J Food Sci Technol (March 2015) 52(3):1383–1393
DOI 10.1007/s13197-013-1170-0

ORIGINAL ARTICLE

# Investigation into solar drying of potato: effect of sample geometry on drying kinetics and $CO_2$ emissions mitigation

**P. P. Tripathy**

Revised: 28 August 2013 / Accepted: 13 September 2013 / Published online: 27 September 2013
© Association of Food Scientists & Technologists (India) 2013

**Abstract** Drying experiments have been performed with potato cylinders and slices using a laboratory scale designed natural convection mixed-mode solar dryer. The drying data were fitted to eight different mathematical models to predict the drying kinetics, and the validity of these models were evaluated statistically through coefficient of determination ($R^2$), root mean square error (RMSE) and reduced chi-square ($\chi^2$). The present investigation showed that amongst all the mathematical models studied, the Modified Page model was in good agreement with the experimental drying data for both potato cylinders and slices. A mathematical framework has been proposed to estimate the performance of the food dryer in terms of net $CO_2$ emissions mitigation potential along with unit cost of $CO_2$ mitigation arising because of replacement of different fossil fuels by renewable solar energy. For each fossil fuel replaced, the gross annual amount of $CO_2$ as well as net amount of annual $CO_2$ emissions mitigation potential considering $CO_2$ emissions embodied in the manufacture of mixed-mode solar dryer has been estimated. The $CO_2$ mitigation potential and amount of fossil fuels saved while drying potato samples were found to be the maximum for coal followed by light diesel oil and natural gas. It was inferred from the present study that by the year 2020, 23 % of $CO_2$ emissions can be mitigated by the use of mixed-mode solar dryer for drying of agricultural products.

**Keywords** Mixed-mode solar dryer · Drying kinetics · Thin layer drying models · $CO_2$ emissions mitigation · Fossil fuels saved

P. P. Tripathy (✉)
Department of Agricultural & Food Engineering, Indian Institute of Technology, Kharagpur 721 302, West Bengal, India
e-mail: punam@agfe.iitkgp.ernet.in

**Abbreviations**

| | |
|---|---|
| a,b,c | Coefficients in thin layer model |
| k, $k_0$, $k_1$, g, n | Constants in the model |
| $A_a$ | Aperture area of solar dryer ($m^2$) |
| $C_{a,}$ | Net annual cost of the solar dryer (Rs) |
| CEF | Carbon emission factor of fuel |
| $C_p$ | Specific heat capacity of the product (J/kg K) |
| $CRF_{d,T}$ | Capital recovery factor |
| CUF | Capacity utilization factor of solar dryer |
| d | Discount rate in fraction |
| $E_m$ | $CO_2$ emissions embodied in the solar dryer (kg/$m^2$) |
| $E_p$ | Specific energy required for drying the product (kJ/kg dry matter) |
| FCO | Fraction of carbon oxidized during combustion of fuel |
| $f_i$ | Fraction of crop currently being dried by $i^{th}$ fuel |
| $f_{pp}$ | Correction factor for the purchasing power of the user |
| $f_r$ | Fraction of crop used in raw form |
| $f_{sol}$ | Correction factor for solar radiation availability |
| $GE_c$ | Potential of mitigating gross fossil $CO_2$ emissions (kg) |
| $MR_{exp,i}$ | Experimental moisture ratio (dimensionless) |
| $MR_{pre,i}$ | Predicted moisture ratio (dimensionless) |
| M | Moisture content, dry basis (kg water/kg dry matter) |
| $M_0$ | Initial moisture content |
| $M_e$ | Equilibrium moisture content |
| m | Annual operation and maintenance cost of solar dryer as a fraction of its capital cost |
| N | Total no of observations |
| n | Number of constants |

| | |
|---|---|
| $NE_c$ | Net annual potential of $CO_2$ emissions mitigation (kg) |
| $p_c$ | Cost of the solar dryer per unit aperture area ($Rs/m^2$) |
| $Q_{dry}$ | Potential amount of a cash crop for solar drying (kg) |
| $Q_{gross}$ | Gross annual crop production (kg) |
| $R^2$ | Coefficient of determination |
| RMSE | Root mean square error |
| $\chi^2$ | Reduced chi square |
| T | Useful life time of the solar dryer (years) |
| $T_p$ | Temperature of product (K) |
| t | Drying period |
| $UC_{dry}$ | Unit cost of solar crop drying (Rs/kg) |
| $UC_{mit}$ | Unit cost of fossil $CO_2$ emissions mitigation (Rs/kg) |
| $\eta_d$ | Thermal efficiency of the solar dryer |
| $\eta_i$ | Efficiency of utilization of ith fuel in a conventional dryer |

**Greek symbols**

$\lambda$ Latent heat of vaporization (kJ/kg)

**Subscripts**

o At the beginning of drying
f Final value of moisture content

## Introduction

Recently, India is facing with a chronic shortage of food due to improper handling and poor storage facilities leading to heavy post-harvest losses up to about 35–40 % (MoFPI 2011). Thermal drying is a most common method of reducing moisture content to a safe storage level that does not permit various microorganisms to grow in the vicinity of food products, and hence, can be preserved safely for a longer period without any wastage. Currently, convective hot air drying using fossil fuels such as coal, diesel oil and natural gas is widely used in industrial food drying applications. The major concerns in these methods are high energy consumption and hence an expensive operation. In addition, there is an increasing concern in the scientific community regarding green house gas emissions resulting in the warming of the climate system from burning of fossil fuels especially in developing countries. The scarcity of fossil fuels along with their rising cost of production and adverse environmental impacts has driven the use of solar energy based technologies in food processing (Eswara and Ramakrishnarao 2013). Application of solar energy for food drying has tremendous potential in sustainable development, especially in the countries like India where this renewable source of energy is abundantly available (Mahapatra and Imre 1990). It is found that the use of solar dryer system with an efficiency of 40 % decreases consumption of conventional energy by 27–80 % (Arata et al. 1993). In order to estimate the quantity of fossil fuel that can be saved by solar drying and $CO_2$ emissions mitigation, it is very much essential to have the knowledge of specific energy consumption of food products during drying. In the past, researchers around the globe have given much importance on the improvement of drying conditions by optimizing the energy requirement. In the food industry, the most prominent goal is to use less energy for removing the maximum amount of moisture to acquire optimum storage conditions for the food products. A number of studies have been performed on energy consumption for drying of various agricultural products (longan, corn, potato slices, etc.) (Tippayawong et al. 2008; Chayjan et al. 2011; Darvishi et al. 2013).

