision of quality-enriched products with a marginal rise in economic effects, which has become increasingly attractive to drying process applications [3, 4].

As a result of the increased energy demand for crop drying, the development of energy-efficient processes have emerged in most technologically advanced nations. Drying techniques can be generally categorized into solar and mechanical drying. The latter involves microwave drying amongst many other methods. The convective air drying technique has been referred to as the commonest technique for crop drying, which covers more than 85% of industrial drying systems [5]. This conventional method is fraught with some technical bottlenecks, such as inadequate heat transfer to food matrix in the falling rate interval as a result of the product's low thermal conductivity, high drying energy consumption, low overall efficiency, gross energy loss (>35%), extensive drying time, poor dried product quality, etc. [6,7]. The desire to ease these challenges to preclude substantial energy demand, product quality, and efficiency decline, as well as to accomplish effective heat treatment has enthused the rising rate of application of microwaves for crop drying.

Amongst the facets of food drying operation, process modeling is considered the most important, since its target is to enable food processors and engineers select the most appropriate process settings and accurately predict the drying rate of a particular crop sample under varying conditions, to effectively size the drying system for optimal performance [8]. Therefore, the application of thin-layer drying models has been considered very apt for describing the drying behaviour of food products [(3, 4, 6, 9 -12]. Moreover, numerous studies on thin-layer modeling of drying behaviours of different crops had been carried out. Researches had been conducted on the impact of microwave power on the drying characteristics and energy efficiency of agricultural products [3, 4, 5, 7, 13]. From the available literature, very insufficient research has been conducted on the drying behaviour of alligator pepper. Consequently, this present study which focused on the influence of applied microwave power on drying energy consumption, efficiency, and energy loss, as well as the drying behaviour of alligator pepper pods was undertaken to fill-up the research gap on microwave drying of alligator pepper pods. It hopes to empirically explore the drying behaviour of the studied crop product and its associated energy parameters at varying microwave power conditions, and estimate the effective moisture diffusivity based on uni-dimensional mass diffusion.

2. Methodology

2.1 Sample preparation

Freshly harvested pods of alligator pepper (*Aframomun Meleguata*) were purchased from a metropolis market (*Orie-ụgba)* in Umuahia, Abia State-Nigeria (Figure 1a). The pod samples were sorted, cleaned, and selected based on maturity, uniformity of size, and viability; and preserved in a refrigerator at 4 ± 0.5°C for 24 hours before the drying experiment [8]. A representative sample of 6 g was dried in an oven dryer by adopting the gravimetric technique at a temperature of 105°C for 24 hours to ascertain its mean initial moisture level [14], obtained as 85.25% (w.b). A batch size of 60.85 ± 0.5 g with mean pod size dimensions (l.w.t) of 5.7 x 3.3 x 1.8 ± 0.15 cm^3 were measured using a digital weighing balance (± 0.01 g precision, YSS_620, Japan) and digital vernier caliper (accuracy of 0.02 mm and resolution of 0.01 mm), respectively.

2.2 Equipment and experimentation

A lab-scale microwave oven (SF20M, Scanfrost, China) operating at 230 V, 50 Hz, and 1050 W, was used for the experimental treatments. The dimensions of the microwave cavity were 440 x 358.5 x 259 mm^3 in size and consisted of a rotating glass plate with a 255 mm diameter at the base of the oven chamber. A batch size of 60.85 ± 0.5 g of the pod samples were arranged in the glass plate positioned at the centre of the drying chamber. Drying was conducted at different applied MW-power levels of 120, 230, 380, 540, and 700 W through the use of the system's control terminal which could regulate both MW-power level and time of magnetron emission. Periodical loss of sample moisture was measured by taking mass measurements of the drying samples on a-YSS_620 electronic mass balance at 2 minutes intervals. The experiment was conducted in 3 replications at every preset power level and mean data were obtained. The new-power was supplied and mass loss checked until the sample moisture levels correspond to a desired moisture content of 10 ± 2% (w.b) (Figure 1b). The recorded mass losses of pod samples were transformed into moisture contents (w.b. and d.b.) by applying Eqs. (1) and (2), respectively [8].

$$m_{\mathrm{wb}} = 1 - \left[\frac{(1-m_{\mathrm{i}}).\mathrm{m_p}}{\mathrm{m_t}}\right] \quad (1)$$

$$m_{\mathrm{db}} = \left[\frac{(m_{\mathrm{i}}+1).\mathrm{m_t}}{\mathrm{m_p}}\right] - 1 \quad (2)$$

2.2 Mathematical modeling and estimation of effective moisture diffusion ($\mathbb{D}_{ef}$)

Moisture diffusivity is a principal transport attribute for simulating the drying behavior of fruits and vegetables. A different approach (superimposition technique) which relates the analytical solution of the Fickian 2nd law to the sample product geometry was established to expedite the estimation of $\mathbb{D}_{ef}$ [15]. The alligator pepper pod which is oval was taken as a cylinder, having an equal surface area with an ellipsoid. The surface area (A_S) of the side of the elliptical pods estimated by turning Eq. (3) about its major axis (b-axis of Figure 2) [9, 16].

(a) (b)

Figure 1. Pictorial outlook of the experimental pod samples: (a) fresh and (b) dried alligator pepper pod samples

$$A_S = 2\pi \int_0^b y\left(\sqrt{y^2+1}\right)dx \qquad (3)$$

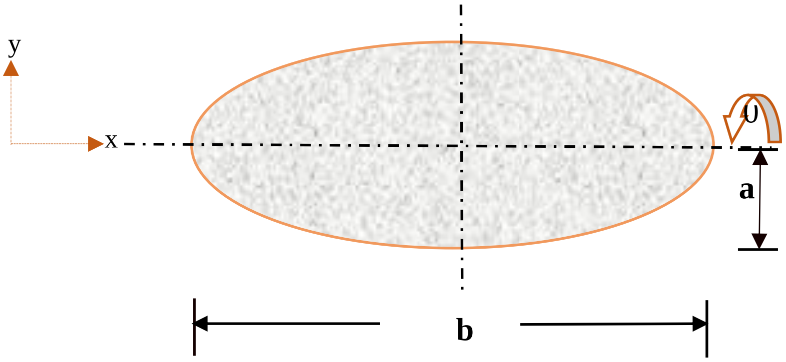


Figure 2. Schematics of the model geometry for alligator pepper pod rotating about its major axis.

