УДК: 663

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DEVELOPMENT OF MIXED MODE SOLAR DRYER FOR RURAL FARMERS OF INDIA: SUSTAINABLE AND GREEN APPROACH FOR DRYING OF AGRICULTURAL PRODUCTS

Drying is a simultaneous heat and mass transfer energy intensive operation. It is widely used as a food preservation technique which is not afforded by many of rural farmers of India results in quality degradation of produce and hence financial losses. In view of improper postharvest methods, energy constraint and environmental impact of conventional drying methods, solar drying could be a practical, economically sustainable and environmentally reliable alternative. In the present work applicability of low cost mixed mode solar cabinet dryer was investigated for drying of commercially important and export oriented agriculture produce material ginger and garlic. The proposed solar cabinet dryer exhibited the environment friendly sustainable approach to dry agricultural produce reasonably rapidly to a safe moisture level without any energy investment, zero emission and simultaneously it also ensures a superior quality of the dried product over the conventional open sun drying methods with low capital investment affordable by rural farmers of India. In this work freshly harvested ginger slices and garlic cloves were successfully dried from initial moisture content of 621.50 to 12.19% (d.b.) and 184.09 % (d.b.) to 16.76% (d.b.) respectively with a significant reduction in drying time. The effective diffusivity of the ginger and garlic slices in the present solar dryer was found to be 5.5×10^{-9} m^2/s *and* 3.86×10^{-9} m^2/s *respectively. Among the tested models Page model was found to be best suitable to describe the drying kinetics of ginger and garlic based on statistical criterion. The moisture ratio obtained experimentally and predicted by Page model showed good agreement and fitted smoothly to straight line. The model attained the highest value of* R^2*, lowest value of* χ^2*, and RMSE, (*R^2*, 0.9823,* χ^2*, 0.003, RMSE, 0.0538) for ginger; similarly,* R^2 *of 0.9882,* χ^2 *of 0.002, RMSE of 0.047 for garlic further confirmed its superiority over the other models. The quality analysis of the dried material in the present solar dryer showed that superior quality product in view of better rehydration, less shrinkage and less colour change from open sun dried material which further confirms the potential of proposed dryer.*

Key Words*: drying, solar, ginger, garlic, page model*

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РАЗРАБОТКА СОЛНЕЧНОЙ СУШИЛКИ СМЕШАННОГО РЕЖИМА ДЛЯ СЕЛЬСКИХ ФЕРМЕРОВ ИНДИИ: УСТОЙЧИВЫЙ И ЭКОЛОГИЧНЫЙ ПОДХОД К СУШКЕ СЕЛЬСКОХОЗЯЙСТВЕННОЙ ПРОДУКЦИИ

Сушка представляет собой одновременную тепло- и массообменную энергоемкую операцию. Он широко используется в качестве метода сохранения пищевых продуктов, который не позволяют себе многие сельские фермеры Индии, что приводит к ухудшению *качества продукции и, следовательно, к финансовым потерям. Ввиду неподходящих методов послеуборочной обработки, нехватки энергии и воздействия традиционных методов сушки на окружающую среду солнечная сушка может быть практичной, экономически устойчивой и экологически надежной альтернативой. В настоящей работе была исследована применимость недорогой сушилки с солнечным шкафом смешанного режима для сушки коммерчески важных и ориентированных на экспорт сельскохозяйственных продуктов, таких как имбирь и чеснок. Предлагаемая солнечная сушилка продемонстрировала экологически безопасный устойчивый подход к сушке сельскохозяйственной продукции достаточно быстро до безопасного уровня влажности без каких-либо затрат энергии, с нулевым уровнем выбросов и одновременно она также обеспечивает превосходное качество высушенного продукта по сравнению с обычными методами сушки на открытом солнце с низким капитальные вложения, доступные сельским фермерам Индии. В этой работе свежесобранные ломтики имбиря и зубчики чеснока были успешно высушены от начального содержания влаги от 621,50 до 12,19 % (по сухому веществу) и от 184,09 % (по сухому веществу) до 16,76 % (по сухому веществу) соответственно со значительным сокращением времени сушки. Было обнаружено, что эффективная диффузионная способность ломтиков имбиря и чеснока в настоящей солнечной сушилке составляет 5,5×10-9 м2/с и 3,86×10-9 м2/с соответственно. Было обнаружено, что среди протестированных моделей модель Пейджа лучше всего подходит для описания кинетики сушки имбиря и чеснока на основе статистического критерия. Влажность, полученная экспериментально и предсказанная по модели Пейджа, показала хорошее соответствие и плавно укладывалась в прямую. Модель достигла самого высокого значения R2, самого низкого значения χ2 и RMSE (R2, 0,9823, χ2, 0,003, RMSE, 0,0538) для имбиря; аналогично, R2 0,9882, χ2 0,002, RMSE 0,047 для чеснока еще раз подтвердили его превосходство над другими моделями. Анализ качества высушенного материала в настоящей солнечной сушилке показал, что продукт имеет более высокое качество с точки зрения лучшей регидратации, меньшей усадки и меньшего изменения цвета по сравнению с материалом, высушенным на открытом солнце, что еще раз подтверждает потенциал предлагаемой сушилки.*

Ключевые слова: *сушка, солярка, имбирь, чеснок, страничная модель.*

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ИНДИЯНЫН АЙЫЛДЫК ФЕРМЕРЛЕРИ ҮЧҮН АРАЛАШ РЕЖИМДЕГИ КҮН КУРГАТКЫЧЫН ӨНҮКТҮРҮҮ: АЙЫЛ ЧАРБА АЗЫКТАРЫН КУРГАТУУ ҮЧҮН ТУРУКТУУ ЖАНА ЖАШЫЛ МАМИЛЕ

