SOLAR ENERGY USAGE IN DRYING TECHNOLOGIES OF MEDICINAL AND SPICE PLANTS

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INTRODUCTION

Topic relevance

Recently, because of the rising demand for medicinal herb raw materials in food, pharmaceutical, dental and other fields, an interest of farmers has increased in growing, preparing for storing and processing of medicinal herb raw materials.

The main condition for preserving the quality of medicinal herb raw materials is a timely reduction of moisture down to the safe 12–14 % of humidity. This determines good organoleptic properties and low losses of biologically active substances.

Drying is an expensive and responsible stage of the technological process. It takes up to 50–70 % of all its production costs. Most of it comes from the preparation of a drying agent during the process of drying, i.e. the production costs of conventional energy sources used to warm the drying agent.

The main yield of medicinal and spices plants are harvested in summer. This period is typical of the largest amount of solar energy and the longest duration of sunlight. It is purposeful to make use of it while reducing concentrated energy consumption during the preparation of the drying agent.

The usage of solar energy in drying technologies is widely studied: starting from the efficiency range of different design and types of solar collectors, to different drying technologies. However, this inexhaustible and environment friendly energy has a fairly big flaw, i.e. its variations in time and high degree of inconsistency. Early in the morning, at night and late in the evening, solar energy is insufficient, whereas at noon, on a hot summer day, solar energy surplus is observed. It is reasonable to accumulate this surplus while using the accumulated heat in case of a deficiency in order to maintain stability of the drying process.

Scientists have studied various surplus solar energy storage systems that employ specific heat of materials or latent heat, i.e., physical changes in a state of materials. There are attempts to solve the solar energy periodicity problem by creating hybrid, photovoltaic and thermal element systems, as well as combining the solar energy conversion systems with heat pumps, biogas production and other installations.

In cool temperate climate zone, conditions favourable for natural medicinal plant raw material drying are not predominant and, for the most part, appear in short periods of time. The usage of concentrated energy to prepare the drying agent is inevitable. Development of sustainable, cleaner medicinal plant raw material drying technologies requires new technical solutions in order to reduce concentrated energy costs. Most of the drying systems and technologies that employ solar energy have been developed and tested in tropical and subtropical climate zones where average solar energy amount on the earth’s surface reaches approx. 1900 kWh m⁻² per year. In cool temperate climate zone, the average amount of solar energy is approx. 1.46–1.9 times lesser, i.e. it reaches up to nearly
1000–1300 kWh m$^2$ per year. This difference between the amount of solar energy calls for the study and evaluation of the solar energy usage possibilities in medicinal plant raw material drying technologies in the temperate climate zone.

**Hypothesis**

Rational usage of solar energy in the temperate climate zone allows reducing the consumption of conventional energy and negative environmental impact in medicinal plant raw material drying technologies.

**The aim**

To identify energy consumption reduction possibilities using solar energy while drying medicinal and spice plants.

**Tasks**

1. To determine solar radiation and consistent patterns of other changes in natural conditions in Lithuania during the harvesting–preparation period of medicinal and spice plants.
2. To determine the impact of drying agent temperature, ventilation intensity and preparation of medicinal and spice plant raw materials for drying on its quality.
3. To determine the consistent patterns in the change of drying agent parameters and the medicinal and spice plant drying process in a dryer with an aerial solar collector.
4. To examine the possibilities of support for the parameters set for the drying agent while using a combination solar energy conversion system with energy accumulation.
5. To evaluate the environmental impact of the designed drying technologies which employ solar energy conversion systems.

**Thesis statements**

1. The quality of dried medicinal and spice plant raw materials (organoleptic and biochemical properties) depends on the method of raw material preparation and the efficiency of the drying technology.
2. While using aerial solar collectors for the preparation of the drying agent, we cannot ensure smooth and uninterrupted drying process of raw materials without using additional energy sources.
3. Stable parameters for the drying agent and a continuous drying process of medicinal and spice plant raw materials can be set (maintained) by using direct and accumulated solar energy.
4. Stable parameters of the drying agent ensures a continuous drying process, reduces energy consumption and helps to preserve the quality of dried products.
5. By using composite solar conversion system with energy accumulation to prepare the drying agent we can withdraw additional energy sources and reduce emissions of air pollution to minimum.

Scientific novelty

It was determined that stable drying speed and shorter drying time of medicinal and spice plant raw materials improves its organoleptic and biochemical properties. The drying process can be accelerated by chopping medicinal and spice plant raw materials.

A continuous process with stable parameters that encompasses preparation of the drying agent and drying medicinal and spice plant raw materials was studied using direct and accumulated solar energy.

The invention No. 6069 under the title “A method to prepare a drying agent using solar radiation energy and an installation to realise it” was designed and registered on at the Lithuanian Patent Office on September 25, 2015. The authors of the invention are: Zvicevičius E., Raila A., Novošinskas H., Čiplienė A. The invention is designed to ensure continuous preparation of the drying agent during the drying process by using solar energy and to reduce changes in the drying agent’s parameters while solar energy radiation is constantly changing.

Practical value

Using tested preparation methods for drying agent along with solar energy a continuous drying process is ensured while using conventional energy for mere purposes of ensuring the operation of devices. Stable parameters of the drying agent improve the quality of the drying process, accelerate drying and decrease energy consumption, at the same time reducing negative environmental impact. This preparation method for drying agent is used in various drying technologies during the drying process of various crop products.

The country’s farmers were introduced with the research results and benefits of experimental dryers in seminars, field days and in science and science promotion publications. Currently, preparation works for designing new medicinal and spice plant driers and preparation of technical tasks in various regions of the country are taking place.

Approval and publication

11 publications under the topic of the dissertation were published, 2 of which are published in journals refereed in the Institute of Scientific Information’s databases “ISI Web of Science” that have citation index. 1 publication is published in another Journal refereed in the Institute of Scientific Information’s database “ISI Web of Science”. 1 publication is published in a reviewed scientific journal which is refereed in another database. 1 publication is
published another reviewed scientific journal. 4 publications are published a scientific journals not assigned to any classification groups. There is 1 registered patent invention at the Patent Bureau of the Republic of Lithuania. Also, 1 information sheet was published. The results of the research were presented in 9 international and 3 national conferences.

