CHAPTER 17

DRYING OF MEDICINAL PLANTS

JOACHIM MÜLLER AND ALBERT HEINDL

University of Hohenheim, Institute of Agricultural Engineering, D-70593 Stuttgart, Germany

Abstract. Drying is the most common method of medicinal plant preservation and, due to high investment and energy costs, drying is also a large expense in medicinal plant production. Drug quality and consequently earnings are significantly influenced by the drying regime. Conventionally, low drying temperatures between 30 and 50°C are recommended to protect sensitive active ingredients, but the decelerated drying process causes a low capacity of drying installations. Therefore, the objective of research in medicinal plant drying is to find the optimum drying temperature for various medicinal plant species in terms of quality and drying costs. Investigations on *Salvia officinalis* are presented as an example. Optimal drying temperature was 50°C, because quality reduction due to discoloration occurred at higher temperatures. Compared to drying at 45°C, drying time was reduced by 60% and energy consumption was reduced by 35%. However, comparisons of different species revealed that no general recommendations can be made, but that each species has to be investigated individually. Influence of drying on microbial count of raw drugs is discussed, because this represents a major problem for medicinal plant growers. Furthermore, different types of dryers are described, suitable for specific plant organs like leaves, flowers, roots or seeds. Special emphasis is laid on the choice of drying temperature, because of its strong influence on economic parameters, such as drying capacity, energy requirement and drug quality. Energy saving measures are discussed, including the cutting of plant material and the recycling of exhaust air in drying. Finally, future prospects of medicinal plant drying are drawn.
Keywords: drying technology; sorption isotherm; drying temperature; product quality; product colour; essential oil; microbial count; energy savings

INTRODUCTION

Drying is the most common and fundamental method for post-harvest preservation of medicinal plants because it allows for the quick conservation of the medicinal qualities of the plant material in an uncomplicated manner. Quality distinction was already made some 4000 years ago in ancient Egypt between medicinal plants dried in the sun and those dried in the shade (Heeger 1989). However, factors such as scale of production, availability of new technologies and pharmaceutical quality standards must be considered for medicinal plant drying in modern times. Natural drying, i.e. drying without auxiliary energy either in the field or in sheds, should only be considered for drying of small quantities. In cases of mass production, the use of technical drying applications is indispensable. For the preservation of active

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ingredients of medicinal plant materials, comparatively low drying temperatures are recommended and, as a result, the drying duration is comparably long. Drying represents 30 to 50% of the total costs in medicinal plant production (Qaas and Schiele 2001) and, therefore, it is crucial that factors determining the high costs are identified. Currently, energy demand of drying represents a significant cost factor, especially with the increased price of fossil fuels. This is largely due to the high moisture content of the flowers, leaves or roots to be dried. For example, drying plant material with a moisture content of 80% will require 4 kg of water removal in order to obtain 1 kg of dried material with a storable moisture content of 11%. Additionally, specific heat requirement, such as 10,000 kJ per kg water removed in the drying of herbal drugs, is twofold in comparison with grain drying. From that, a heating-oil requirement of about 1 l per kg drug arises and, with additional purification losses, heating-oil requirement can still be doubled. Thus, energy requirements of drying are considerable and represent a major expense in the drying procedure, which is already the greatest cost in the processing of medicinal plants. Moreover, drying performance takes authoritative influence on the quality of the product and, therefore, on its value. Optimal combination of dryer design, operational method, energy use and quality maintenance of the product requires crucial managerial decisions. Research is required to support decision-making for the realization of optimal drying conditions.

EQUILIBRIUM MOISTURE CONTENT

Like many other crops, medicinal plants have to be dried before storage. Drying is defined as decreasing moisture content *MC* to preserve the product for extended shelf life. *MC* is commonly defined either as mass of water m_w per total mass noted as *MC w.b.* (*w.b.* for wet basis) in percentage:

$$MC\ w.b. = \frac{m_w}{m_w + m_{DM}} \cdot 100$$

or as mass of water per dry mass m_{DM} noted as *MC d.b.* (*d.b.* for dry basis) frequently as a percentage, but better given as a ratio:

$$MC\ d.b. = \frac{m_w}{m_{DM}}.$$

Unless otherwise mentioned, *MC w.b.* is used below and noted as *MC*.

A further important material property in terms of drying is water activity a_w. The water activity is the relative availability of water in a product, defined as the vapour pressure p of water in the material, divided by that of pure water p_0 at the same temperature:

$$a_w = \frac{p}{p_0} = \frac{RH}{100}.$$

The water activity of a material corresponds to the relative humidity *RH* of the air in the immediate vicinity of the sample, i.e. in the pore volume of a bulk. The *RH* and *MC* of a material are interrelated, reaching equilibrium at constant temperature: equilibrium moisture content *EMC* and equilibrium relative humidity *ERH*, which is described by the sorption isotherm (Figure 1).