Кургатуу − бул бир эле убакта жылуулук жана масса берүү энергияны талап кылган операция. Ал тамак-ашты сактоонун ыкмасы катары кеңири колдонулат, аны Индиянын көптөгөн айылдык фермерлери ала албаган продукциянын сапатынын начарлашына, демек, финансылык жоготууларга алып келет. Түшүм жыйноодон кийинки туура эмес ыкмаларды, энергияны чектөөнү жана кадимки кургатуу ыкмаларынын айлана-чөйрөгө тийгизген таасирин эске алуу менен, күн кургатуу практикалык, экономикалык жактан туруктуу жана экологиялык жактан ишенимдүү альтернатива болушу мүмкүн. Бул иште коммерциялык жактан маанилүү жана экспортко багытталган айыл чарба продукциясынын имбирь жана сарымсак материалдарын кургатуу үчүн арзан аралашма режимдеги күн шкафы кургаткычынын колдонулушу изилденген. Сунушталган күн шкафы кургаткычы экологиялык таза туруктуу мамилени көрсөттү, айыл чарба продукцияларын коопсуз нымдуулук деңгээлине эч кандай энергетикалык салымсыз, нөлдүк эмиссиясыз тез арада кургатуу үчүн колдонулат *жана ошол эле учурда ал кургатылган продуктунун эң жогорку сапатын камсыздайт. Индиянын айылдык фермерлери үчүн жеткиликтүү капиталдык салымдар. Бул иште жаңы жыйналган имбирдин кесиндилери жана сарымсак тиштери алгачкы нымдуулуктун 621,50%тен 12,19%ке чейин (d.b.) жана 184,09% (d.b.) 16,76% (d.b.) чейин ийгиликтүү кургатылган жана кургатуу убактысы бир кыйла кыскарган. Учурдагы күн кургаткычта имбирь жана сарымсак кесиминин эффективдүү диффузивдүүлүгү 5,5×10-9 м2/с жана 3,86×10-9 м2/с деп табылган. Сыналган моделдердин ичинен Пэйж модели имбирь менен сарымсактын кургатуу кинетикасын статистикалык критерийдин негизинде сүрөттөө үчүн эң ылайыктуу деп табылган. Эксперименталдык жол менен алынган жана Пейдж модели тарабынан алдын ала айтылган нымдуулук катышы жакшы макулдашканын жана түз сызыкка жылмакай орнотулганын көрсөттү. Модель имбир үчүн R2 эң жогорку маанисине, χ2 эң төмөнкү маанисине жана RMSE, (R2, 0,9823, χ2, 0,003, RMSE, 0,0538) жеткен; ошол сыяктуу эле R2 0,9882, χ2 0,002, RMSE 0,047 сарымсак дагы башка моделдерге караганда анын артыкчылыгын тастыктады. Учурдагы күн кургаткычындагы кургатылган материалдын сапатын талдоо көрсөткөндөй, жакшыраак регидратация, аз кичирейүү жана ачык күндө кургатылган материалдан түсүнүн азыраак өзгөрүүсүн эске алуу менен, жогорку сапаттагы продукт сунушталган кургаткычтын потенциалын тастыктайт.*

Өзөктүү сөздөр: *кургатуу, күн, имбир, сарымсак, Page модели.*

1. Introduction

Drying has a vital role in postharvest processing. It has always been of great importance for conserving agricultural products and for extending the food shelf life (Doymaz, 2007). Many of the moisture-mediated deterioration reactions and reproduction of micro-organisms causing decay can be prevented by removal of moisture by appropriate drying method. The commercial drying methods are energy intensive with high capital investment and operating cost which is not afforded by rural farmers and also limited resources of fossil fuels and extensive usage are responsible for adverse effects on environment and also economic viability. Open sun drying of various crops is the most widespread conventional method for food preservation practiced in many urban and rural areas of developing countries like India. The major disadvantage of this technique is low quality and hygienic problems of the product. The product gets contaminated from dust, insects, rodents, and other animals which seriously degrade the food quality and ultimately results in a negative trade potential and economical worth. Labor requirement, long drying time (2-3 days), and direct exposure of the produce to sun and wind are the further difficulties with this method. In order to ensure continuous food supply to growing population and to enable the farmers to produce high quality marketable products, efficient and at the same time affordable drying methods are necessary. Varieties of mechanical energy driven dryers are available for preventing the deterioration of products and to reduce the drying time. These conventional dryers and drying techniques are not economical due to high energy cost (Ozbalta & A, 2009). Commercially various energy based drying techniques such as forced convective drying, fluidized bed drying, heat pump drying, microwave drying, freeze drying and many more are available and widely practiced. Diminishing reserves of fossil fuels and increased cost have made drying as an energetically expensive and unaffordable technique for farmers. Studies have shown that even small and most simple oil-fired batch dryers are not applicable for most farmers, due to lack of capital investment and insufficient supply of energy for the operation of dryers. Therefore, the introduction of low cost and locally manufactured solar dryers can offer a promising alternative to reduce the tremendous postharvest losses. The opportunity to produce high quality marketable products seems to be a chance to improve the economic situation of the farmers. However, taking into account the low income of the rural population, the relatively high investment for energy based dryers still remains a barrier to wide application. In view of this, solar dryers can be a good alternative over conventional dryers and open sun drying technique. Solar energy is free, abundant, environmentally clean, sustainable and therefore is recognized as one of the most promising alternative energy. In near future, the large-scale introduction of solar energy systems, directly converting solar radiation into heat, can be looked forward (Bal, Satya, & Naik, 2010). Moderate amounts of fuel wood or fossil fuels currently used in developing countries for the process of food and crop can be replaced by proper use of solar drying technologies (Sopian, Sayigh, & Othman, 2006). The climatic conditions in India are good with about 300 clear and sunny days and theoretical solar power reception, on its land area, is about 5 trillion kWh/year. The daily average solar energy incident over India varies from 5 to 7 kWh/m^2 with about 1500-2000 sunshine hours per year depending upon location, which is far more than current energy consumption (Muneer, Asif, & Munawwar, 2005). The study carried out by Chavda and Kumar (Chavda & Kumar, January 2009) indicates that cost of drying with solar power is only one-third as compared to the cost using a dryer based on conventional fuels. These solar dryers allow for controlled drying by managing the drying parameters such as moisture content, air temperature, humidity, and air flow rate. Adequate drying helps to preserve the flavor, texture, and color of the food, which leads to a better quality product (Whitfield, November 2000). Thus solar dryers are more economical as compared to other dryers if properly employed. Appropriate use of solar drying has significant potential, especially in agricultural areas which suffer from a high proportion of postharvest losses through food spoilage. Ginger and garlic are an important spices cash crop of India. They are among the earliest known oriental spices and being cultivated in India for both as fresh vegetable and as a dried spice. The area under the cultivation in India is 108.6 thousands hectors and the total production of the country is 517.8 thousand tons (Rahman, Karuppaiyan, Kishor, & Denzongpa, 2009). They have varied applications in culinary preparation, bakery products, toiletry products, perfume industries, meat products, wine, and soft drinks making. Dried ginger and garlic are used both as a spice and medicine. They contain an essential oil, which imparts an aroma, starch, gums, proteins, carbohydrate, mineral matter, and fiber (Rahman, Karuppaiyan, Kishor, & Denzongpa, 2009). In Ayurveda and Unani medical field it is termed as an important medicine to cure many diseases, such as rheumatism, piles, dyspepsia, alcoholic gastritis, fabric disease, throat problems, cholera morbus, neuralgia, and pulmonary and catarrhal diseases. It is expected that the world demand of ginger and garlic will be double in the next five years (Singh, Tiroutchelvame, & Patel, 2008). The quality of ginger and garlic produced in India has high content of aroma and pungency but due to improper postharvest processing most of these materials are to be consumed as a fresh vegetable and also some of the good qualities such as visual appeal, texture, aroma, flavor, structure, and color of the material get affected. Several studies have been reported on a variety of solar dryers for drying different fruits, vegetables, and grains (Deshmukh, Wasewar, & Verma, 2011). Few of them are amaranth (Ronah, Knali, Mailutha, & Shitanda, 2010), seed pumpkin (Sacilik, 2007), sweet pepper and garlic (Condor´ı, Echazu, & Saravia, 2001), tomato seed (Sogi, Shivhare, Garg, & Bawa, 2003), grape (Tiris, Ozbalta, Tiris, & Dincer, 1994), pineapple (Bala, Mondol, Biswas, Chowdury, & Janjai, 2003), fig and onion (Gallali, Abujnah, & Bannani, 2000), sour cherry (Akpinar & Bicer, 2007), date palm (Boubekri, Benmoussa, & Mennouche, 2009), mango slices (Akoy, Ismail, Ahmed, & Luecke, 2007), and so forth. Design of different types of solar dryer has been reported by Phoeun et al. (Phoeun, Phol, Romny, Pen, & Bun, 2005). It includes design of solar cabinet dryers, solar box dryers, tunnel dryers, and solar tray dryers for rural farmers. Although various attempts have been made to study the solar drying of various agricultural products, very few works are reported on the solar drying of ginger and garlic and effect on quality parameters, particularly in mixed mode solar cabinet dryer. In view of this, the present study was undertaken to assess the applicability of mixed mode solar cabinet dryer for drying of ginger and garlic. In this study an attempt was made to developed the sustainable drying method for rural farmers with zero emission, low capital investment and without any adverse effect of drying of agricultural produce on environment.