**Scope of the dissertation**

The dissertation is written in the Lithuanian language. It consists of a list of used symbols and abbreviations, introduction, review of literature, research methodology, results and discussion, conclusions, a list of references and a list of publications under the topic of the dissertation. The scope of the dissertation involves 3 chapters, 13 subchapters, 101 pages, 78 figures, 9 tables. 222 references were used in the dissertation.

**2. RESEARCH METHODOLODY**

The drying process of medicinal and spice plant raw materials was studied in Aleksandras Stulginskis University, Faculty of Agricultural Engineering, Institute of Energy and Biotechnology Engineering research laboratories. The biochemical quality of dried medicinal and spice plant raw materials was assessed in the instrumental analysis laboratory at Vytautas Magnus University. The purple coneflower (*Echinaceae purpureae* (L.) Moench) and motherwort (*Leonurus cardiaca* L.) cultivated at Vytautas Magnus University Kaunas Botanical Garden in the medicinal plant collection were used for the research.

Solar radiation usage in drying technologies was studied in a manufacturing dryer of medicinal and spice plants with aerial solar collector and in experimental dryer of medicinal and spice plants with a combined solar conversion system with a storage device.

**2.1. Analysis of natural conditions**

Natural environmental conditions were assessed by analysing the Lithuanian hydro–meteorological station data. A multiannual ambient temperature and humidity, sunlight duration and solar radiation energy were analysed. The analysis of natural conditions was carried between countries located in the temperate climate zone (Lithuania, Poland and Germany) and countries located in the subtropical climate zone (Turkey and Egypt).

**2.2. Drying agent and its preparation**

Studies of the drying process were carried out in 2012 and 2013 with purple coneflower and motherwort.

The moisture content in medicinal and spice plant raw materials was determined by Lithuania’s standard LST 1530:2004 before the drying process.
2.3. Drying research of medicinal and spice plant raw materials

Medicinal and spice plant raw materials were dried using active ventilation in order to determine the influence of the drying environment and technology on the drying process of the areal part of motherwort and purple coneflower plants and the quality of dried raw material. The samples of medicinal and spice plant raw materials were dried until 10 % moisture level.

2.3.1. Drying process in thick immobile layer

Drying research was carried out while drying chopped motherwort and chopped purple coneflower using 3 different options: option I – drying performed using natural ventilation, option II – drying performed using active ventilation, option III – drying performed using active ventilation with heated ambient air. During all the studies, samples were weighed on KERN KVB–TM scales every 6–8 hours, and the height of the dried layer was measured in five different points of the raw materials: one being in the middle of the cylinder and the remaining four – on the opposite edges of the cylinder. Air parameters were measured using temperature and humidity sensors in the testing room and in dried material layer itself. During the production of the drying process, air filtration rate was measured by thermo–anemometer.

For drying of different morphological parts of purple coneflower in elementary layer, Memmert Model UPF 700 drying oven was used. During the studies, the temperature of 39.9±0.3 °C was held with the internal air circulation inside the chamber and outside air circulation between the chamber and the environment. The intensity of outer air circulation was 18.1 chamber volumes per hour. The weight of dried samples and air parameters in the drying oven were recorded every 2–4 hours during drying.

2.3.2. Quality assessment of the drying process of medicinal and spice plant raw materials according to biologically active substances

The biochemical quality of dried medicinal and spice plant raw materials was assessed in the instrumental analysis laboratory at Vytautas Magnus University.

Moisture levels of all studied medicinal and spice plant raw material samples were evaluated under the methodology referred to in the European Pharmacopoeia (Ph. Eur. 2.2.32) (Council of Europe, 2014).

Spectrophotometric studies.

The total phenolic compound quantity was determined using a slightly modified Folin–Ciocalteu method (Singleton, Rossi, 1965).

The total quantity of flavonoids was evaluated using a modified spectrophotometric analysis AlCl₃ colorimetric method (Mabry et al., 1970). Common binding activity of radicals was determined using the DPPH (2,2-diphenyl-1-pikrilhidrazil hydrate) radical bonding method (Brand-Williams et al., 1995).
Effective liquid chromatography with detection of reaction. Quantity of cichoronic acid was additionally determined in thick still layer of purple coneflower during its drying process. Also, the quantity of hyperoside in motherwort was determined (Kaškonienė et al., 2011).

2.4. Research methodology of drying agent preparation systems that use solar energy

Drying agent preparation research using direct thermal energy obtained from solar energy. Studies were carried out in medicinal and spice plant dryer with aerial solar collector with the area of 131 m² integrated into the roof of the dryer to warm the air flow (Fig. 2.1.). The dryer is placed in the geographical 54° 9‘ 7.76“ north latitude and 24° 3‘ 16.94“ east longitude.

Fig. 2.1. Principal scheme of medicinal and spice plant raw materials dryer with aerial solar collector: 1 – outdoor air flow; 2 – heated air flow; 3 – transparent cover; 4 – absorber; 5 – fan; 6 – under sieve cavity; 7 – garner

In order to calculate air and heat flows and assess the effectiveness of the solar collector and the preparation system of the drying agent during research, work intensity was changed with the help of automatic controller and air speed was measured at air intake and outlet openings of the collector. Temperature and humidity sensors recorded environmental air settings along with the air parameters at the upper and lower places of the collector and in the cavity of under the sieve ventilation; also, solar energy radiation of the solar transparent paint was measured with the help of piranometer. All the data was recorded periodically every 10 minutes in the memory of data logger ALMEMO.

Drying agent preparation studies using combined solar radiation energy conversion system (Fig. 2.2). The research was carried out in the experimental medicinal and spice plant dryer with a combined solar energy conversion system and an accumulation device. The dryer is placed in the geographical 55° 7‘ 4.95“ north latitude and 22° 7‘ 37.83“ east longitude.
Fig. 2.2. Principle scheme of the dryer for medicinal plants: 1 – flat-plate type solar collector (8 m² area), 2 – air-type solar collector (12 m² area), 3 and 5 – a pump; 4 – a tank with water for heat storage; 6 – heat exchanger; 7 – air mixing chamber; 8 – drying chambers; 9 – fan

Parameters of environmental air and drying agent were measured with temperature and moisture level sensors, water temperature in a heat accumulation system – with thermocouples, solar radiation energy irradiance – with piranometer. Sensor positions are provided in Fig. 2.2. The air speed was measured next to the intake vent of aerial solar collector and between the aerial collector and the mixing chamber with a thermo anemometer. According to the measurement results, air and heat flows were calculated; also, possibilities to use a combined preparation system for the drying agent while drying medicinal and spice plant raw materials were evaluated.

