EFFECT OF SWIRLING FLOW ON FLUIDISED BED DRYING OF *PIPER NIGRUM*: AN EXPERIMENTAL STUDY

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Piper nigrum (Lada hitam) adalah salah satu rempah ratus terkenal yang banyak digunakan di seluruh dunia terutama sekali di India dan Asia Tenggara. *Piper nigrum* adalah buah berbiji keras dengan diameter kira-kira 5 mm (0.2 inci). Baunya pedas, menusuk, dan beraroma, dan rasanya panas, pahit dan pedas. *Piper nigrum* diproses dari buah hijau mentah dari tanaman lada dan proses pengeringan dilakukan untuk menghilangkan kelembapan. Pengeringan ialah salah satu kaedah paling popular untuk memelihara kegunaan pelbagai produk pertanian. Salah satu proses konvensional dalam pengeringan *piper nigrum* adalah dengan menggunakan pengeringan cahaya matahari. Walaubagaimanapun, kaedah ini boleh mempengaruhi kualiti produk secara negatif, terutamanya kebersihan produk, seperti tercemar oleh habuk, kotoran, dan serangga. Maka kaedah pengeringan yang baru perlu dikaji secara berterusan. *Fluidised bed dryer* (*FBD*) telah digunakan dengan meluas keatas pengeringan bahan mentah atau hasil produk disebabkan kelebihan kecekapan yang baik dan kadar pemindahan haba dan jisim yang tinggi. Kekurangan reka bentuk pengedar angin juga merupakan salah satu kelemahan potensi pengeringan. Kajian ini bertujuan untuk melaksanakan secara eksperimen perbandingan pengeringan *piper nigrum* dengan menggunakan kaedah konvensional dan dengan menggunakan *FBD*. Pengeringan *piper nigrum* menggunakan *FBD* dijalankan dengan mempelbagaikan reka bentuk pengedar angin, iaitu sudut kecondongan 45° dan 67° pengedar angin berlubang sekata. Sebagai tambahan, kajian mengenai pengaruh pengedar angin terhadap hidrodinamik *piper nigrum* dan prestasi aliran angin berpusing terhadap *FBD* telah direkodkan. Eksperimen pengeringan dijalankan menggunakan tiga suhu berbeza: suhu bilik, suhu 40 °C dan suhu 50 °C. Keberkesanan *FBD* disahkan melalui pengurangan peratusan kandungan kelembaban. Kesan reka bentuk pengedar ke atas prestasi hidrodinamik *piper nigrum* dalam *FBD* dikaji dengan menggunakan lima berat yang berbeza (250 g, 500 g, 750 g, 1000 g dan 1250 g). Pengeringan menggunakan *FBD* direkodkan 9 jam menjimatkan masa pengeringan kira-kira 66.7% berbanding pengeringan konvensional yang direkodkan pada 27 jam. Dalam kajian ini, kadar pengeringan *piper nigrum* menggunakan *FBD* yang dikendalikan dengan pengedar sudut kecondongan 45° direkodkan 9.7% lebih tinggi daripada pengedar sudut kecondongan 67° dan 1.6% lebih tinggi daripada dikendalikan dengan pengedar berlubang sekata berdasarkan berat *piper nigrum* selepas pengeringan. Dari eksperimen hidrodinamik, pengedar angin yang menyumbang kepada kejatuhan tekanan udara yang lebih rendah dan pencampuran *piper nigrum* yang lebih baik dalam *FBD* adalah pengedar angin sudut berkecondongan 67° dengan 85.2 mmH_2O pada berat *piper nigrum* 1000 g dan mencapai kelajuan minimum udara pada 0.23m/s. 1000 g ialah berat yang sesuai untuk dikendalikan menggunakan *FBD* dalam eksperimen hidrodinamik. Kesimpulannya, prestasi pengedar angin terbaik yang dapat memberi kelebihan dalam pengeringan telah dikenalpasti iaitu pengedar angin sudut berkecondongan 45° manakala bagi kajian hidrodinamik adalah pengedar angin sudut berkecondongan 67°.

