Recent developments in drying of food products

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Abstract. Drying is a dehydration process to preserve agricultural products for long period usage. The most common and cheapest method is open sun drying in which the products are simply laid on ground, road, mats, roof, etc. But the open sun drying has some disadvantages like dependent on good weather, contamination by dust, birds and animals consume a considerable quantity, slow drying rate and damages due to strong winds and rain. To overcome these difficulties solar dryers are developed with closed environment for drying agricultural products effectively. To obtain good quality food with reduced energy consumption, selection of appropriate drying process and proper input parameters is essential. In recent years several researchers across the world have developed new drying systems for improving the product quality, increasing the drying rate, decreasing the energy consumption, etc. Some of the new systems are fluidized bed, vibrated fluidized bed, desiccant, microwave, vacuum, freeze, infrared, intermittent, electro hydrodynamic and hybrid dryers. In this review the most recent progress in the field of drying of agricultural food products such as new methods, new products and modeling and optimization techniques has been presented. Challenges and future directions are also highlighted. The review will be useful for new researchers entering into this ever needed and ever growing field of engineering.

1. Introduction

Drying is a dehydration process used to remove the moisture present in food products by the application of heat. The heat may be supplied either by hot air or from the solar energy. Drying process is used to preserve the food products for future usage. Drying prevents the growth of bacteria and yeast formation. Drying can be achieved by using open sun drying and greenhouse drying.
methods. The open sun drying is presented in Fig. 1. When compared to greenhouse drying process, open sun drying process is a slow process; dried products will be of low quality due to contamination of dust particles, damages due to rain and moisture present in the air. Also there is a loss of food products due to insects, birds and animals. The quality of products obtained using greenhouse drying process is better because it is carried out in a closed environment. This closed environment is made using special cover materials like polyethylene, polycarbonate, etc. Greenhouse dryers are differentiated based on the structure of the roof such as roof even span and dome shaped dryer and based on the mode of energy transfer such as active (forced circulation)[6], and passive (natural circulation)[24]. Dryers with greenhouse drying are shown in Fig. 2. The main objective of this study is to provide a comprehensive review of literature related to the recent progress in the field of drying of agricultural food products.

Figure 1. Open sun drying

Figure 2. Greenhouse solar dryers

2. Classification of drying systems

Solar dryers are classified as direct absorption type, indirect or convection type and the combination of the both. The pressure inside the drying system plays a vital role in drying of food products. Based on the operating pressure the dryers are classified into atmospheric drying, vacuum drying and freeze drying [10]. It is observed that hot air drying and vacuum drying are commonly used for drying of agricultural products. Also it is observed that hot air drying process is simple and economical[25].
Vacuum drying like microwave drying is more beneficial than hot air drying, because of short drying time, high drying rate and superior quality of dried products[26]. As yielding of microwave drying process is non-uniform it is normally carried out by combining it with other drying process to achieve better quality. Infrared drying is preferable because of uniform heating and high quality of yield. Even though the quality of dried products is good in freeze drying it is not practiced generally because it is an uneconomical process[23]. The type of dryer used is based on the need and the desired properties of drying products. Some of the new systems like desiccant [41], electro hydrodynamic and hybrid dryers [29], vibrated fluidized bed [19]&[48], fluidized bed [37]&[43], freeze [2]&[34], hot air drying [9], infrared[13,14],[16], intermittent [11], microwave [21],[49] & [53],and vacuum [44] have been utilized and investigated by researchers for drying the food products.

3. Analysis of effectiveness of drying systems

Research works have been carried out to analyze the effectiveness of various drying systems by studying the drying characteristics like moisture content, drying air temperature, air velocity, drying rate, drying time, etc. Adam Figiel [2] carried out drying of beetroot cubes using a combined convective-vacuum microwave process by freeze drying. They reported that the results such as compressive strength, antioxidant activity and rehydration have been better than the convection method and also the quality is improved with less drying time in combined method. Amin Hazervazifeh et al [5] studied the drying characteristics of apple slices and found that processing time is less in combined microwave-hot air flow method than microwave radiation and hot air drying process. And minimum energy consumption is observed in microwave radiation process. Atul Patel and Gaurav Patel[6] made CFD analysis of a forced circulation type solar dryer used conventionally for dehydrating vegetables and fruits to obtain operational augmentation in implementing the modifications in pressure and velocity values. A typical fluidized bed dryer is shown in Fig. 3.