Drying processes using solar energy were carried out by traditional open air sun drying and various advance solar dryers. Natural open air sun drying is the inexpensive method of solar energy utilization that is commonly practiced in the rural areas of the developing countries like India, where it is commonly used as a traditional food preservation technique. Several food products like papads (Kumar et al. 2011), vegetables (green chillies, green pea, onions, potatoes, and cauliflower) (Jain and Tiwari 2003), fruits (apricots, grapes, peaches, figs and plums) (Togrul and Pehlivan 2004), fish (Patterson and Ranjitha 2009), pineapple chips and kachris can be sun dried to store them for longer period. These products are tasty and require minimum cooking time. Similarly sun dried carrots, cherries and cranberries can be used as an addition in salads, oatmeal, cookies, muffins, loaves and breads. However, open air sun drying is a relatively slow process and in this process, considerable product losses takes place due to inadequate drying, fungal growth, encroachment of insects, birds and rodents resulting in the reduction of product quality. Hence, properly designed solar dryers should be used for drying agricultural products in developing countries. Several researchers have developed design principles for various classes of solar drying systems like direct (Sodha et al. 1985), greenhouse (Almuhanna 2011), indirect (Akpinar 2010) and mixed-mode (Forson et al. 2007). Out of the various dryer designs, the mixed-mode dryers are found to be the most effective in terms of product drying rate and drying cost (Simate 2003; Bolaji and Olalusi 2008). These mixed-mode solar dryers can improve the quality of the product, while reducing the use of traditional fuels.

In the food industries thin layer drying is an important dehydration technique and the thin layer drying equations are essential tools in mathematical modeling of drying process. They are practical and give sufficiently reliable results. In order to understand the drying behavior of food product or the control of drying operation, it is necessary to determine a

suitable thin layer model. In the last three decades, several categories of theoretical, semi-theoretical and empirical thin layer drying models were developed to describe the drying kinetics of different vegetables and fruits (Ozdemir and Devres 1999). Among all these models, the empirical thin layer drying models are most commonly used to predict the drying behavior of food product for a given drying conditions since they can be formulated easily using experimental data (Afzal and Abe 2000). Fadhel et al. (2011) have determined the thin layer drying characteristics of banana slices in a forced convection indirect solar dryer and found that the Wang and Singh drying model showed better fit to the experimental data. Aghbashlo et al. (2009) selected Page model to be the best describing thin layer drying behavior of potato slices dried in a semi-industrial continuous band drier operating at air temperatures of 50, 60 and 70 °C with air velocities of 0.5, 1 and 1.5 m/s and chain linear velocities of $1.85\times10^{-4}$, $2.22\times10^{-4}$ and $2.78\times10^{-4}$ m/s, respectively. The mathematical modeling of thin layer drying of shelled and unshelled pistachio samples performed in forced and natural convection solar assisted drying cabinet were demonstrated by Midilli and Kucuk (2003) and they deduced that the Logarithmic model could sufficiently describe thin layer forced solar drying of shelled and unshelled pistachio, while the Two term model could define thin layer natural solar drying. Koua et al. (2009) investigated the behaviour of the thin layer drying of plantain banana, mango and cassava experimentally in a direct solar dryer and found that Henderson and Pabis drying model was most suitable for describing the solar drying curves for these fruits. Hence, it is clear that no single thin layer model can describe completely the drying behavior for a whole range of fruits and vegetables for given drying conditions. Also, there is scarce information regarding thin layer drying modeling of potato cylinders and slices in solar dryers, especially for a mixed-mode solar dryer.

Nowadays clean development mechanism (CDM) under the Kyoto Protocol program is the main target to promote solar energy as a climate change option for most of the developing countries. Wohlgemuth and Missfeldt (2000) analyzed a Kyoto mechanism to promote renewable energies for greenhouse gas (GHG) mitigation. From the literature review, it is assessed that the use of solar energy in various thermal applications has been established by several scientists with the aim of reducing $CO_2$ emissions to the atmosphere. Purohit and Michaelowa (2008) have studied and analyzed the $CO_2$ emission potential estimation for solar water heating systems in India. Carbon dioxide emissions from photovoltaic (PV) energy systems and power generation systems using biomass have been designed and evaluated by Sakaki and Yamada (1997) in terms of energy and economics. Dubey and Tiwari (2009) proposed a mathematical model to calculate the total carbon credit earned for solar hybrid PV/T water heater. Kumar and Kandpal (2005) adopted a theoretical approach, assuming some basic input data to assess the potential of fossil $CO_2$ emissions mitigation for India during drying of various crops using indirect type solar dryer.

Little is known about the drying kinetics of potatoes and potential $CO_2$ emission mitigation in a *natural convection mixed-mode solar dryer* since no investigation has been reported so far addressing the performance evaluation in the context of different mathematical models to predict the drying kinetics and estimation of $CO_2$ emissions mitigation. Hence, the following objectives were aimed in the present study.

- Drying of potato cylinders and slices in a laboratory scale designed natural convection mixed-mode solar dryer and assessment of different thin layer drying models through statistical analysis.
- Development of a mathematical framework for estimation of annual $CO_2$ emissions mitigation with the use of solar drying and amount of different fossil fuels saved due to its use.
- To compare and analyze the amount of $CO_2$ emission mitigation potential of different fossil fuels e.g. coal, diesel oil and natural gas for the year 2010 and 2020 while drying potato cylinders and slices, respectively.

## Materials and methods

The food product selected for the study was potatoes which are widely grown and most commonly consumed vegetable around the globe. It contains many vitamins, including vitamin C, riboflavin, thiamine, niacin and is a good source of energy. Its nutritive value and relative ease of production have made it an important component in the rapidly expanding urban agriculture sector, and provides food security as well as employment to several million people in India. Freshly harvested potatoes of *kufri* variety were procured from the local market and these were cut by a knife into cylindrical samples of length 0.05 m and diameter 0.01 m and slices of diameter 0.05 m and thickness 0.01 m. The drying experiments with potato cylinders and slices were performed by a laboratory scale designed natural convection mixed-mode solar dryer (Fig. 1). It was made up of an inclined flat-plate solar collector and a drying chamber in which the potato samples to be dried were placed on a wire mesh tray. Two rectangular slots of size 305 mm × 50 mm were provided at the collector inlet and dryer outlet for natural circulation of air. Both the collector and dryer were made of matt black painted 22 gauge (0.643 mm thickness) aluminum sheet which acted as solar radiation absorber surface. A 3 mm thick transparent glass cover was placed on the top of the collector and dryer to allow the solar radiation to fall directly on the absorber as well as on the drying chamber. Rubber gaskets were provided beneath the glass cover for preventing any heat loss from the system making it air leak-proof. The fibre glass insulation of