ABSTRACT

Piper nigrum (Black pepper) is one of the well-known spices used worldwide, especially in India and Southeast Asia. *Piper nigrum* is a drupe with a diameter of about 5 mm (0.2 inch). Its odour is pungent, penetrating, and aromatic, and its taste is hot, bitter, and spicy. *Piper nigrum* is processed from unripe, raw green berries from the pepper plant, after which the drying process is applied to remove the moisture. Drying is one of the most popular methods of preserving a wide variety of agricultural products. One of the conventional processes in drying the *piper nigrum* is by using sun drying. Unfortunately, sun drying operation may negatively influence product hygiene because of contamination of dust, dirt, and insects. Thus, new drying techniques are continuously being sought. Fluidised bed dryers are widely used to dry wet materials due to the advantages of good mixing efficiency as well as high heat and mass transfer rate. But another reason for poor drying efficiency is a lack of design on the distributor plate. This study aims to investigate drying of piper nigrum using conventional sun drying method and swirling fluidised bed drying. The drying characteristic of *piper nigrum* using a swirling fluidised bed dryer is investigate by varying different designs of fluidised bed dryer's air distributor, namely perforated, 45° and 67° inclination angles of air distributors. In addition, to study the effect of different distributor designs on the hydrodynamics of piper nigrum in a swirling fluidised bed. The drying experiments are conducted using three different temperatures: room temperature, 40 °C, and 50 °C. The effectiveness of the swirling fluidised bed dryer is accessed using the percentage of moisture content reduction. The effect of distributor design on hydrodynamics performance of *piper nigrum* in a fluidised bed dryer was investigated using five different weights (250 g, 500 g, 750 g, 1000 g and 1250 g). Drying using swirling fluidised bed dryer recorded 9 hours saves drying time about 66.7% as compared to conventional drying recorded at 27 hours. In this study, the drying rate of *piper nigrum* using a swirling fluidised bed dryer operated with a 45° inclination angle distributor records 9.7% higher than the 67° inclination angle distributor and 1.6% higher than operated with perforated distributor based on the weight after drying. From the hydrodynamics experiment, the distributor that contributed to lower pressure drops and improved particulate mixing in a swirling fluidised bed dryer was found to be 67° inclination angle distributor with 85.2 mmH_2O at 1000 g of *piper nigrum* and reaching uniform minimum fluidisation at 0.23 m/s. Thus, 1000 g of *piper nigrum* is a suitable weight to operate using swirling fluidised bed dryer in the hydrodynamics experiment. In conclusion, the best distributor performance that could give an advantage in drying using fluidised bed dryer was 45° inclination angle distributor and for hydrodynamics experiment was 67° inclination angle distributor.

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LIST OF SYMBOLS

h_{col}	height of column, m
M	moisture content, g/g
M_e	moisture content in equilibrium state, g/g
M_o	initial moisture content in wet basis, g/g
P	pressure tap, mmH_2O
P_b	bottom pressure, Pa
ΔP_{bed}	pressure drop bed, mmH_2O
P_t	top pressure, Pa
T	temperature, °C
t	drying time, hours
U_{mf}	uniform minimum fluidisation, m/s
v	velocity, m/s
W_d	dry sample weight (without moisture), g
W_i	weight initial before drying, g
W_l	weight loss, g
W_t	sample weight drying at time, g
W_1	weight of sample before drying (oven drying), g
W_2	weight of sample after drying (oven drying), g
ø	diameter, mm
θ	angle, °

LIST OF SUBSCRIPT

b	bottom
bed	bed
col	column
d	dry
e	equlibrium
i	initial
l	loss
mf	minimum fluidisation
t	top

LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
DC	Direct Current
DR	Drying Rate
FAO	Food and Agricultural Organisation
FBD	Fluidised Bed Dryer
FCD	Forced Sun Drying
GDP	Gross Domestic Product
GTD	Greenhouse Tunnel Drying
HC	Hydrodynamic Cavitation
M	Moisture
MC	Moisture Content
MR	Moisture Ratio
OSD	Open Sun Drying
PPO	Polyphenol Oxidise
PV	Photovoltaics
RFBW	Rectangular Fluidised Bed with Wavy Wall
RMSE	Root Mean Square Error
SFBD	Swirling Fluidised Bed Dryer
STD	Solar Tunnel Dryer

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REFERENCES

Abdulazeez, M. A., Sani, I., James, B. D., & Abdullahi, A. S. (2016). Black pepper (Piper nigrum L.) oils. In *Essential Oils in Food Preservation, Flavor and Safety*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-416641-7.00031-6

Advantages & Disadvantages of Fluid Bed Dryer in Pharmaceutical Industry. (n.d.). Retrieved July 4, 2019, from https://www.saintytec.com/advantages-and-disadvantages-of-fluid-bed-dryer/

Agriculture and Food. (2020). https://www.worldbank.org/en/topic/agriculture/overview

Akpinar, E. K. (2010). Drying of mint leaves in a solar dryer and under open sun: Modelling, performance analyses. *Energy Conversion and Management*, *51*(12), 2407–2418. https://doi.org/10.1016/j.enconman.2010.05.005

