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Research Article

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Drying Kinetics of Biltong under Infrared and Convective Hot-Air Conditions

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Abstract Biltong slices products were dried using either the convective dryer or one of two infrared dryers. The products varied in marinating durations (6, 12 and 24 hours) and the product thicknesses (5, 10 and 15 mm). The rate of change of moisture content with time was observed and the data fitted to five popular drying models in order to determine the goodness of fit. The Approximation of Diffusion Model (ADM) best described the drying kinetics of biltong evidenced by the highest R^2 values of the five models fitted.

Keywords Biltong, modeling, thickness marinating, dryer, Pre-treatments, Midilli

1. Introduction

The drying kinetics of different food products have been developed by drying them under different conditions and making observations of the product's drying behaviour [1-6]. However food and agricultural products are complex in composition and behaviour. Since every food and agricultural material has unique characteristics, the application of research results carried out on a given product may not give valid conclusions for a different product. However, understanding the behaviour of a product under a given drying system will confer the benefit of aiding in the design of optimized drying systems and processes for a given product from both a quality and energy use standpoint.

Biltong is a snack that is popular in Southern African and its demand has continued to grow in recent years [7, 8]. It is mainly dried convectively using ambient conditions. However there can be distinct advantages of infrared drying over convective air drying. These advantages include high quality products, energy efficiency, rapid heat transfer rates and a reduction in drying time [9-11]. The objective of this study is therefore, to compare established drying models in their ability to fit biltong drying under convective air and infrared drying systems.

2. Materials and Methods

2.1. Theoretical Considerations

The moisture content of a food material is expressed in terms of dry basis (db) and wet basis (wb) as mathematically presented in equations 1 and 2.

$$M_{db}=\frac{(W_0-W)-W_1}{W_1} \quad (1)$$

$$M_{wb}=\frac{(W_0-W)-W_1}{W_1+W} \quad (2)$$

Where W_0 is the initial mass of the product (kg), W the mass of evapourated water (kg), W_1 is the dry matter mass of the sample (kg) and M is the mass of the moisture in the product in kg of water/kg of wet solid (wb), or kg of water per kg of dry solid (db) [12].

The moisture ratio of food is closely related to the drying kinetics of food and biological materials [12, 13]. It can be represented in a simplified fashion as seen in Eq. 3. It can also be calculated using Eq. 4 under certain conditions [14].

$$MR= \frac{M_t}{M_0} \tag{3}$$

Where, MR is the dimensionless moisture ratio, M_t is the moisture content in dry basis and M_0 is the initial moisture content expressed in dry basis.

$$MR= \frac{M_t - M_e}{M_0 - M_e} \tag{4}$$

Where, MR and M_t are as expressed in equation 3 and M_e is the equilibrium moisture content of the product at the specific drying conditions.

When drying at high temperatures it is justified to equate the equilibrium moisture content to zero thus further simplifying equation 4 as widely described in literature [15-18].

The drying rate (D_R) is defined as the mass of water removed from a product per unit drying time [19]. It is presented in form of equation 5 as suggested by Kaya et al., [5].

$$D_R= \frac{m_t - m_{t+\Delta t}}{\Delta t} \tag{5}$$

Where m_t is the mass of the product at time t, $m_{t+\Delta t}$ is the mass of product at time t+ Δt and D_R is as defined earlier.