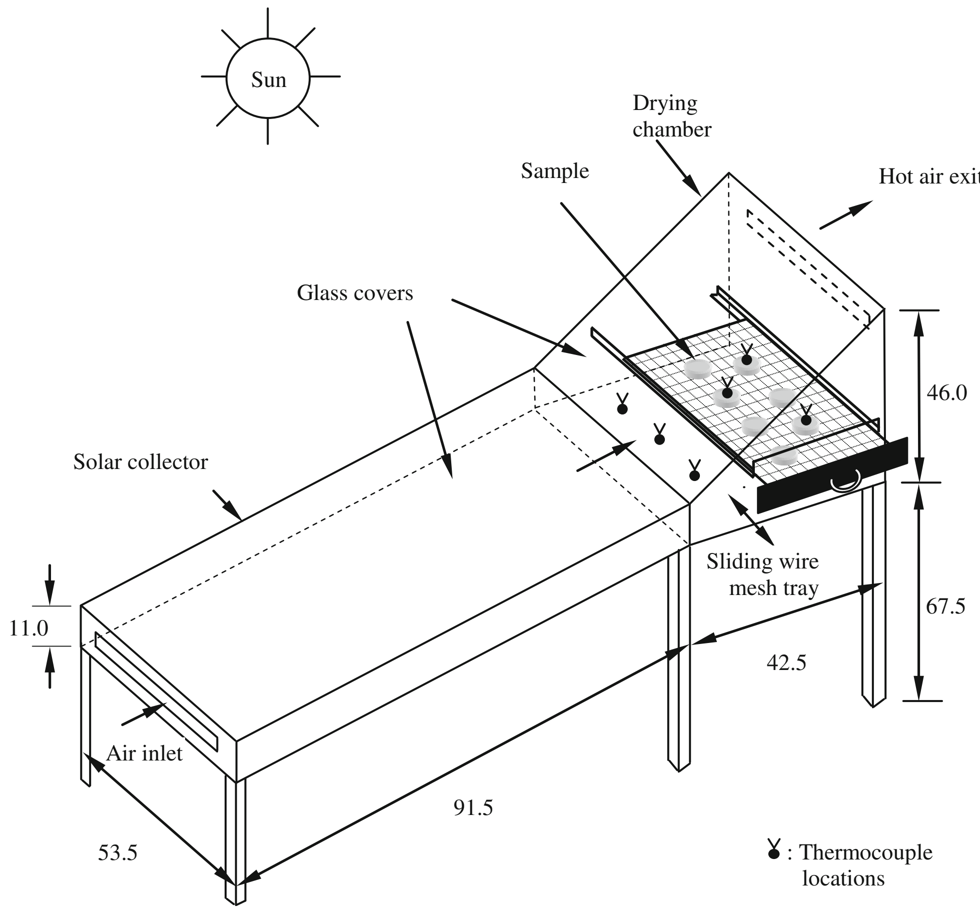


**Fig. 1** Schematic diagram of natural convection mixed-mode solar dryer showing different parts (all dimensions are in cm.)

50 mm thickness was provided at the bottom and sides of the collector-dryer assembly to minimize the thermal losses. The collector-dryer assembly supported by a mild steel angle frame was positioned due south during experimentation.

During the entire drying period, the temperatures of food samples, ambient air and drying air were measured by calibrated K type (chromel-alumel) thermocouples with the help of micro-voltmeter (accuracy±0.001 mV) through a selector switch. Several thermocouples were positioned at different locations just beneath the sample surfaces as well as under the wire mesh tray. The sample weight loss was measured at regular intervals of time, using a precision electronic balance (Precisa 3100c, accuracy±0.01 g, Switzerland). The moisture content of the dried product was obtained according to the AOAC method (AOAC 2002).

Mathematical modelling of solar drying curves

In order to predict the best model describing the drying behavior of potato cylinders and slices, eight commonly used thin layer drying models were tested. The different thin layer drying models used to describe the drying kinetics of potato cylinders and slices are shown in Table 1. Drying curves were fitted to the experimental data of potato cylinders and slices using eight different dimensionless moisture ratio equations as given below:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

Where, MR is the dimensionless moisture content ratio and M, $M_0$ and $M_e$ represent the moisture content of sample at any given time, initial moisture content and equilibrium moisture content, respectively. The moisture content ratio (MR) in Eq. 1 can be simplified to $M/M_0$ due to continuous fluctuation of relative humidity of drying air during solar drying process (Kaymak-Ertekin 2002; Togrul and Pehlivan 2004; Akpinar and Bicer 2008).

The regression analysis was performed using the SIGMAPLOT (version 11.0.0.77), commercial available statistical software. The coefficient of determination, $R^2$ was one of the main criteria for selecting the best equation to describe the drying curve. In addition to $R^2$, the goodness of fit was determined by reduced $\chi^2$ (mean square of the deviations between the experimental and calculated values for the models) and the root mean square error (RMSE). The mathematical formulation for determining these coefficients are shown in Eq. 2, 3 and 4, respectively. The best model describing the thin

layer drying characteristics of potato cylinders and slices was chosen as the one with higher values of $R^2$ and lower values of $\chi^2$ and RMSE (Menges and Ertekin 2006; Gunhan et al. 2005).

$$R^2 = 1 - \left[ \frac{\sum_{i=1}^{n} \left( MR_{pre,i} - MR_{\exp,i} \right)^2}{\sum_{i=1}^{n} \left( \overline{MR}_{pre} - MR_{\exp,i} \right)^2} \right] \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left( MR_{\exp,i} - MR_{pre,i} \right)^2}{N - n} \quad (3)$$

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^{n} \left( MR_{pre,i} - MR_{\exp,i} \right)^2 \right]^{1/2} \quad (4)$$

where $MR_{exp,i}$ is the $i^{th}$ experimental moisture ratio, $MR_{pre,i}$ the $i^{th}$ predicted moisture ratio, N, the number of observations and n, the number of constants.

## Development of framework and computation methodology for specific energy consumption and $CO_2$ emission mitigation

In the present study, a mathematical framework for estimation of specific energy consumption, $CO_2$ emissions mitigation and the amount of different fossil fuels replaced by the use of solar drying has been developed and mentioned below.

### *Estimation of specific energy consumption (SEC)*

During the drying process, the specific energy consumption (*SEC*) was calculated as the sum of the energy required for sensible heating of the product from initial sample temperature, $T_{po}$ to desired temperature, $T_p(t)$ and the energy required for the moisture evaporation from product moisture content, M(t) to desired final moisture content, $M_f$. It is expressed mathematically as:

$$E_p(t) = [1 + M(t)] C_p(t) \left[ T_p(t) - T_{po} \right] + \left[ M(t) - M_f \right] \lambda(t) \quad (5)$$

The *SEC* was calculated as an instantaneous value or as an average value during the entire drying period.

### *Estimation of potential amounts of potato crops*

It is of interest to estimate annual $CO_2$ mitigation based on annual amount of potato crop available for solar drying ($Q_{dry}$). The initial estimate for $Q_{dry}$ of a potato can essentially begin with the gross annual production ($Q_{gross}$) of the crop in the country. However, in areas where there is inadequate availability of solar radiation, the solar dryers cannot be used. A certain fraction of the total production of potato is used in raw form itself. Therefore, a realistic estimate for the potential amount of potato available for solar drying can be obtained from the gross annual production modified by correction factors for

(i) the fraction of crop used in raw form ($f_r$).
(ii) purchasing power of the user ($f_{pp}$) and
(iii) solar radiation availability ($f_{sol}$)

The values of factors $f_r$, $f_{pp}$ and $f_{sol}$ representing fraction of crop used in raw form may vary for different states in India. Therefore a weighted average $f_r$ and $f_{pp}.f_{sol}$ values equal to 0.95 has been used in the present calculation (Kumar and Kandpal 2005; Mani and Rangarajan 1982). The annual amount of potato available for solar drying ($Q_{dry}$) can be found from the following expression:

$$Q_{dry} = Q_{gross}(1 - f_r) f_{pp} f_{sol} \quad (6)$$

The gross annual production of potato in India for 2010 was considered to be 29 million tonnes (FAO 2010). The value of ($Q_{dry}$) on dry basis was obtained by multiplying the Eq. 6 with 0.18 (i.e. 82 % initial moisture content, wet basis from experimental data).