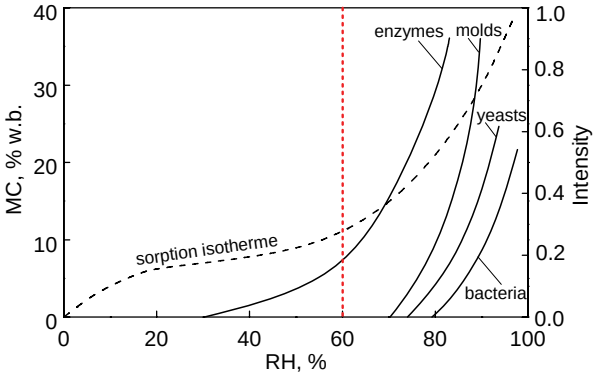

Figure 1. *Moisture content MC of a plant material and intensity of activity of enzymes, molds, yeasts and bacteria vs. relative humidity RH of surrounding air, according to Heiss and Eichner (1990)*

Micro-organisms, like fungi, yeasts and bacteria, increasingly develop at $RH > 70\%$. Since the activity of decomposing enzymes is also enhanced by increasing water activity, a threshold of $RH \leq 60\%$ is recommended to preserve the quality of medicinal plants during storage. Hence, the final *MC* to which the material should be dried can be derived from the sorption isotherm. As the sorption isotherm is a characteristic property of a material, it has to be established for each individual plant species and even for separate plant organs by experiment.

As an example, Figure 2 shows the sorption isotherms for *Artemisia dracunculus* (Arab Mohammad Hosseini et al. 2006). Sorption isotherms for adsorption and desorption show the typical hysteresis effect (Figure 2, left). When equilibrium is approached starting from dry material ($MC<EMC$), water from the surrounding air will be adsorbed in the material and *MC* will rise. When equilibrium is approached starting from moist material ($MC>EMC$), water will be evaporated from the material and *MC* will decrease. However, *EMC* after desorption remains on a higher level than *EMC* after adsorption. Adsorption isotherms are relevant for the storage process, e.g., to prevent the remoistening of dried material by keeping *RH* in the storage room at a suitable level. For drying, the desorption isotherms are relevant. Figure 2 (right) shows that sorption isotherms have a lower course at higher

temperatures. Consequently, the difference between actual *MC* and *EMC* as a driving force for drying will be increased at higher temperatures and drying rate will be accelerated.

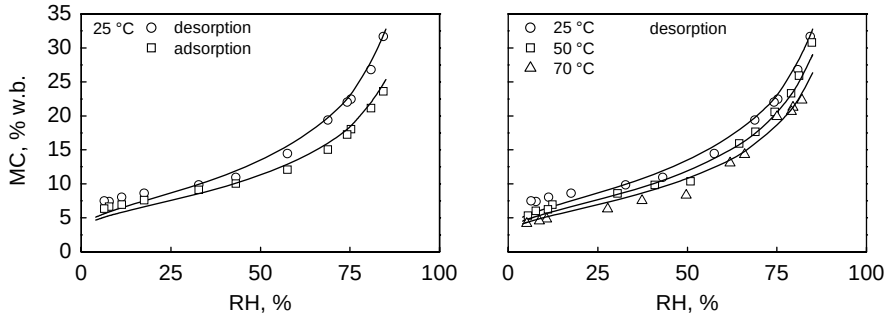

Figure 2. *Sorption isotherms of Artemisia dracunculus L. Left: adsorption and desorption at a temperature of 25°C. Right: desorption at 25, 50 and 70°C (Arab Mohammad Hosseini et al. 2006)*

To facilitate interpolation, sorption isotherms are frequently described by mathematical models. For *A. dracunculus*, the Halsey equation was fitted to the experimental data:

$$EMC = \left(\frac{-\exp(C_1 + C_2 T)}{\ln(ERH/100)} \right)^{1/C_3} .$$

The coefficients for adsorption have been calculated as C_1=4.16, C_2=1.02 and C_3= 1.77. Applying these coefficients and assuming a storage temperature of 25°C, drying to a final moisture content MC_f of 13% would be required for safe storage.

For various medicinal plant species a maximum value of MC_f is prescribed in the European Pharmacopoeia. Some examples are listed in Table 1, showing a range of MC_f between 8 and 12%. There is no obvious correlation between MC_f and the used part of the plant such as root, herb, flower or seed.

For plant species where no MC_f is prescribed in pharmacopoeias, farmers depend on specifications of wholesale buyers or on their own experience. To limit the risk of deterioration during transport and storage, conservative MC_f values are typically applied. This means that the material is often over-dried, resulting in economic losses such as reduced dryer capacity, increased energy costs as well as reduced mass – and possibly quality and value – of goods. Therefore, MC_f has to be established for relevant medicinal plant species. As MC_f depends on the storage temperature, postulating a one-value threshold – as done in pharmacopoeias – is a simplification. To decide on suitable MC_f for specific temperature conditions during transport and storage, the knowledge of *ERH/EMC* relations is required. Beside *A. dracunculus*, data are available for *Mentha* x *piperita*, *Chamomilla recutita*,

Thymus vulgaris (Soysal and Oztekin 1999) and some further species such as *Mentha crispa* (Park et al. 2002), *Mentha viridis*, *Salvia officinalis*, *Lippia citriodora* (Kouhila et al. 2001), but are still missing for numerous major medicinal plant species.