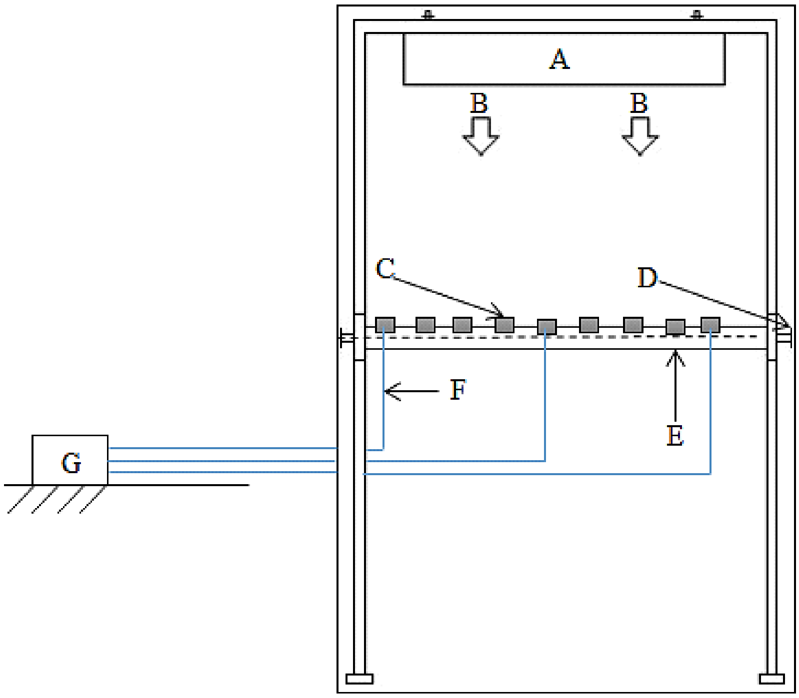

Figure 1: A Cross section of the infrared drying rig depicting the relative positions of the infrared heater (A), the radiating surface (B), biltong sample (C), vertical adjustment fittings (D), drying tray (E), thermocouple (F) and the data logger (G)

2.2. Sample Preparation

The biltong used in this study was sourced from Pick and Pay Supermarket, Pietermaritzburg, South Africa and the quality aspects adhered to as recommended by Dzimba et al., [20]. The slices of 15cm in length and 2.5 cm in width were (1.5 cm, 1 cm or 0.5 cm thick. A marinade was prepared using a commercial spice (Nice and spicy, Home of biltong makers, South Africa) as recommended by FAO [21]. Batches of slices with a thickness of 5, 10 or 15 mm were dipped into the marinade so as to be completely immersed in the marinade and marinated for the set period of time (6, 12 or 24 hours) followed by determination of moisture content [22].

2.3. Drying Experiments

2.3.1. Drying Apparatus

Drying was done using a mechanical oven (Prolab, PRIS, South Africa) operating at an air temperature of 25±0.5°C and a relative humidity of approximately 60% or in one of the infrared heaters (model QF-121210 and model QC-121240 acquired from Omega Engineering, UK while the drying rig was locally fabricated as shown in Fig 1.

2.3.2. Drying Runs

A drying run involved placing samples in the dryer and monitoring the mass using a balance (CQT 202, Adam Core, USA). Thereafter the mass of each slice was measured regularly at preset intervals until the product reached the target moisture level of 20 ±1% wb. The products were then cooled and stored in labelled Ziploc polythene bags (Victoria packaging, Pietermaritzburg, South Africa).

2.4. Evaluation of Products' Drying Characteristics

The experimental data was fitted to five common drying models using Matlab's curve fitting toolbox.
The five models were selected due to their ability to predict the drying kinetics of food products such as beef Jerky and Kaddid [23, 24]. These models are summarized in Table 1.

2.5. Product Quality

The product quality was also measured but the results are presented in another sister publication by Cherono et al. [30].

Table 1: A summary of five drying models used to model the drying kinetics of convective air and infrared drying of biltong

No	Model name	Equation	Reference
1	Page model	$MR = \exp(-kt^n)$	(Hii et al., 2008, [25])
2	Approximation of diffusion model (ADM)	$MR = a[\exp(-kt)]+(1-a)\exp(-kbt)$	(Botelho et al., 2011, [26])
3	Logarithmic model	$MR = a[\exp(-kt)] +c$	(Wang et al., 2007, [27])
4	Simplified Fick's diffusion model (SFD)	$MR = a[\exp(-k(t/L^2))]$	(Mahdhaoui et al., 2013, [28])
5	Midilli model	$MR = a[\exp(-k(t^n))]+bt$	(Midilli et al., 2002, [29])

3. Results and discussion

3.1. Drying Models

The ability of the drying models in representing the drying kinetics under different drying conditions were evaluated based on their ability to fit the data, as represented by the root mean square error (RMSE) and the coefficient of determination (R^2). Table 2 presents the summary of these coefficients for products dried under the convective dryer. It can be seen (Table 2) that ADM best fitted the drying kinetics since it had the highest R^2 values ranging from 0.9938 to 0.9998 for all biltong products dried under the convective dryer. It can further be deduced from Table 2 that except for the simplified diffusion (SDF) model, the k values of the other models in general increased with decrease in product thicknesses. There was also a general decrease in the k values with increasing marinating time. The k values ranged from 0.1294 hr^{-1} to 9.728 x 10^{-7} per hour and are approximately 60 times higher than those of beef jerky presented by Thiagarajan et al. 31]. They are, however, close to those observed by Chabbouh et al. [24] for convectively dried Kaddid.