Al-habsi, N. A. (2019). Food and Bioproducts Processing Effect of solar drying methods on color kinetics and texture of dates. *Food and Bioproducts Processing*, *116*, 227–239. https://doi.org/10.1016/j.fbp.2019.03.012

Al-Khayri, J. M., Jain, S. M., & Johnson, D. V. (2015). Date palm genetic resources and utilization: Volume 2: Asia and Europe. In *Date Palm Genetic Resources and Utilization: Volume 2: Asia and Europe* (Vol. 2). https://doi.org/10.1007/978-94-017-9707-8

Al-Mahasneh, M. A., Rababah, T. M., Bani-Amer, M. M., Al-Omari, N. M., & Mahasneh, M. K. (2013). Fuzzy and conventional modeling of open sun drying kinetics for roasted green wheat. *International Journal of Food Properties*, *16*(1), 70–80. https://doi.org/10.1080/10942912.2010.528108

AOAC. (1999). Official Methods of Analysis International. *Association of Analytical Communities, Gaithersburg*, *17th editi*. https://doi.org/10.4236/am.2012.37106

Azaizia, Z., Kooli, S., Elkhadraoui, A., & Hamdi, I. (2017). ScienceDirect Investigation of a new solar greenhouse drying system for peppers. *International Journal of Hydrogen Energy*, *42*(13), 8818–8826. https://doi.org/10.1016/j.ijhydene.2016.11.180

Azmi, M. Z., Rukunudin, I. H., Ismail, H. A., & Aznan, A. A. (2019). Specific energy consumption and drying efficiency analysis of commercial mixed-flow batch type seed drying system. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *55*(1), 39–50.

Badaoui, O., Hanini, S., Djebli, A., & Haddad, B. (2019). Experimental and modelling study of tomato pomace waste drying in a new solar greenhouse : Evaluation of new drying models. *Renewable Energy*, *133*, 144–155. https://doi.org/10.1016/j.renene.2018.10.020

Bahammou, Y., Tagnamas, Z., Lamharrar, A., & Idlimam, A. (2019). Thin-layer solar drying characteristics of Moroccan horehound leaves (Marrubium vulgare L .) under natural and forced convection solar drying. *Solar Energy*, *188*(July), 958–969.

https://doi.org/10.1016/j.solener.2019.07.003

Bakhurji, A., Bi, X., & Grace, J. R. (2019). Hydrodynamics and solids mixing in fluidized beds with inclined-hole distributors. *Particuology*, *43*, 19–28. https://doi.org/10.1016/j.partic.2018.01.011

Barathiraja, R., Thirumal, P., Thirumalaikumarasamy, D., Kajavali, A., Ashokkumar, M., & Thiyagaraj, J. (2021). Investigation of drying kinetics and qualities of turkey berry in fluidized bed dryer. *Materials Today: Proceedings*, *46*, 7711–7718. https://doi.org/10.1016/j.matpr.2021.02.217

Batcha, M. F. M., & Raghavan, V. R. (2011). Experimental Studies on a Swirling Fluidized Bed with Annular Distributor. *Journal of Applied Sciences*, *11*(11), 1980–1986. https://doi.org/10.3923/jas.2011.1980.1986

Beigi, M., Tohidi, M., & Torki-harchegani, M. (2017). Exergetic analysis of deep-bed drying of rough rice in a convective dryer. *Energy*, *140*, 374–382. https://doi.org/10.1016/j.energy.2017.08.100

Charoux, C. M. G., Ojha, K. S., O'Donnell, C. P., Cardoni, A., & Tiwari, B. K. (2017). Applications of airborne ultrasonic technology in the food industry. *Journal of Food Engineering*, *208*, 28–36. https://doi.org/10.1016/j.jfoodeng.2017.03.030

Chokphoemphun, S., & Chokphoemphun, S. (2018). Moisture content prediction of paddy drying in a fluidized-bed drier with a vortex flow generator using an artificial neural network. *Applied Thermal Engineering*, *145*(September), 630–636. https://doi.org/10.1016/j.applthermaleng.2018.09.087

Chuwattanakul, V., & Eiamsa-ard, S. (2019). Case Studies in Thermal Engineering Hydrodynamics investigation of pepper drying in a swirling fl uidized bed dryer with multiple-group twisted tape swirl generators. *Case Studies in Thermal Engineering*, *13*(January), 100389. https://doi.org/10.1016/j.csite.2018.100389

Chuwattanakul, V., & Eiamsa-Ard, S. (2019). Hydrodynamics investigation of pepper drying in a swirling fluidized bed dryer with multiple-group twisted tape swirl generators. *Case Studies in Thermal Engineering*, *13*(January), 100389. https://doi.org/10.1016/j.csite.2018.100389

