

Energy consumption, thermal utilization efficiency and hypericin content in drying leaves of St John's Wort (*Hypericum Perforatum*)

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Abstract

Massive consumption of energy in the drying industry has prompted extensive research regarding various aspects of drying energy and requirements. Thermal utilization efficiency, specific energy requirement, total energy consumption and hypericin content in drying of St John's Wort were determined using a hot-air dryer. Experiments were conducted at four air temperature levels (40, 50, 60, and 70°C), three air velocities (0.3, 0.7, and 1 m/s) and three sample thicknesses (1, 2 and 3 cm). Based on the results of data analysis, minimum and maximum levels of energy consumption were 0.56 and 3.24 kWh, respectively. The required specific energy decreased with increasing sample thickness. The minimum and maximum required specific energies were 4.41 and 17.53 for 2 cm thick and 4.28 and 13.67 for 3 cm thick layers (kWh/kg), respectively. The maximum and minimum values of thermal utilization efficiency in different treatments were found to be 14% and 72%, respectively. Hypericin content decreased with increasing temperature and increased with air velocity and product sample thickness, so that the minimum and maximum hypericin amounts were 67 and 355 ppm, respectively.

Keywords: sample thickness, air temperature and velocity, St John's Wort, hypericin

Introduction

St John's Wort (*Hypericum Perfoatum*), known as an herbal and perennial plant, has a creeping and vegetative growth in the first year while the desired growth and blooming begins from the second year (Crompton *et al.*, 1988). Important components of St John's Wort are hyperforin (a prenylated phloroglucinol) and hypericin (a naphthodianthrone) (Barnes *et al.*, 2001).

This plant is mostly air-dried in the shade and if dried in direct sunlight, more than 80% of its hypericin content will be lost during the drying process (Buter *et al.*, 1998). Many agricultural products (especially medicinal herbs) have a short supply period and must be preserved and stored for later use. Drying is one of the most common ways for preserving the material. By applying the appropriate drying methods, product quality can be increased and losses reduced (Barbosa-Canovas and Vega-Mercado, 1996).

Problems dealing with using sun energy for the drying of agricultural products, has led to traditional methods (hot air drying) being considered as an alternative for industrial dryers. However, the industrial dryers consume larger amounts of energy but they are considered as an important method of drying.

Qualitative indexes are the main parameters that are verified in the drying process in food and agricultural products. The drying process should be in such a way that would apply minimum changes in products' qualitative indexes. These indexes include physical aspects such as dimensions and size, tex-

ture, shape, wrinkles, and stiffness, as well as chemical changes such as browning reactions, discoloration, changes in vitamins, amino acids, and oxidation of substances (Okos *et al.*, 1992).

Akpinar (2004) studied the energy required for drying of red pepper slices in a laboratory dryer. It was reported that by increasing temperature, total energy consumption as well as rate increase, but these indexes decrease with time (Akpinar, 2004). In another piece of research on convective thin layer drying of pomegranate arils, it was reported that drying time, consumed energy, and required specific energy decrease with increasing temperature (Motevali *et al.*, 2011).

Thermal utilization efficiency is defined as the ratio of sample moisture evaporation latent heat to the energy required for the evaporation of moisture from free water. Thermal utilization efficiency in hot air flow-infrared mixed drying was reported to be 38% for both potato and carrot (Umesh Hebbar *et al.*, 2004).

In research, St John's Wort was dried at 35°C for 3-5 days until reaching a constant dried weight. The dried samples were then stored inside opaque bags at room temperature. This resulted in preservation of the highest amount of hypericin in the leaves (Buter *et al.*, 1998).

The effect of temperature (40, 60, and 70 °C) on drying of peppermint has been investigated (Mahanom *et al.*, 1999). Results showed that at temperatures higher than 60°C, the amount of essence decreases whereas at 80°C the amounts of citronellal and cineole reduce to one eighth. Experiments on drying of thyme showed that natural drying (in the shade) better preserves the essential oils than oven drying at 35°C (Venskutonis *et al.*, 1997). Effect of convective drying on the amount of volatile oils of French and Russian varieties of tarragon leaf was studied by Arab Hosseini *et al.* Plant leaves were dried to 10% dry basis (d.b.) at 40-90°C temperature range and various relative

humidities. Results showed that both drying time and temperature are the most effective factors in preserving the leaf essential oils during the drying process. On the other hand, the effect of relative humidity was not significant. Amounts of volatile oils decreased with drying time reaching the lowest value at 60°C (Arabhosseini *et al.*, 2005).