The surface area of the entire ellipsoidal-shaped pod sample gives:

$$A_S = 4\pi \int_0^b y\left(\sqrt{y^2+1}\right)dx \qquad (4)$$

By equating the $A_{S\text{-ellipsoid}}$ to $A_{S\text{-cylinder}}$, the equivalent radius (r_e) is expressed as:

$$A_{Sellip} = A_{Scyl} = [(2\pi r_e * 2b) + 2\pi {r_e}^2] = 2\pi ab\left[\frac{sin^{-1}(e)}{\frac{e}{b}} + \frac{a}{b}\right] \qquad (5)$$

Where: $e = \sqrt{b^2 - a^2}$; a and b represent mean values of major and minor pod radii, respectfully.

The Fick's 2nd diffusion principle was considered to represent a heat and mass transfer equation for drying of alligator pepper pods, expressed in Eq. (6) as [10], with the use of boundary conditions:

$$\frac{\delta M}{\delta t} = \mathbb{D}_{ef}\hat{V}^2 m \qquad (6)$$

Drying time, t = 0: $m = m_o$

t > 0, r = 0: $\frac{\delta M}{\delta t} = 0$

t > 0, r = r_e, and h = l, $m = m_e$

At increased drying time (MR < 0.95) and reduced cylinder measurements (l and r_e), Fick's expression could be represented by the 1st term in the series expansion given in Eq. (7) [10]:

$$\mathrm{MR} = \frac{m}{m_o} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left\{\frac{-(2n+1)^2\pi^2\mathbb{D}_{ef}t}{z^2}\right\} \qquad (7)$$

Therefore, substituting the moisture ratio expressions for cylinder and slab geometries into the 1st series term of Eq. (5) yield Eqs. (8) and (9), and by applying superimposition methodology, which considered a finite cylinder as a union of an infinite cylinder and infinite slab geometries [9, 15, 16]:

$$MR_{i.sl} = \frac{m}{m_o} = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 \Upsilon_{sl} t}{l^2}\right) \quad (8)$$

$$MR_{i.cyl} = \frac{m}{m_o} = \frac{4}{\beta^2}\exp\left(\frac{-\beta^2 \Upsilon_{cyl} t}{r_e^2}\right) \quad (9)$$

Where: the parameter, β = 2.4048 was obtained from the tables of 1st-kind Bessel expression of zero-order ($J_o(p\propto_n = 0)$ [10]. The constant of expression, $\Upsilon = \mathbb{D}_{ef}$ can be estimated by plotting ln(MR) versus drying time.

The moisture ratio expression for a finite cylinder ($MR_{f.cyl}$) can be simplified from Eqs. (8) and (9) and expressed as Eq. (10) [9, 10]:

$$MR_{f.cyl} = 0.114 * \exp - \left[\frac{\pi^2}{l^2} + \frac{(2.4048)^2}{r_e^2}\right] \quad (10)$$

2.3 Drying rate

The drying rate ($\dot{\varphi}$) of the alligator pepper pod samples was estimated using Eq. (11):

$$\dot{\varphi} = \frac{m_{t+\eth t} - m_t}{\eth t} \text{ (g water g}^{-1}\text{dm min}^{-1}) \quad (11)$$

2.4 Statistical analysis

To effectively model the drying the behavior of alligator pepper pods during the MW-drying process, the measured drying data at varying applied MW-power densities require to be tested by fitting them in the eight (8) frequently used drying models itemized in Table 1 [7, 10]. Comparison of goodness of curve fit to the measured drying data of each model was achieved by applying these three basic statistical indicators: coefficient of correlation (R^2), root mean square error (E_{rms}), and reduced chi-square error (χ^2), calculated using Eqs. (12) and (13) [5, 10, 17, 18]:

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{e,i} - MR_{p,i}\right)^2}{n}} \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{e,i} - MR_{p,i}\right)^2}{n - \Omega} \quad (13)$$

Table 1: Commonly used drying models adopted for curve fitting of drying data of alligator pepper pods.

Model No.	Model Name	Model Equation	Reference
1.	Lewis model	$MR = \exp(-kt)$	[7, 10, 12]
2.	Page model	$MR = \exp(-kt^n)$	[3, 5, 10]
3.	Modified Page model	$MR = \exp[-(K\,t)^n]$	[3, 7, 8]
4.	Logarithmic model	$MR = a\exp(-kt) + bt$	[5, 7, 10]

5.	Midilli et al. model	$MR = a\exp(-kt) + bt$	[6, 8, 12]
6.	Henderson & Pabis model	$MR = a\ \exp(-kt^{n})$	[3, 7, 10]
7.	Approximation of diffusion model	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	[7, 10, 12]
8.	Wang & Singh model	$MR = 1 + at + bt^2$	[3, 5, 7, 10]

The model goodness of fit was evaluated based on higher values of R^2 and lower values of E_{rms} and χ^2 [5, 17]. Multiple linear regression analysis was conducted using Matlab R2015a (Mathworks 8.5.0).

2.5 Activation energy (ζ_e)

The energy of activation refers to the ability of water molecules to exceed the energy barrier during product intra-cellular moisture transport [18]. Greater diffusivity of product moisture is as a result of reduction in ζ_e-value. This is caused by a rise in the mean energy value of the water molecules [18, 19]. A modified Arrhenius equation which relates the rate constant ($\mathbb{D}_{eff}$) of the drying process and the ratio of applied MW-power output to product mass $\left(\frac{\mathrm{m_p}}{\mathrm{P}_a}\right)$ estimates the activation energy of the drying process [10, 11, 18]. When the influence of applied MW-power on the coefficient of effective moisture diffusivity is investigated, a linear relationship is obtained (Eq. 14) and ζ_e-value is estimated from the gradient of the line [5, 10, 18] as:

$$\mathbb{D}_{eff} = \mathbb{D}_{\mathrm{o}}\exp\left(-\frac{\zeta_e \mathrm{m_p}}{\mathrm{p_a}}\right) \quad (14)$$

2.6 Energy and efficiency of microwave drying

The energy consumption per unit mass of the pod sample, which refers to the specific energy demand of the drying process to extract a unit mass of water in the pod samples is expressed in Eq. (15) as [11]:

$$\mathcal{Q}_{s} = \frac{\mathrm{Pt}}{\mathrm{M}_{w}} \quad (15)$$

The energy efficiency for the MW-drying process is referred to as the thermal energy consumed for moisture evaporation from sample surface divided by the supplied MW-heat [5], expressed in Eq. (16):

$$\mathcal{Q}_{eff} = \frac{\mathcal{Q}_{ab}}{Pt} \quad (16)$$

$$\text{But } \mathcal{Q}_{ab} = \mathrm{M}_{w}.\lambda_w \quad (17)$$

The latent heat capacity of the pod samples was estimated using Eq. (18) [6, 11]:

$$\frac{\lambda_{\mathrm{pod}}}{\lambda_{\mathrm{f}}} = 1 + 23\mathrm{e}^{-0.4m} \quad (18)$$