2. Material and Methods

2.1 Experimental Setup: A mixed mode box-cabinet natural circulation solar dryer was developed for the present study as shown in Figure 1. The dryer consists of a primary solar collector (1×0.5) m. A transparent sheet was located over the collector. The fresh air was sucked and heated through the air duct and flows to the drying chamber. A secondary solar collector (0.75 × 0.5) m oriented north-south was covered with a single layer of 0.15×10^{-6} thick UV stabilized polyethylene film and hinged at the top of the drying chamber. It allows the solar radiations to drying chamber and further enhances the drying rate by greenhouse effect. The drying chamber was coated with black paint, thermally insulated with asbestos sheets to minimize the heat loss provided with the support for sample holding mesh trays having area 1m^2. The general rule of thumb is that $1\ \text{m}^2$ of tray area is needed to layout 10 kg of produce. The air is warmed up during its flow through a low pressure drop thermosyphonic primary solar collector. The moisture is removed by natural convection and greenhouse effect by secondary solar collector in drying chamber. The moist air is then discharged through the air vents provided at the top of the drying chamber. Drying studies in solar cabinet dryer were conducted with two replicates. Accurately weighted material (5 kg per batch) were evenly distributed on the sample holding mesh trays. After predetermined time interval reduction of weight of material was noted by using Electronic Weighing balance (Wensar Ltd. India, HPB 310, least count 0.1 gm). The temperature of the air was monitored at primary solar collector, drying chamber, and at the exit of drying chamber by PT-100 sensor thermocouples with accuracy of ±0.5° C at regular time intervals.

2.2 Sample Preparations: Fresh ginger and garlic was purchased from local market of Nagpur, India, and washed thoroughly to remove surface dust and extraneous matter under running water. The clean ginger and garlic was hand peeled by knife. Ginger slices were cut into thin slices of average thickness of 6 ± 0.5 mm and garlic cloves were taken as it is of uniform size. The material was kept at ambient for one hour to remove surface moisture. The initial moisture content of fresh material was determined by hot air oven drying method (Ranganna, 1995). Accurately weighed sample (100 gm) of material was placed in a laboratory oven at the constant temperature of 60° C until the constant weight was achieved. Five replications were taken and average value was calculated on dry basis by following equations. Moisture content on dry basis (% d.b.)

$$M_o(\%\ \text{d.b.}) = \frac{W_w - W_d}{W_d} \times 100 \qquad (1)$$

where M_{initial} is the initial moisture content of ginger on d.b.%, W_w is the wet weight, and W_d is the dry weight of ginger in kg.

2.3 Drying Rate: The drying rates at different timing during solar drying were computed in all experimental conditions using following relationship (Shalini, Ranjan, & Kumar, 2008):

The drying rates at different timing were computed in all experimental conditions using following relationship and reported with respect to wet material.

$$\frac{dM}{dT} = \frac{M_0 - M_t}{t} \qquad (2)$$

where dM/dt is drying rate (kg water/kg of material. min), t is time (min), andM_o andM_t are the initial and final moisture content, respectively.

2.4 Effective Diffusivity: Drying process in falling rate period for food materials is mostly governed by diffusion mechanism (Doymaz, 2007). Fick's second diffusion law has been widely used to describe the moisture removal in falling rate periods. The effective diffusivity of the material can be calculated by assuming constant moisture diffusivity, temperature, and negligible shrinkage during drying process using the following equation:

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}\pi^2}{4L^2}t\right) \qquad (3)$$

where D_{eff} is the effective diffusivity, L is the half of the thickness of ginger slice in meter, and t is the corresponding drying time in sec. The Effective diffusivity can be calculated by plotting experimental ln(MR) versus drying time, gives a straight line with slope of

$$Slope = \frac{D_{eff}\pi^2}{4L^2} \qquad (4)$$

2.5 Mathematical Modeling of Drying Data: Thin layer drying procedure is generally practiced for characterizing the drying parameters (Akgun & Doymaz, 2005). The empirical models present the direct relationship between the average moisture content and drying time by means of regression analysis, neglecting the fundamental of drying process. Full scale experimentation of dehydration processes for different products is not economically feasible; hence, employing the simulation model for drying rate predication may be an easy and valuable tool (Steinfeld & Segal, 1986). To select a suitable model for describing the drying process, experimental results were fitted to various thin layer drying models which are summarized in Table 1. The moisture ratio of ginger and garlic during the drying was calculated by using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (5)$$

The moisture ratio was fitted to five thin layer drying models summarized in Table 1. Suitability of the best model was determined by mainly three statistical criteria, chi-square (χ^2), root mean square error (RMSE) and coefficient of determination (R^2), described as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \qquad (6)$$

$$RMSE = \frac{1}{N}\sum_{i=1}^{N}\left[\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \qquad (7)$$

where $MR_{\text{exp},i}$ and $MR_{\text{pre},i}$ are the experimental and predicted moisture ratio for the same measurement, respectively. N is the number of observation and n is the number of constants in drying model. The best model was chosen as the one with higher coefficient of determination, least reduced chi square, root mean square error, and percent relative error (Menges & Ertekin, 2006).

2.6 Rehydration Study: Rehydration study was carried out by adding 3 gm of dried ginger in 100 mL distilled water at room temperature (34 ± 1° C) the samples were weighed at a regular time interval until the constant weight was achieved by the sample. After rehydration, samples were taken out; surface moisture was absorbed carefully with tissue paper and then weighed. The rehydration capacity was calculated as follows (Deshmukh, Wasewar, & Verma, 2011):

$$\text{Rehydration ratio} = \frac{W_r}{W_d} \qquad (7)$$

Where, W_r and W_d is the weight of the sample after and before rehydration (kg) respectively.

2.7 Measurement of Shrinkage: Shrinkage induced due to drying was measured by volume displacement method. The known weight of the fresh sample was immersed in toluene and immediately volume displaced was recorded. The process was repeated for all the samples dried at all temperatures and microwave densities and corresponding change in volume displaced was noted. The measurement was made as quickly as possible in order to avoid the absorption of toluene by the material. The shrinkage (%S) of the sample was expressed as the ratio of change in volume displaced at any time to the initial volume before drying as follows:

$$\%S = \frac{V_o - V_t}{V_o} \times 100 \qquad (8)$$

Where, V_o and V_t is the volume of the toluene displaced by the sample initially and after drying respectively.