A considerable body of data exists in the literature regarding the energy requirements for drying of various agricultural products like mulberry (Akbulut and Durmus, 2010), garlic cloves (Sharma and Prasad, 2006), pistachio (Midilli and Kucuk, 2003), pomegranate arils (Motevali *et al.*, 2011 a, b), longan (Tippayawong *et al.*, 2008), carrot slices (Aghabashlo *et al.*, 2009) and papad (Kumar, 2013). However, little information is available on energy requirements, specific energy, thermal utilization efficiency and active ingredients of agricultural materials in hot air drying. One of the objectives of this research project was to determine the best drying treatment for St. John's Wort, which was carried out by achieving the highest amount of hypericin preserved while aiming for the lowest specific energy consumption and best thermal utilization efficiency.

Materials and methods

Three Kiln type laboratory dryers were utilized to conduct the drying experiments. The drying chamber was a 40×40×50 cm container located 70 cm above the heating elements (Figure 1). Each dryer has two electrical elements to generate the required heat, one of them is controlled by a digital thermostat and the other is controlled manually. Hot air flow is produced by a blower located under the elements, providing an adjustable flow rate in the range of 180 to 220 m³/h using a dimmer. Two sensors are mounted in the upper and lower parts of the dryer to measure the temperature of the drying air entering and leaving the sample container. Prior to the commencement of each experiment, air temperature was adjusted by the thermostat and the dryers were activated to reach the required temperature. Data collection for thin layer drying experiments was performed through weighting of samples at 5 min intervals using a ±0.001 g digital balance (Sartorius, model PT210, Germany).

All the required plant materials for the experiment were procured from farming and the separation of the leaves from the stems was done manually. Then the samples were packed inside separate plastic bags and refrigerated at 4±1°C. In this state, the total moisture content of the leaves was 39 wet basis (w.b.%). The independent variables at this experiment were: 1) temperature in four levels of 40, 50, 60, and 70°C; 2) air displacement velocity in three levels of 0.3, 0.7, and 1 m/s; and 3) sample thickness at three levels of 1, 2, and 3 cm.

Air parameters were adjusted by measuring tem-

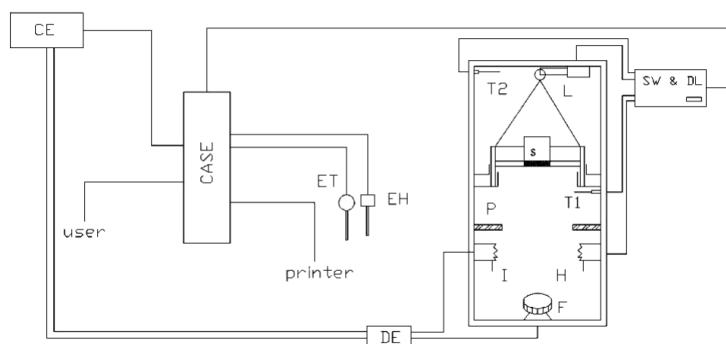


Figure 1: Diagram of the experimental dryer
(F) fan, (H) heat generator, (S) sample, (T₁) Lower thermometer, (T₂) Upper thermometer, (Sw) switches, (DL) data logger, (EC) electronic control system, (DE) electronic driver, (RH) Ambient relative humidity sensor, (TS) Ambient temperature sensor

perature and velocity using a thermometer (Lutron, TM-925, Taiwan), anemometer (Anemometer, Lutron-YK, 80AM, Taiwan) and humidity meter (Testo 650, 05366501, German) was utilized to measure the air relative humidity.

Energy consumption

Energy consumption for drying of St John's Wort layers was calculated using equation 1 (Motevali *et al.*, 2011; Koyuncu *et al.*, 2007):

$$E_t = A \nu \rho_a C_{pda} \Delta T t \quad (1)$$

Where E_t is the total consumed energy in each drying phase (kWh), A , is the sample plate area (m^2), ν , air velocity (m/s), ρ_a , air density (kg/m^3), t , total drying time of each sample (h), ΔT , temperature difference between ambient and hot air ($^{\circ}C$), and C_{pda} , specific heat of air ($kJ/kg^{\circ}C$).

