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Drying kinetics, energy, colour and FTIR spectroscopy analysis on indirect solar dryer with paraffin wax and glass pieces as thermal storage material

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ABSTRACT

This research focuses on developing an innovative Indirect Solar Dryer (ISD) incorporating paraffin wax and glass pieces as Thermal Storage Material (TSM) within the solar collector towards sustainable food preservation for future usage. Experiments were conducted using three distinct configurations of solar dryers: one with glass pieces and paraffin wax, another with glass pieces only, and a third without TSM. Additionally, conventional Open Solar Drying (OSD) was examined for comparison. Comparative analyses were performed on drying kinetics and energy efficiency. Results from the drying kinetics demonstrated a significant decrease in the Moisture Content (MC) of turmeric, from 84.2 % (w.b.) to 8.3 % (w.b.) within 29 h employing the configuration incorporating paraffin wax and glass pieces as TSM. Furthermore, this same configuration exhibited the highest dryer efficiency of 68.3 %. In addition to drying kinetics, Moisture Ratio (MR) was forecasted using twelve drying mathematical models, with the logarithmic model producing the most accurate forecasts ($\chi^2 = 0.0009843$ and $R^2 = 0.9782$). Colour and Fourier Transform Infrared (FTIR) analyses have been investigated to assess the quality of the dried turmeric specimens. The configuration utilizing glass pieces and paraffin wax as integrated TSM yielded the best colour quality. FTIR spectroscopy investigation discovered peaks of the C-H Stretch within the range of 2830–2900 cm^{-1} in the ISD configuration spectrum, whereas these peaks were absent in the OSD spectrum, indicative of uneven drying in OSD. Based on these experimental findings, the designed ISD configuration with integrated glass pieces and paraffin wax TSM demonstrates effective results in reduced drying time and improved food specimen quality. It suggests that the proposed ISD configuration could serve as a sustainable and preferable method for drying in various industries.

1. Introduction

Every year, India produces over 4 lakh tons of fresh turmeric (*Curcuma longa L.*), holding nearly 80 % of the global turmeric producer [1]. This quantity is generated through a region of roughly 50,000 acres. Before being shipped all over the world, the turmeric rhizomes are picked and dried [2]. Drying is the primary technique for preserving food items, requiring a significant amount of energy. It is a crucial procedure used globally to preserve agricultural products, helping to reduce the produce's water activity to a point where deterioration is prevented for a set quantity of hours [3]. The importance of using alternative, renewable resources has increased due to rising fossil fuel prices and shortages [4]. The two oil crises that struck in the first and last decades of the 1970s prompted the creation of solar dryers as a way to reduce energy demand [5]. Agricultural products can be dried with less negative influence on the environment by using renewable energy sources like solar energy. Since sun drying is the least expensive method, it is still commonly employed in many tropical and subtropical nations, although the quality of the dried goods often falls below expectations. Solar crop drying has been practiced since the dawn of humanity. Initially, the techniques were straightforward and frequently inefficient, but they worked rather well. Solar dryer is an effective method of harnessing solar energy and can be considered an advancement over traditional methods [6,7].

According to the amount of solar energy they utilize, solar dryers are categorized as direct, indirect, and mixed modes. In a direct-mode solar dryer, food products are showing to solar radiation directly, causing their temperature to rise and their Moisture Content (MC) to decrease. In the Indirect Solar Dryer (ISD) scenario, the samples are stored in a closed chamber, and they are only exposed to warm air produced by the solar collector to eliminate water content [8]. The effectiveness of a solar

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References

[1] S. Dhakal, W.F. Schmidt, M. Kim, X. Tang, Y. Peng, K. Chao, Detection of additives and chemical contaminants in turmeric powder using FT-IR spectroscopy, Foods 8 (2019), https://doi.org/10.3390/foods8050143.

[2] S. Dhakal, K. Chao, W. Schmidt, J. Qin, M. Kim, D. Chan, Evaluation of turmeric powder adulterated with metanil yellow using FT-Raman and FT-IR spectroscopy, Foods 5 (2016) 36, https://doi.org/10.3390/foods5020036.