Table 1. *Maximum final moisture content MC_f for various medicinal plant species as prescribed in the European Pharmacopoeia (Europäisches Arzneibuch (Ph.Eur. 5.00). European Pharmacopoeia 2005)*

Species	**Drug**	**MC_f, % w.b.**
Althaea officinalis L.	Roots	10
Arnica montana L.	Flowers	10
Calendula officinalis L.	Flowers	12
Chamomilla recutita [L.] Rauschert	Flowers	12
Coriandrum sativum L.	Seed	10
Foeniculum vulgare Mill.	Seed	8
Hypericum perforatum L.	Herb	10
Levisticum officinale Koch	Leaves	12
Malva silvestris L.	Leaves, flowers	12
Melissa officinalis L.	Leaves	10
Mentha x *piperita* L.	Leaves	11
Plantago lanceolata L.	Herb	10
Valeriana officinalis L.	Roots	12
Verbascum phlomoides L.	Herb	12

INFLUENCE OF DRYING AIR CONDITION

Drying behaviour of medicinal plants during convective drying is mainly influenced by the conditions of drying air such as temperature *T*, *RH* and velocity *v*. Figure 3 shows the results of drying experiments with thin layers (30 mm) of *Salvia officinalis* in a laboratory dryer with continuous measuring of sample mass. Based on mass loss, *MC* was calculated. Absolute vapour content of the drying air could be controlled by adjusting dew-point temperature T_{DP} (Müller 1992). Velocity of drying air *v* was varied in a range from 0.2 to 0.6 m/s (T=50°C, T_{DP}=13°C), *RH* in a range from 30 to 70% (v=0.2 m/s, T=50°C) and *T* from 30 to 90°C (v=0.2 m/s, T_{DP} =13°C).

It was found that velocity of drying air has no significant impact on drying behaviour of thin layers. This seems to conflict with practical experiences, where air flow was often limiting the capacity of dryers. But here, material bulks with a height of 0.5 m or more were dried and the air was most likely saturated with water vapour before reaching the top of the bulk, i.e. the lack of saturation deficit of the drying air is limiting the drying process rather than the air velocity *per se*. Greater impact was visible from *RH*. Increasing *RH* from typical ambient conditions to higher values – as it would happen gradually by passing a bulk of drying material – initially increased the drying time. The increase was moderate at first, but when *RH* came

close to *ERH* drying time was increased asymptotically towards infinity. Temperature showed a more distinct influence. By increasing temperature, drying time decreased exponentially. For *S. officinalis*, drying time was reduced from 120 h at 30°C to 2 h at 60°C. The reduction of drying time from increasing air temperature is desired in practice, because capacity of a dryer will be increased and allow for a considerable reduction of drying costs.