Specific heat of air was calculated, to be 1.004 using Eq.2 (Motevali *et al.*, 2011).

$$C_{pda} = 1.004 + 1.88w \quad (2)$$

Conversion of relative humidity to moisture ratio

Relative humidity was converted to moisture ratio using Eq.3 (Motevali *et al.*, 2011).

$$w = 0.622 \frac{\phi P_{vs}}{P - \phi P_{vs}} \quad (3)$$

Where w is Relative humidity; p air pressure (kPa) and P_{vs} , saturated vapour pressure (kPa). This conversion is also possible by using psychrometric charts.

Calculation of the specific energy requirement

The amount of consumed energy in drying of 1 kg of St John's Wort is calculated using eq.4 (Motevali *et al.*, 2011 a, b):

$$E_{kg} = \frac{E_t}{w_0} \quad (4)$$

Where E_{kg} , is the required specific energy, and W_0 , is sample's initial weight.

Thermal utilization efficiency (TUE)

This indicator is defined as the ratio of sample moisture evaporation latent heat to the energy required for the evaporation of moisture from free water. In order to determine the thermal utilization efficiency, equation 5 was used (Umesh Hebbar *et al.*, 2004):

$$T.U.E = \frac{L A_d I_h (M_i - M_o)}{F (100 - M_o)} \quad (5)$$

where L is weight density of St John's Wort layer per unit area (kg/m^2), A_d , total product area (m^2), I_h , latent heat of vaporization (kJ/kg), M_i , Initial moisture content (%w.b.), M_o , final moisture content (w.b.%), F , power of the heat source (kW) and t operation time of the heat source (h). Initial moisture content of samples (M_i) was 39% on the wet basis which was dried to final moisture content (M_o) of 8 (%w.b.). The evaporation latent heat of the product was considered equal to the latent heat at ambient air pressure.

Hypericin content of St John's Wort leaves

Extraction of hypericin

Considering the various air temperatures, velocities, and sample thicknesses, 36 treatments plus a control (traditional drying method, i.e. passive ambient drying (temperature: 19-34 $^{\circ}C$; relative humidity: 27-43%)) were considered in three repetitions for drying of St John's Wort. For extraction of hypericin, a four gram sample of dried leaves from each treatment was placed in a Soxhlet extractor. To remove the chlorophyll, chloroform solvent was added followed by methanol solvent. After purification of the solution, its volume was increased by methanol to 30 ml. The samples were kept in opaque tubes and refrigerated before analysis.

A high performance liquid chromatography instrument (Well Knauer modle Chrom 2000) was used for hypericin determination. The device included a pump (Maxi-star K-1000) and a detector (Spectrophotometer K-2500) which was adjusted at 590 nm. The column used was Erospher 100 C18 with a 25cm length and 4mm diameter, mobile methanol 68%, ethyl acetate 20% and 0.1 mol sodium hydro sulphate 12%. Flow intensity of 1ml/min and 20 μ l of injected sample. Test duration was 30 minutes. Ten mg of Roth TM (Germany) hypericin ($C_{30}H_{16}O_8$) with molecular mass of 504.43 was used as standard when determining the hypericin content of each treatment as follows. Five different concentrations were obtained from the standard sample (116, 133, 155, 186, and 232 ppm) and injected into the chromatograph. Then, given the area under the curve of the unknown substance spectrum and matching it with the calibration curve, the unknown concentration was determined.

Results and discussions

Figures 2, 3 and 4 show the energy requirement for drying of St John's Wort, which is consumed by the dryer's heaters. At higher temperatures, drying time decreases due to increasing thermal gradient inside the substance and consequently increasing the drying rate. Also, drying time decreases with increasing air velocity. This is because vapour pressure decreases with increasing air velocity, thus, the product moisture would encounter less resistance on its way out and exits at higher rate. These obser-