### *Estimation of aperture area of solar dryers to dry ($Q_{dry}$) amount of potato crops*

A solar drying system may be designed to meet the entire useful energy requirement for drying, $E_p$ of potato per unit dry matter of quantity $Q_{dry}$. The aperture area of solar dryer, $A_a$

**Table 1** Mathematical models used to obtain the drying curves of potato cylinders and slices

| Model no | Model name | Model | References |
|---|---|---|---|
| 1 | Newton | $MR = \exp(-kt)$ | Mujumdar (1987) |
| 2 | Modified Page | $MR = \exp[-(kt)^n]$ | Overhults et al. (1973) |
| 3 | Henderson and Pabis | $MR = a \exp(-kt)$ | Zhang and Litchfield (1991) |
| 4 | Logarithmic | $MR = a \exp(-kt) + c$ | Yagcioglu et al. (1999) |
| 5 | Two term | $MR = a \exp(-k_0 t) + b \exp(-k_1 t)$ | Henderson (1974) |
| 6 | Wang and Singh | $MR = 1 + at + bt^2$ | Wang and Singh (1978) |
| 7 | Modified Henderson & Pabis | $MR = a \exp(-kt) + b \exp(-k_0 t) + c \exp(-k_1 t)$ | Karathanos (1999) |
| 8 | Verma et al. | $MR = a \exp(-kt) + (1-a)\exp(-gt)$ | Verma et al. (1985) |

**Table 2** Estimation of embodied energy for mixed-mode solar dryer

| Material | Dimensions (cm) | Total volume ($cm^3$) | Density ($kg/m^3$) | Total wt (kg) | Embodied energy (MJ per kg) | Total energy embodied (MJ) | Total energy embodied (kWh) 1 kWh=MJ/3.6 | Percentage share (%) |
|---|---|---|---|---|---|---|---|---|
| (a) Solar flat plate collector | | | | | | | | |
| Aluminum sheet | (91.5x11x0.06)x2+(91.5x53.5x0.06) | 414.49 | 2770 | 1.14 | 382.73 | 436.31 | 121.20 | 56.02 |
| Glass sheet | (91.5x53.5x0.3) | 1468.57 | 2500 | 3.67 | 22.53 | 82.68 | 22.96 | 10.61 |
| Glass wool | (91.5x11x5)x2+(91.5x53.5x5) | 34541.25 | 50 | 1.72 | 114 | 196.08 | 54.46 | 25.17 |
| Angle Iron | 2x(23x2.5x0.2) | 23 | 7854 | 0.18 | 27.73 | 4.99 | 1.38 | 0.63 |
| Paint | – | 500 ml | 0.910 | $4.55x0^{-4}$ | 144 | 0.0655 | 0.018 | 0.008 |
| Wood | (91.5x11x1x2+91.5x53.5x1) | 6908.25 | 545 | 3.76 | 15 | 56.4 | 15.66 | 7.23 |
| Rubber gasket | (91.5x0.3x53.5)x2 | 2937.15 | 70 | 0.20 | 11.83 | 2.36 | 0.657 | 0.30 |
| (b) Drying chamber | | | | | | | | |
| Aluminum sheet | (42.5x46x0.06)x2+(53.5x42.5x0.06) | 371.02 | 2770 | 1.02 | 382.73 | 390.38 | 108.44 | 57.00 |
| Glass sheet | (59.5x53.5x0.3) | 954.97 | 2500 | 2.38 | 22.53 | 53.62 | 14.89 | 7.82 |
| Glass Wool | (42.5x46x5)x2+(53.5x42.5x5) | 30918.75 | 50 | 1.54 | 114 | 175.56 | 48.76 | 25.63 |
| Angle Iron | 2x(67.5x2.5x0.2) | 67.5 | 7854 | 0.53 | 27.73 | 14.69 | 4.08 | 2.14 |
| Wood | (42.5x53.5x1+42.5x46x1x2) | 6183.75 | 545 | 3.37 | 15 | 50.55 | 14.04 | 7.38 |
| Paint | – | 500 ml | 0.910 | $4.55x10^{-4}$ | 144 | 0.0655 | 0.018 | 0.009 |

required for drying $Q_{dry}$ amount of a potato (on dry basis) can be estimated as

$$A_a = \frac{Q_{dry}.E_p}{365{\cdot}I.CUF{\cdot}\eta_d} \tag{7}$$

Where, I and $\eta_d$ represents the average daily solar radiation available during drying period and the thermal efficiency of the solar dryer, respectively. In the present analysis, the experimental values of these parameters recorded were 19.8 $MJ/m^2$ and 0.5, respectively. It is noteworthy to mention that most parts of India have more than 270 sunny days every year with average daily solar radiation availability in the range of 14.4–25.2 $MJ/m^2$ (Mani and Rangarajan 1982). The CUF represents capacity utilization factor of solar dryer and depends upon

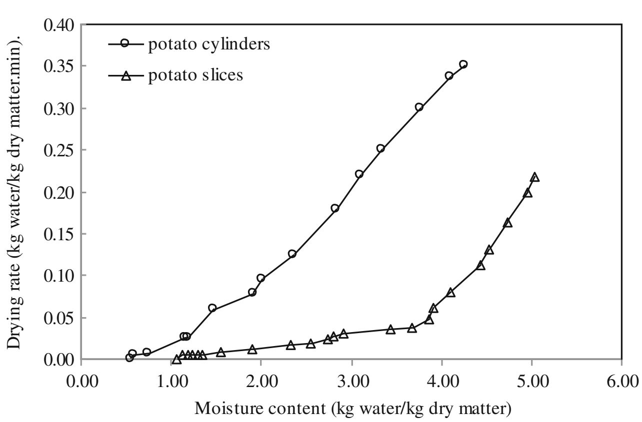


**Fig. 2** Drying rate curves for potato cylinders and slices dried in natural convection mixed-mode solar dryer

(i) the number of days in a year solar dryer is used for drying, and
(ii) the amount of dried potato per batch as a fraction of its rated capacity.

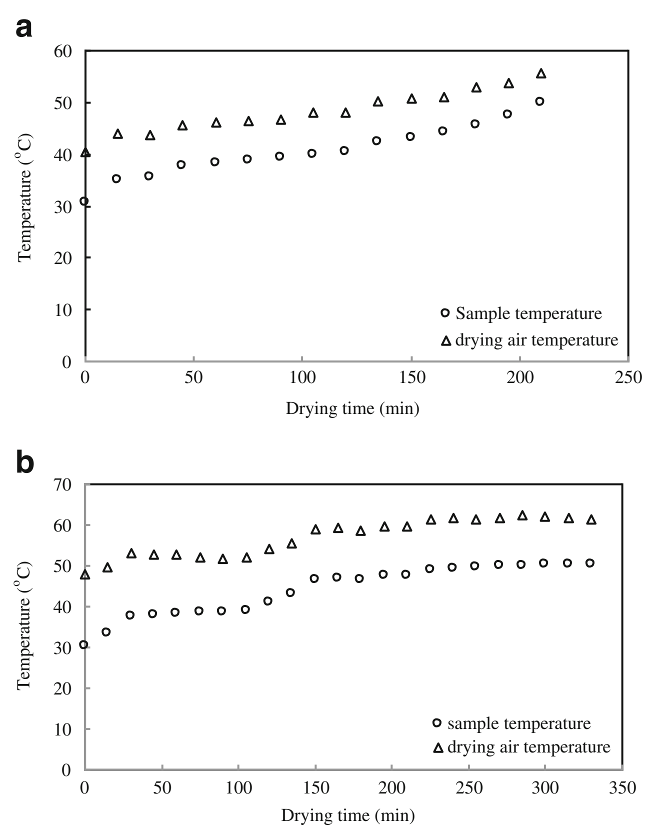


**Fig. 3** Variation of drying air and potato sample temperature as a function of drying time for **a** cylinders and **b** slices

