Electricity consumption of drying and the effect of the dryer and temperature on the chemical quality of nettle leaves (*Urtica dioica* L.), birch leaves (*Betula pendula*, *Betula pubescens*) and roseroot (*Rhodiola rosea* L.)

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Research Article

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Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Data availability

All data analysed during this study are included in this published article and its supplementary information files.

Code availability

Not applicable.

Authors' contributions

The idea of the research arrived from Jaana Väisänen and Leena Favén. The research plan, data collection and interpretation was performed by Eveliina Isosaari. The first draft of the manuscript was written by Eveliina Isosaari and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Abstract

Drying can constitute the majority of the energy costs and thus, manufacturing costs, in plant refining. The use of higher drying temperatures accelerates drying and reduces total electricity consumption. However, higher drying temperatures can also reduce the chemical quality of plants, as heat sensitive compounds can degrade or evaporate. The purpose of the study was to find the optimum drying temperature for nettle leaves (*Urtica dioica* L.), white and silver birch leaves (*Betula pubescens*, *Betula pendula*) and roseroot (*Rhodiola rosea* L.) in terms of electricity consumption and quality. Selected plants were dried with drying oven, convective dryer and vacuum dryer between 40 and 80 °C. The quality was determined by measuring total polyphenol content, antioxidant capacity and active compounds of roseroot. The lowest total electricity consumption was obtained by drying oven, but the highest chemical quality was obtained by vacuum dryer. The optimum drying temperature varied between 65 and 80 °C.

Keywords: drying temperature; electricity consumption; chemical quality; polyphenols; antioxidants

Introduction

The market of natural and organic products, including food, consumer packaged goods, personal care products, cosmetics and supplements, has increased over the years and it's expected to grow even more [1,2]. In the United States, the revenue of natural products grew from US\$ 51 billion to US\$ 64 billion from mid-2015 to mid-2019. In this time, approximately 3600 natural brands emerged in the markets [2].

Due to increasing market, competition and fraud products, it is important be able to stand out from the mass and offer high-quality of products [1-3]. Besides good quality ingredients, also processing should be conducted in a way that preserves quality. Drying, grinding and chopping can cause chemical compounds to degrade or evaporate. This can lead to changes in shape, structure and color, loss of aroma and nutrients and inactivation of bacteria and enzymes [4-6]. However, drying is needed for longer storage time, to prevent the growth and reproduction of micro-organisms, to minimize packaging size and to reduce transport weight [5,6]. By controlling and optimizing the drying conditions, the properties of the ingredients can be preserved to a greater extent and without considerable reduction in quality [6].

Polyphenols are secondary metabolites of plants produced to protect against the UV-radiation and pathogen aggression [7,8]. They also affect color, flavor, odor, astringency, bitterness and oxidative stability of plants and plant-based products [8]. In human diet, polyphenols are recognized as anti-inflammatory, antiviral and antimicrobial [7,9]. Thus, polyphenols are responsible for several quality characteristics of plant-based products.

Several polyphenols also act as antioxidants, which are believed to play a protective role in our health. Antioxidants can prevent the oxidation of other compounds leading themselves being oxidized. In human cells, they can protect proteins, lipids and DNA from oxidation caused by free radicals such as nitrogen and oxygen radicals. In the worst case, free radicals can cause irreversible damage to cellular structures causing cancer or other chronic diseases [10].

Many plants also contain compounds of particular interest. In roseroot (*Rhodiola rosea* L.), these are salidroside, tyrosol, rosin, rosavin, rosin and cinnamyl alcohol. Rosin, rosavin and rosavin are derivatives of cinnamyl alcohol and salidroside is a derivative of tyrosol. Rosarin, rosavin and rosin, known under the collective name of rosavins, are considered the most important compounds of roseroot as they are not found in any other species of the *Rhodiola* genus [11,12].

Drying can cover the most of the energy costs or even total costs of the processing chain [13]. According to Müller & Heindl (2006) [13], drying accounts for 30 to 50% of the total costs of the

production of medicinal plants, where low drying temperatures and long drying times are used. A contemplated selection of the dryer and temperature can reduce the energy consumption of drying. For example, freeze drying and vacuum drying consume more electricity than convective drying, but the quality of dried plants is often higher [4,5,14]. Microwave drying consumes less electricity than convective drying, but the dryer itself is rather expensive [14,15]. Solar drying consumes only energy from the sun, but the drying process is slow and the material is exposed to weather conditions and contaminants [5].

Expensive equipment investments in drying often lead to the use of cheaper conventional dryers such as drying oven or convective dryer [4,5,15]. Hybrid drying, a combination of two drying methods, could improve quality of drying, decrease electricity consumption or shorten the drying time [5]. For example, a microwave-vacuum dryer is considered having the advantages of both microwave dryer and vacuum dryer: low electricity consumption and good quality of plant-based products. Microwave-convective dryer instead enables short drying time, as the penetration of microwaves facilitates the moisture movement from inside of the material to the surface, where hot airflow displaces it [16].