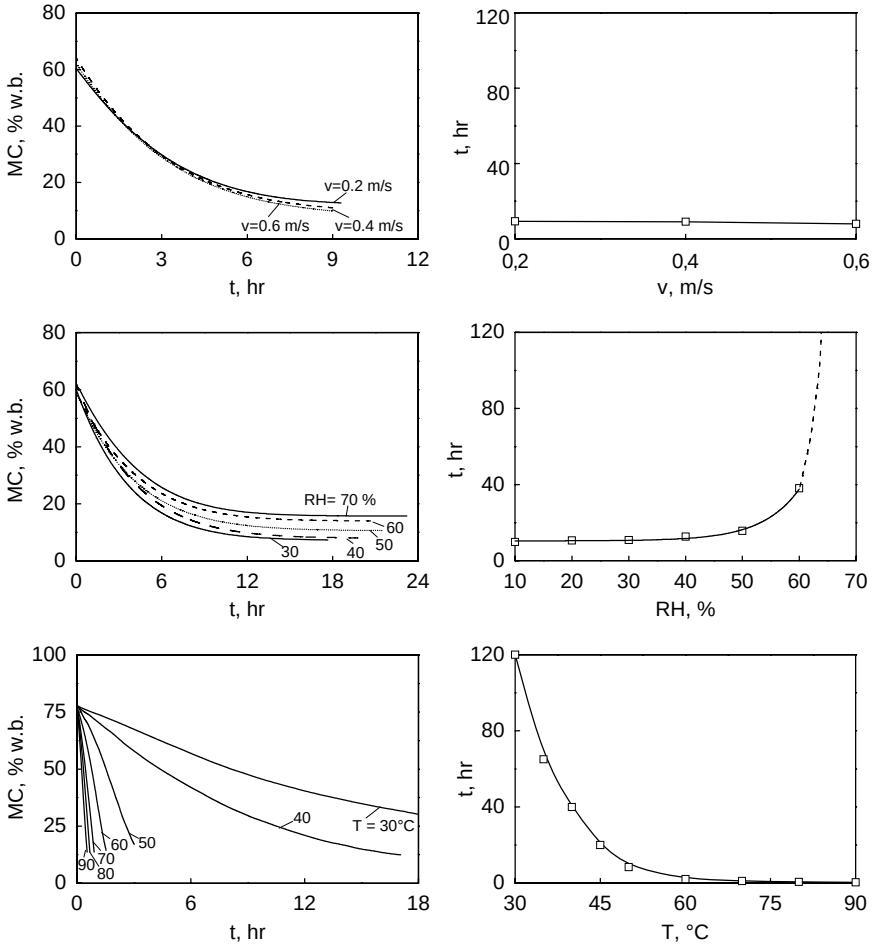

Figure 3. *Drying behaviour of a thin layer (30 mm) of Salvia officinalis leaves in a through-flow laboratory dryer. Top: influence of velocity v of drying air on drying time (T=50°C, T_{DP} =13°C). Centre: influence of relative humidity RH of drying air on drying time (T=50°C, v=0.2 m/s, MC_f=11%). Bottom: influence of temperature T of drying air on drying time t (v=0.2 m/s, T_{DP} =13°C, MC_f=11%) (Müller 1992)*

Response of drying rate to temperature is a characteristic property of medicinal plant species. In similar experiments with flowers of *Chamomilla recutita*, drying time was reduced from 52 h at 30°C to 1.6 h at 60°C (Müller et al. 1996). For roots of *Echinacea angustifolia*, the relation was 56 h at 30°C to 6.5 h at 60°C (Kabganian et al. 2002). Further research is necessary to investigate drying behaviour of major medicinal plant species.

INFLUENCE OF TEMPERATURE OF DRYING AIR ON DRUG QUALITY

Active ingredients

To achieve increased dryer capacity, drying temperature should be chosen as high as possible without reducing the quality of the product. Maximum allowable temperatures depend mainly on the chemical composition of the active ingredients of the medicinal plant species under consideration. For glycoside species, a maximum temperature of 100°C is recommended, for mucilage species 65°C and for essential-oil species 35 to 45°C (Maltry et al. 1975). Due to the high heterogeneity among medicinal plant species, these global recommendations can only serve a rough indication.

An example of the influence of drying temperature on essential-oil reduction rate *EOR* is shown for *S. officinalis* in Figure 4. In Figure 4 (left), *EOR* is plotted vs. *MC* during drying at 60 and 90°C. For drying at 90°C, essential-oil losses of 10% already occurred when *MC* reached 40%, and losses were 90% at *EMC*. For drying at 60°C, no losses of essential oil occurred until *MC* of 10% was reached, but increased to 50% at *EMC*. Since *EMC* for increased temperature is lower than MC_f, *EOR* for *EMC* and MC_f (11%) are plotted for the investigated temperature range in Figure 4 (right). Here it becomes obvious that up to a temperature of 50°C no losses

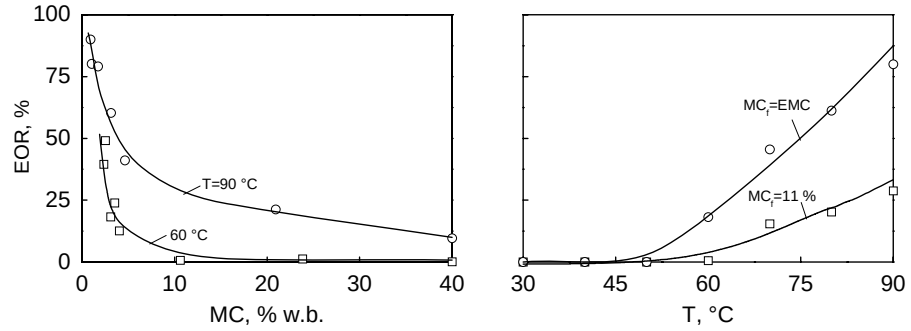

Figure 4. *Influence of temperature T of drying air on essential-oil content of Salvia officinalis. Left: essential oil reduction rate EOR vs. moisture content MC during the course of drying. Right: EOR vs. T for drying to a final moisture content MC_f=11% and for drying to equilibrium moisture content EMC (Müller 1992)*

in essential oil occurred – neither by drying to MC_f nor by drying to *EMC*. That means that in terms of preserving essential oil, this temperature would be suitable

for operating flat-bed dryers where the lower layers are always over-dried. If the drying process can be stopped at MC_f, e.g., in a conveyor dryer, then a drying temperature of 60°C could be applied.

