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Experimental investigation and economic evaluation of a new mixed-mode solar greenhouse dryer for drying of red pepper and grape

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ABSTRACT

This paper presents an experimental analysis to investigate the performance of a novel mixed mode solar greenhouse dryer with forced convection which was used to dry red pepper and sultana grape. The drier consisted of a flat plate solar collector and a chapel-shaped greenhouse. The drying rate in the solar greenhouse dryer could be much higher than that for the open air sun drying. The present drying system practically shortens the drying time of red pepper and grape by 7 and 17 h respectively. The experimental drying curves show only the falling rate period. The payback period of the dryer was found to be 1.6 years, much less than the estimated life of the system (20 years).

1. Introduction

Tunisia is located in the mediterranean region. Tunisia has between 2860 and 3200 h of sunshine per year and receives a daily average solar energy of 4.8 kWh m^{-2} day^{-1} [1]. This abundantly available solar energy can be used for the drying of agricultural products. Solar drying could be an alternative of industrially drying methods. The benefits from the installation and the operation of solar energy systems can be divided into: energy saving and a decrease in environmental pollution [2].

There are different varieties of grapes grown in Tunisia. Grape is an excellent source of vitamins C, B1, and potassium. Sultana grape is a variety of grape in Tunisia. Grape fruits can be used as fresh or dried product. It is dried not only for preservation purposes, but also for modification of the taste, to meet consumer preferences and to increase market value of the product. Red pepper is also an important ingredient in daily cuisine in Tunisia. Pepper is a good source of vitamins A and C, which are important antioxidants [3]. It is consumed both as fresh and dried products. Drying is a postharvest process which creates added value of red pepper [4]. The price of dried pepper always remains high even at the harvesting season.

Open sun drying, where the product is exposed directly to the sun allowing the solar radiation to be absorbed by the material is one of the traditional and oldest methods employed using solar energy, for food preservation in Tunisia. The sun's free energy for drying in open-air is counterbalanced by a multitude of disadvantages, which reduce not only the quantity but also the quality of the final product [5].

Several solar-energy drying systems have been designed as alternatives to the traditional open-sun drying, especially in locations with good sunshine. According to the past researches and studies these dryer systems can be classified in three forms as direct, indirect and mixed mode, depending on arrangement of system components and mode of solar heat utilization [6,7]. Greenhouse dryer comes in the category of the direct solar drying and also sometimes mixed mode drying. The applicability of greenhouses is limited because of high temperature during the warmer months of the year. When not in use for crop production the greenhouse can be used for drying the crop.

A number of studies have been reported on greenhouse crop drying [8–11]. Anil Kumar et al. [12] have studied the effect of mass on convective mass transfer coefficient during open sun and greenhouse drying of onion flakes. Sethi et al. (2009) [13] studied the effects of inclined north wall reflection for improvement in the greenhouse solar drying. This experimental investigation led them to conclude that the greenhouse air increased temperature 1–6.7 °C and 1–4.5 °C respectively under natural and forced convection mode. Cylindrical walk-in type solar tunnel dryer for grape drying was reported by Rathore et al. [14]. The performance of a large-scale greenhouse type solar dryer for drying chilli was investigated by Kaewkiew [15].

Many studies reported on the solar drying system for red pepper and grape have been conducted in The Thermal Process Laboratory,