Table 3 presents a summary of the R^2 and RMSE values for the five models while drying biltong under the LW infrared drying system. It can be seen that the ADM model best fits the data for the infrared drying of the 6 and 12 hour marinated biltong products as evidenced by high R^2 values (ranging from 0.9958 to 0.9997) when compared to those of the other models. The drying data for the 24 hour marinated biltong dried under this drying system fitted to the Midilli model best, with the highest R^2 values being 0.9973, 0.9990 and 0.9989 for the 5, 10 and 15 mm thick slices, respectively. The trend in k values for products dried under the LW infrared system behaved in the same way as those of the convective dryer and ranged between 1.698 x 10^{-6} $hr^{-1}$and 0.3418 per hour.

Table 2: The model coefficients for the Page, Approximation of diffusion (ADM), Logarithmic, Simplified diffusion (SDF) model and the Midilli model, for biltong samples of different thickness and marinating durations then dried in a convective dryer

Marinating duration (hours)	Model	Thickness (mm)	Coefficients					R^2	RMSE
			k (hr^{-1})	n	a	b	c		
6	Page	5	0.1294	0.8161				0.9948	0.03027
		10	0.1122	0.7870				0.9970	0.02260
		15	0.0936	0.7101				0.9968	0.02126
	ADM	5	0.1262		0.7954	0.1456		0.9998	0.00647
		10	0.1187		0.6516	0.1949		0.9996	0.00892
		15	0.1008		0.5283	0.1481		0.9991	0.01242
	Logarithmic	5	0.0987		0.9263		0.060	0.9983	0.01885
		10	0.0754		0.9115		0.066	0.9979	0.02033
		15	0.0538		0.8342		0.139	0.9975	0.02030
	Simplified diffusion	5	2.064E-6		0.9724			0.9902	0.04162
		10	6.142E-6		0.9629			0.9897	0.04199
		15	7.457E-6		0.9398			0.9750	0.05917
	Midilli	5	0.1251	0.8562	1.0080	0.00055		0.9982	0.02093
		10	0.1065	0.8309	1.0070	0.00049		0.9992	0.01356
		15	0.0829	0.7861	1.0050	0.00082		0.9996	0.00719
12	Page model	5	0.0886	0.8121				0.9887	0.04356
		10	0.0746	0.7962				0.9906	0.03847
		15	0.0717	0.7661				0.9904	0.03723
	ADM	5	0.0712		0.8844	0.0360		0.9981	0.01924
		10	0.0647		0.7700	0.12690		0.9977	0.02038
		15	0.0637		0.6972	0.1303		0.9983	0.01684
	Logarithmic	5	0.0686		0.9024		0.094	0.9981	0.01933
		10	0.0555		0.8829		0.193	0.9973	0.02242
		15	0.0513		0.8500		0.148	0.9975	0.02046
	Simplified diffusion	5	1.289E-6		0.9762			0.9828	0.05379
		10	3.819E-6		0.9719			0.9807	0.05527
		15	7.039E-6		0.9643			0.9711	0.06045
	Midilli	5	0.06565	0.9642	0.9966	0.00104		0.9972	0.02544
		10	0.06073	0.9129	1.0060	0.00102		0.9965	0.02775
		15	0.05886	0.8849	1.0090	0.00119		0.9968	0.02555
24	Page model	5	0.06776	0.8329				0.9912	0.03780
		10	0.06737	0.8217				0.9809	0.05526
		15	0.06268	0.7792				0.9923	0.03268
	ADM	5	0.05224		0.9109	-0.020		0.9973	0.02256
		10	0.05177		0.9254	-0.108		0.9938	0.03408
		15	0.04894		0.7974	0.05787		0.9996	0.00819
	Logarithmic	5	0.05632		0.8984		0.096	0.9974	0.02232
		10	0.05215		0.8863		0.122	0.9937	0.03423
		15	0.04585		0.8425		0.156	0.9995	0.00868
	Simplified diffusion	5	9.728E-7		0.9755			0.9859	0.04776
		10	3.848E-6		0.9825			0.9737	0.06488
		15	6.264E-6		0.9667			0.9784	0.05468
	Midilli	5	0.04670	1.0060	0.9903	0.00106		0.9972	0.02513
		10	0.04518	1.0710	0.9937	0.00149		0.9941	0.03639
		15	0.03898	0.9296	1.0040	0.00135		0.9992	0.01246