But, $\lambda_f = 2503 - 2.386 * T$ (kJkg^{-1}). Eq. (19) expresses the specific energy loss during the drying process [11]:

$$\dot{\mathcal{Q}}_{\ell} = \left[1 - \mathcal{Q}_{ef}\right] * \frac{\mathrm{Pt}}{\mathrm{M}_{w}} \qquad (19)$$

3. Results and Discussion

3.1 Drying behaviour

Figure 3 depicts the change in moisture ratio with the drying time of the alligator pepper fruit-pod samples at different power densities/levels during the microwave-convective drying process. The exponential diminution in moisture content with increasing time of drying at varying applied microwave (MW) power densities ranging from 120 – 700 W indicates that the intracellular moisture diffusion process to the sample exterior boundaries is being governed by internal-water diffusion. The curve also demonstrates a high rate of moisture removal in the initial phase of drying, followed by moisture removal in the later phases, as it gradually heads towards the values of equilibrium moisture ratio. Therefore, more rapid product mass transfer was observed at higher MW-power levels because of greater kinetic energy developed in the sample product which produced a substantial water vapor differential between the interior and peripheral regions of the pod samples as a result of the volumetric heating effect of the microwave dryer [3, 4, 20]. However, the total time needed to dry the pod samples from initial to final desired moisture contents of 85.25% (wet basis) and 10 ± 2% (wet basis), respectively were 14.6, 12.5, 11.2, 10.4, and 8.0 mins at 120, 230, 380, 540, and 700 W. This result shows the significance of MW-power densities on drying time, as the drying time could be shortened by 80% by drying at 700 W when compared to convective hot-air drying at 70^{o}C instead of 120 W [3]. Table 2 gives a succinct comparison between MW-drying and other conventional drying techniques concerning drying time, for which the time effectiveness of the drying approach of this current study is shown. Previous works on microwave drying of bio-materials reveal similar drying behavior in the falling- rate phase as reported by Darvishi *et al.* [3, 4], Zarein *et al.* [5], Motevali *et al.* [6], and Surendhar *et al.* [20], for potato slices and pepper, chamomile leaves, apple slices, and turmeric slices, respectively.

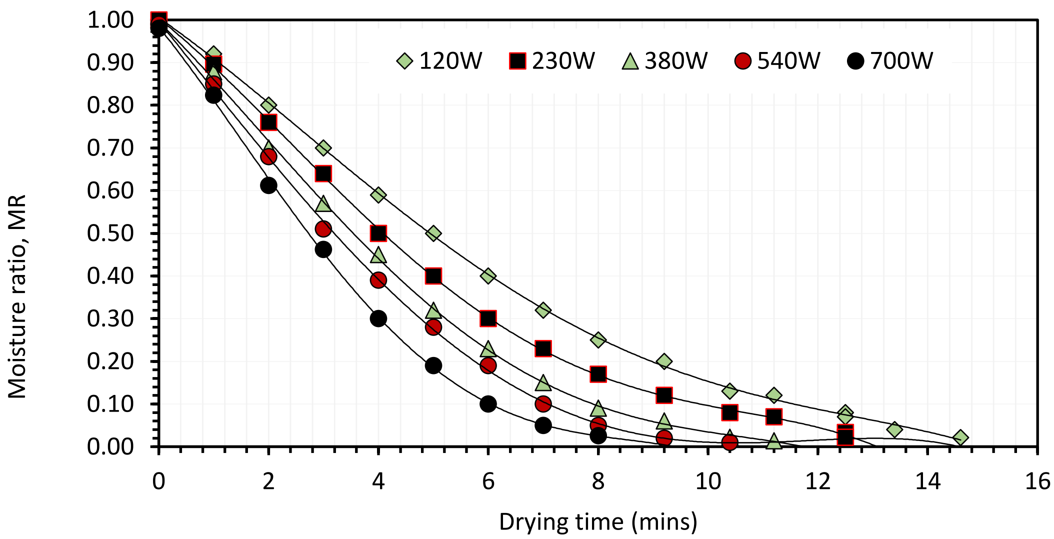


Figure 3. Change in moisture ratio with time of drying at different MW-power levels

Table 2. Drying method comparison with microwave drying.

Drying method	Drying time	References
Microwave	8 – 14.6 mins	Present study
	3.57 – 28.5 mins.	[18]
	4.25 – 25 mins.	[5]
Convective-air	15 – 40 h; 70 – 142 h.	[21, 22]
Solar	16 – 22 h	[23]
Infrared-fluidized bed	≥ 120 mins.	[24]

3.2 Curve fitting of drying data

Summary of the drying results obtained from the model statistics is presented in Table 3, concerning the statistical parameters (R^2, E_{rms}, and χ^2) obtained from the curve-fitting calculations for the moisture ratio against drying duration for the eight (8) selected drying models. In all, the values of the statistical parameters range between: $0.9699 \leq R^2 \leq 0.9998$, $0.007714 \leq E_{rms} \leq 0.12269$, and $0.000501 \leq \chi^2 \leq 0.120036$, signifying good fits.

Table 3. Statistical analysis of the models fitted to the drying data for MW-drying of alligator pepper pods at various applied microwave power densities.

Model No.	Power Density (W)	Model Constants					R^2	E_{rms}	χ^2
		k	n	a	b	c			
1.	120	0.302					0.9714	0.05866	0.027530
	230	0.1959					0.9735	0.05459	0.038740
	380	0.231					0.9929	0.09541	0.081150
	540	0.193					0.9957	0.01733	0.120036
	700	0.174					0.9968	0.12269	0.082630
2.	120	0.1015	1.345				0.9992	0.00689	0.000921
	230	0.1019	1.374				0.9998	0.00771	0.000501
	380	0.1215	1.251				0.9991	0.00792	0.000788
	540	0.1412	1.281				0.9989	0.00801	0.000795
	700	0.1622	1.332				0.9986	0.00844	0.000733
3.	120	0.2799	0.787				0.9714	0.06271	0.027530
	230	0.2369	0.827				0.9750	0.05682	0.003874
	380	0.251	0.812				0.9699	0.00412	0.000411
	540	0.113	0.883				0.9972	0.00527	0.000566
	700	0.317	0.792				0.9986	0.00284	0.000633
4.	120	0.1911		1.294		-0.281	0.9966	0.02957	0.005145
	230	0.1472		1.226		-0.183	0.9950	0.02565	0.007237
	380	0.159		1.471		-0.191	0.9921	0.00614	0.008224
	540	0.236		1.644		0.221	0.9904	0.00826	0.009226
	700	0.429		1.867		0.391	0.9892	0.00544	0.005413