This study attempted to find the optimum drying temperature for nettle leaves (*Urtica dioica* L.), birch leaves (*Betula pubescens*, *Betula pendula*) and roseroot in terms of quality and energy consumption. The selected plants were dried with conventional drying oven, improved convective dryer and vacuum dryer using the temperatures of 40 to 80 °C. The quality of the dried plants was assessed by determining total polyphenol content and antioxidant capacity. In addition, the compounds of roseroot, salidroside, tyrosol, cinnamyl alcohol and rosavins, were analyzed by high performance liquid chromatograph (HPLC).

Materials and methods

Chemicals and reagents

Methanol, Folin-Ciocalteu's phenol reagent, sodium carbonate, copper(II) chloride dihydrate, ammonium acetate, neocuproine, gallic acid (synthesis grade), (±)-6-hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (trolox), rosin, rosavin, rosin, tyrosol and cinnamyl alcohol were purchased from Merck KGaA (Darmstadt, Germany). Salidroside was purchased from Extrasynthese (Genay, France). Acetonitrile and trifluoroacetic acid were purchased from VWR Chemicals (Radnor, PA, USA). Ethanol Etax A was purchased from Altia Oyj (Helsinki, Suomi).

Samples

Cultivated nettle was obtained from a farm in Kainuu, Finland. Birch leaves, including both white birch and silver birch leaves, were collected from freshly felled trees in Central Ostrobothnia, Finland. The

nettle leaves and birch leaves were separated from the stalks and branches prior to drying. Cultivated roseroot was obtained from a farm in Central Ostrobothnia, Finland. The rhizomes and roots of roseroot were chopped into smaller pieces, washed out of the remaining soil and sliced with a vegetable cutter. The nettle leaves, birch leaves and roseroot slices were stored in a freezer at -20 °C until drying.

Drying

Plants were spread out in a thin layer to the drying level and dried at 40, 50, 55, 60, 65, 70 and 80 °C, except of convective dryer, where the highest possible drying temperature was 75 °C. A duplicate drying was performed at each temperature point. The moisture content of the plants was assessed by weighing before and during the drying. After a certain mass loss, usually 63 to 78% depending on the starting moisture, the drying was stopped.

Typically, a moisture content of 8 to 12 m-% is suitable for dried plants. Higher moisture content reduces the shelf-life of plant-based products and enables the growth of micro-organisms [13]. Thus, the aim of the drying was to achieve a moisture content of 12 m-%, as significantly lower moisture content would cause unnecessary electricity consumption.

The electricity consumption of the dryers was measured by an electric kWh meter (Carlo Gavazzi EM340), which was installed between the electric supply and the dryer. The recording of the electricity consumption started after the dryer had reached the drying temperature, and it was recorded for one hour. Data was collected on the drying temperatures of 40, 60 and 80 °C (75 °C with convective dryer) covering the lowest, middle and highest temperature of the drying range. Total electricity consumption was calculated by multiplying the electricity consumption (kWh) by the drying time (h).

Dryers

Three small-scale dryers were used in the drying experiments: conventional drying oven, modified convective dryer and vacuum dryer. The conventional drying oven was a well-insulated laboratory scale Thermo Heraeus T6030 heating and drying oven. The vacuum dryer was also a laboratory scale dryer, Vacucell 55 Eco attached to a vacuum pump Vacubrand MD 4C NT.

A vacuum dryer is similar to a conventional drying oven, except drying occurs in a vacuum without ambient air. The absence of air, especially oxygen, reduces the amount of unwanted chemical reactions and improves the quality of dried plants. Vacuum also intensifies water evaporation, as air and water vapor expand, the material swells and its volume and surface area increase. This leads to better heat transfer between the material and the environment. However, the main disadvantage of the vacuum drying is the high energy consumption [16].

The convective dryer used in the experiments was a modified and improved version of a small-scale Orakas Hyötykasvikuivuri 5521. The thermostat and heat and blower unit of Orakas Hyötykasvikuivuri are located at the bottom of the dryer, making the temperature control challenging and causing heat to deviate unevenly in the dryer. To improve the heat distribution, the dryer was turned on its side to obtain horizontal airflow and the drying shelves were installed in a new position. A new thermostat (Omron E5C PID) was installed in the dryer, improving the accuracy of temperature control. In addition, an air recirculation channel was added to the dryer to recycle warm exhaust air back into the fresh air inlet. This modification improved the energy efficiency and reduced the electricity consumption of the dryer.

Convective drying is perhaps the most common and widely used method for drying fruits, vegetables and medicinal plants. In the drying process, water diffuses to the surface of the material by a moisture concentration gradient, from which hot airflow displaces it. However, the method has downsides: low energy efficiency and thermal conductivity [16-17]. Also, the water diffusion is slow, prolonging the drying and exposing the material more to the oxygen [17]. Convective drying can also cause hardening and shrinkage of the dried plants [16].

Moisture content

The dried plants were ground with IKA A11 analytical mill into fine powder. The samples were stored at RT in plastic jars. The moisture content was determined by drying 1.5 g of sample at 105 ± 5 °C overnight (at least 15h) and calculating the mass loss. A duplicate moisture content was made from each sample.

Extraction

The dried and powdered plants were extracted ultrasonic-assisted. The extraction parameters (solvent, solid-solvent ratio, temperature and extraction rounds) were selected based on limited experiments. Each sample underwent a duplicate extraction and each extract a duplicate analysis to exclude the effect of natural variations and sampling (Fig. 1).