In the theoretical calculations for offsetting solar energy deficit and warming the drying agent, the necessary amount of heat is calculated using the equation:

\[ Q_s = \sum_{i=1}^{n} L_{oro} \cdot c_p \cdot (t_s - \bar{t}_{i,a}) \cdot \tau_n = \sum_{i=1}^{n} L_{o} \frac{m_i \rho_2}{3.6} c_p \cdot (t_s - \bar{t}_{a,i}) \cdot \tau_n \]  

(1)

here \( Q_s \) – quantity of consumed heat, J; \( L_{oro} \) – supplied air flow (through dried layer), kg s\(^{-1}\); \( c_p \) – specific heat of dry air, kJ (kg K\(^{-1}\)); \( \tau_n \) – countable operating time of accumulated heat during one day, hours; \( L_o \) – comparative ventilation intensity, m\(^3\) (t h\(^{-1}\)); \( m_1 \) – weight of dried medicinal-spice herb raw material, t; \( \rho_2 \) – air density, kg m\(^{-3}\); \( t_s \) – set temperature of a drying agent, °C; \( \bar{t}_{a,i} \) – average ambient air temperature in period \( i \), °C

All results obtained during the research were analysed using MS Office, Excel and Mathematica software.
2.5. Assessment of environmental impact of drying agent preparation systems used in medicinal and spice plant raw materials drying technologies

During the research, a necessary quantity of energy to prepare the drying agent was determined. Also, comparative environmental assessment calculations were carried out. During the period of research, the assessment of greenhouse gas emissions was carried out using other energy sources to produce thermal energy, i.e. electricity (produced by Lietuvos elektrinė, Plc), natural gas and solid biofuels. Comparative calorific values used in calculations were taken from Fuel and Energy Balance 2013 reports of Statistics Lithuania. Emission into the environment (CO₂, SO₂ and NOₓ) is calculated using the standard emission factors (Konstantinavičiūtė et al., 2012; Ministry of Economy of the Republic of Lithuania, August 7, 2013).

All results obtained during the research were analysed using MS Office, Excel and Mathematica software.

3. RESEARCH RESULTS AND DISCUSSION

3.1. Comparative analysis of natural conditions in Lithuania

Lithuania is located in the Northern part of the temperate climate zone, characterised by prevailing transfer of air masses from the West and changeable weather. In countries situated in the subtropical climate zone (e.g., Turkey, Egypt), the daily amount of solar energy stays between 1.84 and 7.65 kWh m⁻² throughout the year (Fig. 3.1). Meanwhile in Lithuania, Poland and Germany, the biggest amount of solar energy (1.49 to 5.4 kWh m⁻² per day) is received from April to September, i.e. during the harvesting and preparation period of medicinal and spice plants.

![Potential of solar energy in the moderate and subtropical climate zones](image)

**Fig. 3.1. Potential of solar energy in the moderate and subtropical climate zones**

Maximum solar energy peak in Lithuania is in June – 4.8 kWh m⁻² per day. Minimum peak occurs during harvest – the preparation period of medicinal herbs between April and September with – 3.57 and 2.71 kWh m⁻² per day respectively.
In subtropical zones, the amount of solar energy leads to higher air temperature. Because of higher temperature and less relative air humidity, it has a positive impact on sorption properties (Fig. 3.2). In the subtropical climate zone, during the period from April to September, the average theoretical moisture level is \(8.99\pm 1.62 \text{ g kg}^{-1}\), i.e. 2.52 times higher than the highest moisture level \(3.57 \text{ g kg}^{-1}\) in the temperate climate zone.

**Fig. 3.2.** Comparison of sorption qualities of surrounding air

Having carried out the meteorological data analysis, it was revealed that countries located in the subtropical climate zone have better air sorption properties. During the period of April-September, the average potentially maximum theoretical moisture level is \(8.99\pm 1.62 \text{ g kg}^{-1}\), i.e. 2.52 times higher than in the temperate climate zone. Besides, the amount of solar energy in the subtropical climate zone countries reaches from 1.84 to 7.65 kWh m\(^{-2}\) per day all year round, while solar energy in the temperate climate zone rises above 1.84 kWh m\(^{-2}\) per day during the period between April and September. Maximum amount of solar energy rises up to 5.4 kWh m\(^{-2}\) per day.

**3.2. Medicinal and spice plant raw material drying research**

Two medicinal herb species were chosen for the drying – purple coneflower (*Echinacea purpurea* L. Moench) and motherwort (*Leonurus cardiaca* L.). These perennial herbaceous plants differ in biologically active substances as well as in the properties of their morphological parts.

**3.2.1. Research of drying different morphological parts of purple coneflower**

Stems comprise \(48.7\pm 3.39\%\) of the aerial part of purple coneflower mass. Leaves comprise \(32.5\pm 2.46\%\) of the harvested weight mass. The least part \(18.82\pm 3.23\%\) consist of flowers.

*Drying in the elementary layer.* The initial moisture level of purple coneflower’s separate morphological parts is different. The highest average initial moisture level of leaves was \(79.25\pm 2.09\%\), slightly lower, \(78.39\pm 1.72\%\), of flowers, and the lowest, \(68.18\pm 1.7\%\), in the stems. Leaves dried down to 10\% of moisture in 19.5 hours at fastest, having temperature of \(38.8\pm 0.28 \text{ °C}\) in the
elementary layer (fig. 3.3). Healthy stems and flowers reached the same moisture level only after a 2.3 times longer period, i.e. approximately after 45–47 hours. Although the flower diameter was greater than that of healthy stems, their drying process was smoother and more even. The average drying speed was 1.74 % h\(^{-1}\) for flowers, and 1.52 % h\(^{-1}\) for healthy stems.