	120	0.2304		1.01	-0.02082	0.9937	0.03174	0.006043
	230							
5.	380	-0.0821		1.015	-0.2233	0.9975	0.01831	0.003686
	540	-0.0859		1.183	-0.2961	0.9960	0.01955	0.005127
	700	-0.0877		1.1986	-0.3382	0.9969	0.01684	0.032291
	120	0.646	1. 866	1.045		0.9976	0.06361	0.021745
	230	0.1004	1.380	0.997		0.9995	0.00799	0.000702
6.	380	0.131	1.672	1.194		0.9981	0.02554	0.022573
	540	0.132	1.965	2.176		0.9988	0.03771	0.012238
	700	0.226	1.602	3.171		0.9979	0.06541	0.027743
	120	0.066		8.952	0.473	0.9952	0.12080	0.007620
	230	0.0849		11.63	0.9177	0.9937	0.02888	0.009178
7.	380	0.199		6.554	1.284	0.9967	0.03667	0.052282
	540	0.324		9.115	2.371	0.9981	0.01148	0.062217
	700	0.522		12.62	4.312	0.9979	0.01778	0.445102
	120			0.08227	0.00962	0.9961	0.01988	0.003499
	230			-0.1457	0.00544	0.9967	0.01994	0.004772
8.	380			-0.255	0.0368	0.9958	0.03471	0.029920
	540			-0.9226	0.067	0.9959	0.07719	0.060118
	700			-1.36	0.118	0.9979	0.10668	0.088126

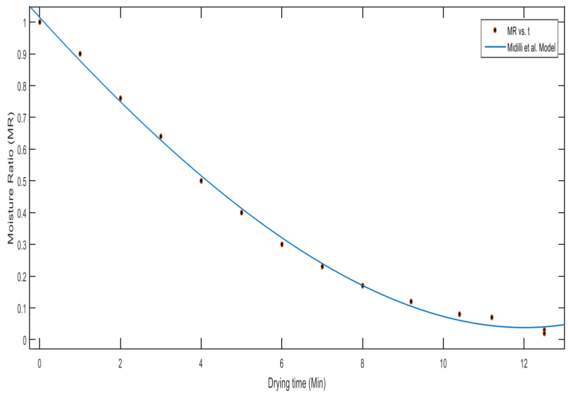
Figure 4a,b shows the experimental and simulated sample moisture ratio by the Page and Midilli et al. models. The process prediction of the Midilli et al. model was slightly below the measured MR-values towards the beginning and later drying phases (Figure 4a), whereas good curve fitting of the experimental data was given by the Page model (Figure 4b). This is also evident in Table 3, as the Page model had higher R^2-value and lower E_{rms}, and χ^2 values in comparison with the Midilli et al. model. Although these two drying models are known for adequate description of drying kinetics of many fruits and vegetable products [10].

The higher prediction ability exhibited by the Page model is, perhaps as a result of its empirical derivation and reformation from the Newton model, whereby all associated model errors have been sufficiently reduced through incorporation of an empirical non-dimensional constant [10]. Figure 5 relates the experimental and the predicted MR-data of the Page model at varying MW-power levels. The model prediction indicated a linear banding of the measured and simulated MR-values, thus adequacy of the model in predicting the drying behavior of alligator pepper pods. Similar outcomes on okra pods, carrots, and onions slices, data palm fruit were reported by Ismail and Idris [8], Doymaz [25], Sharma *et al*. [26], Darvishi and Hazbavi [27], respectively. Multiple regression analysis conducted on the Page model constants (k and n) against the applied MW-power to investigate the effect of the applied power densities on the chosen model yielded the following expressions:

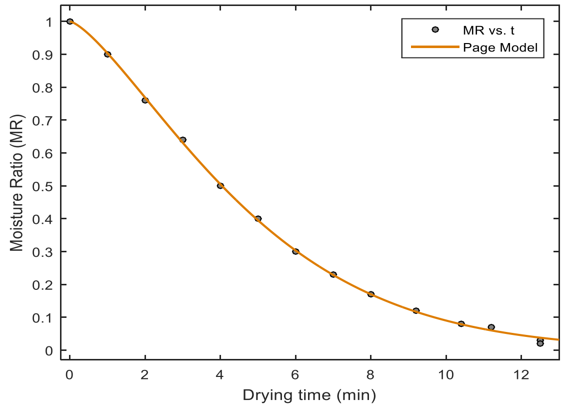
$$\mathrm{MR}(\mathrm{t}, \mathrm{p_a}) = \exp(-\mathrm{k} * \mathrm{t^n}) \quad (20)$$

$$\mathrm{k} = 0.0413 \exp(0.0017\mathrm{p_a}); \qquad [\mathrm{R}^2 = 0.9963] \quad (21)$$

$$\mathrm{n} = 3 \times 10^{-6}\mathrm{p_a}^3 - 3 \times 10^{-3}\mathrm{p_a}^2 + 0.012\mathrm{p_a} - 0.326; \qquad [\mathrm{R}^2 = 0.9925] \quad (22)$$



(a)



(b)

Figure 4. Experimental and simulated MR of alligator pepper pods for: (a) Midilli et al. model, and (b) Page model at varying applied power levels

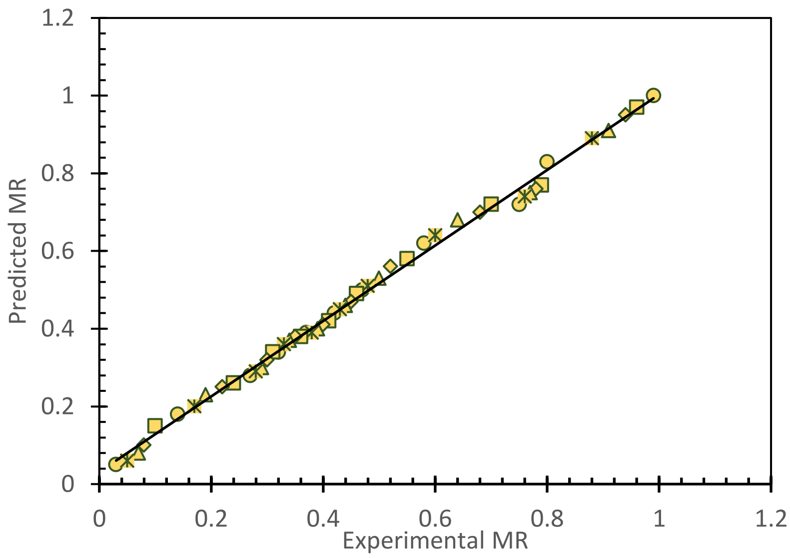


Figure 5. Comparison of experimental MR with simulated MR from the Page model for alligator pepper pods

