Vol. 18(7) pp. 104-109, August 2024
DOI: 10.5897/AJFS2024.2296
Article Number: E8E40EE72402
ISSN: 1996-0794

http://www.academicjournals.org/AJFS

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African Journal of Food Science

Full Length Research Paper

A contradiction-based approach for air velocity choosing in thin-layer drying of cassava root

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Received 22 January, 2024; Accepted 27 March, 2024

The objective of this work is to propose a decision-making tool for the choice of the drying air velocity in thin-layer drying. Formulated as a physical contradiction, the air velocity should be low to promote heat and mass transfers between the air and the cassava slice, and it should be high for humid air extraction and hot air admission in the drying room. Nine cassava slices were dried at T= 25°C, Rh = 10% with a parallel air flow. Three values of the air velocity were used in three different experiments: 0, 0.3 and 0.6 m/s. Data obtained were fitted with the Newton model, values of R^2 were: 0.9988, 0.9981 and 0.9976, decreasing with increasing air velocity. The same data were fitted with the Wangh and Singh model, values of R^2 were: 0.9923, 0.9974 and 0.9984 increasing with increasing air velocity. Therefore, the air velocity should be less than 0.6 m/s based on Newton model, to promote the vaporization of liquid moisture and its uptake, and greater than 0.6 m/s based on Wangh and Singh model, to promote air renewal in the drying room.

Key words: Cassava, thin-layer drying, air velocity, physical contradiction.

INTRODUCTION

Optimizing air speed represents a crucial aspect to improve the efficiency of the thin-layer drying process, a fundamental technique in preserving foods, such as cassava slices. This study delves into the complex relationship between air speed and its impact on drying, seeking to effectively balance moisture removal and final product quality. By analyzing key variables such as air flow, temperature, relative humidity, product mass and pressure conditions, we propose a rigorous methodology to determine how different air velocities affect both drying kinetics and product stability. This research builds on previous scientific evidence (Sadaka and Digvir, 2022; Pratap-Singh et al., 2022; Waghmare et al., 2021; Nukulwar et al., 2021; Nukulwar and Tungikar, 2019, 2020; Zendera and Mutetwa, 2018; Yahya, 2018; Tunde-Akintunde and Afon, 2009; Akpinar and Bicer, 2007) and uses systematic approaches, including the careful selection of thin-layer drying models and the quantitative analysis of the data obtained, to unveil the principles that govern the efficient drying of cassava. The lack of consensus on the ideal air velocity in current drying processes highlights the need for in-depth research that

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Table 1. Ranges and precision of parameter measurements.

Parameter	Unit	Range	Precision
Temperature	°C	0 - 95	±0.2
Relative humidity	%	5 - 95	±2
Air velocity	m/s	0 - 5	±0.05
Mass	kg	0 - 2	±0.1

can contribute practical and theoretical knowledge to the field. Furthermore, we incorporate the Theory of Inventive Problem Solving (TRIZ) (Yao-Tsung et al., 2016; Gadd, 2011) to face and resolve physical contradictions, adopting an innovative approach that goes beyond conventional methods. This study not only enriches the academic literature, but also offers valuable guidelines for the food processing industry, promoting the optimization of drying processes in favor of gains in energy efficiency and quality of the final product.

MATERIALS

A fresh root was obtained from a cassava farm near the city of Ngaoundéré (7°19' N and 13°33'E) (Cameroon). A UNIVERSAL OVENS U, model size 750, from the MEMMERT Heating and Drying Ovens Company was used as dryer. That dryer is designed and tested according to the strict requirements of DIN 12 880: 2007-05. The oven setting temperature ranges from +20 to +300°C with an accuracy of 0.1°C. A two-digit precision balance, HEMA Elektronish AAM, was used to measure the mass of the samples in the range of 0.00 to 2000.00 g. A manual stainless-steel dicer of the Genius Nicer-Dicer Plus TM was used to cut the cassava root in elements of 1 mm thick. A digital vernier caliper was used to measure the thickness of cassava slicers, its measuring range varies from 0 to 200 mm with a precision of ± 0.05 mm. A Chrono-Thermo-Hygrometer-speedometer HAISHI Quartz KD 3610 was used to measure the drying time, the air temperature, the air relative humidity and the air velocity. The range of the operating parameters and the precision of the devices used for measurement are presented in Table 1.