![Fluidized bed dryer](image_url)

Figure 3. Fluidized bed dryer [54, 55]

Dening Jia et al [8] investigated the effect of various parameters on the drying performance of pulsed fluidized vibrated bed of biomass particles and suggested high temperature and gas flow rate for better drying. Fagunwa et al [11] developed an intermittent solar dryer for Cocoa Beans and reported that drying performance is efficient than the traditional method. Jin et al[19] studied the effect of vibration parameters of a vibrated fluid bed dryer using an optical fiber probe approach and proposed an empirical correlation to predict bed voidage. Kejing An et al[23] studied the drying characteristics of ginger rhizome using five different drying process such as hot air drying, freeze drying, infrared drying, microwave drying (MD) and intermittent microwave and convective drying(IM&CD) and found that MD and CD method is good in preserving thermo sensitive materials with less power
consumption. Structures of fresh ginger observed by light microscopy (A), scanning electron micrographs (SEM) of dried gingers (B) and structural changes observed by SEM for (a-HAD), (b-IR), (c-FD), (d-MD) and (e-IM&CD) are presented in Fig. 4.

![Figure 4](image_url)

**Figure 4.** LM (Fresh) and SEM images of ginger (Dried) for various drying process[23]

Liliana Seremet et al [26] investigated the drying characteristics of pumpkin using hot air drying and combined drying process and concluded that the rehydration capacity of hot air drying is higher. Magdalena Zielinska and Anna Michalska [27] evaluated the drying characteristics of blueberries and found that effect of combined hot air convective drying at 90°C and microwave vacuum drying process produces better results in drying time and quality than these processes have been carried out separately. Nadine Sangster et al [32] developed a prototype for an automated cocoa drying house which is equipped with automated roof which is automatically opened during sunlight and closed if sunlight is not there and fermenter, automatic heaters and a remote control feature for the automated components. Oleksii Parniakov et al [34] studied the effects of pulsed electric fields on vacuum freeze-drying for drying PEF treated vacuum cooled apple tissue. It is observed that electroporated tissue samples shows large pores, fast rate of moisture impregnation and large rehydration capacity hence reported that PEF treatment gives better results. Ronak Daghigh et al [39] carried out a review of solar assisted heat pump drying systems for agricultural and marine products. Ruifang Wang et al [40] carried out drying experiments using a hybrid microwave rotary drying system in soybean drying and studied the effect of drum speed, cracking ratio, etc. Ting-Jie Wang et al [45] analyzed and reported the mechanism of vibration energy transfer using wave propagation. Sensors have been used to detect the wave signals produced and calculate the pressure-wave propagation parameters. Yuting Tian et al [50] evaluated the effect of various drying methods on the qualities of the drying product. Mushroom is taken as the studying element under hot air, vacuum, microwave and microwave vacuum methods. They reported that there is a significant rise in the content of total free amino acids and the relative content of sulfur compounds of dried mushrooms in all the four methods. They observed that there is an improvement in nutrient retention and color attributes and larger amounts of taste-active amino acids are maintained and found high rehydration ratio when dried with microwave vacuum method. It is also reported that the collapse in structure also less than the other methods.

4. **Modelling and optimization techniques**

Modelling and optimization techniques like response surface methodology (RSM), fuzzy modelling, etc. are used to analyze the problems, in which one or more responses are influenced by many factors and to find out the quantitative relationship between the response variables and the input control
variables. Also they are used to determine the significant effect of each factor on the response factor by developing mathematical models and to find out the optimal conditions. RSM technique is used by many researchers ([4], [18], [22], [33],[35], [37], [42],[44] &[51]) to optimize the drying effect of various dryers like fluidized bed dryers, on different agricultural products like Artemisia absinthium leaves, coriandrum sativum leaves, coroba slices, kefir powder, ganodermalucidium slices, green peas, olive leaves and soya bean, etc.