Fig. 1 The implementation of the drying trials and quality characterization.

One (1) gram of nettle leaf powder was mixed with 60 ml of deionized water in a 100 ml Erlenmeyer flask with a screw cap. The mixture was sonicated for 30 minutes at 30 °C. Then, the extract was mixed with 20 ml of 94% (v/v) ethanol and filtered through 1.20 µm and 0.45 µm PTFE filters to separate the extract from the solid residue.

One (1) gram of birch leaf powder was mixed with 40 ml of 50% ethanol in a 100 ml Erlenmeyer flask with a screw cap. The mixture was sonicated for 30 minutes at 30 °C. Then, the extract was centrifuged for 10 minutes at 4000 rpm. Ten (10) milliliters of the supernatant was recovered and the solid residue transferred back to the Erlenmeyer flask. The residue was re-extracted with 40 ml of 50% ethanol and centrifuged. Ten (10) milliliters of supernatant was recovered and combined with the first supernatant.

One (1) gram of roseroot powder was mixed with 20 ml of 70% methanol in a 100 ml capful Erlenmeyer flask with a screw cap. The mixture was sonicated for 30 minutes at 30 °C. Then, the extract was centrifuged for 10 minutes 4000 rpm. Five (5) millilitres of the supernatant was recovered and the solid residue was transferred back to the Erlenmeyer flask. The residue was re-extracted with 20 ml of 70% methanol, centrifuged and 5 millilitres of supernatant recovered. The extraction was repeated once more and all three supernatants were combined.

Quality characterization

Total polyphenol content

Total polyphenol content (TPC) was determined by Folin-Ciocalteu's assay using the procedure described by Mota et al. (2012) [18]. Half (0.5) ml of extract was mixed with 2.5 ml of Folin-Ciocalteu's phenol reagent (0.2 M) and 2.0 ml of sodium carbonate solution (75 g/l). The mixture was heated in a water bath at 50 °C for 5 minutes and cooled to RT. The absorbance was recorded by Shimadzu UV-1800 spectrophotometer at 760 nm against reagent blank. Gallic acid (0.01 – 0.10 mg/ml) was used as a standard and the results are expressed as gallic acid equivalents per dry weight (mg GAE/g dw).

Antioxidant capacity by CUPRAC

Antioxidant capacity (AC) was determined by CUPRAC (cupric ion reducing antioxidant capacity) assay using the procedure described by Özyürek et al. (2011) [19]. One (1) ml of copper chloride (0.01 M), 1 ml of ammonium acetate (1.0 M), 1 ml of neocuproine (0.0075 M) and 1 ml of water was mixed with 0.1 ml of extract. The mixture was left to react to dark, at RT, for 30 minutes. The absorbance was recorded by Shimadzu UV-1800 spectrophotometer at 450 nm against reagent blank. Trolox (0.01 –

0.25 mM) was used as a standard and the results are expressed as Trolox equivalents per dry weight (mmol TE/g dw).

HPLC analysis of active compounds in roseroot

The analysis of salidroside, tyrosol, cinnamyl alcohol and rosavins was performed with HPLC, Shimadzu LC-20A Prominence, equipped with diode array detector (DAD). The assay is based on the procedures described by Marchev et al. (2017) [20] and Peschel et al. (2016) [21]. The extracts were filtered through 0.45 µm PTFE filters and transferred into vials. The column was Waters XBridge C18 (3.5 µm, 4.6 x 150 mm) and mobile phases were A: 0.1 % TFA in acetonitrile and B: deionized water. The gradient conditions were as follows: 0 – 10 min 90% B; 10 – 25 min from 90% to 80% B; 25 – 35 min from 80% to 55% B; 35 – 39 min 10% B and 39 min 90% B with 4.5 min post-run time. Other parameters were 1 ml/min flow rate, 30 °C column temperature and 10 µL sample injection. The detection of salidroside and tyrosol occurred at 225 nm and the detection of cinnamyl alcohol and rosavins at 254 nm. Corresponding standards (0.100 – 0.150 mg/ml) were used in the quantification and the results are expressed per dry weight (mg/kg dw).

Results and discussion

Electricity consumption

The electricity consumption of the convective dryer, excluding the energy needed for heating, was 0.23, 0.53 and 0.98 kWh per hour when the drying occurred at 40, 60 and 75 °C, respectively. The electricity consumption of the drying oven was 0.02, 0.04 and 0.08 kWh per hour and the vacuum dryer was 0.33, 0.33 and 0.37 kWh per hour when the drying occurred at 40, 60 and 80 °C, respectively (Suppl. 1, Tab. 1). Thus, the lowest electricity consumption per hour was obtained with the drying oven, followed by the vacuum dryer and the convective dryer. With the vacuum dryer, higher drying temperatures did not increase the electricity consumption per hour as the cabinet is extremely well insulated.

The drying time was the shortest with the convective dryer followed by the vacuum dryer and the drying oven (Suppl. 1, Tab. 1). To obtain the total electricity consumption, the electricity consumption (kWh) per hour was multiplied with the spent drying hours (h). Even with the longest drying time, the drying oven clearly had the lowest total electricity consumption at each temperature. At 40 and 60 °C, the vacuum dryer typically had the highest total electricity consumption. At 80 °C, the drying time was short regardless of the dryer, resulting in the convective dryer having the highest total electricity consumption (Fig. 2).