METHODS

Formulation of a physical contradiction

A technical system is a set of three elements E_1, E_2, E_3, within which E_1, called 'tool' interacts with E_2, called 'product' in the presence of E_3, called 'facilitator' in order to change its physical state, its chemical composition or its shape (Yao-Tsung et al., 2016). The interaction between E_1 and E_2 is called 'Useful function'. A technical contradiction happens in a technical system when trying to improve a characteristic of E_1 or E_2 leads to the deterioration of a characteristic of E_3. A physical contradiction happens when: "An element E_1, E_2 or E_3 should have characteristic "A" in order to perform a useful function and this same element should have characteristic "non-A" in order to satisfy existing limitations and requirements" (Yao-Tsung et al., 2016).

Solving a physical contradiction

The full description of those separation methods is given by Gadd (2011). The ideal final result consists of having characteristic "A" where and when necessary and characteristic "non-A", where and when necessary.

Determination of cassava moisture content

For the determination of the initial and final cassava moisture content, three samples were put into the oven initially set to 105°C for 24 h. The samples' masses were weighed before and after the operation.

The initial moisture content of the cassava samples, dry basis, was calculated using Equation 1:

$$X_i = \frac{M_i - M_d}{M_d} \tag{1}$$

where X_i: the initial moisture content of a sample, dry basis; M_i (kg): the initial mass of the sample; M_d (kg): the dry mass of the sample.

Drying procedure

Three values of the drying air velocity were used in three different experiments. For a specific drying air velocity, three cassava slices were set to dry at 25°C, 10% of relative humidity with a parallel air flow. The mass of each slice is measured every 30 min, and the average of the three masses is used for the calculation of the moisture content at that time according to Equation 2.

$$X_{db}(t) = \frac{M(t) - M_d}{M_d} \tag{2}$$

where X_{db} (t): the moisture content of a sample at time (t), dry basis; M(t) (kg): the mass of the sample at time (t); M_d (kg): the dry mass of the sample.

When the mass of a sample is stable, we consider the corresponding value as final and that value is used to calculate the final moisture content according to Equation 3:

$$X_{f\_db}(t_f) = \frac{M_f(t_f) - M_d}{M_d} \tag{3}$$

where t_f (s): end of the drying time; X_{f_db}: the final moisture content of a cassava sample, dry basis;
M_f (kg): the final mass of a cassava sample; M_d (kg): the dry mass of a cassava sample.

For time values greater than t_f, the oven is set to 105°C for 24 h, the mass of the dried sample is used for modeling the drying kinetic.

The moisture content of cassava samples, wet basis, was calculated according to Equation 4:

$$X_{wb}(t) = \frac{M(t) - M_d}{M_i} \tag{4}$$

where X_{wb} (t): the moisture content of a sample at time (t), wet basis; M(t) (kg): the mass of the sample at time (t); M_i (kg): the initial mass of the sample; M_d (kg): the dry mass of the sample.

RESULTS AND DISCUSSION

The physical contradiction

In thin-layer drying of cassava slices, the physical contradiction takes place in a technical system composed of the drying air, the liquid moisture, and the dryer. The useful function (UF) expected from that technical system

Table 2. Values of initial, final and dried cassava samples.

Experiment no.	M_i (*10^{-3}kg)			M_f (*10^{-3}kg)			M_d (*10^{-3}kg)			Air velocity (m/s)
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	
1	29	31	46	11	12.2	18	10	11	16	±0
2	33	33	26	13.5	12.4	10	12	11	9	0.3
3	41	30	33	15.8	11.4	13.3	14	10	12	0.6

Table 3. Values of equilibrium moisture content of all samples.