![Fig. 3.3. Evolution of moisture level of different morphological parts of purple coneflower when drying in elementary layer: 1 – leaves; 2 – whole stems; 3 – whole flowers](image)

While drying crushed and chopped stems and flowers, their drying process was more intensive; therefore, the drying time decreased. The impact of mechanical effects had an effect mostly during the drying process of stems (Fig. 3.4), the drying time reduced more than 2 times, and drying periods which are characterised by hygroscopic materials can be seen in the drying curves. After 14 hours of drying, crushed stems first reached their decreasing speed period. Constant drying rate period of chopped and healthy stems took 16.5 and 28 hours respectively, i.e. 1.2 and 2 times longer.

![Fig. 3.4. Influence of the method of preparing purple coneflower stems on the duration of drying: 1 – whole; 2 – crushed; 3 – chopped](image)

In the course of drying chopped purple coneflower stems, leaves and flowers in a thick still layer, with drying agent temperature at 44.8±1.5 °C, relative moisture 65.2±3.8 % and the average comparative ventilation intensity equal to 4100±550 m\(^3\)(t h\(^{-1}\)), the drying time of chopped stems was the shortest
(Fig. 3.5). Their moisture levels decreased from 77.1±0.98 % to 13.99 % in 33 hours. The drying time of flowers was 2 times longer, their moisture level reduced by 68 % in 66 hours of drying from 81.6±1.32 % to 13.6±0.5 % respectively. The humidity levels of purple coneflower leaves, which changed most rapidly while drying in the elementary layer, dried the longest; during 66 hours of drying time, the moisture level of leaves decreased from 79.1±0.38 % to 22.71±1.37 %. Leaves reached a recommended moisture content of 12–14 % after 95 hours.

**Fig. 3.5.** Drying dynamics of different morphological parts of purple coneflower in a thick immobile layer: 1 – stems; 2 – flowers; 3 – leaves

Leaves in the thick still layer dried 4.9 times longer than those in the elementary layer. It was influenced by the following processes: decreasing intensity of moisture exchange and height of the mound, as well as the changing porosity and density.

Phenolic acids made up the biggest part of phenolic compounds found in the test samples. In herbal raw materials dried in the elementary layer, the acids amounted to 90 % of the total content of phenolic compounds, whilst in the thick still layer – more than 71 %. The most important compound in this group is cichoric acid (Lapinskienė et al., 1999; Ragažinskienė, 1999). Its amount in flowers, leaves and stems dried in the thick still layer was 24.08±0.6, 11.14±0.36 and 8.48±0.04 mg g⁻¹ RE, respectively.

The same flavonoid content was determined in the stem samples dried in an elementary layer regardless of the preparation method; the content only reached 0.03±0.0015 mg g⁻¹ s.m. RE. However, the mechanical preparation for drying had a direct influence on phenolic compound content and phenolic acids content in the medicinal and spices plant raw materials (Fig. 3.6).

As it has been mentioned above, the duration of drying of crushed and chopped stems decreased by more than twice. This resulted in approx. 30 % higher total phenolic compound and phenolic acid content in raw materials.
3.2.2. Comparative study of medicinal and spice plant raw materials drying technologies

Drying research for purple coneflower and motherwort grass was carried out in the thick still layer using 3 different drying technologies: 1 – drying with active ventilation using heated ambient air; 2 – drying with active ventilation with unheated ambient (outdoor) air; 3 – drying with natural ventilation.

*Studies of drying the grass of purple coneflower.* During the drying of purple coneflower, raw materials dried the fastest using ambient air heated up to 39.2±0.1 °C, while ventilation intensity was 4000 m³(t h)⁻¹ (Fig. 3.7). Moisture levels decreased by 63.7 %, i.e. from 75.67±1.30 % to 12±0.71 % in 80 hours.

![Graph showing the evolution of moisture content in purple coneflower grass.](image)

**Fig. 3.7.** Evolution of moisture of purple coneflower grass: 1 – when drying by active ventilation using heated surrounding air; 2 – when drying by active ventilation using unheated surrounding (outside) air; 3 – when drying by natural ventilation; 4 – optimum moisture of 12–14 %
While drying the purple coneflower using unheated ambient air with the average temperature of $20.87 \pm 2.52 \, ^\circ\text{C}$ and relative humidity content of $62.46 \pm 7.93 \, \%$, the raw materials reached their moisture level of $13.65 \pm 0.64 \, \%$ after 166 hours, i.e. after 2.27 times longer period of time. The slowest drying process occurred when the purple coneflower dried with natural ventilation using unheated ambient air. After drying for 190 hours, the drying process was stopped, and moisture levels of raw material were $57.71 \pm 0.72 \, \%$.

While drying with unheated ambient air for 7 hours, the largest amount of water was moved from the lowest layer of medicinal and spice raw materials from 0.64 to 2.63 g kg$^{-1}$s.o. (Fig. 3.8 a). Continuing the drying process, moisture levels stabilised until the end of drying, i.e. up to 200 hours the average quantity of moved moisture leaves was $0.48 \pm 0.11$ g kg$^{-1}$s.o.

\[ \text{Fig. 3.8. Amount of moisture removed: a) – when drying with unheated surrounding air; b) – when drying with heated surrounding air; 1 – from the lower layer of the material; 2 – from the upper layer of the material} \]

While drying the purple coneflower using active ventilation with heated ambient air, the level of moved moisture content during first 24 hours was up to 1.85 times higher compared to the drying carried out with unheated ambient air whose levels changed from 2.27 to 6.73 g kg$^{-1}$s.o. (Fig. 3.8 b).