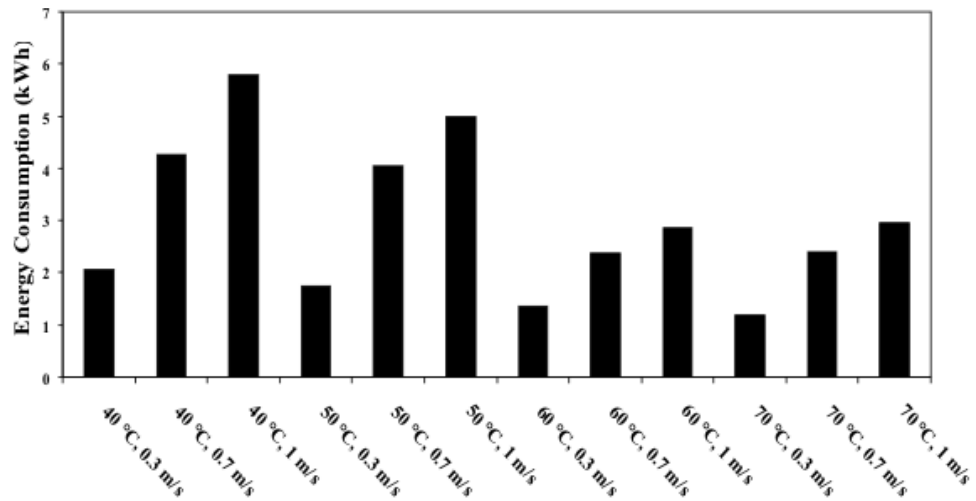


Figure 2: Energy consumption for drying 1cm-thick layer of St John's Wort at different air temperatures and velocities

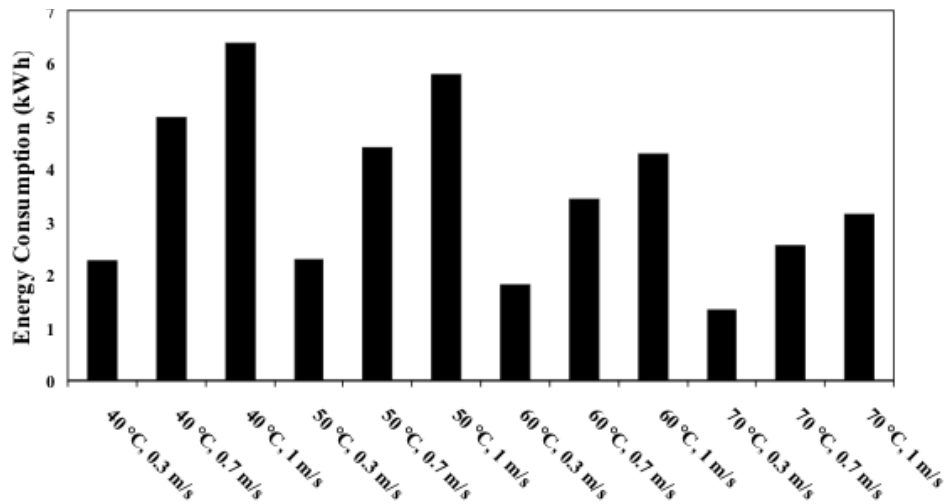


Figure 3: Effect of air velocity and temperature on energy requirement for drying 2cm-thick layer of St John's Wort

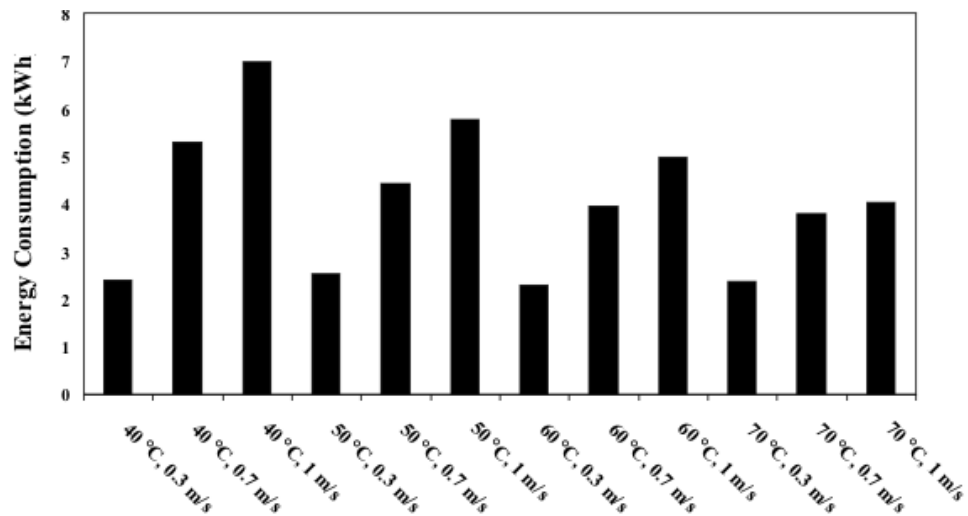


Figure 4: Energy consumption for drying 3 cm-thick layer of St John's Wort at various temperatures and velocities

variations were similar to the results reported previously (Motevali *et al.*, 2011a and b) which are plausible. With increasing product layer thickness in the dryer, drying time and hence the required energy for drying increase (Figures 2, 3 and 4).