**Table 3** Results of statistical analysis and values of regression coefficients obtained from different thin layer drying models for potato cylinders

| Model Name | Model constants | $R^2$ | $\chi 2$ | RMSE |
|---|---|---|---|---|
| Newton | k=0.00744 | 0.9518 | 0.0043071 | 0.063403 |
| ***Modified Page*** | ***k=0.0077030; n=1.473*** | ***0.9956*** | ***0.0003929*** | ***0.019149*** |
| Henderson & Pabis | a=1.093; k=0.0082800 | 0.9683 | 0.002964 | 0.052599 |
| Logarithmic | a=2.098; k=0.0028220; c=−1.065 | 0.9940 | 0.00055 | 0.022657 |
| Two term | a=0.5598; b=0.533; $k_0$=0.00828; k=0.00828 | 0.9683 | 0.003192 | 0.052599 |
| Wang & Singh | a=0.005228; b=0.0000042990 | 0.9925 | 0.0006667 | 0.02582 |
| Modified Henderson & Pabis | a=0.3711; b=0.368; c=0.3537; k=0.0082800; $k_0$=0.00828; $k_1$=0.00828 | 0.9683 | 0.003458 | 0.052599 |
| Verma et al., | a=0.2571; k=0.0074400; g=0.007439 | 0.9518 | 0.0046385 | 0.063403 |

Data in italics represent Modified Page model along with the model constants and statistical parameters, describes the drying kinetics of potato cylinders

*Estimation of gross fossil $CO_2$ emission mitigation*

This section describes the estimation of net fossil $CO_2$ emission mitigation due to the amounts of different fuels that would be saved by solar drying. The solar dryer is capable of meeting the energy requirement for drying of food products and can make significant contribution in the reduction of $CO_2$ emissions as a result of fuel switching. In this study, the fossil fuels like coal, light diesel oil and natural gas have been considered for estimation of $CO_2$ mitigation potential. Based on the efficiencies ($\eta$) of the utilization of different fuels for drying, their respective carbon emission factors (*CEF*) and the fraction of carbon oxidized during combustion (*FCO*), it is possible to estimate the potential of mitigating gross fossil $CO_2$ emissions ($GE_c$) by the use of solar dryers and it can be expresses as:

$$GE_c = \frac{\left[Q_{dry} \cdot CEF \cdot E_p \cdot FCO\right]}{\eta}\left(\frac{44}{12}\right) \tag{8}$$

The efficiencies of conventional drying system based on coal, light diesel oil and natural gas ($\eta$) were assumed to be 60 %, 70 % and 80 %, respectively. Carbon emission factors (CEF) were assumed to be 0.0258, 0.0202 and 0.0153 kg/MJ for coal, light diesel oil and natural gas, respectively (ADB 1998), and the values of FCO used for coal, light diesel oil and natural gas used were 0.9, 0.99 and 0.99, respectively (ADB 1998). In the present calculation, the specific energy consumption required $E_p$ (kJ/kg) for each of the sample geometry namely cylinders and slices were taken from the experimental data and the maximum values of these parameters were used in the analysis.

*Calculation of embodied energy for mixed-mode solar dryer*

In order to express the estimation results in more rational manner, the knowledge of annualized $CO_2$ emissions embodied in construction of given solar dryer is necessary. The different materials used for making of experimental mixed-mode solar dryer were aluminium, toughened glass, glass wool, absorber paint. The results of embodied energy used in the manufacturing of various materials of solar collector and drying chamber are summarized in Table 2(a) and (b), respectively. As can be seen, the maximum embodied energy in making the solar dryer was due to aluminium sheet. It can be further noticed that the embodied energy in solar dryer had been estimated to be 406.55 kWh which was equivalent to 398.41 kg of $CO_2$ (Considering the fact that the average $CO_2$ equivalent intensity for electricity production from coal as a fuel was approx. 0.98 kg of $CO_2$ per kWh) (Watt et al. 1998).

*Estimation of net fossil $CO_2$ emission mitigation*

The following expression for the net annual mitigation in $CO_2$ emissions ($NE_c$) was obtained by subtracting the annualized $CO_2$ emissions embodied in the solar dryer from the gross annual $CO_2$ emissions mitigation potential.

$$NE_c = \frac{\left[Q_{dry} \cdot CEF \cdot E_p \cdot FCO\right]}{\eta}\left(\frac{44}{12}\right) - \left(\frac{E_m A_a}{T}\right) \tag{9}$$

Where $E_m$ represents $CO_2$ emissions embodied in the solar dryer and T is the operational life of solar dryer. The dryer was expected to operate for 10 years (Palaniappan and Subramanian 1998).

*Estimation of unit cost of solar drying*

The unit cost of solar drying is the ratio of total annualized cost of solar dryer to the annual amount of crop dried by the solar dryer. It can be mathematically expressed in Eq. 10 (Kandpal and Garg 2003). The value of cost of the mixed-mode solar dryer is "Rs. 3250/$m^2$". The value of 'm' was considered to be 0.05 and 'd' was 0.12.

**Table 4** Results of statistical analysis and values of regression coefficients obtained from different thin layer drying models for potato slices

| Model name | Model constants | $R^2$ | $\chi2$ | RMSE |
|---|---|---|---|---|
| Newton | k=0.003918 | 0.9327 | 0.005163 | 0.070271 |
| ***Modified Page*** | ***k=0.004277; n=1.557*** | ***0.9907*** | ***0.000765*** | ***0.027054*** |
| Henderson & Pabis | a=1.103; k=0.004479 | 0.9565 | 0.003320 | 0.056356 |
| Logarithmic | a=3.77; k=0.000810; c=−2.732 | 0.9853 | 0.001099 | 0.032417 |
| Two term | a=0.5599; b=0.543; $k_0$=0.004479; k=0.004479 | 0.9565 | 0.003478 | 0.056356 |
| Wang & Singh | a=−0.2610; b=0.0000000577 | 0.9826 | 0.001350 | 0.03674 |
| Modified Henderson & Pabis | a=0.3704; b=0.3722; c=0.3603; k=0.0040; $k_0$=0.004479; $k_1$=0.004479 | 0.9565 | 0.003652 | 0.056356 |
| Verma et al., | a=0.9956; k=0.003918; g=0.003918 | 0.9327 | 0.005408 | 0.070271 |

Data in italics represent Modified Page model along with the model constants and statistical parameters, describes the drying kinetics of potato slices

$$UC_{dry} = \frac{\left[E_p \cdot p_c\left(CRF_{d,T} + m\right)\right]}{365 \cdot CUF \cdot \eta_d . I} \quad (10)$$

$$CRF_{d,T} = \frac{\mathrm{d}(1+\mathrm{d})^{\mathrm{T}}}{(1+\mathrm{d})^{\mathrm{T}} - 1} \quad (11)$$

*Estimation of unit cost of fossil $CO_2$ emission mitigation*

The unit cost of fossil $CO_2$ mitigation is essentially the ratio of net annual cost of solar dryer to net annual fossil $CO_2$ emissions mitigated by its use. The net annual cost of solar dryer is the difference between the annualized cost of purchase, installation, operation and maintenance of the solar dryer and the monetary worth of the fuels substituted by the use of solar dryer for the period of 1 year.