4.1. Response surface methodology (RSM)

Response surface methodology is a method of statistical and mathematical techniques influenced by many factors and to find out the quantitative relationship between the response variables and the input control variables. This method has been initially used for model fitting of physical experiments but later it is used for the design of experiments in process optimization. It is the process of approximating a response function, based on statistical analysis of data which has been obtained at various design points. The relationship between the control parameters and the responses is given in Equation (1) as

\[ Y = f(X_1, X_2, \ldots X_k) + \varepsilon \]  

where \( Y \) is the response variable and \( X_1, X_2, \ldots X_k \) are the independent variables. The function \( f \) is called the true response function. The residual \( \varepsilon \) measures the experimental error. Coefficient of determination (R-square) is used to evaluate the model [46].

4.2. Mathematical modeling techniques of thin layer drying

Many researchers analyzed the drying characteristics of agricultural products using various mathematical models like Newton, Henderson and Pabis, Logarithmic and Weibull, Midilli et al, Page, Modified Henderson and Pabis, Two-Terms, etc. The mathematical models developed can be validated using correlation analysis, reduced chi-square (\( \chi^2 \)) test and root mean square error (RMSE) analysis. Some of the model descriptions used by the researchers are listed in Table 1. Where \( MR \) is moisture ratio, \( M_t \) is moisture content at any given time (kg water kg\(^{-1}\) solids), \( M_e \) standing for equilibrium moisture content (kg water kg\(^{-1}\) solids) and \( M_0 \) representing the initial moisture content.

### Table 1. Typical mathematical Models of thin layer drying

| Sl.No. | Model name                  | Model description                                    |
|-------|----------------------------|------------------------------------------------------|
| 1     | Approximation of diffusion  | \( MR = a \exp(-kt) + (1-a)\exp(-kbt) \)            |
| 2     | Henderson and Pabis model   | \( MR = a \exp(-kt) \)                              |
| 3     | Modified Henderson and Pabis| \( MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht) \)  |
| 4     | Logarithmic                 | \( MR = a \exp(-kt) + c \)                          |
| 5     | Midilli et al               | \( MR = a \exp(-kt) + bt \)                         |
| 6     | Newton model                | \( MR = \exp(-kt) \)                                |
| 7     | Page model                  | \( MR = \exp(-kt) \)                                |
| 8     | Modified page model         | \( MR = \exp(-kt)n \)                               |
| 9     | Two term model              | \( MR = a \exp(kot) + b \exp(-kt1) \)               |
| 10    | Two term exponential        | \( MR = a \exp(-kt) + (1-a)\exp(-kat) \)           |
| 11    | Verma et al.                | \( MR = a \exp(-kt) + (1-a)\exp(-gt) \)            |
| 12    | Wang and Sing               | \( MR = 1 + at + bt^2 \)                            |
| 13    | Weibull                     | \( MR = \exp(-t/b)^a \)                             |
Abano et al [1] investigated the drying characteristics like air velocity, drying time, etc. of tomato slices using RSM modeling technique and the ideal drying condition is predicted using desirability index technique. Akpinar [3] investigated the drying characteristics of mint leaves using an indirect forced convection solar dryer. The experimental values are analyzed using ten models and exergy analysis is also carried out to study the impact of parameters considered. Ali Abasi Surki et al [4] optimized the operating parameters in drying of soybean using RSM. A three-level, four-factor fractional factorial design is applied for optimization. Diamante et al [7] developed a new mathematical model for thin layer for drying of fruits. Gokhan Gurlek et al [12] developed a new solar tunnel dryer in drying of tomato and compared twelve different mathematical models to predict the drying characteristics and reported that the two-term model gives better results. Hosain Darvishi et al [15] developed seven mathematical models to describe the characteristics of thin layer drying of pepper samples and reported that the Midilli model is more suitable for thin layer samples. They concluded that energy efficiency is increased when increase in microwave power and moisture content in microwave drying of pepper by varying the power values.