2.8 Color Analysis: Color analysis for fresh, open sun-dried, and solar-dried ginger and garlic samples was done on three randomly selected slices at 10 different locations. The color of both samples was determined by using Chromameter CR-400 (Minolta, Japan). Three parameters for the dried samples, $L*$ (lightness), $a*$ (redness), and $b*$ (yellowness), were used to study the changes in color. $L*$ represent the lightness or darkness of the sample on the scale of 0–100 where white = 100 and dark = 0. Hunter $a*$ represent redness (+) or greenness (−). Hunter $b*$ represent yellowness (+) or blueness (−). The total color difference (ΔE) was determined using the following equations (Phoungchandang & Saentaweesuk, 2011):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (9)$$

$$\Delta L^* = L^* - L^*_o, \Delta a^* = a^* - a^*_o, \ \Delta b^* = b^* - b^*_o \qquad (10)$$

The Chroma (C) and Hue angle (h) was calculated from colour values as follows:

$$Chroma\ (C) = (a^{*2} + b^{*2})^{1/2} \qquad (11)$$

$$\text{Hue angle h} = \tan\left(\frac{b^*}{a^*}\right) \qquad (12)$$

Where L^*, a^*, b^* and L^*_o, a^*_o, b^*_o are the color parameters of dried and fresh samples used as the reference respectively.

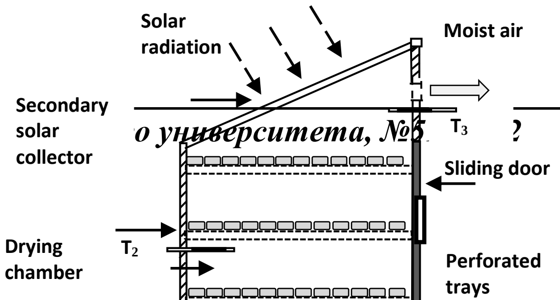

Figure 1: Mixed mode box-cabinet natural circulation solar dryer.

3. Results and Discussion

3.1. Drying Characteristics: Figure 2 compares the temperature developed inside the solar cabinet dryer with ambient temperature throughout the drying period. It was observed that the temperature developed in the dryer was always greater than the ambient temperature. The temperature in the drier varied between 38°C to 70°C, with a considerable difference with ambient temperature. The average temperature inside the dryer was found to be 57±8.5°C. For most of the food materials the recommended drying temperature is 60-70°C (Abalone, Cassinera, Gaston, & Lara, 2004). This confirmed that the present solar cabinet dryer can be effectively used for drying of agricultural product such as ginger and garlic. The drying curve for ginger and garlic slices are shown in Figure 3, where the moisture content decreased continuously with drying time. The moisture removal rate was found to be faster initially, up to 200 min. As the drying progressed, the rate of moisture removal decreased with time. It is typical drying behavior for agricultural materials reported by many researchers. Ginger and garlic with initial moisture content of 621.50% (% d.b.) and 184.09 (% d.b.) were successfully dried up to 12.19 (% d.b.) and 16.76 (% d.b.) respectively. The maximum drying period require for this was observed to be 480-500 min (6-8 hours) which is quiet less compare to conventional open sun drying (2-3 days) (Singh, Tiroutchelvame, & Patel, 2008).

Figure 4 shows the variation of drying rate with moisture content for ginger and garlic. It has been observed that drying rate decreased continuously with decrease in moisture content of the material. This behaviour may be due to high amount of free moisture availability, which was easily removed in the initial stage of drying (Garware, Sutar, & B, 2008). There was no constant rate period observed in both the cases and most of the drying occurred in falling rate period only. This may be due to material surface was no longer saturated with water and drying rate was controlled by diffusion of moisture from interior of solid to the surface. The drying rate showed fluctuations at some instants and decreased with time (Figure 5). These fluctuations in the drying rate may be due to change in intensity of solar radiations falling on dryer. Hence drying rate will depend on moisture content as well as intensity of solar radiations. These results are in agreement with the observations of the earlier researchers based on the thin layer drying studies (Garware, Sutar, & B, 2008).

