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Thermal analysis and performance evaluation of a solar tunnel greenhouse dryer for drying peppermint plants

M.M. Morad, M.A. El-Shazly, K.I. Wasfy*, Hend A.M. El-Maghawry

Agricultural Engineering Department, Faculty of Agriculture, Zagazig University, Egypt

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ABSTRACT

Three identical solar tunnel greenhouse dryers under forced convection mode were installed for drying peppermint plants. Thermal analysis of the solar tunnel greenhouse peppermint dryer was investigated based on thermal balance equations in order to predict its performance. Performance of solar greenhouse dryer was studied as a function of change in plant conditions, air flow rates and peppermint loads under two fan operating systems and evaluated in terms of system temperatures, drying rate, drying efficiency, product quality and drying cost.

The obtained data revealed that drying peppermint as leaves reduce the drying time and achieve the highest percent of volatile oil compared with drying whole plants. Drying peppermint at flow rate of 2.10 m^3/min, load the greenhouse by about 4 kg/m^2 and operate the greenhouse by continuously fan operating system tends to increase the drying rate by 22.78% and 24.8% for whole plants and leaves comparing with periodical system.

1. Introduction

Peppermint (*Mentha pepperita* L.) is one of the most important medicinal and aromatic plants because it has a wide range of industrial uses and widely accepted by the public for its flavoring and pharmaceutical properties. Main properties of peppermint are antiseptic, antispasmodic, carminative, cephalic, simulative and stomachic. It mainly consumed as a fresh or in many forms (liquid, aromatic oil and dried). The aromatic oil of peppermint contains many components which are used in manufacturing of pharmaceuticals. Mint has highly water content of 78–84%, w/w, so drying process plays an important role in inhibition the microorganism growth and make substantial reduction in weight, volume, minimizing packaging, storage and costs [1]. The cultivated area with peppermint plants in Egypt amounted to be about 334.74 ha and the total value of peppermint plants production in Egypt is 16260 Mg [2].

A greenhouse is essentially an enclosed structure, which traps the short wavelength solar radiation and stores the long wavelength thermal radiation to create a favorable micro-climate for higher productivity. A greenhouse heating system is used to increase the thermal energy storage inside the greenhouse during the day or to transfer excess heat from inside the greenhouse to the heat storage area. This heat is recovered at night to satisfy the heating needs of the solar tunnel greenhouse dryer. Thus, the temperature inside the dryer will be increasing steadily, thereby ensuring quicker drying of the products than the open sun drying method. Mint drying at trays dryer with air ambient was studied. Air heated up for 40, 50, 60, 70 and 80 °C, being evaluated the production of the extracted essential oils after the drying with the production obtained for the fresh plant. With base in the obtained results, it can be concluded that the largest extractive productions were obtained when the drying process was happened with 50 °C for the air temperature [3]. A new low cost design for a forced convection tunnel greenhouse drier has been built, tested and red sweet pepper and garlic were used as loads. Results indicated that a good drying rate, final moisture content and dried product aspect were obtained. Not observing appreciable deteriorations in the final color of the dried products [4]. Thin layer organic tomatoes were dried to the final moisture content of 11.50 from 93.35% w.b. in four days of drying in the solar tunnel dryer as compared to five days of drying in the open sun drying. Drying curves showed only a falling drying rate

* Corresponding author. Tel.: +20 1119900982; fax: +20 552267567.
E-mail addresses: drmorad555@yahoo.com (M.M. Morad), shazly_mah@yahoo.com (M.A. El-Shazly), kamal.moursy@gmail.com (K.I. Wasfy), hendelmaghawry@yahoo.com (H.A.M. El-Maghawry).

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Nomenclature

A	cross sectional area of the tunnel greenhouse window, m^2
A_{cc}	surface area of the polyethylene covers, m^2
A_d	net surface area of the drying box, m^2
C_P	specific heat of the air, J/kg °C
C_{pp}	specific heat of peppermint, kJ/kg °C
HC	hourly cost, L.E./h
L.E.	Egyptian pound, EGP (currency of Egypt)
L_h	latent heat of vaporization of water in peppermint, kJ/kg
m_a	air flow rate, kg/s
M_f	final moisture content of drying load, % w.b
m_i	mass of peppermint in the dryer, kg
M_i	initial moisture content of drying load, % w.b
M_t	moisture content (kg water/kg dry matter) at time (t)
M_{t+dt}	moisture content (kg water/kg dry matter) at time (t + dt)
m_w	mass of water evaporated from the peppermint during the dehydration process, kg
P	productivity, kg/h
R	total flux solar radiation, W/m^2
T_{ai}	air temperature inside the greenhouse,°C
T_p	bulk temperature of the peppermint,°C
T_{ao}	ambient air temperature outside the greenhouse,°C
U_0	overall heat transfer coefficient, W/m^2 °C
V	air velocity, m/s
ρ	air density, kg/m^3

