The Canadian society for engineering in agricultural, food, and biological systems

CSAE **SCGR**

La société canadienne de génie agroalimentaire et biologique

Paper No. 05-030

Development and Trends in Drying of Herbs and Specialty Crops in Western Canada

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Written for presentation at the
CSAE/SCGR 2005 Meeting
Winnipeg, Manitoba
June 26 - 29, 2005

Abstract

Heat sensitive properties (aromatic, medicinal, culinary, colour) provide specialty crops with their high market value. Care must be taken when drying specialty crops not to cause extreme losses of heat sensitive properties. Therefore, they must be dried at low temperatures for longer periods of time resulting in large power requirements for dryer operation. In an attempt to establish a basis for a dryer design for preserving western Canadian grown herbs and specialty crops, numerous literature and contacts were consulted in order to compare current dehydration methods based on pre-established criteria. Such criteria involved final product quality, capital cost, power requirements, simplicity, operating cost, capacity, safety and environmental issues. Coriander was dehydrated in two different drying units (thin layer convection and microwave) in order to compare the two methods in terms of final product quality and overall dryer simplicity and operation. A third type of dryer (re-circulating heat pump) was also investigated in numerous literature sources, along with the other two. The conclusions from this study were used to select a dryer on which to base the design of a laboratory scale dehydration unit for herbs and specialty crops.

Keywords: Drying, dehydration, herbs, specialty crops, convection, heat pump, microwave

INTRODUCTION

Production of specialty crops in western Canada has risen greatly in the past decade. This has been stimulated by the trend by many consumers to look for more natural food products, ethnic foods, organically produced products, and alternative medicines, as well as by the trend for farmers to grow alternative crops for economic reasons (SAFRR, 2002). The term specialty crops is used for a group of crops comprising of lentils, mustard and canary seed, to name a few. Also falling under the veil of specialty crops are herbs and spices, which are commonly grown for their culinary and medicinal attributes. The majority of these desired properties are heat sensitive. Herbs commonly produced in Saskatchewan include Coriander, Dill, Caraway and Echinacea.

Just like any other biological product, herbs are susceptible to rotting and degradation which can render the product unsuitable for consumption, or at least make them visually unappealing for consumers. This is generally not a problem for small scale producers who harvest and sell the product within days of harvest. However, it is a concern for producers who have larger crops and cannot sell or process the entire harvest before degradation begins.

Post-harvest preservation and management methods are numerous, but many are not economically feasible. Perhaps one of the most widely used herb preservation methods is dehydration. This method involves the use of a heat source to increase the air temperature in the vicinity of the herbs to be dried. Thermal energy is used to evaporate moisture at the product surface causing a vapor pressure gradient between the product surface and interior. This gradient is what causes moisture to diffuse to the product surface. Care must be taken to set drying parameters such that the herbs are not exposed to excessively high temperatures, causing major losses of their medicinal, culinary, visual, and nutraceutical properties, negatively affecting the product value. Under the right conditions, drying can produce a sufficiently shelf-stable product without major losses in herb value.

Currently, there appears to be no standard method for herb drying in western Canada; each producer employs their own techniques. Small scale producers will normally bundle herbs together and hang them to dry in warm, dark places such as sheds. On a larger scale, the labour requirements for this would be very high. Some common drying trends include the use of gas-fired dryers and commercially available dehumidifiers.

The dried product utilization finds numerous applications; milling or granulated particles for satisfying ingredient functions in the nutraceutical industry, flavourings for baking and culinary purposes, exporting, etc. Drying also enhances the transportation and handling characteristics of herbs and spices.

The present work explores current herb dehydration trends. Numerous literature resources were consulted in order to establish the advantages and disadvantages of selected drying techniques, and to determine what is available for producers in terms of herb drying equipment. A study was conducted which dehydrated coriander in two drying units. The two dryers (thin layer convection and microwave) were studied for their preservation of product quality, as well as overall dryer simplicity and operation. A third dryer type, incorporating a re-circulating heat pump, was also reviewed in literature in order to determine its potential application for herb and spice dehydration. Results were used to select a drying apparatus on which to base the design of a new laboratory scale dehydration unit for herbs and specialty crops.