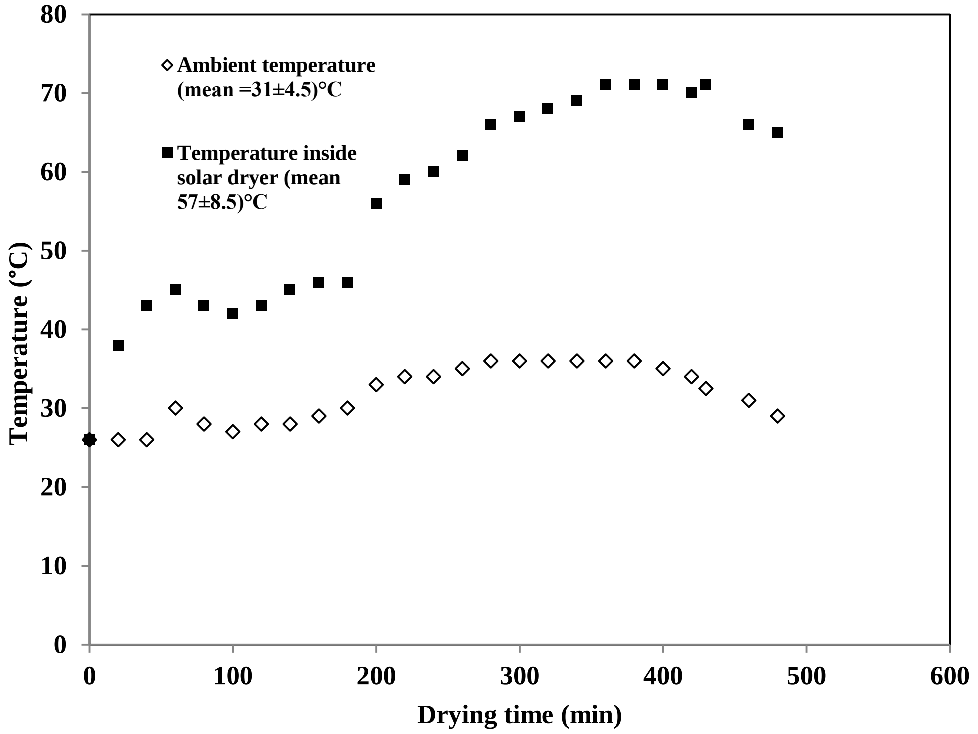

Figure 2: Comparison of ambient and solar dryer temperature with drying time

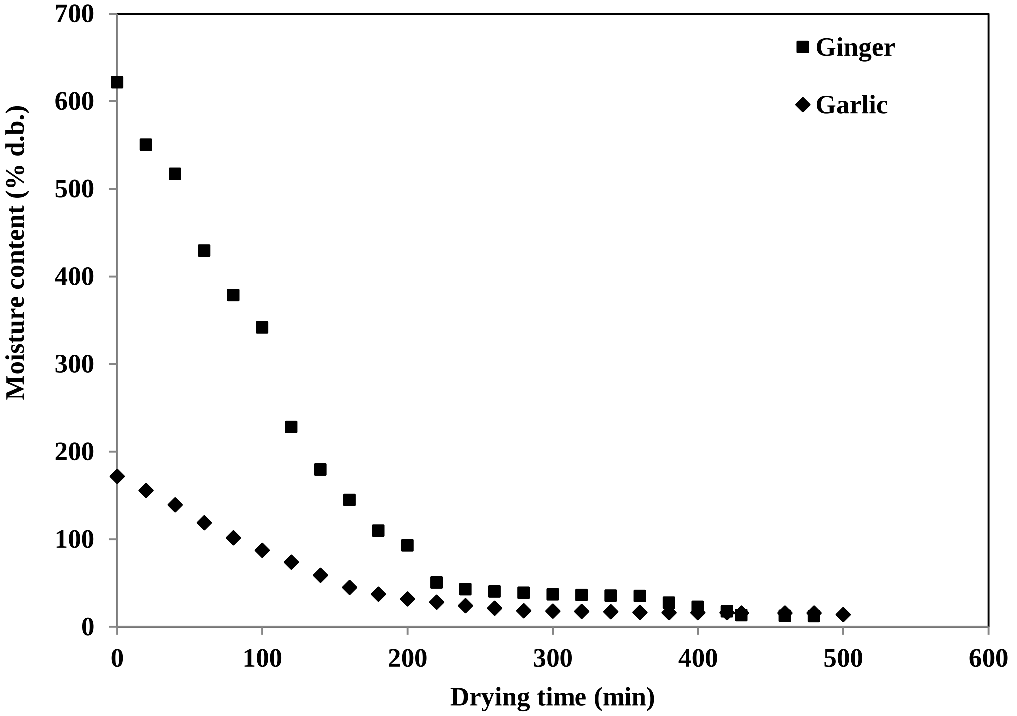

Figure 3: Variation of moisture content with drying time

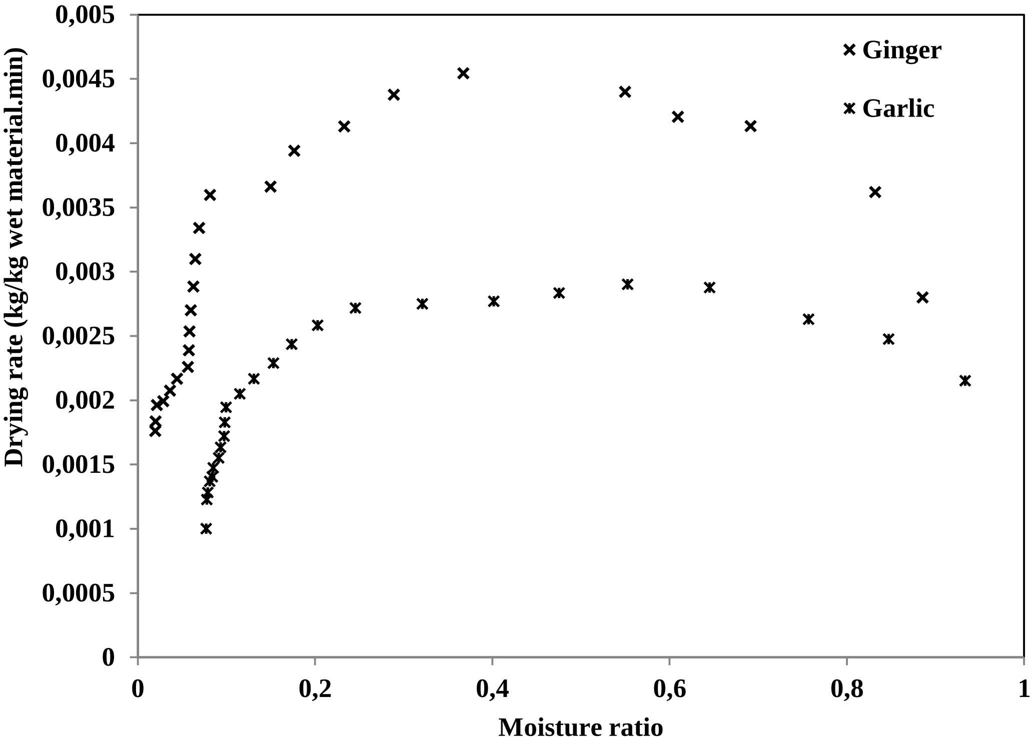

Figure 4: Variation of drying rate with moisture ratio

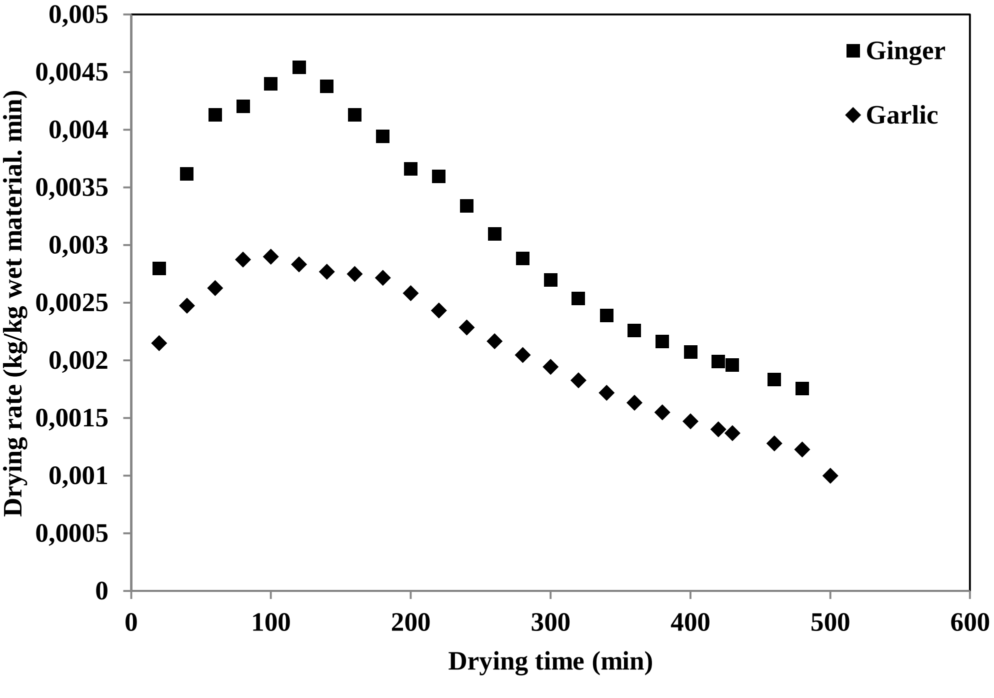

Figure 5: Variation of drying rate with drying time

3.2 Mathematical modelling of drying data: The experimental drying data obtained by solar drying of ginger and garlic was fitted to five selected thin layer drying models from Table 1 by relating the drying time with dimensionless moisture ratio. The regression analysis was done and suitability of the model was decided based on value of coefficient of determination (R^2), should be close to one, low value of chi-square (χ^2), root mean square error (RMSE) (Ronah et al., 2010). The model coefficients and parameters are presented in Table 2. From regression analysis, it can be seen that the Page model better described the drying kinetics of the ginger with R^2 of 0.9823, χ^2 of 0.003, and RMSE of 0.0538 for ginger; similarly, R^2 of 0.9882, χ^2 of 0.002, RMSE of 0.047 for garlic in the present solar dryer as compared to other thin layer drying models.

Figure 6 and 7 represents the variation of experimental and predicted moisture ratio using the Page model with drying time for ginger and garlic. It can be seen that the Page model showed the best agreement between experimental and predicted values of moisture ratio. The experimental moisture ratio was plotted against the predicted value of moisture ratio to validate the Page model as shown in Figure 8 and 9. The result showed smooth data points around the fitted line. This confirms the goodness of the tested developed model to estimate the moisture content of ginger and garlic in drying process for present solar dryer.