3.3 Drying rate

The moisture content of food materials determines their MW-energy absorptivity, [6] as it varies proportionally with microwave power to effect drying. Examination of Figure 6 identifies two separate phases in all, viz: warming up and falling-rate behaviors. The early short warming-up period tallies with sample product heating and as a result of non-isothermal drying settings, which is succeeded by a falling-rate phase indicated by a gradual rise in the intracellular resistance to heat and moisture transport. This emanates as a result of incomplete water surface, instead capillary travel from the sub-region must precede moisture evaporation. The rates of peripheral evaporation were increased at the start of the drying operation which led to higher absorption of MW-power, thus increased drying rate and reduced drying time, due to increased mass transport. As can be seen, the rate of drying is conspicuously influenced by the applied power of the microwave system, as the MW-power is increased. Subsequently, as the process of drying progressed, loss of moisture in the pod samples lessened the MW-power absorptivity of the samples which resulted in a drop in the drying rate. Results of similar trends from other researchers [3, 4, 16, 28-30] for other food products like tomato, okra, garlic, pepper, potato, and Cuminum cyminum corroborated these findings.

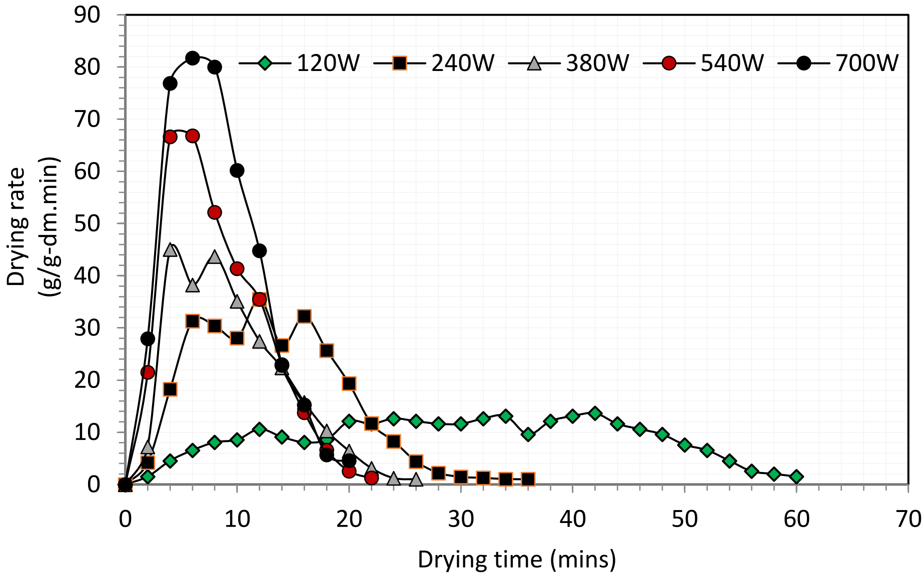


Figure 6. Relationship between drying rate and time at varying applied MW-powers

3.4 Effective moisture diffusivity ($\mathbb{D}_{ef}$) and activation energy (ζ_e)

The product moisture content had a substantial impact on the effective diffusivity of alligator pepper pods. Changes in moisture diffusivity with moisture content are given in Figure 7. Higher effective diffusivity was obtained at reducing moisture content and increasing MW-power. Similarly, with further drying at any given moisture level, increasing the MW-power increases the effective moisture diffusion of the product sample, which reduced the drying time as a result of the rising thermal energy that increased the entropy of the product moisture, thus increased random movement of molecules of the sample water leading to enhanced $\mathbb{D}_{ef}$. This possibly signifies that at decreasing moisture content, the vapour permeability is enhanced, as far as the capillary structures of the pods are open. The pod temperature increases swiftly at the early phase of the drying process, because of further assimilation of microwave heat, given the high loss coefficient of the product at increased moisture content (m). This results in a gross upsurge in the vapor pressure of fruit/pod water which stimulates the pressure-controlled capillary opening. However, in the first phase of drying, diffusion of internal water perhaps characterized the capillary transport of moisture; whereas as drying advanced, the later phase of drying is marked by vapour diffusion the drying. Similar observations in the change of effective moisture diffusion with product moisture content were reported by Darvishi *et al.* [3, 4], Zarein *et al.* [5], and Celma *et al.* [31] for slices of pepper, potato; apple, and tomato, respectively.

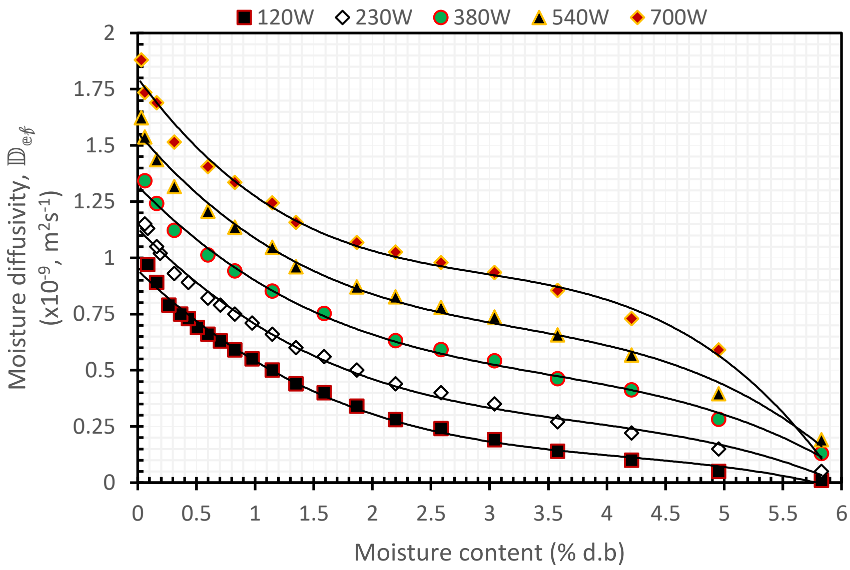


Figure 7. Effect of sample moisture content on the effective moisture diffusivity at varying MW-power levels.