[3] S.W. Sharshir, A. Joseph, G. Peng, A.W. Kandeal, A.S. Abdullah, G.B. Abdelaziz, E. M.A. Edreis, Z. Yuan, Recent efforts in developing agricultural product drying processes using solar energy, Sol. Energy 257 (2023) 137–154, https://doi.org/10.1016/J.SOLENER.2023.04.022.

[4] S. Matallah, S. Boudaoud, A. Matallah, M. Ferhaoui, The role of fossil fuel subsidies in preventing a jump-start on the transition to renewable energy: Empirical evidence from Algeria, Resour. Policy 86 (2023) 104276, https://doi.org/10.1016/j.resourpol.2023.104276.

[5] S.-S. Ma, C.-Y. Tseng, Y.-R. Jian, T.-H. Yang, S.-L. Chen, Utilization of waste heat for energy conservation in domestic dryers, Energy 162 (2018) 185–199, https://doi.org/10.1016/j.energy.2018.08.011.

[6] A.E. Kabeel, M. Abdelgaied, Performance of novel solar dryer, Process Saf. Environ. Prot. 102 (2016) 183–189, https://doi.org/10.1016/J.PSEP.2016.03.009.

[7] A. Kushwah, A. Kumar, M.K. Gaur, Optimization of drying parameters for hybrid indirect solar dryer for banana slices using response surface methodology, Process Saf. Environ. Prot. 170 (2023) 176–187, https://doi.org/10.1016/J.PSEP.2022.12.003.

[8] J.P. Ekka, D. Kumar, A review of industrial food processing using solar dryers with heat storage systems, J. Stored Prod. Res. 101 (2023) 102090, https://doi.org/10.1016/J.JSPR.2023.102090.

[9] G. Verma, N. Dewangan, H. Kumar Ghritlahre, M. Verma, S. Kumar, Y. Kumar, S. Agrawal, Experimental investigation of mixed mode ultraviolet tent house solar dryer under natural convection regime, Sol. Energy 251 (2023) 51–67, https://doi.org/10.1016/j.solener.2022.12.052.

[10] Y. Mohana, R. Mohanapriya, T. Anukiruthika, K.S. Yoha, J.A. Moses, C. Anandharamakrishnan, Solar dryers for food applications: Concepts, designs, and recent advances, Sol. Energy. (2020), https://doi.org/10.1016/j.solener.2020.07.098.

[11] A. Lingayat, P. Das, Gilago, M.C., V.P., C. A detailed assessment of paraffin waxed thermal energy storage medium for solar dryers. Sol. Energy 261 2023 14–27. https://doi.org/https://doi.org/10.1016/j.solener.2023.05.047.

[12] A.A.A. Abueluor, M.T. Amin, M.A. Abuelnour, O. Younis, A comprehensive review of solar dryers incorporated with phase change materials for enhanced drying efficiency, J. Energy Storage 72 (2023) 108425, https://doi.org/10.1016/J.EST.2023.108425.

[13] S. Ebadi, S.H. Tasnim, A.A. Aliabadi, S. Mahmud, An experimental investigation of the charging process of thermal energy storage system filled with PCM and metal wire mesh, Appl. Therm. Eng. 174 (2020) 115266, https://doi.org/10.1016/j.applthermaleng.2020.115266.

[14] W.H. Li, S. Lai-Iskandar, D. Tan, L. Simonini, J.P. Dudon, F.N. Leong, R.Y. Tay, S. H. Tsang, S.C. Joshi, E.H.T. Teo, Thermal conductivity enhancement and shape stabilization of phase-change materials using three-dimensional graphene and graphene powder, Energy Fuels 34 (2020) 2435–2444, https://doi.org/10.1021/acs.energyfuels.9b03013.