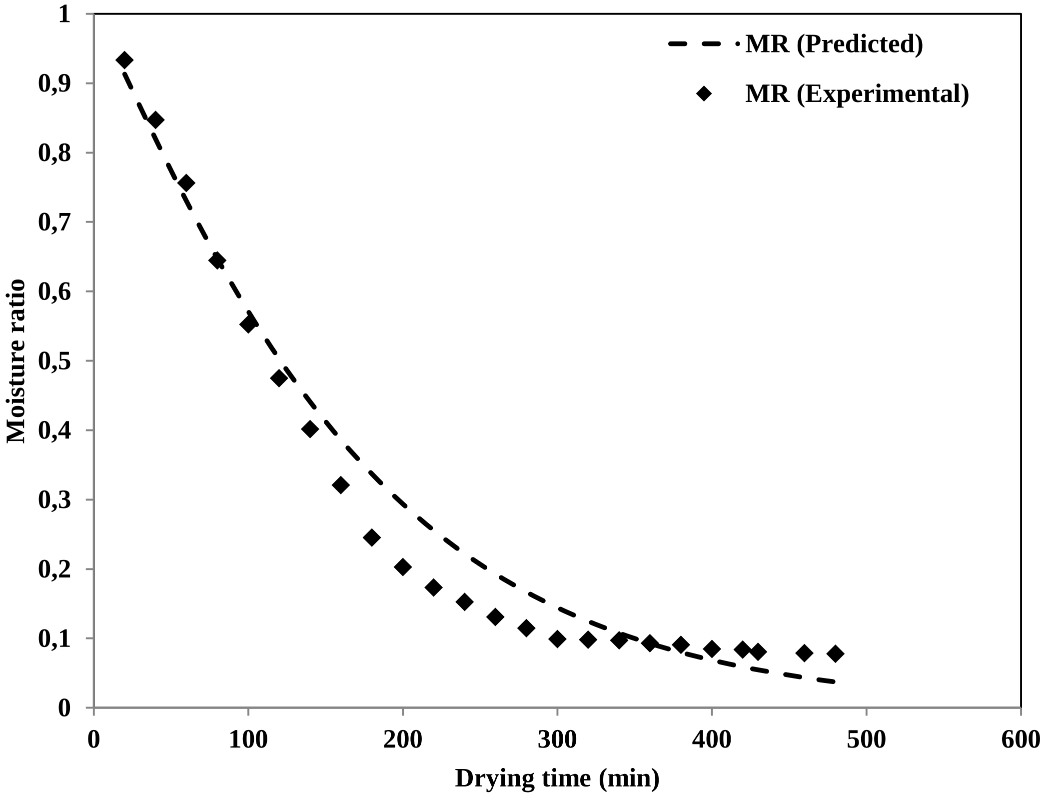

Figure 6: Comparison of experimental and predicted moisture ratio with drying time by Page model for ginger

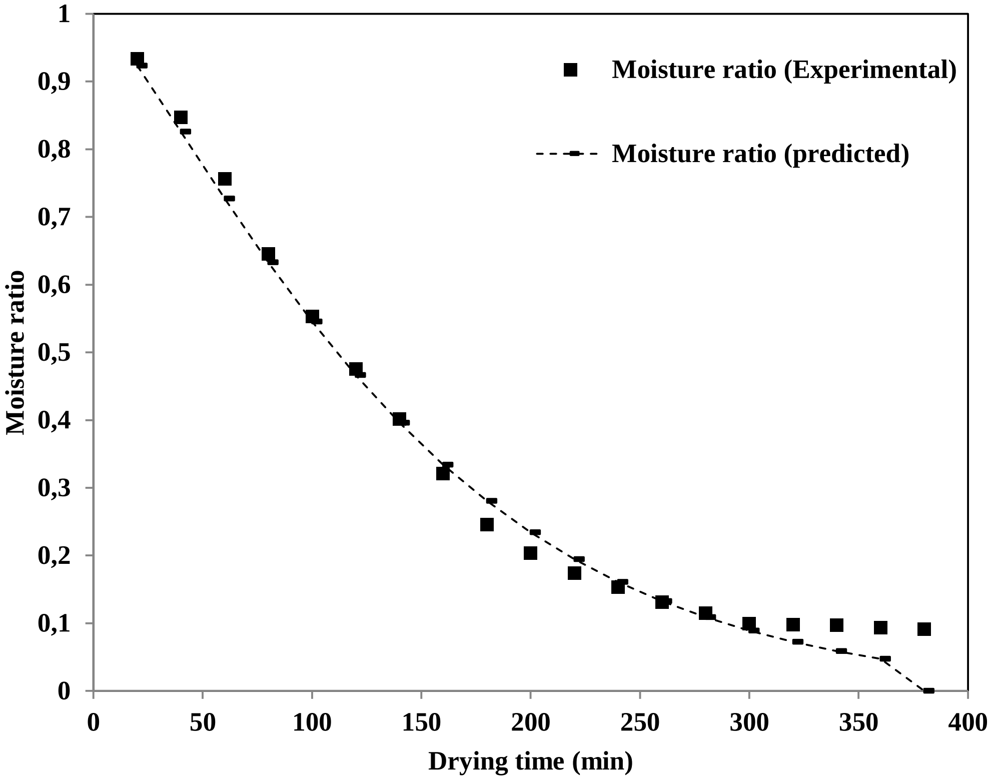

Figure 7: Comparison of experimental and predicted moisture ratio with drying time by Page model for garlic

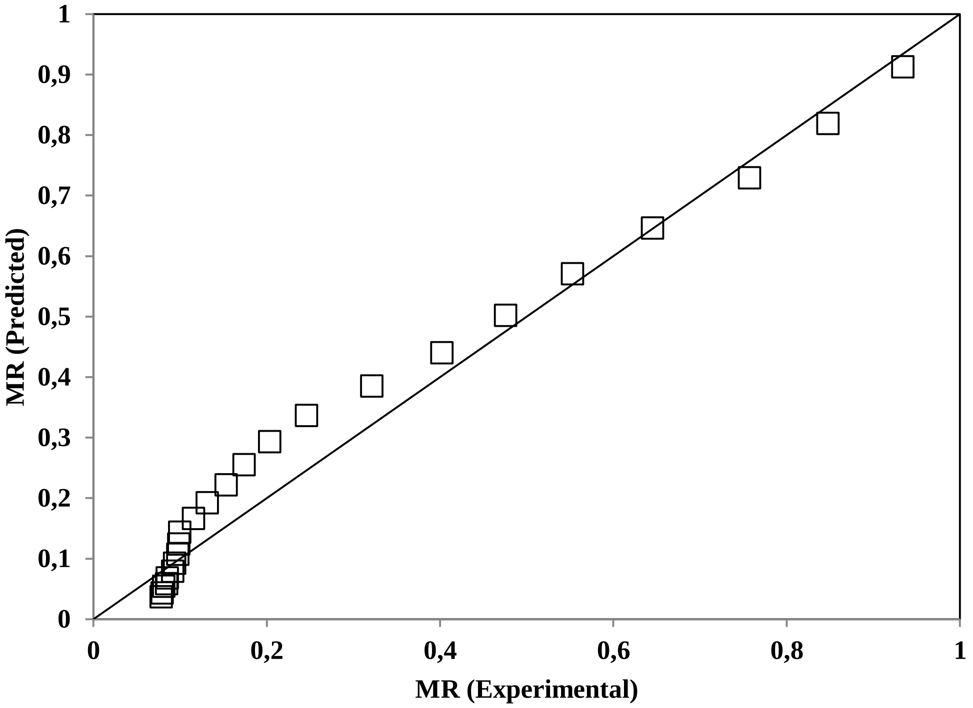

Figure 8: Comparison of experimental and predicted moisture ratio by Page model for ginger