Danilo, L., Barrientos, P., Diego, J., Oquendo, T., Andrea, M., Garzón, G., Lucia, O., & Álvarez, M. (2019). E ff ect of the solar drying process on the sensory and chemical quality of cocoa (Theobroma cacao L .) cultivated in Antioquia , Colombia. *Food Research International*, *115*(52), 259–267. https://doi.org/10.1016/j.foodres.2018.08.084

Darvishi, H., Khoshtaghaza, M. H., & Minaei, S. (2015). Effects of fluidized bed drying on the quality of soybean kernels. *Journal of the Saudi Society of Agricultural Sciences*, *14*(2), 134–139. https://doi.org/10.1016/j.jssas.2013.09.002

Daud, W. R. W. (2008). Fluidized Bed Dryers — Recent Advances. *Advanced Powder Technology*, *19*(5), 403–418. https://doi.org/10.1016/s0921-8831(08)60909-7

Det, paulus amin. (n.d.). *Harvesting, Processing, Drying and Storage of Pepper*.

Dibagar, N., Amiri, R., Jan, S., & Hossain, S. (2019). Deep bed rough rice air-drying assisted with airborne ultrasound set at 21 kHz frequency : A physicochemical investigation and optimization. *Ultrasonics - Sonochemistry*, *53*(July 2018), 25–43. https://doi.org/10.1016/j.ultsonch.2018.12.011

Djebli, A., Hanini, S., Badaoui, O., & Haddad, B. (2020). Modeling and comparative analysis of solar drying behavior of potatoes. *Renewable Energy*, *145*, 1494–1506. https://doi.org/10.1016/j.renene.2019.07.083

drying parameter. (n.d.). Retrieved July 5, 2019, from https://www.ptonline.com/knowledgecenter/plastics-drying/drying-basics/drying-parameters

El-sebaii, A. A., & Shalaby, S. M. (2012). Solar drying of agricultural products : A review. *Renewable and Sustainable Energy Reviews*, *16*(1), 37–43. https://doi.org/10.1016/j.rser.2011.07.134

EL khadraoui, A., Hamdi, I., Kooli, S., & Guizani, A. (2019). Drying of red pepper slices in a solar greenhouse dryer and under open sun: Experimental and mathematical investigations. *Innovative Food Science and Emerging Technologies*, *52*(April 2018), 262–270. https://doi.org/10.1016/j.ifset.2019.01.001

Eltawil, M. A., Azam, M. M., & Alghannam, A. O. (2018). Solar PV powered mixed-mode tunnel dryer for drying potato chips. *Renewable Energy*, *116*, 594–605. https://doi.org/10.1016/j.renene.2017.10.007

Fan, K., Zhang, M., & Mujumdar, A. S. (2017). Application of airborne ultrasound in the convective drying of fruits and vegetables: A review. *Ultrasonics Sonochemistry*, *39*(March), 47–57. https://doi.org/10.1016/j.ultsonch.2017.04.001

Food. (2021). Wikipedia, the Free Encyclopedia. https://en.wikipedia.org/wiki/Food#cite_note-2

Gamboa-santos, J., Montilla, A., Andrés, J., Villamiel, M., & Garcia-perez, J. V. (2014). Air-borne ultrasound application in the convective drying of strawberry. *JOURNAL OF FOOD ENGINEERING*, *128*, 132–139. https://doi.org/10.1016/j.jfoodeng.2013.12.021

Ganesapillai, M., Regupathi, I., & Murugesan, T. (2008). An empirical model for the estimation of moisture ratio during microwave drying of plaster of Paris. *Drying Technology*, *26*(7), 963–978. https://doi.org/10.1080/07373930802142978

Growing consumption. (2020). European Commission. https://ec.europa.eu/knowledge4policy/growing-consumerism_en#:~:text=Unless consumers' behaviour and consumption,%25 respectively%2C compared to 2012.