Fig. 2 Total electricity consumption of the dryers in the drying of nettle leaves, birch leaves and roseroot, where ● is the drying oven, ● the convective dryer and ● the vacuum dryer.

**The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.*

The drying of nettle leaves occurred fast and therefore, total electricity consumption remained reasonable. With the drying oven and the convective dryer, temperatures between 40 and 80 °C did not significantly affect total electricity consumption. However, the vacuum dryer achieved 46 and 77% lower total electricity consumption when the nettle leaves were dried at 60 and 80 °C instead of 40 °C, respectively.

The drying of birch leaves took approximately two to three times longer than the drying of nettle leaves (Suppl. 1, Tab. 1). The drying temperature did not have notable effect on total electricity consumption of the drying oven. However, the total electricity consumption of the convective dryer was 61 and 48% lower when dried at 60 and 75 °C instead of 40 °C, respectively. Total electricity consumption of the vacuum dryer was 62 and 78% lower when dried at 60 and 80 °C instead of 40 °C, respectively.

Roseroot was dried in few millimeters' thick slices, slowing the transfer of water to the surface, significantly extending the drying time compared with nettle leaves and birch leaves [16]. At 40 °C, the drying took considerably more than 12 hours, so the drying was allowed to continue overnight. This resulted in all three dryers having the same drying time at 40 °C, causing a really high total electricity consumption for the convective dryer and the vacuum dryer. Total electricity consumption of the convective dryer was up to 256% higher and vacuum dryer up to 340% higher when dried at 40 °C instead of 60 °C, respectively. Thus, total electricity consumption could be considerably reduced by increasing the drying temperature from 40 °C to 60 or 80 °C.

Depending on the temperature and the dried material, total electricity consumption of the drying oven was 5 to 18 times lower than that of the convective dryer and 2 to 22 times lower than that of the vacuum dryer. Differences in total electricity consumption of the dryers increased as the drying time lengthened. The greatest differences between the dryers were observed when the roseroot slices were dried at 40 °C.

Moisture content

The moisture content of dried nettle leaves varied between 4.52 – 21.68 m-%, 3.08 – 27.33 m-% and 3.66 – 22.27 m-% when dried with the drying oven, convective dryer and vacuum dryer, respectively. The moisture content of dried birch leaves varied between 4.23 – 11.16 m-%, 2.51 – 10.19 m-% and 3.24 – 7.64 m-% and the moisture content of roseroot between 4.70 – 15.02 m-%, 4.61 – 12.30 m-% and 2.05 – 16.40 m-% when dried with the drying oven, convective dryer and vacuum dryer, respectively (Suppl. 2, Tab. 1.). The moisture content of nettle leaves was relatively high in part of the samples. Therefore, the dried samples were extracted and analyzed as fast as possible to avoid the growth and effect of micro-organisms on the results.

Chemical quality

TPC correlates strongly with AC. TPC of dried nettle leaves varied from 4.19 to 6.13 mg GAE/g dw with the drying oven, from 4.87 to 6.67 mg GAE/g dw with the convective dryer and from 9.91 to 17.84 mg GAE/g dw with the vacuum dryer. AC varied from 0.031 to 0.051 mmol TE/g dw with the drying oven, from 0.038 to 0.056 mmol TE/g dw with the convective dryer and from 0.129 to 0.195 mmol TE/g dw with the vacuum dryer (Suppl. 3, Tab. 1). Thus, significantly higher TPC and AC were achieved with the vacuum dryer. The difference in TPC and AC between the convective dryer and the drying oven is small, but slightly higher contents were measured from nettle leaves dried with the convective dryer (Fig. 3).

Fig. 3 Total polyphenol content (TPC) and antioxidant capacity (AC) of dried nettle leaves, where ● is the drying oven, ● the convective dryer and ● the vacuum dryer.

**The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.*

Based on TPC and AC, the optimum drying temperature for nettle leaves appears to be 65 °C when dried with the vacuum dryer, 65 to 75 °C when dried with the convective dryer and 50 °C when dried with the drying oven. Thus, the highest TPC and AC are achieved at the drying temperatures of 50 - 75 °C (Fig. 3).

Shonte et al. (2020) [4] found that compared with fresh and freeze-dried nettles, oven-dried nettles had the lowest β -carotene, vitamin A and ascorbic acid content but the highest total phenol content and antioxidant activity. The loss of β -carotene, vitamin A and ascorbic acid in the oven drying was suspected to be due to higher drying temperature (70 °C), which could cause the degradation or oxidation of the compounds. Also, Multari et al. (2018) [22] discovered in the drying of quinoa seeds and Delgado-Nieblas et al. (2015) [23] in the drying of naranjita pomace, that higher TPC was obtained when higher drying temperatures were used.

The increase of TPC at high drying temperatures is most likely caused by the positive effect of temperature on extraction. High drying temperature improves the release of polyphenols from the cellular structures of plants, raising their solubility in the extraction phase [4,22]. In addition, the breakage of bonds between polyphenols and sugars at high drying temperatures leads to the formation of aglycones that react better with Folin-Ciocalteu's reagent in the polyphenol assay [4,24].