Table 3: The model coefficients for the Page, Approximation of diffusion (ADM), Logarithmic, Simplified diffusion (SDF) model and the Midilli model, for biltong samples of different thickness and marinating durations then dried under a long wavelength (LW) infrared system

Marinating duration (hours)	Model	Thickness (mm)	Coefficients					R^2	RMSE
			k (hr^{-1})	n	a	b	c		
6	Page	5	0.3040	0.8780				0.9914	0.03000
		10	0.2400	0.7846				0.9886	0.03244
		15	0.1644	0.7692				0.9956	0.01717
	ADM	5	0.3418		3.6940	0.9974		0.9958	0.04084
		10	0.2643		0.6075	0.1716		0.9980	0.01426
		15	0.2933		0.4296	0.1622		0.9997	0.00508
	Logarithmic	5	0.1218		0.9191		0.099	0.9984	0.01383
		10	0.2504		0.8453		0.156	0.9957	0.02109
		15	0.1784		0.7552		0.237	0.9980	0.01214
	Simplified diffusion	5	6.508E-6		0.9860			0.9862	0.03795
		10	1.588E-5		0.9565			0.9724	0.05054
		15	2.132E-5		0.9445			0.9749	0.04078
	Midilli	5	0.3044	0.9905	1.0130	0.00732		0.9977	0.01751
		10	0.2324	0.9069	1.0160	0.00660		0.9947	0.02467
		15	0.1662	0.8574	1.0090	0.00649		0.9987	0.01026
12	Page model	5	0.2607	0.7828				0.9890	0.03021
		10	0.2154	0.7599				0.9951	0.01890
		15	0.1800	0.7436				0.9958	0.01630
	ADM	5	0.3387		0.3917	0.01596		0.9996	0.00522
		10	0.3296		0.5050	0.18290		0.9995	0.00636
		15	0.0235		0.0917	0.12870		0.9997	0.00270
	Logarithmic	5	0.1994		0.7803		0.201	0.9951	0.01818
		10	0.1685		0.8282		0.156	0.9963	0.01697
		15	0.0589		0.7170		0.277	0.9991	0.00506
	Simplified diffusion	5	4.412E-6		0.9529			0.9719	0.04829
		10	1.276E-5		0.9339			0.9729	0.04454
		15	2.176E-5		0.9283			0.9693	0.04385
	Midilli	5	0.2545	0.8842	1.0170	0.0051		0.9982	0.01326
		10	0.2167	0.8182	1.0150	0.0036		0.9984	0.01156
		15	0.1837	0.7920	1.0140	0.0035		0.9982	0.01145
24	Page model	5	0.0952	0.8662				0.9881	0.02821
		10	0.0650	0.8825				0.9954	0.01642
		15	0.0461	0.8796				0.9982	0.00826
	ADM	5	0.0913		0.9481	-0.622		0.9962	0.01672
		10	0.0586		0.9709	-0.990		0.9990	0.00802
		15	0.0774		0.4065	0.1965		0.9987	0.00716
	Logarithmic	5	0.1225		0.7727		0.246	0.9969	0.01520
		10	0.0759		0.7741		0.231	0.9988	0.00882
		15	0.0526		0.7277		0.269	0.9988	0.00702
	Simplified diffusion	5	1.698E-6		0.9817			0.9801	0.03649
		10	4.639E-6		0.9832			0.9905	0.02361
		15	7.175E-6		0.9836			0.9943	0.01458
	Midilli	5	0.0896	1.0520	1.0070	0.00985		0.9973	0.01478
		10	0.0599	1.0220	1.0010	0.00597		0.9990	0.00833
		15	0.0452	0.9590	0.9995	0.00370		0.9989	0.00710