The values of $\mathbb{D}_{ef}$ and corresponding m-values were be correlated by a polynomial function of 3rd degree, expressed by Eq. (23):

$$\mathbb{D}_{ef} = (am^3 + bm^2 + cm + d) \times 10^{-9} \qquad (23)$$

The regression constants for MW-drying of alligator pepper pods at varying MW-applied power levels are shown in Table 4. High values of correlation coefficient, $0.9865 \leq R^2 \leq 0.9954$ suggest good polynomial fit, and also accounted for 99% of the disparity in the experimental $\mathbb{D}_{ef}$ and m-values.

Table 4. Coefficients of regression of the effective moisture diffusion of alligator pepper fruit at different applied power levels.

Applied power (W)	a	b	c	d	R^2
120	-0.0088	0.1098	-0.5043	0.9447	0.9912
230	-0.0108	0.1226	-0.5366	1.1301	0.9943
380	-0.0121	0.1272	0.5366	1.3205	0.9954
540	-0.0163	0.159	-0.6115	1.5562	0.9923
700	-0.0088	0.1098	-0.5043	0.9447	0.9865

The mean $\mathbb{D}_{ef}$ − values were estimated from the arithmetic mean of $\mathbb{D}_{ef}$ obtained at varying product moisture content levels as illustrated in Figure 4. Table 5 displays the mean values of $\mathbb{D}_{ef}$ at varying applied MW-powers, which ranged between the given limit of $10^{-6} \leq \mathbb{D}_{ef} \leq 10^{-11}$ m^2s^{-1} for agro-based materials [5, 20]. The values are at good par with the reported $\mathbb{D}_{ef}$-values of most fruit vegetables reported in Darvishi *et al*. [3, 4] and Zarein *et al.* [5]. The variations in the $\mathbb{D}_{ef}$-values obtained could be as a result of material composition, structural arrangement, variety of product sample, as well as method of calculation.

Table 5. Mean $\mathbb{D}_{ef}$ −values of alligator pepper pods undergoing MW-convective drying.

Applied MW-power (W)	Effective moisture diffusivity, $\mathbb{D}_{ef}$ (x 10^{-9} m^2s^{-1})
120	0.473 ± 0.112
230	0.64 ± 0.02
380	0.737 ± 0.18
540	0.956 ± 0.22
700	1.207 ± 0.13

The minimum energy requirement of water molecules for capillary diffusion of sample moisture, otherwise known as activation energy, ζ_e was estimated by plotting $\ln(\mathbb{D}_{ef})$ against the ratio of sample quantity to applied power $\left(\frac{m_p}{p_a}\right)$ as depicted in Figure 8. A linear relationship was obtained in the scope of the studied MW-power levels, signifying Arrhenius's reliance. The $\mathbb{D}_{ef}$ reliance of alligator pepper pods on the MW -power can be expressed by Eq. (24):

$$\mathbb{D}_{ef} = 9.87 \times 10^{-9} \exp\left(\frac{-13.1 m_p}{p_a}\right); \ R^2 = 0.9918 \qquad (24)$$

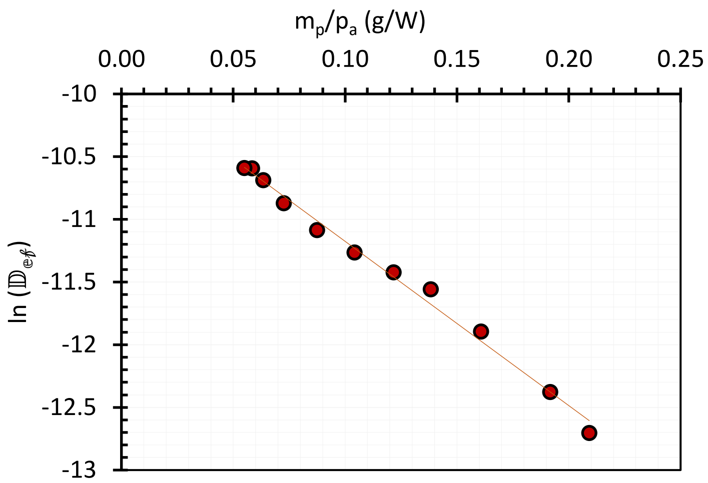


Figure 8. Correlation between the natural log. of effective moisture diffusion and sample quantity/MW-power for alligator pepper pods

The ζ_e-value of the alligator pepper pod was obtained to be 13.1 Wg^{-1}. This value is comparable with that of mint leaves (12.28 Wg^{-1}), pepper slices (14.12 Wg^{-1}), potato slices (14.94 Wg^{-1}), shrimp (12.8 Wg^{-1}), and pandanus leaves (13.6 Wg^{-1}) as reported by Ozbek and Dadali [32], Darvishi *et al.* [3, 4], Darvishi *et al.* [23], Rayaguru and Routray [33], respectively. The ζ_e-value obtained in this study is lower than those reported by Motevali *et al.* [34] for sweet and sour pomegranate (16.68 and 24.22 Wg^{-1}, respectively). No comparison was made on the $\mathbb{D}_{ef}$ and ζ_e-results of alligator pepper fruit with those of other drying techniques because of the unavailability of published data. However, it is pertinent to note that lower ζ_e-value signifies greater moisture diffusion in the pod sample during drying operation [3, 35].

3.5 Energy considerations

Variations in the energy-associated indices with moisture content during MW-drying of alligator pepper fruit are illustrated in Figures 9 and 10. The amount of energy consumed per unit mass of sample (specific energy consumption) increases constantly with moisture reduction [6, 36], which consequently enhanced the efficiency of the drying process and reduced energy loss. Given the drying characteristics of agro-based materials and the fact that the lesser the amount of water contained in a product sample, the greater will be the quantity of energy required per kilogram of water extraction for additional drying. At the least sample moisture content of 0.021% (d.b), the system consumed a maximum specific energy of 25.47 $MJkg^{-1}$ at a microwave power of 540 W, whereas the least specific energy consumption of 12.94 $MJkg^{-1}$ at 230 W was obtained at a moisture content level of 4.955% d.b.