The effect of high drying temperatures on extraction efficiency is likely to explain the increase in AC as well. Antioxidants may also form in chemical reactions during drying or may be preserved to a greater extent due to the inactivation of oxidative enzymes [4].

TPC of dried birch leaves varied from 41.78 to 46.22 mg GAE/g dw with the drying oven, from 45.33 to 52.63 mg GAE/g dw with the convective dryer and from 57.62 to 65.31 mg GAE/g dw with the vacuum dryer. AC of birch leaves varied from 0.420 to 0.535 mmol TE/g dw with the drying oven, from 0.458 to 0.575 mmol TE/g dw with the convective dryer and from 0.608 to 0.689 mmol TE/g dw with the vacuum dryer (Suppl. 3, Tab. 2).

Also, with birch leaves, the highest TPC and AC were achieved when dried with the vacuum dryer. The drying temperature does not appear to have significant effect on TPC or AC of birch leaves. Only slightly higher contents were obtained at 65 to 80 °C when dried with the drying oven and the convective dryer. With the vacuum dryer, the quality remained similar throughout the temperature range (Fig. 4).

Fig. 4 Total polyphenol content (TPC) and antioxidant capacity (AC) of dried birch leaves, where
 ● is the drying oven, ● the convective dryer and ● the vacuum dryer.

**The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.*

Keinänen & Julkunen-Tiitto (1996) [25] studied the effect of various drying methods, including oven drying, on the content of individual polyphenols in birch leaves. They found the content of flavonoid glycosides to be higher in the oven drying at 80 °C than at 40 °C, but the content of other polyphenols was slightly lower. They suspected that the differences between temperatures could be explained by the different thermostability of the compounds and slower inactivation of enzymes at 40 °C.

TPC of dried roseroot slices varied from 92.24 to 180.78 mg GAE/g dw with the drying oven, from 90.33 to 209.39 mg GAE/g dw with the convective dryer and from 105.19 to 195.81 mg GAE/g dw with the vacuum dryer. AC varied from 1.287 to 1.734 mmol TE/g dw with the drying oven, from 1.242 to

1.970 mmol TE/g dw with the convective dryer and from 1.430 to 1.863 mmol TE/g dw with the vacuum dryer (Suppl. 3, Tab. 3).

Unlike in the results of nettle and birch leaves, the differences between the dryers are hardly significant with roseroot slices. Only slightly higher TPC and AC are obtained with the vacuum dryer when dried at 40 - 65 °C and with the convective dryer when dried at and above 70 °C. This may indicate that the polyphenols and antioxidants of roseroot do not oxidize sensitively in the presence of air, and therefore the vacuum dryer does not distinguish itself from other dryers. The highest TPC and AC were obtained when the drying temperature was 70 - 80 °C (Fig. 5).

Fig. 5 Total polyphenol content (TPC) and antioxidant capacity (AC) of dried roseroot rhizomes and root, where ● is the drying oven, ● the convective dryer and ● the vacuum dryer.

**The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.*

The ratio of rosavins (rosarin, rosavin and rosin) to salidroside is one way to demonstrate the quality of roseroot, as rosavins are the most important compounds of the plant. The highest rosavins to salidroside ratios (1.77 – 2.05) were typically obtained at drying temperatures between 60 and 65 °C, and the lowest at 50, 55 and 70 °C (Fig. 6). This may be due to an increase in the content of rosavins or a decrease in the content of salidroside at 60 - 65 °C.

Fig. 6 Ratio of rosavins to salidroside, where ● is the drying oven, ● the convective dryer and ● the vacuum dryer.

**The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.*

High standard deviation of salidroside, rosavin, rosin and tyrosol content does not allow reliable conclusions about the effect of drying temperature or dryers on the results (Fig. 7). Peschel et al. (2013) [26] found that the rhizomes of roseroot contain 2.5 to 3.5 times more rosavins than the roots. Thus, the ratio of rhizomes to roots in the samples affects the content of active compounds. This could explain the high standard deviation, as the ratio of roots to rhizomes of the samples was not determined.

The standard deviation of rosin and cinnamyl alcohol is lower compared with other compounds, and a trend can be seen: the contents increase as the drying temperature rises. The highest rosin and cinnamyl alcohol content were achieved when dried at 70 °C (Suppl. 3, Tab. 4).

Fig. 7 Content of salidroside, rosavin, rosarin, rosin, tyrosol and cinnamyl alcohol in the rhizomes and roots of roseroot, where ● is the drying oven, ● the convective dryer and ● the vacuum dryer.

**The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.*

Peschel et al. (2016) [21] found that the content of rosavins in the rhizomes of roseroot slightly decreased at high drying temperature (65 °C), but the content of salidroside increased. The drying temperature (45 and 65 °C) did not seem to affect cinnamyl alcohol content. Thus, the results of Peschel et al. (2016) [21] are somewhat contrasted with this study. However, Peschel et al. (2016) [21] dried the rhizomes for five days at both 45 and 65 °C, which is an unnecessarily long heating period at 65 °C.

Thomsen et al. (2011) [27] found that the content of rosavins was significantly higher when the rhizomes of roseroot were dried at or below 50 °C. They also noticed that if the rhizomes were dried at low drying temperatures, the content of rosavins decreased less during one-year storage. To salidroside content, the drying temperature did not appear to have an effect, but the cinnamyl alcohol content increased at high drying temperatures (60 – 80 °C), which is in line with this study.