Specific energy consumption

Figures 5, 6 and 7 show the specific energy consumption for drying 1 kg of St John's Wort in various thicknesses (1, 2, and 3cm) at various temperatures and air velocities. Specific energy at a given temperature increases with air velocity while it decreases with temperature for a constant air velocity. The minimum and maximum values of required specific energy for drying a 1 cm layer sample (at different temperatures and air flow velocities) were 5.31 and 26.06 kWh/kg, respectively. Also, the minimum and maximum required specific energies were 4.41 and 17.53 for 2 cm thick layer and 4.28 and 13.67 for the 3 cm thick layer treatments (kWh/kg), respectively. Energy requirement decreased with increasing layer thickness from 1 to 2 cm and

from 2 to 3 cm, such that (at a given air temperature and velocity), the maximum specific energy was associated with the 1 cm thick layer. This is because with increasing material thickness, sample weight in the dryer also increases. Specific energy is thus calculated by substituting the value of the required energy obtained from equation 1 as well as the sample weight (at various thicknesses) into equation 4.

Thermal utilization efficiency

Thermal utilization efficiency for hot air drying of St John's Wort varied from 21% to 72% for sample thickness of 1 cm, from 17% to 66% for thickness of 2 cm, and from 14% to 58% for thickness of 3 cm (Table 1). Since in each experiment the latent heat of vaporization of water (λ), initial moisture content (M_i), and the final moisture content (M_o) were constant and given the applied thermal capacity (Q), thermal utilization efficiency of the dryer depends on the performance of the heat source and sample's initial weight ($L.A_d$).

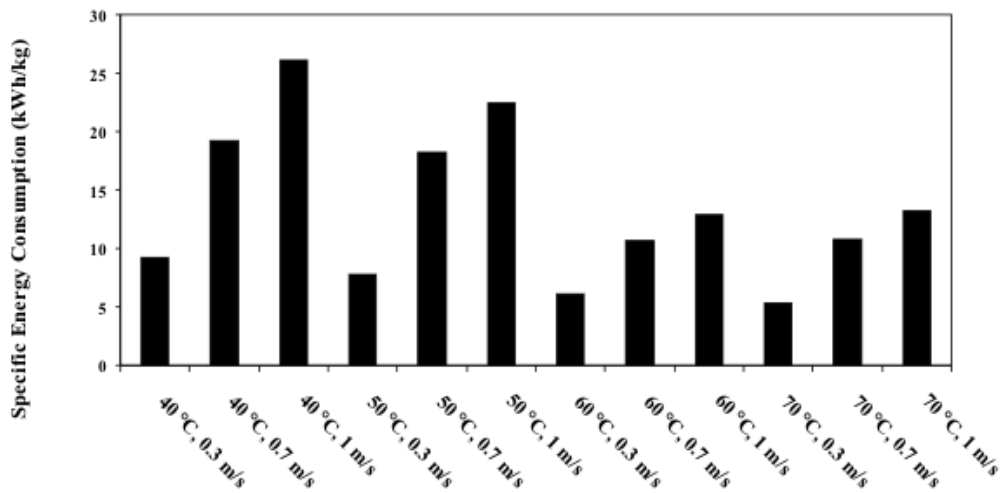


Figure 5: Effect of air velocity and temperature on specific energy consumption for drying a 1cm-thick layer of St John's Wort