Hence, the net annual cost ($C_a$) of the solar dryer was estimated as

$$C_a = A_a \left\{ p_c\left(CRF_{d,T} + m\right) - \frac{\left(365 ICUF \eta_d P_{f,i}\right)}{\eta_i} \right\} \quad (12)$$

The unit cost of fossil $CO_2$ emission mitigation was expressed as

$$UC_{mit} = \frac{A_a \left\{ p_c\left(CRF_{d,T} + m\right) - \frac{\left(365 ICUF \eta_d P_{f,i}\right)}{\eta_i} \right\}}{\left\{ \frac{Q_{dry} . CEF . E_p . FCO}{\eta} \left(\frac{44}{12}\right) - \left(\frac{E . A_a}{T}\right) \right\}} \quad (13)$$

The market prices for coal, light diesel oil and natural gas had been considered to be "Rs. 0.27/MJ", "Rs. 0.42/MJ" and "Rs. 0.12/MJ", respectively.

## Results and discussion

Drying kinetics of potato cylinders and slices in a mixed-mode solar dryer

Potato cylinders and slices were dried progressively from an initial moisture content of 82 % (wb) to a final safe moisture content of 12 % (wb) with an effective drying period of 210 min and 330 min, respectively in the laboratory scale

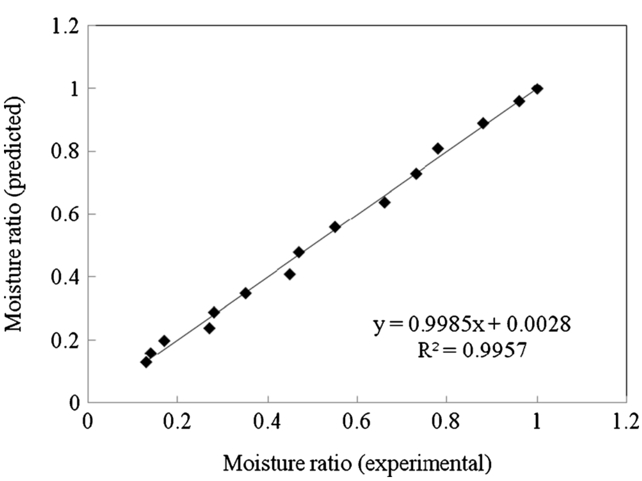


**Fig. 4** Comparison between experimental and predicted dimensionless moisture content values obtained from Modified Page model for potato cylinders

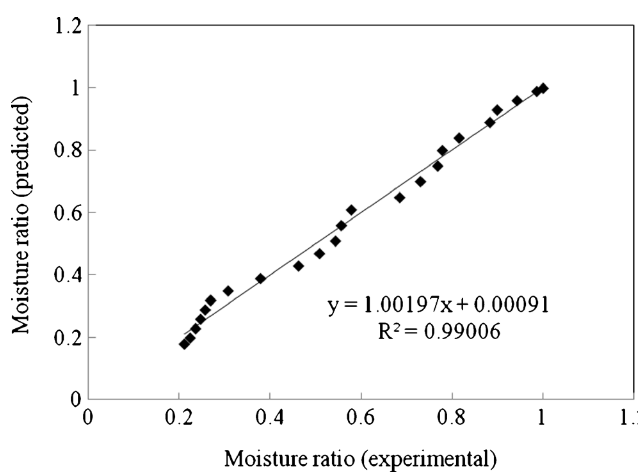


**Fig. 5** Comparison between experimental and predicted dimensionless moisture content values obtained from Modified Page model for potato slices

**Table 5** Estimation of useful energy requirement and unit cost for solar drying of potato cylinders and slices for the year 2010

| Potato Sample | Annual amount of potato for drying (kg dry basis) | Total energy requirement for drying (MJ/kg of dry matter) | Aperture area of solar dryer ($m^2$) | Unit cost of solar drying (Rs/kg) |
|---|---|---|---|---|
| Cylindrical | 19343.52 | 126467.93 | 106056.82 | 4.04 |
| Slice | 19343.52 | 134166.65 | 112512.97 | 4.29 |

mixed-mode solar dryer. Figure 2 shows the drying rate curve for potato cylinders and slices. It is clearly evident that no constant drying rate period was observed in the drying curve and drying occurs only in the falling rate period for both the sample geometries. The drying rate is faster at the beginning because initially water evaporates from the surface but subsequently, the drying rate decreases with decrease in moisture content as water has to be evaporated from inside of the food material which is moved to the surface. Hence, in the present case the governing physical mechanism of the moisture movement process is due to internal moisture diffusion phenomenon. Analysis of the experimental data also showed that there was faster moisture evaporation in cylindrical samples as compared to slices because of smaller volume per unit surface area of the product (Islam and Flink 1982). The variation of food product and drying air temperature with time for potato cylinders and slices are illustrated in Fig. 3(a) and (b), respectively. It can be noticed that for both the sample geometries the rise in sample temperature is relatively less as compared to that of drying air temperature as expected.

## Evaluation of model parameters

The experimental drying data were converted to dimensionless moisture ratio and in order to model the moisture ratio as a function of drying time, eight thin layer drying models were fitted to the experimental data. The statistical analysis of the models along with their estimated parameters is presented in Tables 3 and 4 for potato cylinders and slices, respectively. For all the models tested, values of coefficient of determination lie in the range of 0.9327–0.9956 indicating that all the models can satisfactorily describe the drying of both the sample geometries. However, among all the drying models tested, the *Modified Page model* obtained has the highest values of $R^2$ and lowest values of $\chi^2$ and RMSE. From the Modified Page model, the values of statistical parameters obtained were: $R^2 - 0.9956$, $\chi^2 - 0.0003929$, *RMSE* $- 0.01914$ *for potato cylinders and* $R^2 - 0.9907$, $\chi^2 - 0.000765$, *RMSE* $- 0.02705$ *for slices*, *respectively*. Similar results were obtained by Akpinar et al. (2003). They have experimentally investigated the thin layer drying behavior of potato slices with thicknesses of 12.5 and 8 mm in a convective cyclone dryer by using several thin layer drying models. The obtained values of Modified Page model parameters for potato slices were: $k = 0.010531$, $n = 0.93228$ with $R^2 - 0.9994$, $\chi^2 - 0.0000892$. It was also observed that potato slices were perfectly dried at different drying air temperatures of 60, 70 and 80 °C and drying air velocities of 1 and 1.5 m/s in the time period of 460–740 min and 280–520 min, respectively, and the process is diffusion controlled phenomenon. Figures 4 and 5 compares the experimental moisture ratio data with those predicted with the Modified Page model for potato cylinders and slices, respectively. It has been observed that the predictions using the Modified Page model showed moisture ratio values fit along the straight line, justifying the suitability of this model for describing drying characteristics of potato.