Rodríguez et al. (2016) [28] noticed in the drying of maqui berries that high drying temperatures often caused less degradation of individual phenolic acids and flavonoids. They concluded that in some cases this could be due to conversion, as hydrolysable tannins can convert to ellagic acid and gallic acid. The conversion may also explain the increase in cinnamyl alcohol content at high drying temperatures, as cinnamyl alcohol is a precursor to rosarin, rosavin and rosin [11,12]. However, that does not explain the increase in rosarin content.

Thermal load, consisting of the combined effect of heat exposure time and temperature, may have undesirable effects on the content of active compounds [28]. In the drying of mulberry leaves, Katsube et al. (2009) [29] found that the antioxidant capacity and contents of individual polyphenols were higher when dried at 80 and 110 °C instead of 70 °C. This may have been due to higher thermal load, as the drying time is longer at 70 °C. However, the same phenomenon was not observed when dried at 40 and 60 °C instead of 70 °C. Consequently, the thermal load does not solely explain why higher rosarin content, cinnamyl alcohol content, TPC and AC were observed in this study at high drying temperatures.

Conclusions

Standard deviation of TPC and AC was lower in birch leaves than in nettle leaves and roseroot. This was probably due to homogenization, as birch leaves were easy to mix and divide into small drying batches. Standard deviation of roseroot was likely to be higher because the roots and rhizomes were dried in slices and their ratio was not determined. Nettle leaves had high moisture content in some samples, possibly affecting microbiological activity and quality, thus increasing the standard deviation.

Drying temperature from 40 to 80 °C did not significantly affect TPC or AC of birch leaves. For nettle leaves, slightly higher TPC and AC were typically obtained when dried between 65 and 70 °C and for roseroot when dried between 70 and 80 °C depending on the dryer. The greatest differences in quality were observed between the dryers. The highest TPC and AC were clearly obtained with the vacuum dryer, except in the case of roseroot. With roseroot, the vacuum dryer barely provided higher TPC and AC at low temperatures and at 70 °C and above, the convective dryer provided slightly higher results.

The content of rosin and cinnamyl alcohol in the rhizomes and roots of roseroot increased as the drying temperature increased. The highest contents were obtained at 70 °C. Due to high standard deviation, the effect of the drying temperature on the content of salidroside, rosin, rosin and tyrosol could not be determined. The effect of the dryers on the content of salidroside, tyrosol, cinnamyl alcohol and rosin was also left uncertain.

Total electricity consumption decreased when the plants were dried at high drying temperatures, as the drying time was shorter. The faster the plants are dried, the faster the dryer will also be released to dry the next batch, enabling more plants being dried in a given time. Higher drying temperatures also prevent the growth of micro-organisms and reduce their content in dried plants [30]. Consequently, several reasons advocate the use of higher drying temperatures.

Plants can contain several compounds of interest that are desired to preserve during drying. In this case, the preservation of the compounds should be examined separately. However, if the energy costs or investments on the dryer are high compared with the increase in compound contents, improving quality is not economically viable. Thus, balancing quality and costs requires compromises in drying temperature and dryer, as well as knowledge on their impact on quality. Drying at 60 to 70 °C is a good temperature compromise, where TPC and AC were high, energy consumption remained moderate and the temperature may not yet be too high for heat sensitive compounds.

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1. SUPPLEMENT

Table 1. Drying time of the plants and electricity consumption of dryers.

Nettle leaves				
Dryer	Parameter	40°C	60°C	80/*75°C
Convective dryer	Drying time (h)	1.93	0.85	0.50
	Electricity consumption (kWh)	0.23	0.53	0.98
	Total electricity consumption (kWh)	0.44	0.45	0.49
Drying oven	Drying time (h)	4.67	1.75	1.00
	Electricity consumption (kWh)	0.02	0.04	0.08
	Total electricity consumption (kWh)	0.07	0.07	0.08
Vacuum dryer	Drying time (h)	2.50	1.33	0.50
	Electricity consumption (kWh)	0.33	0.33	0.37
	Total electricity consumption (kWh)	0.81	0.44	0.19
Birch leaves				
Dryer	Parameter	40°C	60°C	80/*75°C
Convective dryer	Drying time (h)	8.33	1.42	1.00
	Electricity consumption (kWh)	0.23	0.53	0.98
	Total electricity consumption (kWh)	1.88	0.74	0.98
Drying oven	Drying time (h)	12.00	3.67	1.42
	Electricity consumption (kWh)	0.02	0.04	0.08
	Total electricity consumption (kWh)	0.18	0.15	0.11
Vacuum dryer	Drying time (h)	6.83	2.58	1.33
	Electricity consumption (kWh)	0.33	0.33	0.37
	Total electricity consumption (kWh)	2.22	0.85	0.49
Roserooot				
Dryer	Parameter	40°C	60°C	80/*75°C
Convective dryer	Drying time (h)	22.75	2.75	2.53
	Electricity consumption (kWh)	0.23	0.53	0.98
	Total electricity consumption (kWh)	5.12	1.44	2.48
Drying oven	Drying time (h)	22.75	5.08	1.87
	Electricity consumption (kWh)	0.02	0.04	0.08
	Total electricity consumption (kWh)	0.34	0.20	0.14
Vacuum dryer	Drying time (h)	22.75	5.08	3.08
	Electricity consumption (kWh)	0.33	0.33	0.37
	Total electricity consumption (kWh)	7.39	1.68	1.14

*The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.