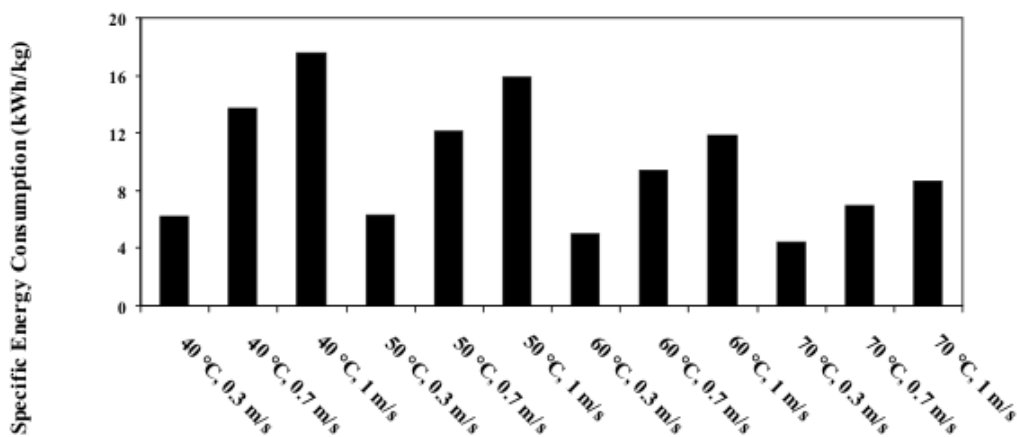


Figure 6: Effect of air velocity and temperature on specific energy consumption for drying a 2 cm-thick layer of St John's Wort

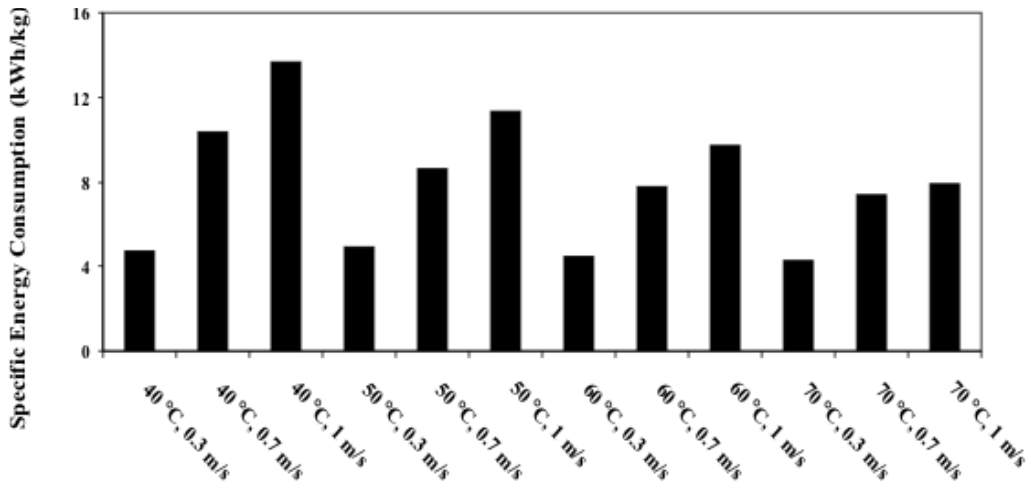


Figure 7: Effect of air velocity and temperature on specific energy consumption for drying a 3 cm-thick layer of St John's Wort

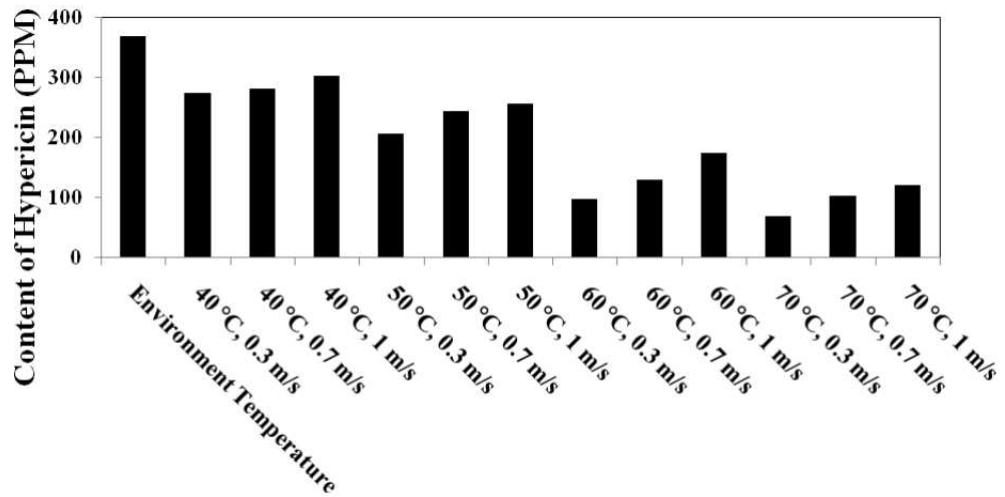


Figure 8: Effect of air velocity and temperature on the hypericin content of 1 cm-thick layer of sample