[15] S. Madhankumar, K. Viswanathan, M.I. Taipabu, W. Wu, A review on the latest developments in solar dryer technologies for food drying process, Sustain. Energy Technol. Assess. 58 (2023) 103298, https://doi.org/10.1016/J.SETA.2023.103298.

[16] J. Vásquez, A. Reyes, N. Pailahueque, Modeling, simulation and experimental validation of a solar dryer for agro-products with thermal energy storage system, Renew. Energy 139 (2019) 1375–1390, https://doi.org/10.1016/j.renene.2019.02.085.

[17] P. Sudhakar, A review on performance enhancement of solar drying systems, IOP Conf. Ser. Mater. Sci. Eng. 1130 (2021) 12042, https://doi.org/10.1088/1757-899X/1130/1/012042.

[18] A. El Khadraoui, S. Bouadila, S. Kooli, A. Farhat, A. Guizani, Thermal behavior of indirect solar dryer: nocturnal usage of solar air collector with PCM, J. Clean. Prod. 148 (2017) 37–48, https://doi.org/10.1016/j.jclepro.2017.01.149.

[19] S. Esakkimuthu, A.H. Hassabou, C. Palaniappan, M. Spinnler, J. Blumenberg, R. Velraj, Experimental investigation on phase change material based thermal storage system for solar air heating applications, Sol. Energy 88 (2013) 144–153, https://doi.org/10.1016/j.solener.2012.11.006.

[20] M. Islam, M.I. Islam, M. Tusar, A.H. Limon, Effect of cover design on moisture removal rate of a cabinet type solar dryer for food drying application, Energy Procedia 160 (2019) 769–776, https://doi.org/10.1016/j.egypro.2019.02.181.

[21] P. Rani, P.P. Tripathy, Drying characteristics, energetic and exergetic investigation during mixed-mode solar drying of pineapple slices at varied air mass flow rates, Renew. Energy 167 (2021) 508–519, https://doi.org/10.1016/j.renene.2020.11.107.

[22] S. Kumar, N. Dewangan, G. Verma, H.K. Ghritlahre, M. Verma, Y. Kumar, S. Agrawal, S. Shekhar, Performance analysis of natural and forced convection mixed mode UV tent house solar dryer for potato drying, Energy Sources Part A-Recovery Util. Environ. Eff. (2023) 11482–11504, https://doi.org/10.1080/15567036.2023.2259839.

[23] J.P. Ekka, K. Bala, P. Muthukumar, D.K. Kanaujiya, Performance analysis of a forced convection mixed mode horizontal solar cabinet dryer for drying of black ginger (Kaempferia parviflora) using two successive air mass flow rates, Renew. Energy 152 (2020) 55–66, https://doi.org/10.1016/j.renene.2020.01.035.

[24] S. Vijayan, T.V. Arjunan, A. Kumar, Exergo-environmental analysis of an indirect forced convection solar dryer for drying bitter gourd slices, Renew. Energy 146 (2020) 2210–2223, https://doi.org/10.1016/j.renene.2019.08.066.

[25] M. Cousins, J. Adelberg, F. Chen, J. Rieck, Antioxidant capacity of fresh and dried rhizomes from four clones of turmeric (Curcuma longa L.) grown in vitro, Ind. Crops Prod. 25 (2007) 129–135, https://doi.org/10.1016/j.indcrop.2006.08.004.

[26] N. Dhiman, V.K. Tripathi, J. Dwivedi, R.K. Gupta, K.M. Tripathi, Photoactive graphene aerogel from biomass for the visible-light-induced degradation of pharmaceutical residues, ACS Sustain. Resour. Manag. 1 (2024) 1068–1075, https://doi.org/10.1021/acssusresmgt.3c00088.

[27] H. Kalluru, S.S. Kondaveeti, S. Telapolu, M. Kalachaveedu, Turmeric supplementation improves the quality of life and hematological parameters in breast cancer patients on paclitaxel chemotherapy: a case series, Complement. Ther. Clin. Pract. 41 (2020) 101247, https://doi.org/10.1016/j.ctcp.2020.101247.