Gu, F., Tan, L., Wu, H., Fang, Y., & Wang, Q. (2013). Analysis of the blackening of green pepper (Piper nigrum Linnaeus) berries. *Food Chemistry*, *138*(2–3), 797–801. https://doi.org/10.1016/j.foodchem.2012.11.033

Halim, L. A., Basrawi, M. F., Yudin, A. S. M., & Faizal, S. N. (2020). Fluidized bed drying of stingless bee pot-pollen: Performance of swirling distributor. *IOP Conference Series: Materials Science and Engineering*, *863*(1). https://doi.org/10.1088/1757-899X/863/1/012006

Hamdi, I., Kooli, S., Elkhadraoui, A., Azaizia, Z., & Abdelhamid, F. (2018). Experimental study and numerical modeling for drying grapes under solar greenhouse. *Renewable Energy*, *127*, 936–946. https://doi.org/10.1016/j.renene.2018.05.027

Haron, N. S., Zakaria, J. H., & Batcha, M. F. M. (2017a). Hydrodynamics study on drying of pepper in swirling fluidized bed dryer (SFBD). *IOP Conference Series: Materials Science and Engineering*, *226*(1). https://doi.org/10.1088/1757-899X/226/1/012053

Haron, N. S., Zakaria, J. H., & Batcha, M. F. M. (2017b). *Recent advances in fluidized bed drying Recent advances in fluidized bed drying*. https://doi.org/10.1088/1757-899X/243/1/012038

Hilares, R. T., Dionízio, R. M., Prado, C. A., Ahmed, M. A., Silva, S. S., & Santos, J. C. (2019). Pretreatment of sugarcane bagasse using hydrodynamic cavitation technology : Semi-continuous and continuous process. *Bioresource Technology*, *290*(July), 121777. https://doi.org/10.1016/j.biortech.2019.121777

Hossain, M. A., & Bala, B. K. (2007). *Drying of hot chilli using solar tunnel drier*. *81*, 85–92. https://doi.org/10.1016/j.solener.2006.06.008

Islam, M. H. (2012). *Fluidized Bed Dryer*. http://www.atozstudyzone.com/2012/11/fluidized.html

Jayatunga, G. K., & Amarasinghe, B. M. W. P. K. (2019). Drying kinetics, quality and moisture diffusivity of spouted bed dried Sri Lankan black pepper. *Journal of Food Engineering*, *263*(December 2018), 38–45. https://doi.org/10.1016/j.jfoodeng.2019.05.023

Jia, D., Bi, X., Lim, C. J., Sokhansanj, S., & Tsutsumi, A. (2016). Biomass drying in a pulsed fluidized bed without inert bed particles. *Fuel*, *186*, 270–284. https://doi.org/10.1016/j.fuel.2016.08.100

Jia, D., Cathary, O., Peng, J., Bi, X., Lim, C. J., Sokhansanj, S., Liu, Y., Wang, R., & Tsutsumi, A. (2015). Fluidization and drying of biomass particles in a vibrating fluidized bed with pulsed gas flow. *Fuel Processing Technology*, *138*, 471–482. https://doi.org/10.1016/j.fuproc.2015.06.023

Joy, C. M., Peter Pittappillil, G., & Jose, K. (2002). Drying of Black Pepper (Piper nigrum L.) Using Solar Tunnel Dryer. *PertanikaJ. Trap. Agric. Sci*, *25*(1), 39–45.

Kaleta, A., Górnicki, K., Winiczenko, R., & Chojnacka, A. (2013). Evaluation of drying models of apple (var. Ligol) dried in a fluidized bed dryer. *Energy Conversion and Management*, *67*, 179–185. https://doi.org/10.1016/j.enconman.2012.11.011

Kamble, L. V., Pangavhane, D. R., & Singh, T. P. (2014). Experimental investigation of horizontal tube immersed in gas-solid fluidized bed of large particles using artificial neural network. *International Journal of Heat and Mass Transfer*, *70*, 719–724. https://doi.org/10.1016/j.ijheatmasstransfer.2013.11.073

Kamenan, B., Magloire, P., Koffi, E., & Gbaha, P. (2019). Journal of the Saudi Society of Agricultural Sciences Evolution of shrinkage , real density , porosity , heat and mass transfer coefficients during indirect solar drying of cocoa beans. *Journal of the Saudi Society of Agricultural Sciences*, *18*(1), 72–82. https://doi.org/10.1016/j.jssas.2017.01.002

Kang, J. L., Chen, W. F., Ciou, Y. C., Wong, D. S. H., & Jang, S. S. (2017). Investigation of Hydrodynamic Behaviour in random packing using CFD simulation. *Computer Aided Chemical Engineering*, *40*, 13–18. https://doi.org/10.1016/B978-0-444-63965-3.50004-0

Khew, C. Y., Koh, C. M. M., Chen, Y. S., Sim, S. L., & Augustine Mercer, Z. J. (2022). The current knowledge of black pepper breeding in Malaysia for future crop improvement. *Scientia Horticulturae*, *300*(November 2021), 111074. https://doi.org/10.1016/j.scienta.2022.111074