Ibrahim Doymaz [16] studied the effect of various infrared power levels on drying kinetics of carrot pomace and reported that among the twelve mathematical models developed Aghbashlo et al model is better. Ibrahim Doymaz [17] studied the effect of various infrared power levels on drying kinetics of pomegranate seeds and reported that the drying time is reduced when the power level is increased. Also they developed ten mathematical models and concluded that among the ten models The Page, Midilli et al and Weibull models have better prediction qualities than the other models. Jose Vasquez et al [20] implemented fuzzy control systems for a solar drying system integrated with thermal energy storage system and reported that the new arrangement works satisfactorily and energy is saved considerable amount than the old methods in drying of mushroom, plum and peach. Jose Vasquez et al [20] implemented fuzzy control systems for a solar drying system integrated with thermal energy storage system and reported that the new arrangement works satisfactorily and energy is saved considerable amount than the old methods in drying of mushroom, plum and peach.

Lemuel M. Diamante et al [25] developed a new mathematical model for thin layer drying of fruits. Malaisamy et al [28] designed an efficient drier and implemented modeling and conventional PI controller and Fuzzy controller for maintaining temperature in the heating chambers for drying process for the efficient usage of solar energy and solar powered electrical energy for heating process. Also they compared the response with PI and concluded that Fuzzy shows better performance than PI and cardamom dryer provide better performance than copra dryer. Midilli et al [30] developed a new model to evaluate the drying characteristics for single layer drying process and also verified the effectiveness of the model with experimental data. Further they compared the new one with other available models using data obtained from literature and concluded that it is an effective model.

Minaei et al [31] analyzed the drying characteristics using 11 mathematical models in drying of pomegranate arils and reported that Midilli model is best suited for vacuum drying and Page model is for microwave drying technique. Pengfei Zhao et al [36] investigated the drying characteristics and kinetics of Shengli lignite and analyzed using seven thin layer models. They concluded that among four methods of drying vibrated medium fluidized bed has been given better results and the simulation using the Midilli–Kucuk model is best suited than the other models in dewatering the lignite. Reuss et al [38] used TRNSYS simulation model for the wood drying process based on the physical properties of the drying product and concluded that the solar drying process is more advantageous. Siewkian chin et al [42] optimized the drying condition of convective hot air in drying of Ganodermalucidium slices using RSM. They concluded that drying temperature have significant effect than the other factors considered. Vega-Galvez et al [47] studied the drying characteristics of olive-waste cake using convective process with five different temperatures and tested with various mathematical models and concluded that the modified Henderson and Pabis is best suited to describe the drying curves among the other models. Zafer Erbay et al [51] optimized the operating conditions in drying of olive leaves using RSM. Zdravko Sumic et al [52] dried fresh red currants using vacuum drying and optimized the
process parameters such as temperature, pressure and drying time using RSM, regression analysis and ANOVA. They concluded that the results show improved physic-chemical properties of lyophilized samples when compared to conventional method.

5. Conclusions

In this review the most recent progress in the field of drying of agricultural food products such as new methods, new products and modeling and optimization techniques has been presented. The quality of products obtained using greenhouse drying process is better because it is carried out in a closed environment. Hot air drying and vacuum drying are used for drying of agricultural products in which hot air drying process is simple and economical. Processing time is less in combined microwave-hot air flow method than microwave radiation and hot air drying process. In infrared drying, uniform heating and high quality of yield can be achieved. Indirect mode forced convection dryer performance is better than other methods. Solar drying system accommodated with phase change material will accelerate the drying performance of the system even during nights. Simulation models can be used to forecast and analyze the new systems developed. An improvement in nutrient retention and color attributes and larger amounts of taste-active amino acids are maintained and found high rehydration ratio when dried with microwave vacuum method. Further research work in developing hybrid drying systems and drying systems to improve energy savings are needed.

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