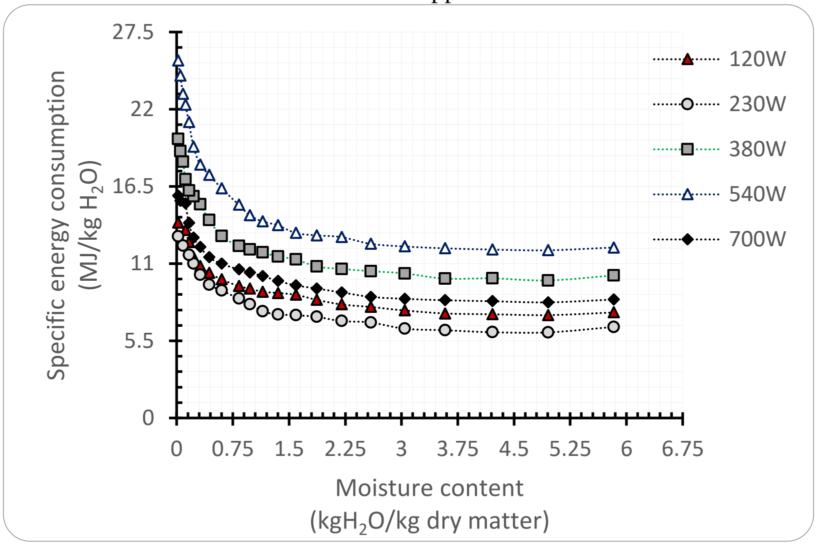


Figure 9. Effect of moisture content of alligator pepper fruit on the specific energy consumption at varying applied MW-powers

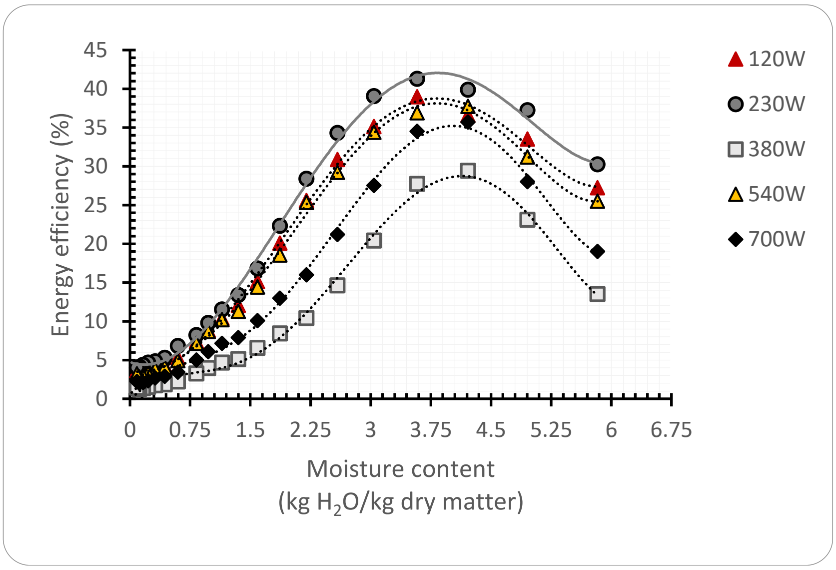


Figure 10. Change in drying energy efficiency moisture content at different MW-powers

The early stage of the drying process was marked with greater drying energy efficiency, given rise to increased absorption of MW-power. Given the decreasing trend of the product moisture, there is a reduction in the MW-energy absorbed by the pod samples, which increased the reflected applied MW-power [5, 6, 37]. Consequently, it was noticed that an increase in the applied MW-power encourages specific energy loss (Figure 11), which diminishes the drying energy efficiency. The reports of Darvishi *et al.* [3, 4], Zarein *et al.* [5], and Soysal *et al.* [37] for MW-drying of pepper and potato slices, apple slices, and parsley, respectively substantiated this observation. The best energy efficiency of the system was obtained from an MW-power level of 230 W.

The mean specific energy consumption ($\mathcal{Q}_{sp}$) for drying a batch size of alligator pepper pod samples is given in Figure 12. The $\mathcal{Q}_{sp}$-values ranged between $8.39 \leq \mathcal{Q}_{sp} \leq 16.21$ MJkg^{-1} of water, whereas the energy efficiency values ranged from 29.4 to 41.26% for the range of the studied applied MW-powers. The least specific energy consumption (8.39 MJkg^{-1}) and the maximum energy efficiency of drying (41.26%) were obtained at MW-power of 230 W. There was no literature report on energy consumption and process efficiency of alligator pepper pod for comparison, but a similar result was obtained by Darvishi *et al.* [3] for pepper slices. Khoshtaghaza *et al*. [38] reported a minimum specific energy of 50.94 MJkg^{-1} for soybean kernels in a microwave-fluidized bed dryer. The energy value obtained from this study falls within the drying energy threshold (5.21 – 90.4 MJkg^{-1}) for agricultural products [39].