While drying the purple coneflower in the thick still layer using heated ambient air, the drying time which shortened more than twice resulted in larger quantities of biologically active substances (Fig. 3.9).

\[ \text{Fig. 3.9. Amount of biologically active substances in the dried grass of purple coneflower: 1 – after drying with heated surrounding air; 2 – after drying with heated surrounding air} \]

$R_{TPC}=13.07; \ R_{TFC}=0.77; \ R_{TPAC}=10.16; \ R_{\text{cichoric acid}}=1.99; \ R_{RSA}=9.21$
In the purple coneflower dried with heated ambient air with the temperature of 39.2±0.1 °C, the total phenolic compound was determined to be 31.6 % higher than in the raw materials dried with unheated ambient air at 91.85 mg g\textsubscript{s.m.}\textsuperscript{-1} RE and 62.84 mg g\textsubscript{s.m.}\textsuperscript{-1} RE respectively. Up to 46.1 % lower quantity of cichoric acid and 51.2 % lower quantity of flavonoids at 8.49 mg g\textsubscript{s.m.}\textsuperscript{-1} RE, 3.56 mg g\textsubscript{s.m.}\textsuperscript{-1} RE respectively were determined in the raw materials dried with ambient air.

**Tests of drying of motherwort grass.** Motherwort plants dried with natural ventilation as the purple coneflower dried the poorest and the longest. Due to the long and complex drying, after 120 hours of drying, the drying process of motherwort was stopped, the humidity level dropped from 76.0±1.1 % to 53.1±0.9 % (Fig. 3.10).

![Graph showing moisture content vs. drying time for different ventilation methods](image)

**Fig. 3.10.** Evolution of moisture of motherwort grass: 1, 2, 3 – when drying by active ventilation using surrounding air heated to 47.2±0.15 °C, with comparative ventilation intensity of 2000, 4000 and 6000 m\textsuperscript{3}(t h\textsuperscript{-1}), respectively; 4 – when drying using unheated surrounding (outside) air; 5 – when drying by natural ventilation; 6 – optimum humidity of medicinal–spice plant material (12–14 %)

Motherwort reached the optimum 12–14 % moisture content the fastest (within 20 hours) after it had been dried with active ventilation using ambient air heated to 47.2±0.15 °C at 6000 m\textsuperscript{3}(t h\textsuperscript{-1}) ventilation intensity. While drying raw materials using the drying agent of same parameters, only lowering the ventilation intensity to 4000 and 2000 m\textsuperscript{3}(t h\textsuperscript{-1}), the process of drying lasted 1.98 and 4.7 times longer respectively, i. e. motherwort reached the moisture level of 11.9–12.3 % after 39.5 and 94 hours.

A shorter drying time, as in the case of purple coneflower, resulted in higher phenolic compounds. The biggest amount of phenol compounds 83.88±4.19 mg g\textsubscript{s.m.}\textsuperscript{-1} RE in motherwort raw materials was after it was dried using active ventilation with heated ambient air when \( L_0=6000 \text{ m}^3\text{(t h)}^{-1} \) (Fig. 3.11). The smallest amount of phenolic compounds 67.96±3.40 mg g\textsubscript{s.m.}\textsuperscript{-1} RE was determined in medicinal raw materials which were dried using active ventilation with heated ambient air when \( L_0=2000 \text{ m}^3\text{(t h)}^{-1} \).
Fig. 3.11. Amount of biologically active substances in dried grass of motherwort: 1, 2, 3 – dried by active ventilation using surrounding air heated to 47.2±0.15 °C, with comparative ventilation intensity of 2000, 4000 and 6000 m³(t h)^{-1}; 4 – dried by active ventilation using unheated surrounding air L_{0}=4000 m³(t h)^{-1}; a, b, c – there is no statistically reliable difference between columns marked by the same letter when \( R_{TPC}=9.09 \); \( R_{TFC}=1.43 \); \( R_{RSA}=3.49 \)

However, at the maximum intensity of ventilation 6000 m³(t h)^{-1}, 2 times smaller quantity of hyperoside was determined 1.83±0.2 mg g_s.m.^{-1} RE compared to other drying techniques (Fig. 3.12)

Fig. 3.12. Influence of different drying technologies on the amount of hyperoside in the grass of motherwort: 1, 2, 3 – dried by active ventilation using surrounding air heated to 47.2±0.15 °C, with comparative ventilation intensity of 2000, 4000 and 6000 m³(t h)^{-1}; 4 – dried by active ventilation using unheated surrounding air L_{0}=4000 m³(t h)^{-1}; a – there is no reliable difference between data marked by the same letter; \( R_{a}=0.26 \)

Having carried out the study of medicinal and spice plant raw materials, it was observed that motherwort gives up its moisture levels to the drying agent more easily compared with the purple coneflower.

A shorter drying time had a positive impact on organoleptic and biochemical properties of medicinal–herb raw material.

The results of the experiments carried out reveal that, under natural conditions in Lithuania, medicinal and spice plant raw materials save the best organoleptic properties and the biggest quantity of biologically active substances when raw materials are dried using heated ambient air.
3.3. Use of solar energy to prepare the drying agent

The most intensive solar radiation as the biggest number of sunlight hours in Lithuania coincides with the harvest–preparation period of medicinal and spices plant raw materials. In order to reduce air pollution emissions to the environment and consumption of conventional energy in preparation technologies of medicinal and spice plant raw materials, it is appropriate to use solar energy for the preparation of the drying agent.

3.3.1. Drying agent preparation studies using areal solar collector

The experimental studies of drying agent preparation were carried out under production conditions in a medicinal and spice plant dryer with 131 m$^2$ of aerial solar collector area.

During the experimental studies, it was determined that, between 9:00 a.m. and 8:00 p.m. hours, i.e. within 11 hours, an area of 131 m$^2$ of aerial solar collector produces from 397.4 to 616.4 MJ of heat respectively when instantaneous power per one solar collector varies from 25.7±33 to 54.6±46.5 kW (Fig. 3.13).