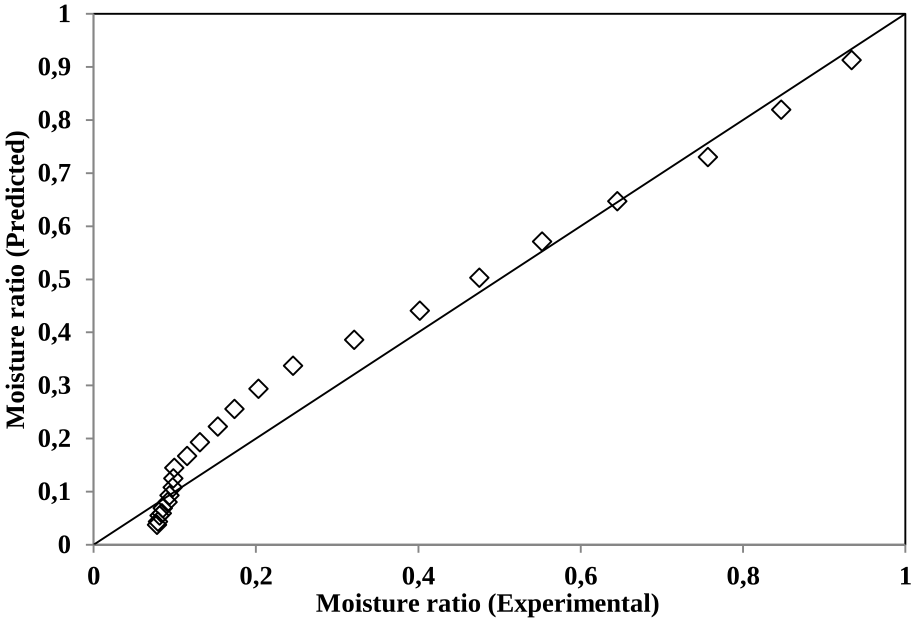

Figure 9: Comparison of experimental and predicted moisture ratio by Page model for garlic

3.3 Effective Diffusivity: Present study revealed that, drying mainly occurred in falling rate period. During the falling rate drying period the mass transfer is govern by internal resistance. In this case Fick's second law can be effectively used to calculate effective diffusivity of the material. The effective diffusivity of the ginger and garlic in the present solar dryer was calculated by plotting ln(MR) with drying time as shown in Figure 10 and using equation (3), where slope of the straight line gives the effective diffusivity of the sample. The effective diffusivity of the ginger and garlic slices in the present solar dryer was found to be 5.5×10^{-9} m^2/s and 3.86×10^{-9} m^2/s respectively, which is within the range of 10^{-9} to 10^{-11} m^2/s reported in the literature for drying of food material.

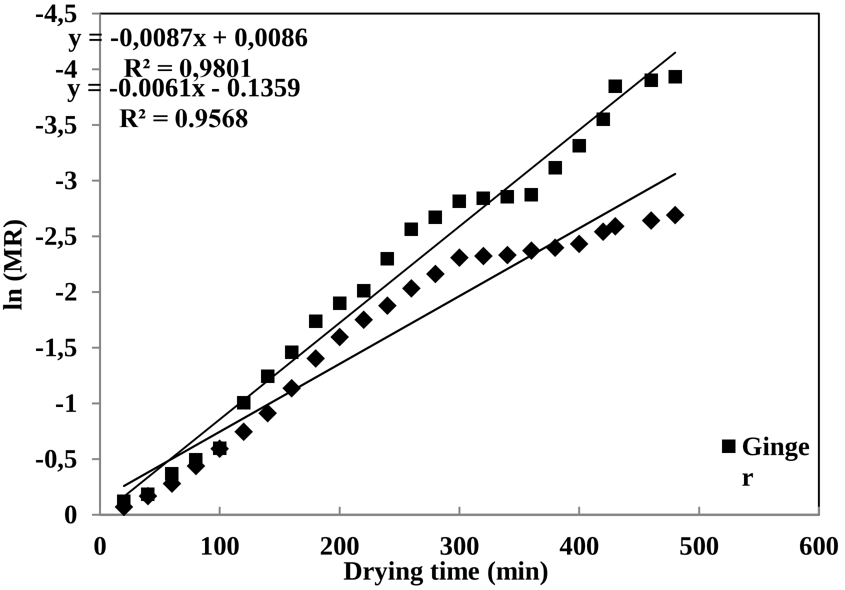

Figure 10: Plot of ln(MR) versus drying time for determination of effective diffusivity

3.4 Quality analysis

3.4.1 Rehydration Ratio: The success of any drying method lies on the quality of product dried. The rehydration ratio is the mass of rehydrated sample to the mass of dry sample. Considering that most of the products are rehydrated at their final use, it is necessary to study the rehydration behaviour of the dehydrated products. Theoretically, if there are no adverse effects on the integrity of the tissue structure, it should absorb the water to the same moisture content as the initial product before drying. However, the nature of the internal pore structure and mechanical properties of the dried material will influence the moisture uptake during rehydration. Rehydration capacity of the open sun dried and solar dried ginger and garlic samples were determined by using Equation (7). It was observed that the solar dried samples showed a good rehydration capacity as compare to open sun dried material (Figure 11). Rehydration ratio of solar dried ginger and garlic was found to be 3.14±0.05 and 2.33±0.17 for solar drying and 2.12±0.01 and 1.96±0.05 for open sun drying respectively. The lower rehydration ratio in open sun drying may be due to hardened structure of the solid material thereby reducing the ingress of water molecule due to prolonged exposure of the material to open sun (longer heat exposure). The satisfactory rehydration ratio was observed in case of solar drying due to shortened drying time and less exposure of the material to high drying regime as compare to open sun drying.

3.4.2 Colour analysis: Colour is the major deciding parameter for the acceptability of dried material. Table 18 and 19 shows the colour parameters L^*, a^*, b^* values, total colour change index (ΔE), chroma and the calculated Hue angle h for ginger and garlic. The parameters L^*, a^* and b^* values represent light - dark spectrum, green to red and the blue and yellow spectrum, respectively. The colour parameters are related to browning reaction where a decrease in L* values, an increase in a* values and a decrease in Hue angles (h) indicate more browning. The solar dried ginger and garlic showed the higher L* value as compared to open sun drying method. This showed that the solar dried material was observed to be brighter as compare to open sun driying method. similarly lower a* and Hue angle value for both the material showed the less browning reaction in solar drying as compare to open sun drying method. Figure 11compares the total colour change index ΔE from fresh ginger and garlic by both the drying method. It was observed that more colour change was observed in case of open sun drying method as compare to solar drying method for both the materials. This confirmed the superiority of solar drying over conventional open sun drying for the retention of colours.