[28] S. Gupta, G. Ghoshal, Plant protein hydrogel as a delivery system of curcumin: characterization and in vitro release kinetics, Food Bioprod. Process. 143 (2024) 66–79, https://doi.org/10.1016/J.FBP.2023.10.007.

[29] A. Borah, K. Hazarika, S.M. Khayer, Drying kinetics of whole and sliced turmeric rhizomes (Curcuma longa L.) in a solar conduction dryer, Inf. Process. Agric. 2 (2015) 85–92, https://doi.org/10.1016/j.inpa.2015.06.002.

[30] A. Khieokhajonkhet, T. Roatboonsongsri, P. Suwannalers, N. Aeksiri, G. Kaneko, K. Ratanasut, W. Inyawilert, W. Phromkunthong, Effects of dietary supplementation of turmeric (Curcuma longa) extract on growth, feed and nutrient utilization, coloration, hematology, and expression of genes related immune response in goldfish (Carassius auratus), Aquac. Rep. 32 (2023) 101705, https://doi.org/10.1016/j.aqrep.2023.101705.

[31] N. Komonsing, P. Khuwijitjaru, M. Nagle, J. Müller, B. Mahayothee, Effect of drying temperature together with light on drying characteristics and bioactive compounds in turmeric slice, J. Food Eng. 317 (2022) 110695, https://doi.org/10.1016/j.jfoodeng.2021.110695.

[32] R. Aggarwal, S.K. Sonkar, K.M. Tripathi, Visible light promoted hydrogen production by diesel soot-derived onion-like carbon nanoparticles, Carbon N. Y. 208 (2023) 436–442, https://doi.org/10.1016/j.carbon.2023.03.064.

[33] J.I. Ballesteros, L.H.V. Lim, R.B. Lamorena, The feasibility of using ATR-FTIR spectroscopy combined with one-class support vector machine in screening turmeric powders, Vib. Spectrosc. 130 (2023) 103646, https://doi.org/10.1016/j.vibspec.2023.103646.

[34] S. Duraipandi, A. Sreekumar, Investigation on the performance of a natural convection solar dryer with novel palmitic and sebacic acid eutectic phase change material for thermal energy storage applications, J. Energy Storage 77 (2024) 109908, https://doi.org/10.1016/j.est.2023.109908.

[35] P.M. Arunkumar, N. Balaji, S. Madhankumar, Performance analysis of indirect solar dryer with natural heat energy retention substances for drying red chili, Sustain. Energy Technol. Assess. 64 (2024) 103706, https://doi.org/10.1016/j.seta.2024.103706.

[36] Q. Wang, S. Li, X. Han, Y. Ni, D. Zhao, J. Hao, Quality evaluation and drying kinetics of shitake mushrooms dried by hot air, infrared and intermittent microwave–assisted drying methods, Lwt 107 (2019) 236–242, https://doi.org/10.1016/j.lwt.2019.03.020.

[37] P. Ganesh Kumar, V.S. Vigneswaran, K. Balaji, S. Vinothkumar, R. Prabakaran, D. Sakthivadivel, M. Meikandan, S.C. Kim, Augmented v-corrugated absorber plate using shot-blasting for solar air heater – Energy, Exergy, Economic, and Environmental (4E) analysis, Process Saf. Environ. Prot. 165 (2022) 514–531, https://doi.org/10.1016/J.PSEP.2022.07.036.

[38] S. Madhankumar, K. Viswanathan, W. Wu, Energy, exergy and environmental impact analysis on the novel indirect solar dryer with fins inserted phase change material, Renew. Energy 176 (2021) 280–294, https://doi.org/10.1016/j.renene.2021.05.085.

[39] K. Viswanathan, S. Wang, Experimental investigation on the application of preheated fish oil ethyl ester as a fuel in diesel engine, Fuel 285 (2021) 119244, https://doi.org/10.1016/j.fuel.2020.119244.