*Fig. 3.13. Change of solar energy radiation flow, received by solar collector, and of the amount of converted heat when the air flow in the aerial solar collector is 1.86–2.21 kg s$^{-1}$: 1 – instantaneous power input to solar collector (7 Aug 2012); 2 – instantaneous power input to solar collector (8 Aug 2012); 3 – converted amount of heat (7 Aug 2012); 4 – converted amount of heat*

During the experimental studies an average daily temperature of 19.8±4.0 °C and relative humidity levels of 70.5±9.6 % were recorded (Fig. 3.14). Maximum values of solar irradiance ranged from 1:00 p.m. to 3:00 p.m. hours, and during individual days during this period it ranged from 332.7±359.3 to 722.1±410.2 W m$^{-2}$. On average under such natural conditions aerial solar collector heats the drying agent from 7.5 to 14 °C, i.e. the temperature of the drying agent supplied on the layer of medicinal and spice plant raw materials was 30.4±3.2 °C. Relative humidity levels of air decreased 1.84 times on average, i.e. relative humidity of drying agent – 38.2±8.0 %.
During the studies, the air speed in the aerial solar collector was amended from 0.4 to 2.9 kg s\(^{-1}\). The largest power and efficiency of the aerial solar collector was at 1.83–2.02 kg s\(^{-1}\) (Fig. 3.15). It means that at 560±50 W m\(^{-2}\) of solar irradiance and higher than 2.02 kg s\(^{-1}\) air flow in the collector, the air flows through the collector too fast and fails to transmit the whole extracted heat flux.

In medicinal and spice plant raw materials dryer, when the average solar irradiance is 453.3±317.9 W m\(^{-2}\), an aerial 131 m\(^2\) solar collector which is integrated into the roof of a building raises the ambient temperature by 8 °C on average during a period from 10:00 a.m. to 6:00 p.m. hours, i.e. the average temperature of the drying agent reaches up to 31.3 °C. It means that during 8 hours a solar collector produces 468.74±134.4 kWh of thermal energy.

During night hours, the temperature of the drying agent is close to the temperature of the ambient air. A reduced temperature of the drying agent and its volatility extends the drying period of medicinal and spice plant raw materials. And that leads to bigger losses of biologically active materials as well as mycobiotics pollution.
3.3.2. Drying agent preparation studies using a combined solar conversion system

The use of thermal energy converted from solar energy to prepare the drying agent faces a problem, i.e. the dependence of solar energy on time and natural conditions. In order to solve this problem, a technological solution was created, and an invention No. 6069 was registered under the title of “A method to prepare a drying agent using solar radiation energy and an installation to realise it”. The developed work was assessed according to the results of carried out experimental studies; also, chopped motherworts were used during in the studies.

During the experimental studies, the duration of sunlight was 16.0±0.1 hours per day. The largest solar irradiance of 881±261 W m\(^{-2}\) getting into collector was recorded at 1:30 p.m. (Fig. 3.16).

![Fig. 3.16. Change of solar energy radiation and outside air temperature through the day: 1 – solar energy radiation as established (measured), W m\(^{-2}\); 2 – theoretical (calculated) solar energy radiation, W m\(^{-2}\); 3 – outside air temperature, °C](image)

During the studies, the ventilation intensity of motherworts were controlled as well as air flow that was transported through collector: from 367 m\(^3\) h\(^{-1}\) to 1577 m\(^3\) h\(^{-1}\). Thus, the air flow per collector area unit varied from 0.0085 m\(^3\) (s m\(^{-2}\))\(^{-1}\) to 0.0365 m\(^3\) (s m\(^{-2}\))\(^{-1}\) or 0.011 kg(s m\(^{-2}\))\(^{-1}\) to 0.0472 kg(s m\(^{-2}\))\(^{-1}\).

The temperature of drying agent inside the solar collector rose to 30 °C when solar irradiance on the collector was 380–400 W m\(^2\), and the relative air flowing through the collector was 0.011 kg(s m\(^2\))\(^{-1}\). The air temperature of the drying agent was not influenced by the solar collector when solar irradiance was lower (Fig 3.17).
Fig. 3.17. Influence of solar energy radiation on the temperature of drying agent:
1 – solar energy radiation; 2 – temperature of the air passing through the collector;
3 – temperature of surrounding air.

During a clear day when the sun’s irradiance is 576±268 W m⁻², the aerial solar collector heats ambient air on an average of 19.81±10.85 °C (when relative air flow in the collector is 0.029±0.018 kg(s m⁻³)⁻¹) (Fig. 3.17). The highest temperature of air flow out of the collector is 69.5 °C. Large quality losses of raw materials can be obtained if air with such temperature is supplied to the layer of medicinal and spice plant raw materials (Belghit et al., 2000; Fatouh et al., 2006; Kouhila et al., 2002; Müller, Heindl, 2006).

In a case when the air–type solar collector preheated ambient air above the earlier set temperature of 30–40 °C, flows of preheated and not preheated ambient air entering the mixing chamber were regulated. The proportion of air pre–warmed in the collector with the air pumped from the environment is described by mixing ratio $k_s$. Mixing ratio $k_s$ increases when the temperature of the outgoing air from the air–type solar collector goes up (Fig. 3.18).

\begin{align*}
k_s &= -0.0007t_k^2 + 0.0898t_k - 1.9653 \\
R^2 &= 0.967
\end{align*}

Fig. 3.18. Dependence of mixing coefficient on the temperature of air passing through aerial solar collector.

In the daytime, the air-type solar collector converts solar radiation energy to heat and uses it for direct heating of the drying agent. Meanwhile, the heat flow converted by a flat-plate solar collector is accumulated in water tanks and is
employed during the dark period of the day or when the power of the air-type solar collector is not sufficient to ensure consistent parameters of the drying agent.

During the daylight hours, over 10 hours 99.93 MJ of heat energy was accumulated in a storage tank when irradiance flow falling on the platter solar collector was $4743\pm1973$ W per hour (Fig. 3.19). The amount of heat energy accumulated in the tank varied in accordance with the third grade polynomial, $R = 0.997$.

![Graph](image_url)

**Fig. 3.19.** Evolution of accumulated amount of heat: 1 – instantaneous power of solar collector; 2 – amount of accumulated heat

Under conditions when chopped motherwort plants are ventilated at the intensity of $6000\, m^3 (t\, h)^{-1}$, the accumulated heat is sufficient for 6.5 hours. The reduction of the ventilation intensity down to $3000\, m^3 (t\, h)^{-1}$ would make the amount of stored heat sufficient for 12 hours, i.e. at a favourable air condition until the time when an air-type solar collector is capable of warming ambient air up to $30\, ^\circ C$ required for drying.

Variation of the drying agent parameters in the experimental dryer with an installation for solar energy storage during the experimental research is shown in Fig. 3.20.