EMC (%)	V=0 m/s	V=0.3 m/s	V=0.6 m/s
Sample 1	10.82	11.45	9.90
Sample 2	9.75	11.45	12.66
Sample 3	13.82	12.15	11.45

Table 4. Influence of air velocity on drying time.

t_f (h)	V=0 m/s	V=0.3 m/s	V=0.6 m/s
Sample 1 (h)	11	07	05
Sample 2 (h)	13	06	04
Sample 3 (h)	13	07	04

is the elimination of liquid moisture from the cassava slice surface. The physical contradiction can be stated as follows: ''The drying air velocity should be low in order to allow the heating and the vaporization of the liquid moisture and the drying air velocity should be high for the evacuation of humid air from the drying room and the admission of hot and dry air.

The solution of the physical contradiction

The use of TRIZ inventive principle ≠1 ''Segmentation'' helps to achieve the useful function (UF) step by step. A step has two periods: in the first one, the drying air heats the liquid moisture and up takes moisture vapor; low air velocity is needed. In the second period, humid air is extracted from the drying room, replaced by hot and dry air; high air velocity is needed. The use of TRIZ inventive principle ≠33 ''Homogeneity'' helps to decide the end of a step and the end of the whole drying process. A drying step ends when the drying air has no more heat to transfer to the liquid moisture. The whole drying process ends when the cassava slice has no more liquid moisture to transfer to the drying air.

Cassava moisture content

The initial, final and dried masses of cassava samples presented in Table 2 were used for the calculation of moisture content. From those calculations, we found that the average initial moisture content of cassava samples, dry basis, was X_{db}= 1.89 ± 0.09. That value is between 1.80 and 2.6, range proposed by Zidenga et al. (2012), Nayar (2011), Sayre et al. (2011) and Zhang et al. (2007).

Equilibrium moisture content (EMC)

The values of the final and dry masses of cassava samples, given in Table 2 were used for the calculation of equilibrium moisture content, according to Equation 4. Values of equilibrium moisture content are presented in Table 3 for all the samples and for air velocity set to 0, 0.3 and 0.6 m/s. All the values in that table are in the range of 8 to 15% considered in the literature as valid for the conservation of dried cassava roots (Tunde-Akintunde and Afon, 2009; Mkandawire, 2008; Kajuna et al., 2001). Although all the samples are obtained from the same cassava root, only two of them have the same equilibrium moisture content. This can be explained by the fact that the samples are all different from a chemical point of view. It appears secondly that monitoring air velocity has no influence on the equilibrium moisture content of samples.

The drying time

The drying times of all the samples are presented in Table 4. They range from 11 to 13 h, from 6 to 7 h, and from 4 to

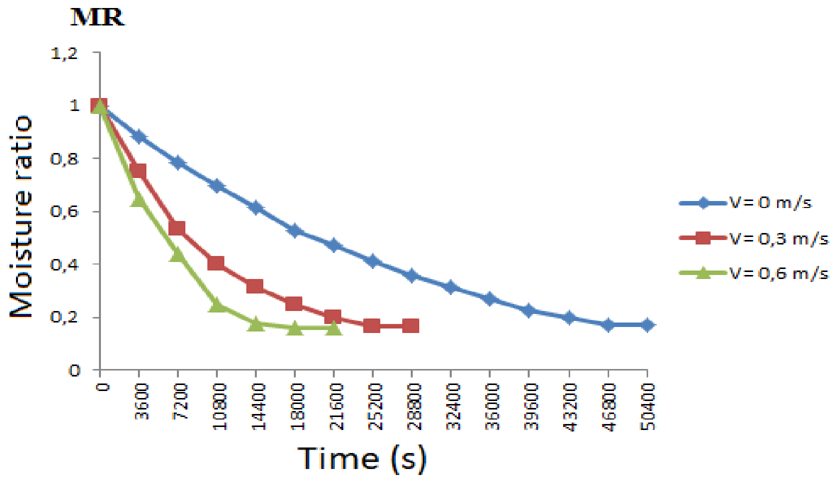

Figure 1. Drying kinetics of cassava samples for T= 25°C, Rh = 10 %, parallel flow.