Khosravi Bizhaem, H., & Basirat Tabrizi, H. (2013). Experimental study on hydrodynamic characteristics of gas-solid pulsed fluidized bed. *Powder Technology*, *237*, 14–23. https://doi.org/10.1016/j.powtec.2013.01.001

Köksal, M., & Vural, H. (1998). Bubble size control in a two-dimensional fluidized bed using a moving double plate distributor. *Powder Technology*, *95*(3), 205–213. https://doi.org/10.1016/S0032-5910(97)03337-8

Lakshmi, D. V. N., Muthukumar, P., & Nayak, P. K. (2021). Experimental investigations on active solar dryers integrated with thermal storage for drying of black pepper. *Renewable Energy*, *167*, 728–739. https://doi.org/10.1016/j.renene.2020.11.144

Lingayat, A., Chandramohan, V. P., & Raju, V. R. K. (2017). Design , Development and Performance of Indirect Type Solar Dryer for Banana Drying. *Energy Procedia*, *109*(November 2016), 409–416. https://doi.org/10.1016/j.egypro.2017.03.041

Liu, Y., Peng, J., Kansha, Y., Ishizuka, M., Tsutsumi, A., Jia, D., Bi, X. T., Lim, C. J., & Sokhansanj, S. (2014). Novel fl uidized bed dryer for biomass drying. *Fuel Processing Technology*, *122*, 170–175. https://doi.org/10.1016/j.fuproc.2014.01.036

Lu, P., Cao, Y., Pan, W. P., & Ma, C. (2011). Heat transfer characteristics in a horizontal swirling fluidized bed. *Experimental Thermal and Fluid Science*, *35*(6), 1127–1134. https://doi.org/10.1016/j.expthermflusci.2011.03.007

Meziane, S. (2011). Drying kinetics of olive pomace in a fluidized bed dryer. *Energy Conversion and Management*, *52*(3), 1644–1649. https://doi.org/10.1016/j.enconman.2010.10.027

Mghazli, S., Ouhammou, M., Hidar, N., Lahnine, L., Idlimam, A., & Mahrouz, M. (2017). Drying characteristics and kinetics solar drying of Moroccan rosemary leaves. *Renewable Energy*, *108*, 303–310. https://doi.org/10.1016/j.renene.2017.02.022

Mobolade, A. J., Bunindro, N., Sahoo, D., & Rajashekar, Y. (2019). Traditional methods of food grains preservation and storage in Nigeria and India. *Annals of Agricultural Sciences*, *64*(2), 196–205. https://doi.org/10.1016/j.aoas.2019.12.003

Morad, M. M., Wasfy, K. I., & El-maghawry, H. A. M. (2017). Thermal analysis and performance evaluation of a solar tunnel greenhouse dryer for drying peppermint plants. *Renewable Energy*, *101*, 992–1004. https://doi.org/10.1016/j.renene.2016.09.042

Nguegwouo, E., Sone, L. E., Tchuenchieu, A., Tene, H. M., Mounchigam, E., Njayou, N. F., & Nama, G. M. (2018). Ochratoxin A in black pepper, white pepper and clove sold in yaoundé (Cameroon) markets: Contamination levels and consumers' practices increasing health risk. *International Journal of Food Contamination*, *5*(1), 1–7. https://doi.org/10.1186/s40550-017-0063-9

Ouaabou, R., Nabil, B., Hidar, N., Lahnine, L., & Idlimam, A. (2018). *Valorization of solar drying process in the production of dried Moroccan sweet cherries*. *172*(November 2017), 158–164. https://doi.org/10.1016/j.solener.2018.05.079

Özahi, E., & Demir, H. (2015). *Drying performance analysis of a batch type fluidized bed drying process for corn and unshelled pistachio nut regarding to energetic and exergetic efficiencies*. *60*, 85–96. https://doi.org/10.1016/j.measurement.2014.09.073

Özbey, M., & Söylemez, M. S. (2005). Effect of swirling flow on fluidized bed drying of wheat grains. *Energy Conversion and Management*, *46*(9–10), 1495–1512. https://doi.org/10.1016/j.enconman.2004.08.005

Prakash, O., & Kumar, A. (2014). Solar greenhouse drying: A review. *Renewable and Sustainable Energy Reviews, 29,* 905–910. https://doi.org/10.1016/j.rser.2013.08.084

Promvonge, P., Boonloi, A., Pimsarn, M., & Thianpong, C. (2011). Drying characteristics of peppercorns in a rectangular fl uidized-bed with triangular wavy walls ☆. *International Communications in Heat and Mass Transfer*, *38*(9), 1239–1246. https://doi.org/10.1016/j.icheatmasstransfer.2011.06.002