![Graph](image_url)

**Fig. 3.20.** Evolution of parameters of drying agent in a medicinal herb dryer with solar energy accumulation device: 1 – solar energy radiation; 2 – temperature of air passing through aerial solar collector; 3 – temperature of drying agent (air supplied into the layer of medicinal-spice plant material layer); 4 – surrounding air temperature
In the experimental dryer for medicinal plants, by using a hybrid solar collector system with heat accumulation, in cool temperate climate zone, the optimal drying mode for motherwort drying was maintained around the clock. As a result of the comparative theoretical research, it was determined that analogous dryers would consume from 81 to 235 kWh of electrical or other concentrated fossil energy to dry 150 kg of motherwort.

3.3.3. Environmental impact assessment of the use of solar conversion systems for the preparation of the drying agent

Drying 100 kg of medicinal plant raw materials from 75 % to 12 % of moisture level, its mass decreases by 71.6 %. It means that during the drying process a 71.6 kg of water must be subsequently evaporated from medicinal and spice plant raw materials. For such an amount of water to be evaporated during the period from April to September, the average of 65.1±6.8 kWh of thermal energy is needed to warm the drying agent up to 30 °C. This amount of thermal energy can be obtained after consumption of 65.1±6.8 kWh of electricity or after burning 7.7±0.8 m³ of natural gas or 13.8±1.4 kg of wood, but the usage of normal fuels releases air pollution to the environment (Table 3.1).

Table 3.1. Environmental impact of using different technologies for the preparation of the drying agent, when 65±7 kWh of thermal energy is used for heating up the drying agent in order to dry 100 kg of material to 12 % humidity.

<table>
<thead>
<tr>
<th>Type of fuel / energy</th>
<th>Amount of fuel (energy) used</th>
<th>Air pollution</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CO₂, t</td>
<td>SO₂, kg</td>
</tr>
<tr>
<td>100 % usage of usual energy sources</td>
<td></td>
<td>40,8±4,2</td>
<td>29,3±3,0</td>
</tr>
<tr>
<td>Electricity, kWh</td>
<td>65,1±6,8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas, m³*</td>
<td>7,7±0,8</td>
<td>14,7±1,5</td>
<td>0,07±0,01</td>
</tr>
<tr>
<td>Wood, kg*</td>
<td>13,8±1,4</td>
<td>26,3±2,7</td>
<td>33,5±3,5</td>
</tr>
<tr>
<td>70 % usage of solar radiation energy, 30 % usage of thermal energy from other sources</td>
<td>19,5±2,0</td>
<td>12,2±1,3</td>
<td>8,8±0,9</td>
</tr>
<tr>
<td>Electricity, MWh</td>
<td>2,3±0,2</td>
<td>4,4±0,5</td>
<td>0,02±0,002</td>
</tr>
<tr>
<td>Natural gas, m³*</td>
<td>4,1±0,4</td>
<td>7,9±0,8</td>
<td>10,1±1,0</td>
</tr>
<tr>
<td>Wood, kg*</td>
<td>0,02±0,002</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* when calculating the required amount of fuel and greenhouse emissions, assumed efficiency coefficient of the systems was 0.9.

Using aerial solar collectors for the preparation of the drying agent heat demand can be met up to 70 %. However, conventional energy sources are used only at night or due to unfavourable natural conditions when irradiance of the sun is too low at a given moment. It means that during the preparation of the drying agent, while using aerial solar collectors, air pollution emissions that are emitted into the environment can be reduced up to 70 %, i. e. in this case, 4.4–12.2 t of CO₂, 0.02–33.1 kg of SO₂ and 7.4–18.6 kg of NOₓ will escape into
the environment. After using a combined solar conversion system with an accumulation device for preparation of the drying agent, air pollution can be reduced up to 100%.

CONCLUSIONS

1. During the period of harvest-preparation for medicinal and spice plants, Lithuania has about 50% of the annual rainfall, and one month has an average of 10 rainy days. The duration of sunlight is 1345 hours or 7–8 hours per day. Solar radiation intensity is 4.1±0.8 kWh per day. Lithuanian natural conditions are close to Poland’s and Germany’s natural conditions.

2. Plants dried with heated ambient air at 4000 m³(t h)⁻¹ ventilation intensity possess the best properties. Drying mechanically affected purple coneflower stems using heated ambient air, the drying time was reduced from 43 hours to 19.5 hours, and phenolic compounds and phenolic acids in raw materials remained on average 30 % higher.

3. In medicinal plant dryer with 131 m² air solar collector integrated into the roof of the building, when solar irradiance was 453.3±317.9 W m² and the ambient air temperature of 23.1±3.8 °C from 10:00 a.m. to 6:00 p.m. maintained at 31.3±3.8 °C temperature desiccant. It means that external solar collector, within 8 hours, converts 468.7±134.4 kWh of thermal energy. The largest air solar collector efficiency factor was 0.6, while comparative air flow from 1.8 to 2.0 kg s⁻¹ was moving over the panels.

4. By reducing the drying process intensity dependency on the solar radiation, a dryer with combined radiated energy conversion system which accumulates thermal energy was created. Studies have shown that in such a dryer when optimally managing the plant drying process, stable performance and continuous drying without additional energy sources are maintained all day (Invention No. 6069 "A method to prepare a drying agent using solar radiation energy and an installation to realise it").

5. It was found that, in order to dry 100 kg of moist medicinal and spice plant raw materials, heating the dryer agent to 30 °C requires 65.1±6.8 kWh of thermal energy. By using air solar panels for dryer preparation, 70 % of fossil fuel (fuel oil) or biofuel (wood) consumption can be reduced along with the air pollution emissions to the environment. This way, CO₂, SO₂, NOₓ emissions would decrease by 14.1±2.4 tons, 17.6±1.8 kg and 23.6±2.5 kg respectively compared to 100 % liquid fuel and 18.4±1.9 tons, 23.5±2.4 kg and 17.4±1.8 kg respectively, compared with 100 % use of wood. Using a combination solar conversion system with accumulation to warm the drying agent, air pollution emissions are reduced to a minimum.
LIST OF PUBLICATIONS

Articles assessed in the “Web of Science” database and containing a citation index


Other publications assessed in the “Web of Science” database


Currently reviewed scientific publications which are assessed in other databases


Other reviewed scientific publications

(articles in confirmed scientific journals of Lithuania and continuous publications, articles in other scientific journals, printed scientific reports of conferences, articles from encyclopedia)

Articles not included in scientific publications groups
(In science popularization publications, not reviewed conference material etc.)