Colour

As many medicinal plant species are used as tea, colour is an essential quality criterion because it is directly apparent to consumers. For colour measurement, the CIELAB system is frequently applied using lightness *L**, chroma *C** and hue *h* as parameters (Pank et al. 1999). In a comparison study of these parameters involving ranking by a panel of specialists, *h* proved best to represent quality in terms of colour of dried *A. dracunculus* (Arab Mohammad Hosseini 2005).

The effect of the temperature of the drying air on the colour of *S. officinalis* is shown in Figure 5. From 50 to 55°C a discontinuity in the colour parameters was visible, most apparent for *h*, which decreased from 112 to 87 degrees (Figure 5 left). This means that *h* was changing from the green to the red region, which indicates the browning that was also visually apparent. Browning occurred early during the drying process, but when the leaves were pre-dried for a certain time at 50°C, a subsequent increase to 60°C did not affect colour. The right-hand chart in Figure 5 shows that a pre-drying phase of 3 h is sufficient to prevent colour changes. Based on this knowledge, a conveyor dryer can be controlled following a staged temperature regime to achieve high drying capacity via high temperatures without affecting quality in terms of colour.

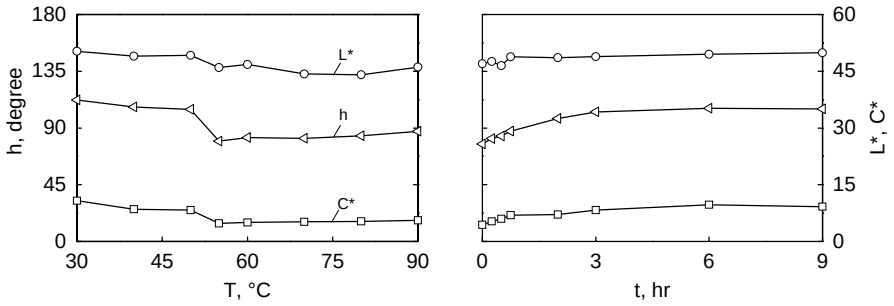

Figure 5. *Influence of drying on lightness L*, chroma C* and hue h of Salvia officinalis leaves. Left: influence of temperature T of drying air. Right: influence of duration of pre-drying period at 50°C before switching to 60°C (Müller 1992)*

Microbial status

Exceeding the thresholds for microbial count is the most frequent reason for rejection of medicinal plant material from growers by the pharmaceutical industry (Baier and Bomme 1996). Official thresholds of colony-forming units *CFU* in terms of aerobic bacteria, molds, enterobacteria and *E. coli* are postulated in the European

Pharmacopoeia (Table 2). There is a special 'category 4' for herbal medicinal products consisting solely of one or more herbal drugs. Category 4 is divided into 4A, when boiling water is added before use, and 4B, when boiling water is not added. Thresholds of microbial count are higher for category 4A than 4B. Also relevant for medicinal plant production is category 3B, which is valid for preparations for oral administration containing 'raw materials of natural origin'. Here the thresholds for microbial count are lower than in category 4 but in terms of aerobic bacteria are still higher than in category 3A, which is the most stringent one.

Table 2. *Thresholds of microbial count of medicinal plant material according to the European Pharmacopoeia (Europäisches Arzneibuch (Ph.Eur. 5.00). European Pharmacopoeia 2005)*

Category	Application	Aerobic bacteria	Molds	Entero-bacteria	*E. coli*
4 A	Herbal medicinal products to which boiling water is added before use	10^7	10^5		10^2
4 B	Herbal medicinal products to which boiling water is not added before use	10^5	10^4	10^3	nil in 1g
3 B	Preparations for oral administration containing raw materials of natural origin	10^4	10^2	10^2	nil in 1g
3 A	Preparations for oral and rectal administration	10^3	10^2		nil in 1g

Post-harvest processes such as collection of plant material in the field, transport to the farm and drying are often suspected to increase microbial contamination of medicinal plants. When the bulk of harvested material is not ventilated, auto-heating due to respiration activity provides favourable conditions for micro-organism growth, in terms of temperature and humidity (Böttcher and Günther 1995). A study on *Hypericum perforatum*, however, revealed that the microbial count is already high before harvest (Graf et al. 2002). The left-hand chart in Figure 6 shows that most samples taken before harvest just met the requirements of class 4B. Drying the material in a conveyor dryer reduced the original microbial count and the raw drug met the highest quality classes 3A and 3B (Figure 6, right). In a flat-bed dryer the microbial count could only be reduced in the bottom layer, meeting class 4A requirements.