Puspasari, I., Tasirin, S. M., Pin, N. P., & Yaakob, Z. (2014). *Hydrodynamic Characteristics of Group D Particles (Paddy Grains) in a Conical-Based Spouted Bed with and Without Draft Tube*. *29*(11), 1350–1356. https://doi.org/10.5829/idosi.wasj.2014.29.11.1641

Puspasari, I., Zainal, M., Talib, M., Ramli, W., Daud, W., & Tasirin, S. M. (2012). Chemical Engineering Research and Design Fluidization characteristics of oil palm frond particles in agitated bed. *Chemical Engineering Research and Design*, *91*(3), 497–507. https://doi.org/10.1016/j.cherd.2012.08.018

Rabha, D. K., Muthukumar, P., & Somayaji, C. (2017). Experimental investigation of thin layer drying kinetics of ghost chilli pepper (Capsicum Chinense Jacq .) dried in a forced convection solar tunnel dryer. *Renewable Energy*, *105*, 583–589. https://doi.org/10.1016/j.renene.2016.12.091

Ralph, N., Noor, M., Thrinadh, B., Kumar, P. V., & Moisture, Þ. (2019). Materials Today : Proceedings A comparative study of drying kinetics and quality of Indian red chilli in solar hybrid greenhouse drying and open sun drying. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2019.05.433

Ringeisen, B., Barrett, D. M., & Stroeve, P. (2014). Concentrated solar drying of tomatoes. *Energy for Sustainable Development*, *19*, 47–55. https://doi.org/10.1016/j.esd.2013.11.006

Rosli, M. I., Abdul Nasir, A. M. im, Takriff, M. S., & Ravichandar, V. (2020). Drying sago pith waste in a fluidized bed dryer. *Food and Bioproducts Processing*, *123*, 335–344. https://doi.org/10.1016/j.fbp.2020.07.005

Scherer, G. W. (1990). Theory of Drying. *Journal of the American Ceramic Society*, *73*(1), 3–14. https://doi.org/10.1111/j.1151-2916.1990.tb05082.x

Senadeera, W., Bhandari, B. R., Young, G., & Wijesinghe, B. (2003). Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying. *Journal of Food Engineering*, *58*(3), 277–283. https://doi.org/10.1016/S0260-8774(02)00386-2

Seremet, L., Botez, E., Nistor, O. V., Andronoiu, D. G., & Mocanu, G. D. (2016). Effect of different drying methods on moisture ratio and rehydration of pumpkin slices. *Food Chemistry*, *195*, 104–109. https://doi.org/10.1016/j.foodchem.2015.03.125

Shabanian, J., & Chaouki, J. (2017). Effects of temperature, pressure, and interparticle forces on the hydrodynamics of a gas-solid fluidized bed. *Chemical Engineering Journal*, *313*, 580–590. https://doi.org/10.1016/j.cej.2016.12.061

Shukrie, A., Anuar, S., & Alias, A. (2015). Heat Transfer of Alumina Sands in Fluidized Bed Combustor with Novel Circular Edge Segments Air Distributor. *Energy Procedia*, *75*, 1752–1757. https://doi.org/10.1016/j.egypro.2015.07.453

Singh, P., Shrivastava, V., & Kumar, A. (2017). Recent developments in greenhouse solar drying: A review. *Renewable and Sustainable Energy Reviews*, *September*, 0–1. https://doi.org/10.1016/j.rser.2017.10.020

Sivakumar, R., Saravanan, R., Elaya Perumal, A., & Iniyan, S. (2016). Fluidized bed drying of some agro products - A review. *Renewable and Sustainable Energy Reviews*, *61*, 280–301. https://doi.org/10.1016/j.rser.2016.04.014

Sobrino, C., Ellis, N., & de Vega, M. (2009). Distributor effects near the bottom region of turbulent fluidized beds. *Powder Technology*, *189*(1), 25–33. https://doi.org/10.1016/j.powtec.2008.05.012

Sreenivasan, B., & Raghavan, V. R. (2002). Hydrodynamics of a swirling fluidised bed. *Chemical Engineering and Processing*, *41*(2), 99–106. https://doi.org/10.1016/S0255-2701(00)00155-0

Tagnamas, Z., Bahammou, Y., Kouhila, M., & Hilali, S. (2020). Conservation of Moroccan truf fl e (Terfezia boudieri) using solar drying method. *Renewable Energy*, *146*, 16–24. https://doi.org/10.1016/j.renene.2019.06.107