period, samples dried in the solar tunnel dryer were completely protected from insects, rain and dusts, and the dried samples were of high quality in terms of color and hygienic. This system can be used for drying various agricultural products. Also, it is simple in construction and can be constructed at a low cost with locally obtainable materials [5]. In order to study the drying of red pepper in open sun and greenhouse conditions drying experiments at constant laboratory conditions and at varying outdoor conditions were carried out. It was found that the laboratory model overestimates the drying process under time varying conditions; a correction factor was then introduced in the formulation of the model to adjust these predictions. The results also have confirmed the consistency of the model at laboratory under constant conditions and in open sun and greenhouse conditions [6]. Drying characteristics of sweet basil leaves were studied and investigated under different drying conditions. Three different drying air relative humidity (34.0, 27.3 and 22.4%) and three different drying air velocity (1.1, 1.5 and 2.0 m/s) were functioned during this laboratory experiment. The obtained data showed that, the drying rate increased as the air speed increased, although the effect is not as pronounced when the air speed increased from 1.1 to 2.0 m/s [7]. A natural convection solar tunnel greenhouse dryer was designed and developed for studying the drying characteristics of tomatoes. The performance of the dryer was studied (drying time and product quality) in comparison with open sun drying method. It was found that the solar tunnel greenhouse dryer took only 29 h for reducing the moisture content of tomatoes from 90% (w.b.) to 9% (w.b.) whereas the open sun drying took 74 h for the same. Also, the quality of dried tomatoes produced from solar tunnel dryer is much superior compared to that of open sun drying [8]. The drying method, velocity and temperature of drying air influence the quantity and quality of the active ingredients present in aromatic and medicinal plants. In spite of all technical developments, the choice of the correct drying temperature remains a central economic and ecological criterion in the drying of medicinal plants [9]. A contact dryer that transferred energy to drying plants mainly by heat conduction was developed and tested by mixing or not mixing batches of 15 kg of chopped peppermint plants. The contact dryer had three main operational units: a drying table, a mobile mixing/aeration car, and a control panel. The contact dryer was operated with one of four drying programs. All programs affected the completion duration of drying, essential oil content, and dried product color differently. The shortest drying time (15 h) was obtained using the drying program of gradually increased water temperature from 55 to 60 to 75–80 °C in 6 h and mixing/aeration. However, mixing and aeration changed the product color slightly more and partially increased essential oil loss. These drawbacks can be alleviated by selecting the appropriate duration of mixing and aeration [10]. Two identical prototype solar dryers (direct and indirect) having the same dimensions were used to dry whole mint. Both prototypes were operated under natural and forced convection modes. The results indicated that drying of mint under different operating conditions occurred in the falling rate period, where no constant rate period of drying was observed. Also, the obtained data revealed that the drying rate of mint under forced convection was higher than that of mint under natural convection [11].

It is noticed that renewable energy in food industry particularly in drying process is growing and mainly in developing countries. Optimization and design tend to reduce the drying time of products for maximum possible efficiency with minimum cost [12]. To overcome the practical difficulties of open sun drying, three identical solar tunnel greenhouse dryers under forced convection mode were constructed which basically operates on the principle of green house effect, for drying peppermint whole plants and leaves depending on thermal analysis. Various operational parameters such as plant conditions, peppermint loads, air flow rates

Table 1
Physical properties of peppermint plants.

Physical properties	Average value
Plant height, cm	27.50
Average leaf area, cm^2	4
Thickness of peppermint leaves, mm	0.25
Average number of leaves per plant	15:20
Fresh mass of whole plant, g	5
Fresh mass of 100 leaves, g	15
Bulk density of fresh leaves, kg/m^3	30.15
Moisture content of whole plant, %	84.43
Moisture content of leaves, %	83.52