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Nomenclature

m	mass of the product (g)
m_d	dry matter of the product (g)
M_e	moisture content in equilibrium state (dry basis)
M_0	initial moisture content (kg/kg) in dry basis
M_t	moisture content at time, t (kg/kg) in dry basis
MR	moisture ratio
DR	dying rate (kg/kg h^{-1})
C_a	annualized cost of dryer (DT)
C_{ac}	annual capital cost (DT)
C_b	selling price of branded dried product (DT/kg)
C_{cc}	capital cost of dryer (DT)
C_{dp}	cost of fresh product per kg of dried product (DT/kg)
C_{ds}	cost per kg of dried product for domestic solar dryer (DT/kg)
C_{fp}	cost per kg of fresh product (DT/kg)
C_m	annualized maintenance cost (DT)
C_{re}	annual electricity cost for fans (DT)
C_s	cost of drying per kg of dried product in dryer (DT/kg)
F_c	capital recovery factor
F_s	salvage fund factor
i	rate of inflation
d	rate of interest on long term investment
D	number of days of use of domestic dryer per year
D_b	number of drying days per batch
M_d	mass of dried product removed from solar dryer per batch (kg)
M_f	mass of fresh product loaded in solar dryer per batch (kg)
M_y	mass of dried product removed of the dryer per year (kg)
n	life of solar dryer (year)
N	payback period (year)
S_b	saving per batch for solar dryer (DT/kg)
S_d	saving per day for domestic solar dryer in the jth year (DT)
Sj	annual savings for domestic solar dryer in the jth year (DT)
S_1	saving during first year for solar dryer (DT)
S_{kg}	savings per kg in comparison to branded product for solar dryer (DT/kg)
V	salvage value (DT)
V_a	annualized salvage value (DT)
w_R	total uncertainty in measurement of result
$w_1, w_2, \ldots w_n$	uncertainties in independent variables
w_{tm}	total uncertainty in the measurement of time of mass loss values
w_{ml}	total uncertainty in the measurement of mass loss values
w_{mq}	total uncertainty in the measurement of the moisture quantity
w_{DR}	total uncertainty in the calculated of drying rate
w_{MR}	total uncertainty in the calculated of moisture rate
G_o	solar radiation outside greenhouse (W/m^2)
G_i	solar radiation inside greenhouse (W/m^2)
RH_o	relative humidity of the air outside greenhouse (%)
RH_i	relative humidity of the air inside greenhouse (%)
t	time (s, h, min)
T_a	ambient temperature (°C)
T_{co}	outlet temperature collector (°C)
T_g	temperature inside greenhouse (°C)

The Research and Technology Center of Energy Tunisia. Farhat et al. (2004) [1] validated the Passamia and Saravia model [16,17] on the red pepper under greenhouse tunnel and in open-air. Fadhel el al. have studied solar drying grape in three different processes, open sun drying, natural convection solar dryer and under tunnel greenhouse. These tests show that the solar tunnel greenhouse drying is satisfactory and competitive to a natural convection solar drying process [18]. Experiments inside a wind tunnel were conducted to study the drying of red pepper in open sun and greenhouse conditions [19] where solar radiation was simulated by a 1000 W lamp, for different external parameters (incident radiation, ambient temperature and air velocity). A simple drying model of red pepper related to water evaporation process was developed and verified. Further study was conducted Fadhel et al. [20] to dry hot red pepper in three different processes, open sun drying, natural convection solar dryer and under tunnel greenhouse and it was concluded that the solar tunnel greenhouse dryer must be improved to become competitive to the solar air dryer.

The present study was undertaken to study and compare the thin layer drying characteristics of Sultana grape and red pepper in the new solar greenhouse dryer and under open sun. The economics aspects of drying have been investigated in this study.

2. Materials and methods

2.1. Description of the solar greenhouse dryer system

The solar greenhouse forced convection drying system has been installed at the Research and Technology Centre of Energy (CRTEn) in Borj Cedria (North of Tunisia): Latitude 36°43′N and Longitude 10°25′E. The system essentially consists of two parts: (1) a flat plate solar air collector, and (2) an experimental East–West oriented chapel-shaped greenhouse (Fig. 1).

The solar collector consists of insulator, absorber and cover glass. The length, the width and the total volume of the collector are 2 m, 1 m and 0.28 m^3, respectively. The 0.004 m thick transparent glass cover was placed 0.05 m apart the absorber. A copper corrugated plate of 0.001 m thick used as the absorber plate was placed 0.04 m apart the insulator. The solar air collector back and sides were insulated with 0.05 m layer of polyurethane, with heat conductivity 0.028 W/m K, to decrease thermal losses. There are two air gaps between cover glass and the absorber and between the absorber and the insulator through which ambient air is sucked by a centrifugal fan from lower side of the collector to the greenhouse. The solar collector was oriented full south and inclined 37° to horizontal plane.

The experimental greenhouse occupy a floor area equal to 14.8 m^2, 3.7 m wide, 4 m long and 3 m high at the center. The greenhouse walls and roof are covered by plexiglass with 0.003 m of thickness. To exhaust the moist air from the greenhouse, it was equipped with two centrifugal fans. This drying system has a maximum capacity of drying 80 kg of peppers and 130 kg of grapes. It could accommodate four trays in stacks with a total drying area of 40 m^2; and the dimension of one tray is 2.5 m × 4 m.

2.2. Experimental procedure

In the drying experiments, red pepper and Sultana grape were used as the test samples in the dryer and open sun. During the drying experiments, the weather was generally sunny and no rain