2. SUPPLEMENT

Table 1. Average moisture content of the dried plants from each dryer at each temperature.

Temp. (°C)	Moisture content of nettle leaves (m-%)			Moisture content of birch leaves (m-%)			Moisture content of roseroot (m-%)		
	Drying oven	Convec. dryer	Vacuum dryer	Drying oven	Convec. dryer	Vacuum dryer	Drying oven	Convec. dryer	Vacuum dryer
40	21.34 ± 0.34	23.86 ± 3.47	20.34 ± 1.94	5.75 ± 0.02	7.74 ± 2.07	5.18 ± 1.55	7.80 ± 0.10	5.85 ± 0.35	4.70 ± 0.70
50	17.62 ± 3.63	13.06 ± 0.66	18.01 ± 2.11	8.28 ± 0.37	9.55 ± 0.64	6.30 ± 1.05	9.55 ± 2.25	10.20 ± 2.10	7.30 ± 0.20
55	11.34 ± 1.28	11.61 ± 5.01	14.77 ± 1.98	7.02 ± 1.27	6.47 ± 1.43	4.52 ± 0.66	11.95 ± 1.65	9.00 ± 0.00	5.25 ± 0.25
60	10.66 ± 0.85	8.97 ± 1.58	10.95 ± 1.27	7.15 ± 0.39	8.73 ± 0.05	7.14 ± 0.51	11.85 ± 0.40	10.46 ± 1.50	7.86 ± 1.98
65	14.45 ± 3.22	11.17 ± 4.29	9.09 ± 3.72	8.16 ± 1.84	5.93 ± 1.14	5.75 ± 1.10	12.42 ± 2.29	7.86 ± 3.25	9.23 ± 7.18
70	5.73 ± 1.21	8.43 ± 3.83	15.73 ± 0.41	8.41 ± 2.75	4.43 ± 0.25	4.18 ± 0.44	13.76 ± 1.26	7.10 ± 1.50	5.05 ± 2.17
80/*75	6.20 ± 0.28	10.58 ± 6.01	10.82 ± 7.16	5.66 ± 1.43	3.03 ± 0.52	4.86 ± 1.62	9.35 ± 4.65	8.25 ± 0.75	5.30 ± 2.80

*The convective (convec.) dryer could not reach 80 °C, so the highest drying temperature was 75 °C.

3. SUPPLEMENT

Table 1. Total polyphenol content (TPC) and antioxidant capacity (AC) of nettle leaves at each drying temperature.

Temp. (°C)	Drying oven		Convective dryer		Vacuum dryer	
	TPC (mg/g)	AC (mmol/g)	TPC (mg/g)	AC (mmol/g)	TPC (mg/g)	AC (mmol/g)
40	4.43 ± 0.12	0.038 ± 0.003	4.87 ± 0.69	0.040 ± 0.007	12.29 ± 1.36	0.156 ± 0.016
50	6.13 ± 0.42	0.051 ± 0.005	6.28 ± 0.83	0.038 ± 0.012	13.98 ± 1.91	0.165 ± 0.016
55	4.26 ± 0.09	0.038 ± 0.001	5.77 ± 0.43	0.046 ± 0.004	13.86 ± 0.22	0.163 ± 0.009
60	4.66 ± 0.35	0.036 ± 0.003	6.45 ± 0.68	0.052 ± 0.005	12.83 ± 1.37	0.141 ± 0.021
65	4.60 ± 0.28	0.035 ± 0.003	6.51 ± 1.36	0.055 ± 0.009	17.84 ± 2.75	0.195 ± 0.044
70	4.69 ± 0.67	0.034 ± 0.005	6.04 ± 1.69	0.050 ± 0.012	13.80 ± 0.94	0.158 ± 0.020
80/*75	4.19 ± 0.27	0.031 ± 0.003	6.67 ± 0.22	0.056 ± 0.001	9.91 ± 1.39	0.129 ± 0.020

*The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.

Table 2. Total polyphenol content (TPC) and antioxidant capacity (AC) of birch leaves at each drying temperature.

Temp. (°C)	Drying oven		Convective dryer		Vacuum dryer	
	TPC (mg/g)	AC (mmol/g)	TPC (mg/g)	AC (mmol/g)	TPC (mg/g)	AC (mmol/g)
40	42.40 ± 2.44	0.420 ± 0.034	45.33 ± 0.49	0.458 ± 0.004	65.31 ± 1.37	0.687 ± 0.023
50	44.09 ± 2.51	0.460 ± 0.038	48.14 ± 1.51	0.498 ± 0.017	57.62 ± 3.85	0.611 ± 0.062
55	44.24 ± 1.21	0.437 ± 0.017	45.59 ± 4.62	0.472 ± 0.052	64.74 ± 4.23	0.685 ± 0.051
60	43.70 ± 1.38	0.440 ± 0.021	46.10 ± 2.33	0.485 ± 0.023	58.97 ± 2.92	0.608 ± 0.039
65	44.01 ± 1.33	0.438 ± 0.014	51.51 ± 0.99	0.521 ± 0.033	65.14 ± 1.02	0.689 ± 0.010
70	41.78 ± 0.82	0.497 ± 0.026	52.63 ± 1.54	0.539 ± 0.022	58.45 ± 2.48	0.665 ± 0.022
80/*75	46.22 ± 0.82	0.535 ± 0.018	50.27 ± 0.65	0.575 ± 0.024	59.29 ± 1.11	0.686 ± 0.028

*The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.