## Effect of sample shape on specific energy consumption

It was found that the values of specific energy consumption are 6.935 MJ/kg dry matters and 6.538 MJ/kg dry matters for slices and cylinders with initial moisture content of 5.03 and 4.26 kg water/kg dry matter, respectively. The rapid mass evaporation of cylinders due to higher surface heating effects resulting from more exposed area per unit mass resulted to lower SEC values.

## Estimation of net $CO_2$ mitigation

The computation methodology described in the above section of this paper was used to estimate the potential of using mixed-mode solar dryer for potato. However, estimation of the three different correction factors required detailed relevant data on the crop (production levels, drying characteristics etc.), purchasing power of the potential users and solar radiation availability at desegregated levels. Similarly, for estimating the fuel savings and $CO_2$ emissions mitigation potential, the prevailing fuel mix used for drying of the crop should be known.

**Table 6** Estimation of unit cost of fossil $CO_2$ emission mitigation for different fuels for drying potato cylinders and slices for the year 2010

| Sample | $CO_2$ mitigated (tonne) | | | Unit cost of $CO_2$ Emissions Mitigation (Rs/kg) | | |
|---|---|---|---|---|---|---|
| | Coal | Light Diesel Oil | Natural Gas | Coal | Light Diesel Oil | Natural Gas |
| Cylinder | $1.36 \times 10^4$ | $8.93 \times 10^3$ | $4.46 \times 10^3$ | 1.56 | 0.26 | 13.26 |
| Slice | $1.44 \times 10^4$ | $9.47 \times 10^3$ | $4.74 \times 10^3$ | 1.56 | 0.26 | 13.26 |

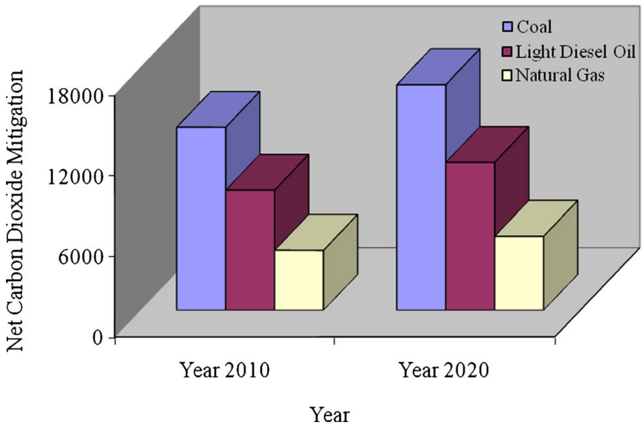


**Fig. 6** Net $CO_2$ emission mitigation due to different fossil fuels saved by mixed-mode solar drying of potato cylinders for the year 2010 and 2020

The values of annual amount of potato to be dried, useful energy requirement for drying unit amount of potato cylinders and slices are presented in Table 5. The aperture area of solar dryer required for drying the estimated amount and unit cost of solar drying have been calculated by using Eqs. 7 and 10 and has been tabulated. As can be found, the unit cost of solar drying of potato slices is found to be higher compared to cylinders, as expected because the useful energy required for drying potato depends on its initial and final moisture content. Separate estimates of the unit cost of fossil $CO_2$ emissions mitigation for different fuels for cylinder and slice samples of potato are presented in Table 6. It may be noted that the unit cost of $CO_2$ emission mitigation is lowest for light diesel oil replacement for drying "Rs. 0.26/kg" and highest for natural gas replacement "Rs. 13.26/kg". The higher value in case of natural gas is due to low carbon emission factor, low market price and high thermal efficiency of utilization of natural gas. The amount of fuel replaced by solar dryer increases with an increase in its capacity utilization factor leading to a reduction in the net annual cost of dryer and an increased fossil $CO_2$ emissions mitigation. Therefore, the unit cost of fossil $CO_2$ emissions mitigation decreases with an increase in capacity utilization factor of a solar dryer. It can also be seen from Fig. 6 that the net annual $CO_2$ emission mitigation potential for potato cylinders are highest for coal followed by light diesel oil and natural gas for the year 2010 as well as for 2020. Similar trend in the bar graph can be observed for slices as shown in Fig. 7. It was inferred from the present study that by the year 2020, 23 % of $CO_2$ emissions can be mitigated by the use of mixed-mode solar dryer for drying of agricultural products.

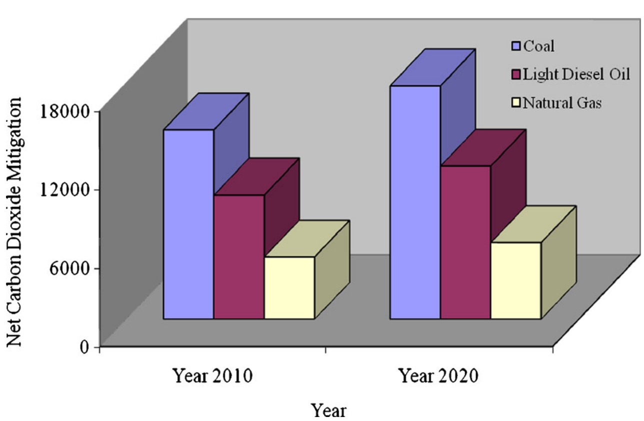


**Fig. 7** Net $CO_2$ emission mitigation due to different fossil fuels saved by mixed-mode solar drying of potato slices for the year 2010 and 2020

## Conclusions

Drying experiments were conducted successfully with potato cylinders and slices using a natural convention solar dryer in changing climatic conditions and the followings are the main conclusions in the present investigation:

- The initial moisture content of potato cylinders and slices was progressively decreased to a safe moisture content of 12 % within effective drying period of 210 min and 330 min, respectively in the laboratory scale *natural convection mixed-mode solar dryer*. The experimental data suggested that there was faster moisture evaporation in cylindrical samples as compared to slices because of smaller volume per unit surface area of the product.
- In order to explain the drying behavior of potato samples in the mixed-mode solar dryer, eight different thin layer drying models were tested and compared statistically. It was suggested that *Modified Page model* suited the best to describe the drying kinetics of both potato cylinders and slices.
- A mathematical framework has been proposed to estimate the annual $CO_2$ emissions mitigation and amount of different fossil fuels saved while drying potato samples by a mixed-mode solar dryer. It has been found from the theoretical analysis that the application of solar energy in food drying has great potential for fossil $CO_2$ emissions mitigation.
- Among different fossil fuels investigated, the replacement of *coal* with solar energy for drying resulted in the maximum $CO_2$ mitigation potential and consequently the amount of fuel saved followed by light diesel oil and natural gas.
- Results of energy analysis revealed that for both the sample geometries, decreasing product moisture content during drying resulted in significant reduction in specific energy consumption.

The rigorous analysis in present investigation suggested potential choice of mixed-mode solar dryer for various vegetables and fruits as its use by food processing industries and farmers mitigates the emission of green house gases while simultaneously contributing to reasonable drying rate.

**Acknowledgment** The author would like to thank Dr Subodh Kumar, Centre for Energy Studies, IIT Delhi for providing the solar dryer to carry out the experiments.