3.4.3 Shrinkage: Shrinkage is one of the most important physical changes that the food suffers during drying due to reduction of its external volume. Loss of water and heating cause stresses in the cellular structure of the food leading to change in shape and decrease in dimension. Shrinkage of food materials has a negative consequence on the quality of the dehydrated product. Changes in shape, loss of volume and increased hardness causes in most cases a negative impression in the consumer. Time and temperature have a reasonable impact on the value of the dried samples (Abasi et al., 2009). Figure 11 showed that both the drying methods yield the considerable shrinkage of the materials. However open sun drying method results in higher shrinkage (68 to 78%) as compare to solar drying (61 to 70%). This may be due to longer drying time in open sun drying increases the amount of heat given to food material which results in a considerable shrinkage. Therefore, contractile stresses occurred in the cellular structure of the food material which intensifies shrinkage. However, the value of shrinkage became constant at the final stages of the drying process, which is the result of the sample structure stabilization made by a firm layer formed on its surface. Prolonged drying times increases shrinkage and toughness, reduce the bulk density and rehydration capacity of the dried product and cause serious damage to the flavour, colour and nutrients (Phoungchandang & Saentaweesuk, 2011) (Abalone, Cassinera, Gaston, & Lara, 2004) (Garware, Sutar, & B, 2008).

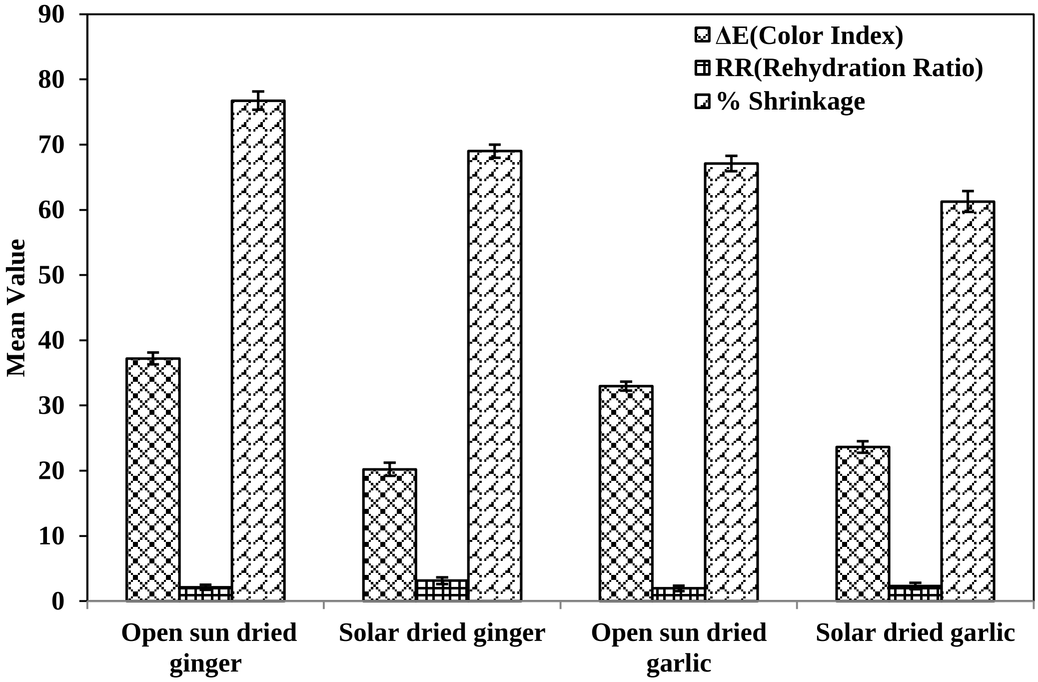

Figure 11: Comparison of colour rehydration ratio and % shrinkage by different drying methods

Table 1: Thin layer drying models applied to drying data of ginger and garlic (Domiyaz, 2008)

Model Name	Model Equation
Newton	$MR = exp(-kt)$
Page	$MR = exp(-kt^n)$
Modified Page	$MR = exp[(-kt)^n]$
Henderson and Pabis	$MR = a\ exp(-kt)$
Wang and Sing	$MR = 1 + at + bt^2$

Table 2: Statistical results and model coefficients obtained from selected thin layer drying models for mixed mode solar cabinet dryer

Model No.	Model	Model coefficients and constants	R^2	RMSE	χ^2	Material
1	Newton	k = 0.0039	0.9574	0.0557	0.00324	Ginger
2	**Page**	**k=0.00325** **n= 1.1765**	**0.9823**	**0.0538**	**0.003**	
3	Henderson & Pabis	k= 0.0047 a= 1.305	0.9638	0.014	0.0049	
4	Wang & Singh	a = -0.0025 b = 1×10^{-6}	0.946	0.0731	0.0058	

5	Modified Page Model	k = 0.0034 n=1.675	0.9753	0.055	0.0034	
1	Newton	k = 0.0054	0.9369	0.0760	0.006	Garlic
2	Page	k=0.003 n= 1.1285	0.9882	0.047	0.002	
3	Henderson &Pabis	k= 0.0054 a= 0.779	0.882	0.0908	0.008	
4	Wang and Singh	a = -0.0051 b = 7×10^{-6}	0.9823	0.0395	0.003	
5	Modified Page Model	k = 0.0065 n=1.1283	0.958	0.039	0.003	

***Bold** fonts indicates the suitability of particular model over other models.*

4. Conclusion

In the present study, solar cabinet dryer exhibited sufficient sustainable ability to dry ginger and garlic reasonably rapidly to a safe moisture level without any energy investment and any adverse effect on environmental. Simultaneously it ensures a superior quality of the dried product over the conventional open sun drying method. The maximum drying time required to dry ginger from of 621.50 to 12.19% (d.b.) and garlic from 184.09 to 16.76% (d.b.) was found 460 to 500 min which is a significant reduction as compare to open sun drying methods (2-3) days and approximately equal to commercial dryers. Thin layer drying studies showed that constant rate period was absent and the entire drying process occurred in falling rate period. The drying time was found to be drying rate and moisture content dependent. The effective diffusivity of the ginger and garlic slices in the present solar dryer was found to be 5.5×10^{-9} m^2/s and 3.86×10^{-9} m^2/s respectively. Among the tested models Page model was found to be best suitable to describe the drying kinetics of ginger and garlic based on statistical criterion. The moisture ratio obtained experimentally and predicted by Page model showed good agreement and fitted smoothly to straight line. The model attained the highest value of R^2, lowest value of χ^2, and RMSE, (R^2, 0.9823, χ^2, 0.003, RMSE, 0.0538) for ginger; similarly R^2 of 0.9882, χ^2 of 0.002, RMSE of 0.047 for garlic further confirmed its superiority over the other models. The quality analysis of the dried material in present solar dryer showed that superior quality product in view of better rehydration, less shrinkage and less colour change from open sun dried material. Low capital investment and operating cost, zero emission and sustainable energy source further confirmed the superiority and potential of solar cabinet dryer for drying of ginger, garlic and other agricultural products.

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