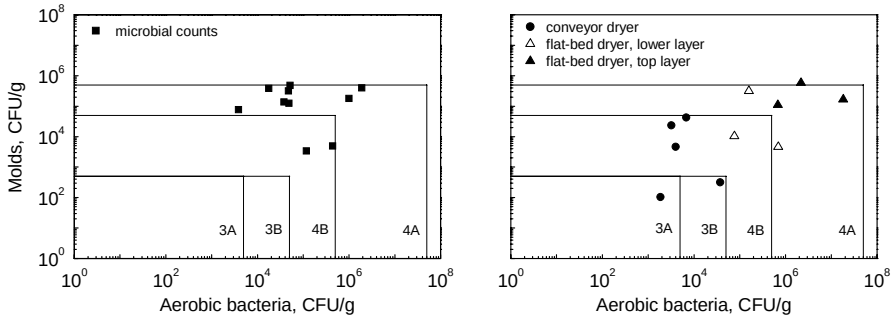

Figure 6. *Presentation of microbial count (colony-forming unit CFU) of Hypericum perforatum according to the classification of the European Pharmacopoeia. Left: material before harvest. Right: material after drying in a conveyor dryer and in a flat-bed dryer in bottom and top layer (Graf et al. 2002)*

In the conveyor dryer, the microbial count of bacteria, molds and yeasts decreased continuously during drying, whereas in the top layer of the flat-bed dryer the microbial count increased (Figure 7). In the bottom layer of the flat-bed dryer, microbial count did not change during drying. Due to the high variability of *CFU*, differences were only significant for the decrease of bacteria in the conveyor dryer. Nevertheless, it can be stated that microbial count is already high in the field and is not increased during drying when 'state of the art' technology is used.

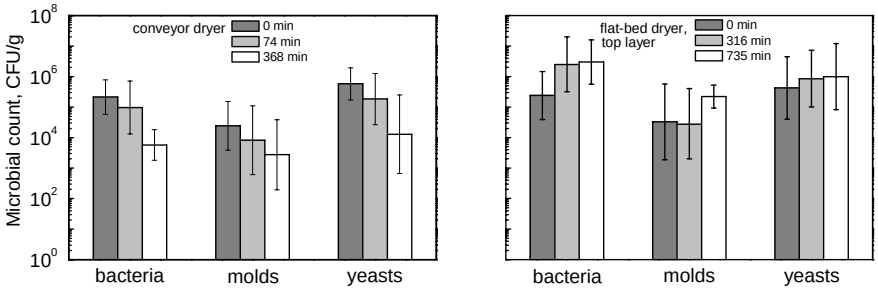

Figure 7. *Microbial count (colony-forming unit CFU) of Hypericum perforatum during the course of drying. Left: conveyor dryer. Right: top layer of a flat-bed dryer (Graf et al. 2002)*

DRYER DESIGN

The active ingredients of different medicinal plants typically are concentrated in certain parts, e.g., leaf, flower, fruit, bark or root, and therefore, harvest and drying of plant parts is usually selective. As a result, the dryer design must correspond to the plant parts to be dried. For seed drugs, such as fennel or caraway, typical grain dryer types can be used. For the drying of flowers, fruits and roots, tray dryers or belt dryers, types typically preferred for the drying of hops or vegetables, are used

more predominantly. For the drying of herbs, the drying procedure is determined by the choice of the processing chain. In Figure 8, processing chains of lower (left) and higher (right) mechanization levels are represented. With less mechanization, the total herb is dried in a flat-bed dryer – comparable to hay ventilation. After drying, the herb is crushed, whereby the leaf particles are removed from the worthless stalks (Veselinov et al. 2004). As the stalks are often 50% of the harvest material and they dry more slowly than the leaf material, this procedure is obviously marked with considerable energy losses. With higher mechanization, the herb is cut before the drying and is separated in leaf and stalk parts by winnowing. The remaining leaf particles are dried in the directly connected conveyor dryer. The smaller the particle size is, the higher the drying speed and drying rate of the unit. Likewise, the specific energy demand of water removal is reduced. However, it must be considered that a processing plant with conveyor dryer causes significantly higher investment costs in comparison with the flat-bed drying. The desired particle size for herb drugs and leaf drugs is usually between 10 and 50 mm. For root drugs, cubes with a cut-edge length of about 10 mm are preferred. A prerequisite for a qualitatively high-value product is a sharp cut with minimal bruising. The material has to be dried immediately after cutting. Otherwise, fermentation processes, discoloration and chemical decomposition of the active ingredients of the plant material can quickly set in. After drying, a process of subsequent winnowing can be used in order to remove stalk particles.

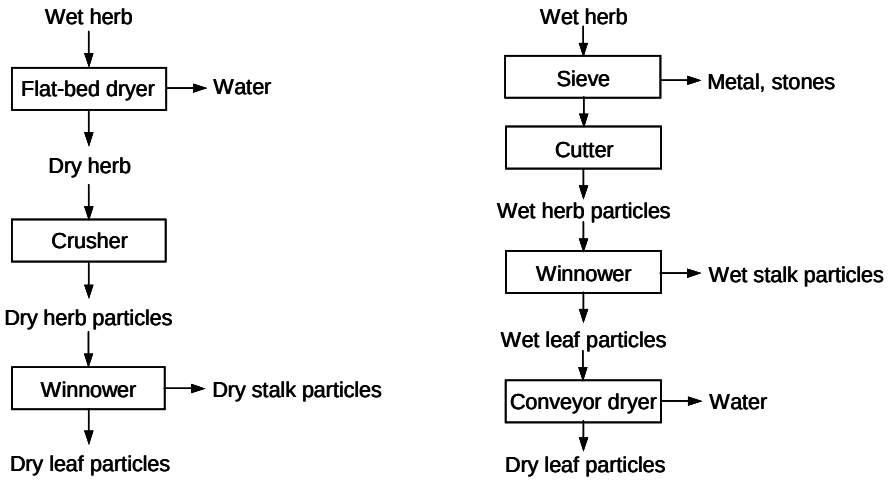

Figure 8. *Processing of herbs. Left: low-mechanized processing line. Right: high-mechanized processing line*