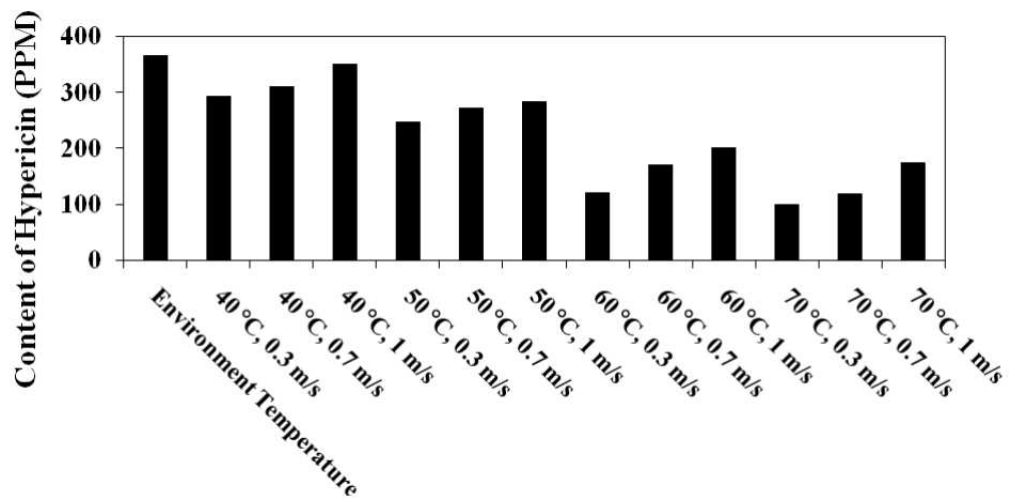


Figure 9: Effect of air velocity and temperature on the hypericin content of 2 cm-thick layer of sample

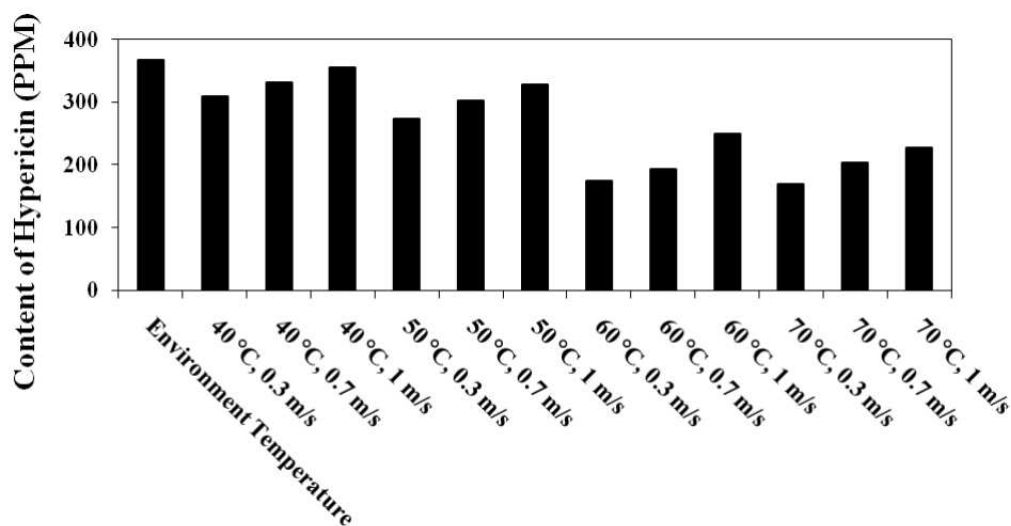


Figure 10: Effect of air velocity and temperature on content the hypericin of 3 cm-thick layer of sample

The highest efficiency in drying of St John's Wort was observed at 70°C temperature, 0.3 m/s air velocity, and 3 cm sample thickness, which is due to the higher performance of the heaters resulting in higher air temperature and lower air velocity. The reason is that the chamber's air temperature control system is designed to be activated whenever air temperature in the chamber drops below the desired value. The lowest utilization efficiency is related to 70°C treatment in which the heaters have the lowest on time. Despite high thermal utilization efficiency at 40°C, since the drying process is quite lengthy, it is not desirable.