Table 5. Values of constants in Newton and Wangh and Singh models

Models		**Constants**	**V=0 (m/s)**	**V=0.3 (m/s)**	**V=0.6 (m/s)**
Designation	**Equation**				
Newton	$MR(t) = Exp(-kt)$	k (s^{-1})	3.87×10^{-5}	8×10^{-5}	12.12×10^{-5}
Wangh and Singh	$MR(t) = a_1 \cdot t^2 + a_2 \cdot t + 1$	a_1 (s^{-2})	4.75×10^{-10}	1.66×10^{-9}	3.43×10^{-9}
		a_2 (s^{-1})	-4.23×10^{-5}	-7.89×10^{-5}	-12.01×10^{-5}

5 h for air velocity of 0, 0.3 and 0.6 m/s, respectively. For air velocity set to 0 m/s, the sample 2 with a lesser initial mass had the same drying time with the sample 3. This can be explained by the fact that it required more time to expel more moisture, reaching a lower value for the equilibrium moisture content. The longest drying time is reduced by 69.23% decreasing from 13 h for V = 0 m/s to 4 h for V = 0.6 m/s.

Kajuna et al. (2001) dried 5 mm cube size of cassava roots at 65°C, the EMC of cubes was reached after 125, 150 and 175 min for one, two and three layers, respectively. Afriyie et al. (2008) observed that to dry 1 cm layer of cassava root, 15 h is required for T= 50°C, 8 h 45 min for T= 60°C and 7 h 30 min if T= 70°C. In those two cases, no mention is made on the value of the drying air velocity and the nature of the air flow. In this work, an air velocity ranging between 0 and 0.6 m/s influences the drying time. This finding is not in agreement with what has been reported early by Kajuna et al. (2001) according to whom drying is independent of air velocity in the range of 0.15 to 0.81 m/s.

Drying kinetics

Figure 1 presents the drying kinetics of cassava samples for air velocity set to 0, 0.3 and 0.6 m/s; T = 25°C, Rh = 10% and parallel air flow. A drying kinetic is obtained for a specific value of the drying air velocity by representing the moisture ratio (MR) of cassava samples versus time.

All the drying kinetics obtained had two parts: in the first one, the moisture ratio of each sample decreased with time, while in the second part, it remained constant.

Mathematical modeling of drying curves

The drying data obtained (moisture ratio versus time) for different values of air velocity were fitted by the Newton and Wangh and Singh models. The models were evaluated based on the coefficient of determination (R^2), the reduced Chi-square (χ^2) and the root mean square error (RMSE). The ability of a theoretical model to describe the drying behavior of cassava samples for different values of air velocity is based on the highest value of R^2, the lowest value of χ^2 and the lowest value of RMSE. Prior to the use of Newton and Wangh and Singh models, drying data was used to calculate their constants. Table 5 presents values of theoretical model constants for air velocity set to 0, 0.3 and 0.6 m/s. As it can be seen, constants k (s^{-1}) and a_1 (s^{-2}) increased with air velocity, while the value of a_2 (s^{-1}) decreased.

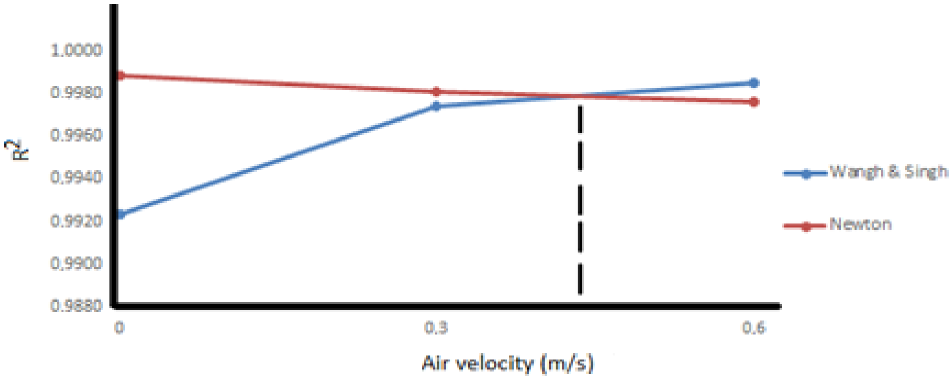

Figure 2. Trends of R^2 VS air velocity.