Flat-bed dryers

Flat-bed dryers show the most favourable drying system concerning investment costs. The harvest material is bulked up to 150 cm on a grated floor and dried by forced air with the use ventilators (Troitzsch 1961). For the reduction of the drying time, the drying air is usually heated indirectly by oil or gas heating systems. However, the bulk must be turned and loosened several times to avoid over-drying of lower layers and the formation of compaction zones. However, the filling and emptying of the dryer is very time-consuming even if done by crane (Maltry et al. 1975). A special construction is presented of a solar greenhouse dryer into which a flat-bed dryer was integrated with a cost-effective construction cover of greenhouse foil (Müller et al. 1989) (Figure 9). The roof surface serves as a solar collector during the summer months when the fossil-fuel requirement can be substituted completely, even with Central-European irradiation levels (Müller et al. 1994).

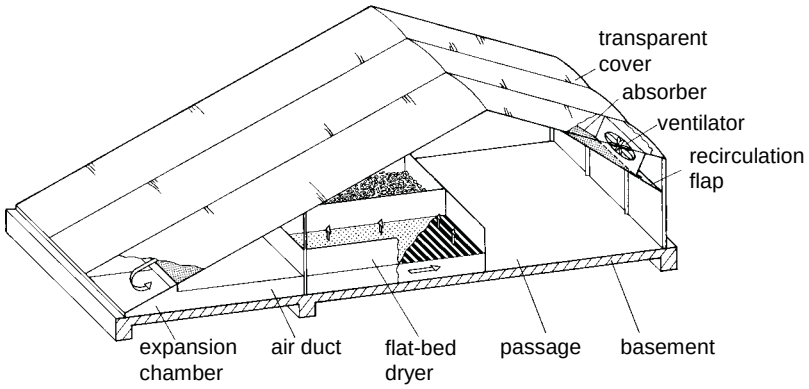

Figure 9. *Flat-bed dryer integrated in a solar greenhouse dryer (Müller 1992)*

Conveyor dryer

For the drying of roots, flowers and cut herbs, primarily conveyor dryers with three to five belts are used. The fresh material is steadily raised with the help of a conveyor belt to the uppermost drying belt (Figure 10). Bulk heights for cut roots range up to 5 cm and up to 20 cm for cut herb. With the turnover of drying material from a higher belt to a lower belt, the drying material is loosened and mixed at the same time. The air flow is adapted for each drying belt according to the amount of water that is evaporating, i.e. the air flow is increased from bottom belt to top belt. In the same manner, the air temperature can be increased, because the cooling effect of evaporation prevents overheating in the upper belts. Therefore, belt dryers can be operated at higher temperatures than batch dryers, which means the drying capacity is increased without excessive temperature stress of the drying product. Furthermore, belt speed is reduced from top to bottom to utilize the drying surface

better by raising the bulk height of the drying material. By mechanical filling, turning and emptying, the labour requirement is lowered in comparison with flat-bed dryers. However, continuous operation requires constant control, and therefore, a shift-operation set up.

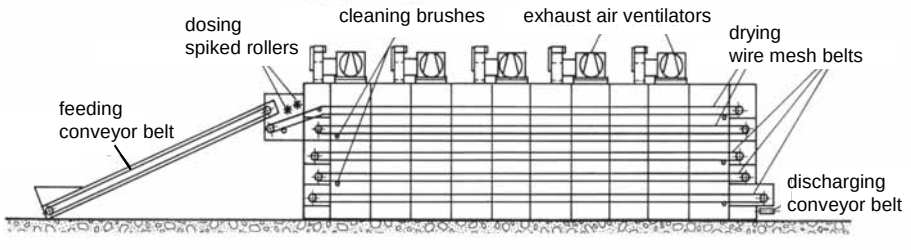

Figure 10. *Conveyor dryer with five drying belts (Heindl and Müller 1997)*

Comparison of different dryer types

In Table 3, different dryer designs suited for drying of herbs are presented. For the solar greenhouse dryer, values of the pure solar application are given as well as for supplemental heating with an oil burner during the night, which corresponds to a contribution of 70% to the total energy input. For the example of peppermint, drying duration and capacity are compared. Due to the alternating operational mode, the flat-bed dryer shows a prolonged drying time and therefore a reduced drying rate. Respective to bulk height and drying temperature, daily throughputs of 3 to 8 kg dry goods per m² dry area are reached. With the possibility of the temperature grading in the conveyor dryer, drying volume can be increased so that a daily throughput of 14.5 kg/m² is reached.