Tasirin, S. M., Kamarudin, S. K., Jaafar, K., & Lee, K. F. (2007). The drying kinetics of bird's chillies in a fluidized bed dryer. *Journal of Food Engineering*, *79*(2), 695–705. https://doi.org/10.1016/j.jfoodeng.2006.02.032

The Editors of Encyclopaedia Britannica. (n.d.). *black pepper*. Encyclopedia Britannica. https://www.britannica.com/plant/black-pepper-plant

Tiwari, A. (2016). *A Review on Solar Drying of Agricultural Produce*. *7*(9). https://doi.org/10.4172/2157-7110.1000623

Tregambi, C., Chirone, R., Montagnaro, F., Salatino, P., & Solimene, R. (2016). Heat transfer in directly irradiated fluidized beds. *Solar Energy*, *129*, 85–100. https://doi.org/10.1016/j.solener.2016.01.057

Udomsirichakorn, J., Basu, P., Salam, P. A., & Acharya, B. (2013). Effect of CaO on tar reforming to hydrogen-enriched gas with in-process CO2 capture in a bubbling fluidized bed biomass steam gasifier. *International Journal of Hydrogen Energy*, *38*(34), 14495–14504. https://doi.org/10.1016/j.ijhydene.2013.09.055

Vakhshouri, K., & Grace, J. R. (2010). Effects of the plenum chamber volume and distributor geometry on fluidized bed hydrodynamics. *Particuology*, *8*(1), 2–12. https://doi.org/10.1016/j.partic.2009.05.005

Wilkins, R., Brusey, J., & Gaura, E. (2018). Modelling uncontrolled solar drying of mango waste. *Journal of Food Engineering*, *237*(October 2017), 44–51. https://doi.org/10.1016/j.jfoodeng.2018.05.012

Wu, K., Gao, L., Yuan, Z., Li, B., Zhu, W., Wu, Y., Zhang, K., Lu, D., & Luo, D. (2018). Effect of moisture content and length of flexible filamentous particles on cluster characteristics in a fluidized bed dryer. *Chemical Engineering Research and Design*, *136*, 403–416. https://doi.org/10.1016/j.cherd.2018.06.009

Yahya, M. (2016). *Experimental Study on a Solar Tunnel Heat Pump Dryer for Cocoa Beans*. *9*(7), 325–336.

Yahya, M., Fahmi, H., Fudholi, A., & Sopian, K. (2018). Performance and economic analyses on solar-assisted heat pump fluidised bed dryer integrated with biomass furnace for rice drying. *Solar Energy*, *174*(September), 1058–1067. https://doi.org/10.1016/j.solener.2018.10.002

Yang, N., Zhou, Y., & Qi, T. (2018). The heat transfer between an immersed surface of moving lignite and small particles in a fluidized bed equipped with an inclined slotted distributor. *Experimental Thermal and Fluid Science*, *92*(December 2017), 366–374. https://doi.org/10.1016/j.expthermflusci.2017.11.017

Yang, X., Zhao, Y., Luo, Z., Chen, Z., & Song, S. (2011). Effects of sintered metal distributor on fluidization quality of the air dense medium fluidized bed. *Mining Science and Technology*, *21*(5), 681–685. https://doi.org/10.1016/j.mstc.2011.03.009

Yogendrasasidhar, D., & Setty, Y. P. (2019). Engineering Science and Technology , an International Journal Experimental studies and thin layer modeling of pearl millet using continuous multistage fluidized bed dryer staged externally. *Engineering Science and Technology, an International Journal*, *22*(2), 428–438. https://doi.org/10.1016/j.jestch.2018.10.010

Yudin, A. S. M. (2017). *PERFORMANCE CHARACTERISTICS OF AIR DISTRIBUTOR DESIGNS IN A FLUIDIZED BED*. UNIVERSITI MALAYSIA PAHANG.

Yudin, A. S. M., Anuar, S., & Oumer, A. N. (2016). Improvement on particulate mixing through inclined slotted swirling distributor in a fluidized bed: An experimental study. *Advanced Powder Technology*, *27*(5), 2102–2111. https://doi.org/10.1016/j.apt.2016.07.023

ZAVATTA, G. (2014). *Agriculture Remains Central to the World Economy. 60% of the Population Depends on Agriculture for Survival*. Economy. http://www.expo2015.org/magazine/en/economy/agriculture-remains-central-to-the-world-economy.html

Zhao, G., Shi, X., Wu, Y., Wang, M., Zhang, M., Gao, J., & Lan, X. (2019). 3D CFD simulation of gas-solids hydrodynamics and bubbles behaviors in empty and packed bubbling fluidized beds. *Powder Technology*, *351*, 1–15. https://doi.org/10.1016/j.powtec.2019.04.003