Information Sheets


Normative documents

SAULĖS ENERGIJOS NAUDOJIMAS VAISTINIŲ-PRIEŠKONINIŲ AUGALŲ DŽIOVINIMO TECHNOLOGIJOSE

REZIUMĖ

Didėjanti vaistinės-prieškoninės augalinės žaliavos paklausa, skatina kurti bei tobulinti jau esamas žaliavos ruošimo technologijas. Vaistiniai-prieškoniniai augalai ir paruošta žaliava vertinama pagal juose sukauptą ir išsaugotą biologiškai veikliųjų medžiagų kiekį ir sudėtį. Daugelio nuimtų augalų drėgnumas siekia 70–80 %, todėl svarbu laiku ji sumažinti iki saugaus 12–14 % drėgnumo. Pastaraisiais dešimtmečiais intensyviai ieškoma naujų ir draugiškų aplinkai energijos šaltinių, tinkančių džiovinimui technologijose. Šio darbo tikslas – nustatyti energijos sąnaudų mažinimo galimybes džiovinant vaistinius-prieškoninius augalus, panaudojant saulės energiją. Mažinant džiovinimo procesų priklausomybę nuo saulės energinės apšvietos kaitos ir neigiamą poveikį aplinkai buvo sukurta džiovykla su kombinuota saulės spinduliutės energijos konversijos sistema, akumuliuojanti šiluminę energiją. Eksperimentiniai tyrimai nustatytų, kad tokio tipo džiovykloje optimaliai valdant vaistinių-prieškoninių augalų džiovinimo procesą, palaikomi stabilus džioviklio parametrai ir nepertraukiamas džiovinimas be papildomų energijos šaltinių visą parą. (Išradimas Nr. 6069 „Džioviklio ruošimo panaudojant saulės spinduliutės energiją būdas ir įrenginys tam būdu realizuoti“). Taip pat buvo nustatyta, kad rausvažiedė ežiuolė ir paprastoji sukutžolė geriausias savybes išsaugojo jos džiovinant pašildytu aplinkos oro, kai lyginamas ventiliavimo intensyvumas 4000 m³(t h)⁻¹. Džiovinant mechaniskai paveiktus rausvažiedės ežiuolės stiebus pašildytu aplinkos oro, jų džiūvimo trukmė sutrumpėjo nuo 43 val. iki 19,5 val., o fenolinų junginių ir fenolinų rūgščių kiekis žaliavoje išliko vidutiniškai 30 % didesnis.

Hipotezė: vidutinio klimato zonoje racionaliai naudojant saulės energiją galima sumažinti įprastinės energijos sąnaudas ir neigiamą poveikį aplinkai vaistinės-prieškoninės augalinės žaliavos džiovinimo technologijose

Darbo tikslas: nustatyti energijos sąnaudų mažinimo galimybes džiovinant vaistinius-prieškoninius augalus panaudojant saulės energiją

Darbo uždaviniai

1. Nustatyti saulės spinduliutės ir kitų gamtinių šaltinių įtaką dėsningumui Lietuvoje vaistinių-prieškoninių augalų įprastinių poveikį aplinkai vaistinės-prieškoninės augalinės žaliavos džiovinimui ir paprastų pašildytų aplinkos oro, kai lyginamas ventiliavimo intensyvumas 4000 m³(t h)⁻¹.
2. Nustatyti džioviklio temperatūros, ventiliavimo intensyvumo ir vaistinės-prieškoninės augalinės žaliavos paruošimo džiovinimui įtaką jos kokybei.
3. Nustatyti džioviklio parametrų ir vaistinių-prieskoninių augalų džiovinimo proceso kitimo dėsningumus džiovykloje su oriniu saulės kolektoriumi.
4. Ištirti džioviklio užsiduotų parametrų palaikymo galimybes, naudojant kombinuotą saulės energijos konversijos sistemą su energijos akumuliavimu.
5. Įvertinti sukurtų džiovinimo technologijų, naudojančių saulės energijos konversijos sistemas, poveikį aplinkai.

Disertacijos ginamieji teiginiai

1. Ekologiškai užaugintos ir paruoštos vaistinės-prieskoninės augalinės žaliavos kokybė (organoleptinės ir bio cheminės savybės) priklauso nuo augalo morfologinių dalių savybių, žaliavos paruošimo būdo ir džiovinimo technologijos efektyvumo.
2. Pastovius džioviklio parametrus ir nepertraukiamą vaistinės-prieskoninės augalinės žaliavos džiovinimo procesą galima sukurti (palaikyti) naudojant tiesioginę ir akumuliuotą saulės energiją.
3. Džioviklio paruošimui naudojant kombinuotą saulės konversijos sistemą su energijos akumuliavimu galima sumažinti neigiamą poveikį aplinkai.
Brief information about the author

Aušra Čiplienė (Janulevičiūtė) was born on August 31, 1985, in Kaunas region. In 2003, she graduated from high school in Noreikiškės. In 2003-2007 she acquired a Bachelor’s degree of Engineering in Agricultural Product Storage and Processing at the Lithuanian University of Agriculture. In 2007-2009, she acquired a Master’s degree in Mechanical Engineering in the field of Technology Science at the Lithuanian University of Agriculture. In 2010-2014, she took on doctoral studies in Environmental Engineering in the field of Technology Science at Aleksandras Stulginskis University. Since 2014, she has been working as an assistant at the Institute of Energy and Biotechnology Engineering at Aleksandras Stulginskis University.

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SAULĖS ENERGIJOS NAUDOJIMAS VAISTINIŲ-PRIESKONINIŲ AUGALŲ DŽIOVINIMO TECHNOLOGIJOSE

AUŠRA ČIPLIENĖ

Daktaro disertacijos santrauka