Values of the coefficient of determination R^2 were: 0.9988, 0.9981 and 0.9976 for the Newton model and 0.9923, 0.9974 and 0.9984 for the Wangh and Singh model for the drying air velocity of 0, 0.3 and 0.6 m/s, respectively. All the values obtained are greater than 0.9, meaning a good correlation between experimental and theoretical data for all three drying air velocity. In the Newton model, values of R^2 decreased as the drying air velocity increased from 0 to 0.6 m/s. This observation can be used as base for drying cassava slices at low values of drying air velocities. In the Wangh and Singh model, values of R^2 increased with the drying air velocity; it becomes therefore interesting to dry cassava slices at greater values of drying air velocity. Similar values of the coefficient of determination were reported in the literature for various food products (Waghmare et al., 2021; Nukulwar et al., 2021; Akpinar and Bicer, 2007; Akpinar et al., 2003; Doymaz and Pala, 2002; Karathanos and Belessiotis, 1999). Figure 2 presents trends of the coefficient of determination vs air velocity for the Newton and Wangh and Singh models.

It appears from Figure 2 that the whole drying process can be conducted at a single value ranging from 0.4 to 0.5 m/s. Apart from this zone, two values are needed for the air velocity during drying.

Values of the Chi-square (χ^2) were: 9.29×10^{-4}, 5.13×10^{-4} and 8.36×10^{-4} for the Newton model and 2×10^{-2}, 9.7×10^{-3} and 3×10^{-2} for the Wangh and Singh model for the drying air velocity of 0, 0.3 and 0.6 m/s, respectively. Values of the Chi-square (χ^2) obtained with the Newton model were a hundred time lower than those given by the Wangh and Singh model, showing a good agreement with the experimental results. Values of the Chi-square (χ^2) obtained by Tunde-Akintunde and Afon (2009), when drying pretreated cassava chips ranged from 8.94×10^{-2} to 13.33×10^{-3}. They were better than those obtained with the Wangh and Singh model, but the Newton model provided the best results.

Values of the RMSE were: $2.83\times10^{-}2$, 1.96×10^{-2} and 2.36×10^{-2} for the Newton model and 13.44×10^{-2}, 8.56×10^{-2} and 14.22×10^{-2} for the Wangh and Singh model. With lower values, the Newton model better fitted the experimental results.

Conclusion

Moving ideally the drying air in the drying room can help minimize energy and time during drying operations. Heat and mass transfers should be done at low air velocity in closed drying room. Air expulsion from the drying room and air admission into it should be done at high air velocity.

For experimental validation, nine cassava slices were set to dry at T= 25°C, Rh = 10% with a parallel air flow. Three values of the drying air velocity were used in three different experiments V= 0 m/s, V = 0.3 m/s, and V = 0.6 m/s. The initial moisture content of cassava samples was found to be $X_{db}=1.89 \pm 0.09$, dry basis. All the final moisture content of cassava samples ranged from 9.75 to 13.82%, wet basis. The drying times ranged from 11 to 13 h, 6 to 7 h and 4 to 5 h for V = 0 m/s, V = 0.3 m/s and V = 0.6 m/s, respectively. Fitted with the Newton model, values of the coefficient of determination (R^2) were: 0.9988, 0.9981, and 0.9976 for V= 0 m/s, V = 0.3 m/s and V = 0.6 m/s, respectively. R^2 decreased as the drying air velocity increased. Fitted with the Wangh and Singh model, values of R^2 were 0.9923; 0.9974 and 0.9984 for V= 0 m/s, V = 0.3 m/s and V = 0.6 m/s respectively. R^2 increased with the drying air velocity. Based on the values of R^2 obtained from the mathematical models, the drying air velocity should be taken around 0 m/s based on Newton model, to give priority to the vaporization of the liquid moisture and its up take, and greater than 0.6 m/s based on Wangh and Singh model to promote the evacuation of humid air.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

This work was supported by the Institut de la Francophonie pour le Développement Durable (IFDD/Canada)/Projet de Déploiement des Technologies et Innovations Environnementales (PDTIE)/Projet d'Excellence en Production d'Innovations Technologiques en Agro-Industries de l'Université de Ngaoundéré (PEPITA-UN) funded by the Organisation Internationale de la Francophonie (OIF), the Organization of African, Caribean and pPacific States and the European Union (EU) (FED 220/421-370).