Determination of hypericin content resulting from various treatments

As shown in Figures 8 to 10, at constant air velocity (0.3 m/s), the amount of hypericin obtained from the dried plant material increases with layer thickness under similar temperature conditions. On the other hand, in all cases, the material dried in ambient conditions (traditional drying) had the maximum amount of hypericin. Figures 8 to 10 indicate that increasing temperature, decreasing the hypericin content and the highest decrease occurs at 70°C. Analysis of variance results for hypericin content under various drying condition are given in Tables 2, 3 and 4. Hypericin content increases with

air velocity and sample thickness, the maximum being observed at 3 cm thickness, 40°C temperature, and air velocity of 1 m/s. Under these conditions, the amount of hypericin was the same as that obtained in the traditional drying method. This is because temperature and drying time are the main factors influencing hypericin preservation during the drying process. On the one hand, drying at low temperatures preserves the dark glands in leaves containing hypericin, and on the other hand, increasing air velocity speeds up the drying processes which help in preservation of hypericin. Also, increasing sample thickness, results in more uniform temperature distribution in different layers leading to reduced thermal stresses. Results obtained in this experiment are similar to the findings reported in the literature for other medicinal plants. (Mahanom *et al.*, 1999; Venskutonis *et al.*, 1997; Arabhosseini *et al.*, 2005; Buter *et al.*, 1998).

Conclusions

The following conclusions are drawn based on convective drying of St John's Wort:

1. Energy consumption decreased with increasing temperature and increased with air velocity and sample layer thickness in the dryer.
2. Specific energy requirement decreased with increasing temperature and sample layer thick-

Table 1: Thermal utilization efficiency under various drying conditions

Sample layer thickness (cm)	1			2			3			
	Air velocity (m/s)	0.3	0.7	1	0.3	0.7	1	0.3	0.7	1
Temperature (°C)										
40	29	23	21	24	20	17	22	16	14	
50	51	43	39	41	34	29	39	30	19	
60	68	59	47	64	52	43	55	46	34	
70	72	65	57	66	63	54	58	52	49	

Table 2: ANOVA results for hypericin content data

Source of variation	df	Sum squares (SS)	Mean squares (MS)	F
replication	2	1.538	0.769	0.93
(A)Temperature	4	73.926	18.481	22.40*
(B)Velocity	3	87.891	29.297	35.51*
Temperature× velocity (A×B)	12	75.114	6.259	7.58*
(C)Depth	3	72.972	24.324	29.48*
Temperature× depth (A×C)	12	77.22	6.435	7.8*
Velocity× depth (B×C)	9	12.492	1.388	1.68 ^{ns}
Temperature× Velocity× depth (A×B×C)	36	34.02	0.945	1.14 ^{ns}
Error	158	130.35	0.825	

* significant difference at 1 % probability level

^{ns} non significant at 1 % probability level

Table 3: Comparison of the means for hypericin content using Duncan's multiple range test (interaction of temperature and velocity)

Velocity (m/s)	Temperature (°C)			
	40	50	60	70
0.3	292.33 ^g	242 ^e	131.33 ^b	112.66 ^a
0.7	308 ^g	272.33 ^f	165 ^c	142.33 ^b
1	342.66 ^h	289.33 ^g	208.66 ^d	174.33 ^c

Table 4: Comparison of the means for hypericin content using Duncan's multiple range test (interaction of temperature and material depth)

Depth (cm)	Temperature (°C)			
	40	50	60	70
1	285 ^f	234 ^e	133 ^b	96 ^a
2	319.33 ^g	268.66 ^f	166 ^c	132.66 ^b
3	338.66 ^h	301 ^{fg}	206 ^d	200.66 ^d

ness while it increased with increasing air velocity.

- Thermal utilization efficiency decreased with increasing temperature in such a way that the lowest thermal utilization efficiency occurred at 40°C and the highest efficiency occurred at 70°C. Also, increasing material thickness resulted in increasing the thermal utilization efficiency at any given air temperature and velocity.
- Hypericin content of the leaves at constant thickness decreased with increasing temperature, while it increased with air velocity and material thickness.
- Based on energy consumption, thermal utilization efficiency and hypericin content post-drying, the best condition for drying of St John's Wort is 50 to 60°C temperature and 0.7 m/s air velocity.

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