## References


ADB (1998) Asia Least-Cost Greenhouse Gas Abatement Strategy (ALGAS) India. Asian Development Bank (ADB), Manila

Afzal TM, Abe T (2000) Simulation of moisture changes in barley during far infrared radiation drying. Comput Electron Agric 26:137–145

Aghbashlo M, Kianmehr MH, Arabhosseini A (2009) Modeling of thin-layer drying of potato slices in length of continuous band dryer. Energy Convers Manage 50(5):1348–1355

Akpinar E, Midilli A, Bicer Y (2003) Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modeling. Energy Convers Manage 44(10):1689–1705

Akpinar EK (2010) Drying of mint leaves in a solar dryer and under open sun: modelling, performance analyses. Energy Convers Manage 51(12):2407–2418

Akpinar EK, Bicer Y (2008) Mathematical modelling of thin layer drying process of long green pepper in solar dryer and under open sun. Energy Convers Manage 49:1367–1375

Almuhanna EA (2011) Utilization of a solar greenhouse as a solar dryer for drying dates under the climatic conditions of the eastern province of Saudi Arabia. Part I. Thermal performance analysis of a solar dryer. J Agr Sci 4(3):237–246

AOAC (2002) Official methods of analysis, 17th edn. Association of Official Analytical Chemists, Arlington

Arata A, Sharma VK, Spagna G (1993) Performance evaluation of solar assisted dryers for low temperature drying application-II Experimental results. Energy Convers Manage 34(5):417–426

Bolaji BO, Olalusi AP (2008) Performance evaluation of a mixed-mode solar dryer. AU J Tech 11(4):225–231

Chayjan RA, Parian JA, Esna-Ashari M (2011) Modeling of moisture diffusivity, activation energy and specific energy consumption of high moisture corn in a fixed and fluidized bed convective dryer. Span J Agric Res 9(1):28–40

Darvishi H, Asl AR, Asghari A, Najafi G, Gazori HA (2013) Mathematical modeling, moisture diffusion, energy consumption and efficiency of thin layer drying of potato slices. J Food Process Technol 4:215

Dubey S, Tiwari GN (2009) Analysis of PV/T flat plate water collectors connected in series. Sol Energy 83:1485–1498

Eswara AR, Ramakrishnarao M (2013) Solar energy in food processing-a critical appraisal. J Food Sci Technol 50(2):209–227

Fadhel MI, Abdo RA, Yousif BF, Zaharim A, Sopian K (2011) Thin-Layer drying characteristics of banana slices in a force Convection indirect solar drying, Recent researches in Energy and Environment. In: EE 2011: 6th IASME/WSEAS International Conference on Energy and Environment, 23–25 Feb 2011, Cambridge, United Kingdom

FAO (2010) Food and Agriculture Organization of the United Nations. http://www.fao.org. Accessed 26 Feb 2013

Forson FK, Nazha MAA, Rajakaruna H (2007) Modelling and experimental studies on a mixed-mode natural convection solar crop dryer. Sol Energy 81(3):346–357

Gunhan T, Demir V, Hancioglu E, Hepbasli A (2005) Mathematical modelling of drying of bay leaves. Energy Convers Manage 46(11–12):1667–1679

Henderson SM (1974) Progress in developing the thin layer drying equation. Trans ASAE 17:1167–1172

Islam MN, Flink JM (1982) Dehydration of potato. I. Air and solar drying at low air velocities. J of Food Technology 17:373–385

Jain D, Tiwari GN (2003) Thermal aspects of open sun drying of various crops. Energy 28:37–54

Kandpal TC, Garg HP (2003) Financial evaluation of renewable energy technologies. Macmillan India Limited, New Delhi

Karathanos VT (1999) Determination of water content of dried fruits by drying kinetics. J Food Eng 39:337–344

Kaymak-Ertekin F (2002) Drying and rehydrating kinetics of green and red peppers. J Food Sci 67:168–175

Koua KB, Fassinou WF, Gbaha P, Toure S (2009) Mathematical modeling of the thin layer solar drying of banana, mango and cassava. Energy 34:1594–1602

Kumar A, Kandpal TC (2005) Solar drying and $CO_2$ emissions mitigation: potential for selected cash crops in India. Sol Energy 78(2): 321–329

Kumar M, Khatak P, Sahdev RK, Prakash O (2011) The effect of open sun and indoor forced convection on heat transfer coefficients for the drying of papad. J Energ South Af 22(2):40–46

Mahapatra AK, Imre L (1990) Role of solar agricultural drying in developing countries. Int J of Ambient Energy 11:205–210

Mani A, Rangarajan S (1982) Solar radiation over India. Allied Publishers Private Limited, New Delhi

Menges HO, Ertekin C (2006) Thin layer drying model for treated and untreated Stanley plums. Energy Convers Manage 47(15–16):2337–2348

Midilli A, Kucuk H (2003) Mathematical modeling of thin layer drying of Pistachia by using solar energy. Energy Convers Manage 44(7): 1111–1122

MoFPI (2011) Ministry of food processing industries, government of India, New Delhi; 2011. Annual Report, 2010–11. www.mofpi.nic.in

Mujumdar AS (1987) Handbook of industrial drying. Marcel Dekker, New York

Overhults DD, White GM, Hamilton ME, Ross IJ (1973) Drying soybeans with heated air. Transactions of the ASAE 16:195–200

Ozdemir M, Devres YO (1999) The thin layer drier characteristics of hazelnut during roasting. J Food Engg 42:225–233

Palaniappan C, Subramanian SV (1998) Economics of solar air preheating in south Indian tea factories: a case study. Sol Energy 63: 31–37

Patterson J, Ranjitha G (2009) Qualities of commercially and experimentally sun dried fin fish, Scomberoides tol. Afr J Food Sci 3(10):299–302

Purohit P, Michaelowa A (2008) CDM potential of solar water heating systems in India. Sol Energy 82:799–811

Sakaki K, Yamada K (1997) $CO_2$ mitigation by new energy systems. Energy Convers Manage 38(1):S655–S660

Simate IN (2003) Optimization of mixed mode and indirect mode natural convection solar dryers. Renew Energy 28:435–453

Sodha MS, Dang A, Bansal PK, Sharma SB (1985) An analytical and experimental study of open sun drying and a cabinet type drier. Energy Convers Manage 25:263–271

Tippayawong N, Tantakitti C, Thavornun S (2008) Energy efficiency uimprovements in longan drying practice. Energy 33:1137–1143

Togrul IT, Pehlivan D (2004) Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. J Food Eng 65:413–425

Verma LR, Bucklin RA, Endan JB, Wratten FT (1985) Effects of drying air parameters on rice drying models. Trans ASAE 28:296–301

Wang CY, Singh RP (1978) A single layer drying equation for rough rice. ASAE Paper No. 78–3001. MI, USA: St. Joseph.

Watt M, Johnson A, Ellis M, Quthred N (1998) Life cycle air emission from PV power systems. Progress Photovolt Res Appl 6:127

Wohlgemuth N, Missfeldt F (2000) The Kyoto mechanisms and the prospects for renewable energy technologies. Sol Energy 29(4):305–314

Yagcioglu A, Degirmencioglu A, Cagatay F (1999) Drying characteristic of laurel leaves under different conditions. In: A Bascetincelik (Ed.). Proceedings of the seventh international congress on agricultural mechanization and energy. Adana, Turkey: Faculty of agriculture, Cukurova University; p. 565–569

Zhang Q, Litchfield JB (1991) An optimization of intermittent corn drying in a laboratory scale thin layer dryer. Dry Technol 9:383–395