[40] S. Wang, V. Karthickeyan, E. Sivakumar, M. Lakshmikandan, Experimental investigation on pumpkin seed oil methyl ester blend in diesel engine with various injection pressure, injection timing and compression ratio, Fuel 264 (2020) 116868, https://doi.org/10.1016/j.fuel.2019.116868.

[41] N. Nadir, H. Bouguettaia, S. Boughali, D. Bechki, Use of a new agricultural product as thermal insulation for solar collector, Renew. Energy 134 (2019) 569–578, https://doi.org/10.1016/j.renene.2018.11.054.

[42] D. Semmar, S. Betrouni, D. Lafri, Etude et Réalisation d'un Capteur Solaire à Air, Rev. Des Energies Renouvelebles 15 (1998) 1112–2242.

[43] S. Algarni, S. Mellouli, T. Alqahtani, K. Almutairi, A. Khan, A. Anqi, Experimental investigation of an evacuated tube solar collector incorporating nano-enhanced PCM as a thermal booster, Appl. Therm. Eng. 180 (2020) 115831, https://doi.org/10.1016/j.applthermaleng.2020.115831.

[44] H. Atalay, E. Cankurtaran, Energy, exergy, exergoeconomic and exergo-environmental analyses of a large scale solar dryer with PCM energy storage medium, Energy 216 (2021) 119221, https://doi.org/10.1016/j.energy.2020.119221.

[45] A. Fudholi, K. Sopian, M.H. Yazdi, M.H. Ruslan, M. Gabbasa, H.A. Kazem, Performance analysis of solar drying system for red chili, Sol. Energy 99 (2014) 47–54, https://doi.org/10.1016/j.solener.2013.10.019.

[46] E. Baniasadi, S. Ranjbar, O. Boostanipour, Experimental investigation of the performance of a mixed-mode solar dryer with thermal energy storage, Renew. Energy 112 (2017) 143–150, https://doi.org/10.1016/j.renene.2017.05.043.

[47] D.V.N. Lakshmi, P. Muthukumar, A. Layek, P.K. Nayak, Performance analyses of mixed mode forced convection solar dryer for drying of stevia leaves, Sol. Energy 188 (2019) 507–518, https://doi.org/10.1016/j.solener.2019.06.009.

[48] S. Srithanyakorn, S. Bunchan, B. Krittacom, R. Luampon, Comparison of mixed-mode forced-convection solar dryer with and without stainless wire mesh in solar collector, Clean Energy 7 (2023) 1316–1329, https://doi.org/10.1093/ce/zkad058.

[49] G.A. Mabasso, V.C. Siqueira, O. Resende, W.D. Quequeto, V. Schoeninger, M.L. F. Simeone, E.A.S. Martins, D.S. Crippa, The effect of intermittent drying with variable resting times on quality parameters of corn obtained after storage, LWT 182 (2023) 114855, https://doi.org/10.1016/j.lwt.2023.114855.

[50] Z. Chen, Y. Xia, S. Liao, Y. Huang, Y. Li, Y. He, Z. Tong, B. Li, Thermal degradation kinetics study of curcumin with nonlinear methods, Food Chem. 155 (2014) 81–86, https://doi.org/10.1016/j.foodchem.2014.01.034.

[51] J.P. Ekka, P. Muthukumar, K. Bala, D.K. Kanaujiya, K. Pakshirajan, Performance studies on mixed-mode forced convection solar cabinet dryer under different air mass flow rates for drying of cluster fig, Sol. Energy 229 (2021) 39–51, https://doi.org/10.1016/j.solener.2021.06.086.

[52] R. Ouaabou, B. Nabil, M. Ouhammou, A. Idlimam, A. Lamharrar, S. Ennahli, H. Hanine, M. Mahrouz, Impact of solar drying process on drying kinetics, and on bioactive profile of Moroccan sweet cherry, Renew. Energy 151 (2020) 908–918, https://doi.org/10.1016/j.renene.2019.11.078.