Table 3. *Specifications of a flat-bed dryer, a solar dryer and a conveyor dryer for Mentha piperita (Source: Heindl and Müller 1997)*

Dryer type	**Flat-bed dryer[1]**	**Solar dryer[2]**	**Conveyor dryer**
Operational mode	batch-wise	batch-wise	continual
Drying time, h	96-120	120 (48)	7-10
Capacity, kg/m² d	5.3	2.7 (8.0)	14.5
Air velocity, m/s	0.15	0.1	0.7-0.15*
Air temperature, °C	35-40	20-45 (40)	48-40*
Plant material	herb	herb	leaf particles**

[1] after (Maltry et al. 1975)
[2] average daily irradiation = 5 kWh/m², values in parentheses for operation with 70% supplemental heating from oil burner
* graded
**10-30 mm diameter

Drying with partly recirculated air

For efficiency reasons the drying air cannot be allowed to become completely saturated with vapour, i.e. the exhaust air leaves the dryer with an unused drying potential. In order to reduce this energy loss, during mixed-air operation a part of the warm exhaust air is fed back into the system and mixed with the incoming air. In systems with limited heating potential, higher drying temperatures can be reached in this manner. However, mixed-air operation is narrowly limited at low-temperature drying. An increase in air recirculation leads to the rise of the *RH* of the drying air and, consequently, to a lengthening of the drying duration. Table 4 quantifies these circumstances through the results of lab tests (Müller 1992). In mixed-air operation with *S. officinalis*, *RH* of the drying air is increased to 20% and the specific power demand sinks by 75%, while the drying duration slightly increases by about 8%. By further increasing air recirculation to *RH* of 40%, the energy demand is lowered by about 84% and the drying duration rises by 30%. Additional recirculation leads to no added energy conservation, but causes a substantial lengthening of the drying time. As a limit for the mixed-air operation with *S. officinalis*, 20% *RH* of the drying air is recommended. With *C. recutita* the same trends arose, but here the limit of *RH* was 30%. Beside the energy aspect, the change of the product quality must be also considered with drying at elevated air humidity. With *C. recutita*, a negative change of the oil components appeared with *RH* of more than 50% marked by accelerated degradation via chemical reactions.

Table 4. *Reduction of specific energy demand by partly recirculating drying air for drying of Salvia officinalis and Chamomilla recutita (air velocity v = 0,2 m/s; dew-point temperature T_{DP} = 13°C; relative humidity RH increasing according to rising amount of recirculated air) (Source: Heindl and Müller 1997)*

Species	Temperature/ relative humidity	Energy demand reduction	Drying duration increase
S. officinalis	50°C / 20 %	75 %	8 %
S. officinalis	50°C / 40 %	84 %	30 %
S. officinalis	50°C / 50 %	85 %	50 %
C. recutita	60°C / 30 %	44 %	10 %
C. recutita	60°C / 60 %	50 %	30 %

OUTLOOK

For the savings of fossil fuels and the reduction of CO_2 emissions, measures should be adopted in drying to increase energy savings. Aside from the technical possibilities addressed above, procedures for heat recovery by heat exchangers and the use of solar collectors for the heating of drying air are additionally documented (Heindl 2000). Also, preliminary trials with the use of plant oil in a block-type thermal power station are already presented (Schröder 1995).

In especially temperature-sensitive materials, it is also possible to dry the heated

air through dehumidification by means of a heat pump. Whereas small constructions with capacities up to 450 kg of fresh material exist (Herold et al. 1991), use in larger dryers is not feasible as the high electro-energy demand creates considerable difficulties (Rust 1991). A possible solution to the problem presented is the use of a novel adsorptive air-drying procedure using $CaCl_2$, by which thermal energy in the low-temperature area can be utilized (Waldenmaier 2000).

In certain medicinal plants, the use of microwaves to support warm air drying can be adopted in the future. In a laboratory trial, better colour retention and a higher concentration of active contents were recorded with simultaneous reduction of the microbiological contamination (Von Hörsten 1999). As a specialized procedure, substitution by microwaves in the vacuum convection drying of *Valeriana officinalis* was examined and a qualitatively high-value product was obtained (Heindl and Müller 2002). In the practical execution, a multi-stage single-belt dryer with intermediary microwave zone is conceivable. Through combined drying and sterilization by microwaves, fulfilment of the market niche for high-value products required by industrial pharmaceutical processors would be possible.

In spite of all technical developments, the choice of the correct drying temperature remains a central economic and ecological criterion in the drying of medicinal plants. The values recommended in literature and those used in practice are often far apart, confirming that there is an urgent need for research on this topic.

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