Table 4: The model coefficients for the Page, Approximation of diffusion (ADM), Logarithmic, Simplified diffusion (SDF) model and the Midilli model, for biltong samples of different thickness and marinating durations then dried under a short wavelength (LW) infrared system

Marinating duration (hours)	Model	Thickness (mm)	Coefficients					R^2	RMSE
			k (hr^{-1})	n	a	b	c		
6	Page	5	0.4702	0.7911				0.9975	0.01397
		10	0.3506	0.8095				0.9971	0.01518
		15	0.3033	0.7980				0.9980	0.01146
	ADM	5	0.6469		0.5536	0.2348		0.9998	0.00446
		10	0.4138		0.4580	0.2359		0.9993	0.00818
		15	0.2977		0.3420	0.2031		0.9994	0.00668
	Logarithmic	5	0.5166		0.8690		0.121	0.9986	0.01171
		10	0.4246		0.8455		0.149	0.9980	0.01330
		15	0.3566		0.7956		0.196	0.9981	0.01182
	Simplified diffusion	5	8.924E-6		0.9472			0.9835	0.03819
		10	2.821E-5		0.9537			0.9847	0.03492
		15	4.912E-5		0.9515			0.9845	0.03202
	Midilli	5	0.4786	0.8722	1.0030	0.00881		0.9994	0.00800
		10	0.3846	0.8837	0.0095	1.00600		0.9985	0.01238
		15	0.3132	0.8675	1.0040	0.00980		0.9990	0.00926
12	Page model	5	0.5199	0.7181				0.9892	0.02818
		10	0.3736	0.8915				0.9983	0.01123
		15	0.3237	0.8327				0.9960	0.01584
	ADM	5	0.7547		0.7207	0.09126		0.9989	0.00955
		10	0.4505		0.7248	0.24090		0.9995	0.00637
		15	0.3980		0.8170	-0.0120		0.9997	0.00489
	Logarithmic	5	0.6700		0.8148		0.188	0.9985	0.01106
		10	0.4950		0.8891		0.112	0.9995	0.00671
		15	0.4059		0.8109		0.193	0.9997	0.00463
	Simplified diffusion	5	9.232E-6		0.9341			0.9577	0.05586
		10	3.042E-5		0.9787			0.9945	0.02031
		15	5.762E-5		0.9662			0.9860	0.02974
	Midilli	5	0.5487	0.9029	1.0060	0.02308		0.9976	0.01504
		10	0.3909	0.9672	1.0040	0.01077		0.9994	0.00753
		15	0.3411	0.9777	1.0030	0.02094		0.9996	0.00582
24	Page model	5	0.5815	0.8903				0.9970	0.01693
		10	0.4030	0.8954				0.9915	0.02660
		15	0.3808	0.9283				0.9923	0.02343
	ADM	5	0.7700		0.9276	0.0190		0.9994	0.00789
		10	0.6924		0.9833	0.7203		0.9980	0.01361
		15	0.6845		0.9978	2.0020		0.9978	0.01340
	Logarithmic	5	0.6978		0.9263		0.079	0.9994	0.00892
		10	0.5924		0.8953		0.124	0.9979	0.01393
		15	0.4811		0.8783		0.144	0.9975	0.01433
	Simplified diffusion	5	1.319E-5		0.9822			0.9935	0.02514
		10	3.587E-5		0.9870			0.9874	0.03232
		15	6.221E-5		0.9952			0.9902	0.02647
	Midilli	5	0.6041	1.0010	1.0030	0.01392		0.9994	0.00889
		10	0.4182	1.0892	1.0050	0.02227		0.9992	0.00909
		15	0.3873	1.1323	1.0050	0.02653		0.9995	0.00657

Table 4 presents a summary of model coefficients for drying under the SW infrared dryer. It is observed that there is a general increase in the k values with increase in marinating duration for all slice thicknesses, with k values ranging from 8.924 x 10^{-6} per hour to 0.7700 per hour. The high values are consistent with the higher drying rates observed in this dryer when compared to k values of the convective and LW infrared system. The ADM model best fitted the data of the 6 and 12 hour marinated biltong when drying under the SW infrared system with the highest R^2 values ranging from 0.9993 to 0.9998, while the Midilli model gave the highest R^2 values for all the 24 hour marinated products. When the product thickness was varied, the k values varied in a manner similar to the one observed in both the convective and LW infrared drying systems. It can be concluded that of the five models considered the ADM model had the best fit of the infrared drying of biltong data under the prevailing experimental conditions. The ADM model was also the best fit under convective drying of biltong products previously marinated for the 12 and 24 hour prior to drying. This model also reasonably fitted data from convective air drying of biltong products that had previously been marinated for 6 hours. It can be observed from Table 2, 3 and 4 that there is an increase in the rate constant (k) with dryer type such that k for SW >k for LW >k for convective dryer.