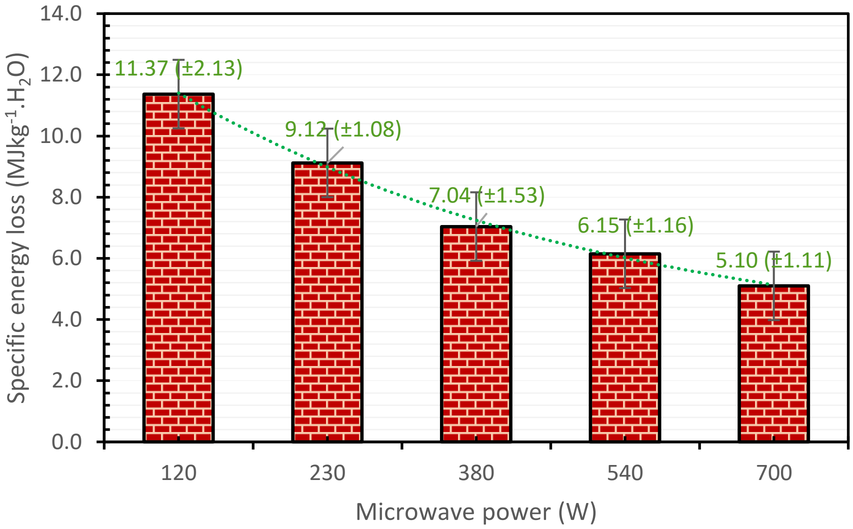


Figure 11. Variation of specific energy loss with applied MW-power

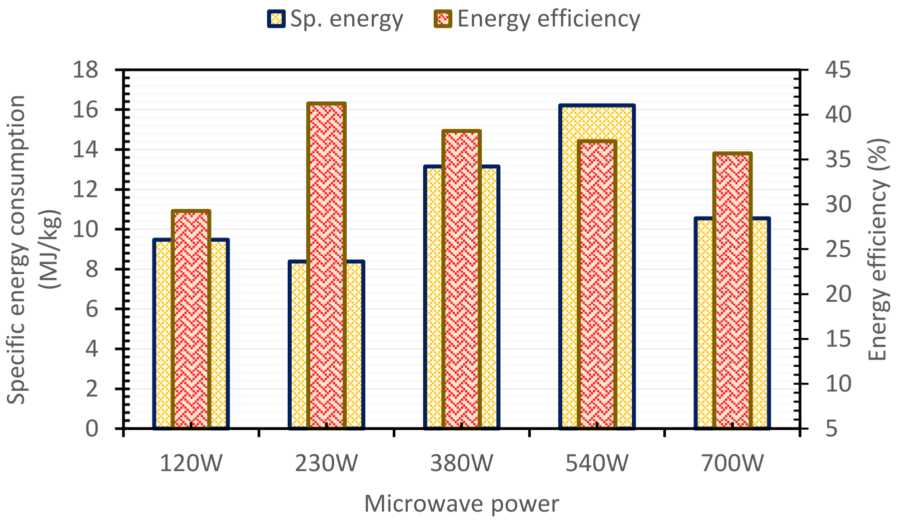


Figure 12. Mean specific energy consumption and energy efficiency for drying of alligator pepper fruit at varying applied MW-powers

However, the loss in specific energy varied between $5.10 \leq \dot{Q}_\ell \leq 11.37$ MJkg^{-1}.H_2O, which showed that 53.85 to 70.19% of the supplied energy was not utilized for the drying of alligator pepper fruit samples (Figure 8). Darvishi [11] obtained specific energy loss of 67.4 to 86.1% in microwave drying of soybean samples for applied power range of 200 to 600 W. A 3rd-order polynomial function describes the system energy loss as given in Eq. (25), with a high coefficient of correlation (R^2) of 0.9968, signifying strong agreement between energy loss and applied microwave power. It also shows that a larger proportion (99.68%) of the experimental inconsistency could be accounted for by a 3rd-degree poly-function [40, 41].

$$\hat{\dot{Q}}_{\ell} = -0.0275\mathrm{P}_a{}^3 + 0.5039\mathrm{P}_a{}^2 - 3.7386\mathrm{P}_a + 14.666 \qquad [\mathrm{R}^2 = 0.9968] \qquad (25)$$

4. Conclusion

In this paper, the impact of microwave applied power on the energy parameters and drying characteristics of alligator pepper pods were investigated. Results showed that the drying behaviour of alligator pepper pods was characterized by an exponential reduction in moisture content at varying applied microwave power levels, which occurred in the falling rate phase and was described by the page model through curve fitting computation. The drying time required to reduce the sample initial moisture content level (85.25% w.b) to the final desired moisture content (10 ± 2% w.b) varied between 8.0 - 14.6 mins at MW-power levels of 120 and 700 W, respectively. Greater diffusion of the pod moisture was observed as pod moisture content reduced and applied MW-power level increased. The values of $\mathbb{D}_{ef}$ ranged between $0.473 \times 10^{-9} \pm 0.112$ - $1.207 \times 10^{-9} \pm 0.13$ m^2s^{-1}, whereas the activation energy was estimated to be 13.1 Wg^{-1}.

The specific energy consumption for microwave drying of alligator pepper pods varies with moisture content and applied MW-power. Reducing the pod moisture content will not only increase the specific energy demand of the system but also cause a significant reduction in lost energy. The mean specific energy demand of a-60.85 ± 0.5 g batch process varies between 8.39 - 16.21 $MJkg^{-1}$ at moisture content levels and MW-powers of 4.955% d.b. and 0.021% d.b; 230 and 540 W, respectively. The maximum energy efficiency of 41.26% was obtained at the least specific energy and MW-power of 230 W. Results also revealed that the mean energy loss of the system varied between 5.10 - 11.37 $MJkg^{-1}$water. An optimum applied MW-power level of 230 W was estimated for specific energy demand and energy efficiency for microwave drying of alligator pepper pods. The results of this experimental study find practical relevance in the design and operation of microwave commercial-scale process control of medicinal and aromatic plant-based products.

Therefore, considering the medicinal and economic benefits of alligator pepper products, it will be interesting to conduct future experimental studies on optimization of process energy demand, system variables, and pod quality parameters of different drying systems (in single and hybrid modes) for enhanced dried pod quality, packaging, storability, and energy-efficient system design. Also, determining the shrinkage coefficient through studies on volume shrinkage variation of alligator pepper pods as a function of the water content is of great importance.

Nomenclature

a, b	Measured minor and major pod radii (mm), respectively
$a, \mathscr{b}, c,$ and d	Regression coefficients
$\mathbb{D}_o$	Pre-exponential factor (m^2s^{-1})
l	Measured mean length of pods (cm)
$\mathcal{m}$	Sample moisture content (% d.b)
$\mathcal{m}_i$	Initial moisture content of the pod sample (% w.b)
m_p	Initial mass of pod samples (g)
$MR_{e,i}$	ith-experimental moisture ratio

$MR_{p,i}$	i^{th}-predicted moisture ratio
$MR_{i.cyl}$	Moisture ratios of the infinite cylinder
$MR_{i.sl}$	Moisture ratios of the infinite slab
$m_{t+\partial t}$	Moisture level per unit time (g water/g dm)
MW	Microwave
M_w	Mass of evaporated water (g)
m_{wb}	Moisture content (% wet basis, w.b)
m_{wb}	Moisture content (% dry basis, d.b)
m_t	Mass of pod samples at time, t (g)
n	Number of terms (positive whole number); no. of experimental observational points
P	Mean MW-power (W)
p_a	Applied microwave power (W)
Q_{ab}	Absorbed energy (MJ)
Q_{eff}	Energy efficiency of drying (%)
$\hat{Q}_{\ell}$	Specific energy loss ($MJkg^{-1}H_2O$)
Q_s	Specific energy consumption ($MJkg^{-1}H_2O$)
r_e	Calculated equivalent radius of the cylinder geometry (cm)
t	Time of drying (min); mean measured pod thickness (cm)
v	Air velocity (ms^{-1})
W	Mean measured pod width (cm)
z	Slab half-thickness (mm)

Greek letters

Ω	Number of model parameters
λ_f	Sample free water latent heat capacity ($kJkg^{-1}$)
λ_{pod}	Pods' latent heat capacity ($kJkg^{-1}$)
λ_w	Latent heat of water vapourization (2260 Jkg^{-1})

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