3. SUPPLEMENT

Table 3. Total polyphenol content (TPC) and antioxidant capacity (AC) of roots and rhizomes of roseroot at each drying temperature.

Temp. (°C)	Drying oven		Convective dryer		Vacuum dryer	
	TPC (mg/g)	AC (mmol/g)	TPC (mg/g)	AC (mmol/g)	TPC (mg/g)	AC (mmol/g)
40	110.52 ± 1.24	1.399 ± 0.012	109.08 ± 4.87	1.385 ± 0.046	120.75 ± 5.97	1.558 ± 0.063
50	120.60 ± 13.35	1.610 ± 0.122	124.50 ± 2.44	1.648 ± 0.057	127.34 ± 5.40	1.700 ± 0.160
55	92.24 ± 4.93	1.287 ± 0.028	110.29 ± 23.67	1.572 ± 0.323	118.71 ± 14.83	1.676 ± 0.190
60	101.41 ± 9.99	1.483 ± 0.162	90.33 ± 8.26	1.320 ± 0.132	105.19 ± 2.16	1.527 ± 0.049
65	111.27 ± 10.65	1.293 ± 0.196	108.91 ± 7.89	1.242 ± 0.251	120.73 ± 4.91	1.430 ± 0.268
70	164.37 ± 30.65	1.542 ± 0.270	180.15 ± 5.25	1.657 ± 0.049	161.21 ± 23.51	1.446 ± 0.214
80/*75	180.78 ± 10.48	1.734 ± 0.117	209.39 ± 9.04	1.970 ± 0.112	195.81 ± 6.38	1.863 ± 0.072

*The convective dryer could not reach 80 °C, so the highest drying temperature was 75 °C.

Table 4. Content of active compounds of roots and rhizomes of roseroot at each drying temperature.

Drying oven						
Temp. (°C)	Salidroside (mg/g)	Rosarin (mg/g)	Rosavin (mg/g)	Rosin (mg/g)	Tyrosol (mg/g)	Cinnamyl alc. (mg/g)
40	4378 ± 1922	3057 ± 602	149 ± 85	1862 ± 1079	176 ± 101	6644 ± 1469
50	4561 ± 1487	2684 ± 510	189 ± 26	1001 ± 66	180 ± 55	4541 ± 503
55	6310 ± 1974	3081 ± 858	294 ± 44	966 ± 377	188 ± 162	5852 ± 1732
60	4259 ± 1513	4185 ± 333	729 ± 209	2131 ± 946	88 ± 10	7741 ± 518
65	4487 ± 1201	4353 ± 881	1598 ± 881	2044 ± 1096	56 ± 7	7885 ± 162
70	6757 ± 176	4937 ± 429	3417 ± 1598	1813 ± 307	160 ± 11	7744 ± 820
80	6452 ± 837	4554 ± 136	2749 ± 276	1650 ± 50	203 ± 15	7032 ± 645
Convective dryer						
40	4996 ± 2254	3220 ± 688	201 ± 59	1834 ± 1283	127 ± 80	6848 ± 1782
50	5132 ± 451	2749 ± 65	458 ± 38	725 ± 117	174 ± 150	4772 ± 282
55	5338 ± 574	3566 ± 492	658 ± 38	975 ± 182	95 ± 52	6644 ± 1399
60	3085 ± 469	3394 ± 333	398 ± 278	1503 ± 965	76 ± 18	6481 ± 123
65	4339 ± 883	4327 ± 92	1362 ± 94	1766 ± 924	53 ± 4	8246 ± 181
70	7432 ± 749	5160 ± 133	2045 ± 659	1700 ± 217	151 ± 29	8805 ± 419
75	4079 ± 785	4605 ± 172	1816 ± 429	2910 ± 369	143 ± 5	7493 ± 371
Vacuum dryer						
40	4478 ± 1972	3276 ± 582	1260 ± 1070	1769 ± 1151	127 ± 69	6164 ± 959
50	4646 ± 275	2666 ± 116	1460 ± 17	532 ± 31	112 ± 76	4195 ± 325
55	5836 ± 1676	3460 ± 738	2789 ± 2107	881 ± 691	99 ± 61	5450 ± 2798
60	4177 ± 1872	4101 ± 383	1235 ± 789	1789 ± 998	89 ± 16	7828 ± 299
65	4874 ± 1668	4255 ± 439	731 ± 200	2531 ± 1427	82 ± 21	8451 ± 514
70	7494 ± 2326	5043 ± 564	1620 ± 295	1889 ± 235	135 ± 54	9600 ± 848
80	6930 ± 1738	5327 ± 367	1193 ± 71	1972 ± 121	149 ± 6	9082 ± 1017

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