Fig. 2 is a presentation of the observed and estimated MR values as a function of drying time for 5 mm thick products marinated for 12 hours and dried under the LW infrared drying system. It is observed that although all the models generally fitted the data, both the Page and SDF models were underestimating the products moisture content as the end of the drying process approached. This lack of fit could possibly be due to the fact that the two models are highly dependent the external moisture transfer mechanism between the product and surrounding air [4, 32] yet internal moisture transfer is more important in this case. The SDF model which is a simplified theoretical model takes into account the internal moisture transfer characteristics of the product. However, this is not the limiting factor during the drying process in the Infrared systems in the present study and does not account for the external moisture transfer process. The ADM model is a semi-theoretical model and is able to reasonably predict moisture transfer from the products fairly well as indicated by high R^2 and low RMSE values in most of products that were dried under different drying and pre-treatment conditions.

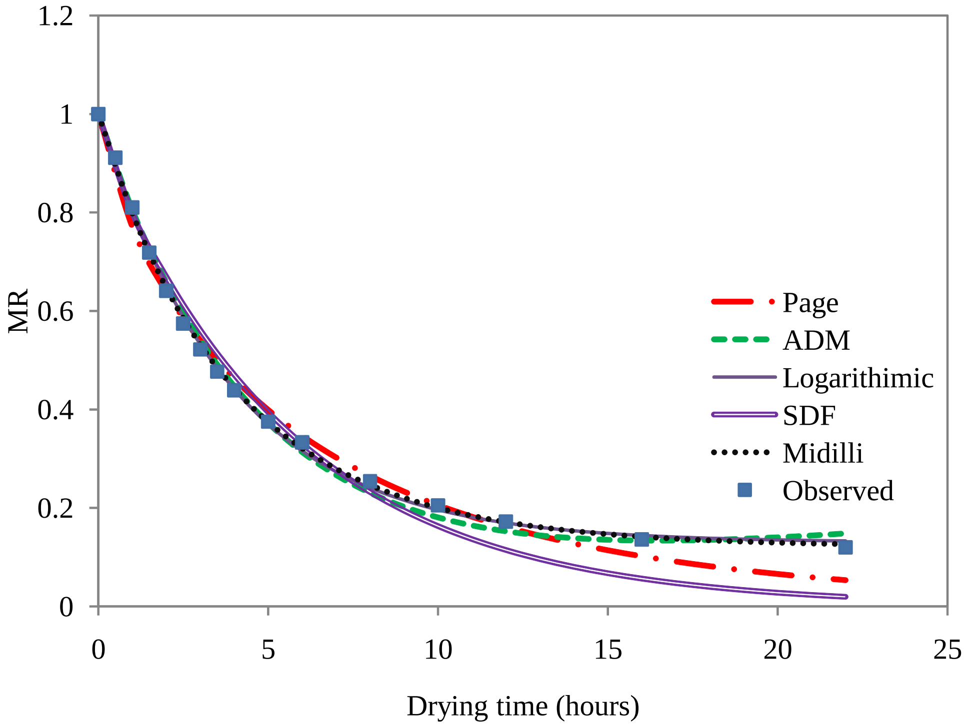

Figure 2: The MR values estimated from drying plotted alongside the observed MR values and as a function of drying time, representing biltong slices that were 5 mm thick, marinated for 12 hours and then dried in the Short Wavelength (SW) infrared dryer

4. Conclusion

Infrared drying of biltong can be up to 95% shorter when compared to the traditional convective drying system. The product thickness affects the drying rate with thinner products generally drying faster while the marinating duration has varied effects under different drying systems in terms of drying rates and specific energy consumption. The approximation of diffusion model best explained the drying kinetics of convective and infrared drying of biltong.

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