REFERENCES

Afriyie JK, Nazha MAA (2008). Experimental investigations of a chimney dependent solar crop dryer. Renewable Energy 34(1):217-222.

Akpinar EK, Bicer Y (2007). Modelling of the drying of eggplants in thin-layers. International Journal of Food Science and Technology 40:273-281.

Akpinar EK, Midilli A, Bicer Y (2003). Single layer drying behavior of potato slices in a convective cyclone and mathematical modeling. Journal of Energy Conversion and Management 44:1689-705.

Doymaz L, Pala M (2002). Hot-air drying characteristics of red pepper. Journal of Food Engineering 55:331-335.

Gadd K (2011). TRIZ for Engineers: Enabling Inventive Problem Solving, First Edition. © 2011 John Wiley & Sons, Ltd. Published 2011 by John Wiley & Sons, Ltd. ISBN: 978-0-470-74188-7.

Kajuna STR, Silayo VCK, Mkenda A, Makungu PJJ (2001). Thin-layer drying of diced cassava roots. African Journal of Science and Technology (AJST). Science and Engineering 2(2):94-100.

Karathanos VT, Belessiotis VG (1999). Application of thin-layer equation to drying data of fresh and semi-dried fruits. Journal of Agricultural Engineering Research 74:355-361.

Mkandawire RW (2008). Status of cassava drying in Malawi. A survey report.

Nayar A (2011). Grants aim to fight malnutrition. Nature. doi:10.1038/news.2011.233.

Nukulwar MR, Vinod B, Tungikar (2021). A review on performance evaluation of solar dryer and its material for drying agricultural products. Materials Today: Proceedings 46(2021):345-349.

Nukulwar MR, Tungikar VB (2020). Design and development of steam-based solar dryer for agricultural products. InProceedings of International Conference in Mechanical and Energy Technology: ICMET 2019, India 2020 Jun 2 (pp. 365-375). Singapore: Springer Singapore.

Nukulwar MR, Tungikar VB (2019). Thin Layer Mathematical Modelling of Turmeric in Indirect Natural Conventional Solar dryer. Journal of Solar Energy Engineering 142(4):041001.

Pratap-Singh A, Shaba N, Mandal R, Singh A (2022). Sustainable processing through efficient use of energy and minimizing waste production. In book: Non-thermal processing in Agri-Food-Bio Sciences (pp. 723-748).

Sadaka S, Digvir SJ (2022). Cereal grain drying system, Storage of cereal grains and their products (Fifth Edition). Pp. 293-329.

Sayre R, Beeching JR, Cahoon EB, Egesi C, Fauquet C, Fellman J, Fregene M (2011). The BioCassava plus program: biofortification of cassava for sub-Saharan Africa. Annual Review of Plant Biology 62:251-272.

Tunde-Akintunde TY, Afon AA (2009). Modelling of Hot-Air Drying of Pretreated Cassava Chips. Agricultural Engineering International: the CIGR Ejournal 12(2):34-41.

Waghmare RB, Perumal AB, Moses JA, Dharamacrishnan CA (2021). Recent developments in freeze-drying of Foods, Innovative Food processing technologies. A Comprehensive Review 82-89.

Yahya M (2018). Performance analysis of solar drying system using double pass solar air collector with finned absorber for drying copra, Contemporary Engineering Sciences 11:523-536,

Yao-Tsung K, Chia-Chen L, Li-Hui L (2016). A Contradiction-Based Approach for Innovative Product Design, MATEC Web of Conferences 68, 05001 (2016) DOI: 10.1051/matecconf/20166 ICIEA 2016.

Zendera W, Mutetwa M. (2018). Design and evaluation of a cassava solar dryer. Journal of Scientific Research in Engineering and Technology 2(1):2455-5681

Zhang BG, Zhou YD, Ning W, Xie DB (2007). Experimental Study on Energy Consumption of Combined Conventional and Dehumidification Drying. Drying Technology 25(3):471-474.

Zidenga T, Leyva-Guerrero E, Moon H, Siritunga D, Sayre RT (2012). Extending cassava root shelf life via reduction of reactive oxygen species production. Plant Physiology 159:1396-1407.