LITERATURE REVIEW

Trends in Saskatchewan

While numerous literature resources on laboratory dryer experimentation are available, it was difficult to find literature pertaining to current drying trends and techniques of producers, specifically those in Saskatchewan. The research and development department at the Prairie Agricultural Machinery Institute (Leduc, Personal communication, 2005) shared their experiences, and indicated that there is currently no standard method for drying herbs in Saskatchewan. It was stated that many producers utilize abandoned agriculture buildings (i.e. barns), where it is warm and dry, to dehydrate herb crops. The status of current drying methods and trends were also discussed with the Saskatchewan Herbs and Spice Association (SHSA), who also reported there are no current standard drying methods (Connie Kehler, Personal Communication, 2005).

Process management

Tabil *et al.* (2001) suggested that material size and shape affect drying rate. Stems will take longer to dry than leaves. So it is important to sort leaves and stems before drying process. This may not necessarily affect the proper selection of a drying unit, but may have more to do with dryer management. Bailey *et al.* (1993) explained that a more uniform drying of ginseng could be obtained in a tray dryer if larger roots were placed closer to the heat source, which would require pre-sorting the material. It was also noted that rotating the trays throughout the dehydration process could improve dryer efficiency.

Convection drying

The majority of research into herb dehydration examines the effect of convective drying on the ability of the dried material to retain its heat sensitive properties. Li and Morey (1987) reported that drying air temperature had the greatest effect on drying rates and quality during thin-layer drying of American ginseng, particularly below moisture contents of 28 to 30% wet basis (w.b.).

Several studies have since concluded that temperature is the principal factor affecting drying rate and quality. For example, Rocha *et al.* (1992) found that the length of time required to dry mint to 0.5 kg water/kg dry matter ranged from 5 hrs at 30°C to 5 min at 100°C. It was also noted that the influence of other drying parameters was less prevalent and appeared only at the beginning of the drying process.

One major advantage of convection dryers is the relatively low cost associated with dehydrating biological materials. Singh (1994) developed a small scale cabinet dryer and determined that cauliflower, cabbage and onion slices could be dehydrated from approximately 90% moisture content (w.b.) to 8%, w.b. for a cost of US$0.086/kg, US$0.11/kg and US$0.095/kg, respectively. It was noted that drying times ranged from 11 – 14 hours.

Das *et al.* (2001) developed a recirculatory cabinet dryer for dehydrating fruits and vegetables. Along with a relatively low thermal heat efficiency of 22.16%, Das also reported non-uniform drying along the length of the trays for blanched potato chips.

High loss of heat sensitive properties during convective drying is a common theme in many studies. Kabganian *et al.* (1999) monitored the effect of drying temperature in a convection oven on marker compounds (echinacoside, among others) during drying of *Echinacea angustifolia* root. It was concluded that echinacoside was reduced by 30% when the material was dried at 30°C and by 55% when dried at 60°C. Tetenyi (1990) varied air temperature from 40 – 100°C in 5°C steps when convection drying basil, rosemary, sage, terragon, majoram, savory and thyme. It was found that volatile oils decreased with increasing temperature.

A study by Diaaz-Maroto *et al.* (2002) concluded that air-drying of bay leaves at ambient temperature and oven-drying at 45°C brought about small losses in the volatile compounds. The report went on to explain that convection oven-drying may be a good method for preserving the sensory characteristics of this spice, in that it can be completed in a shorter time and under more closely monitored conditions than other drying methods. This report demonstrates that there is large variation in literature as to the efficacy of convection dryers in preserving heat sensitive properties, and as a result final product quality may be difficult to control during convective drying.

The loss of heat-sensitive compounds during convection drying can be reduced by lowering air drying temperatures. Schooley and Reynolds (year unknown) concluded the optimum drying temperatures for ginsenoside recovery in ginseng roots was reported as 32 – 38°C. Adapa (personal communication, 2005) suggested that in order to efficiently preserve heat sensitive properties in herbs, air drying temperature should be within the range of 30 – 45°C. While it has been documented that air temperatures above this range cause degradation of heat sensitive properties, air temperatures falling below this range will be unsuccessful in dehydrating herbs in time before spoilage occurs.

Other than recommending optimum air temperature ranges for convective drying, much of the reviewed literature fails to establish optimum ranges for air velocity and relative humidity. Also, very few papers discuss the optimization and design of convective drying units. Literature on dryer design for herbs was almost non-existent. While many papers provide recommendations, previous dryer design appears to be from either experience or complex mathematical modeling, there does not appear to be information on intermediate, practical engineering designs of herb dryers. Kiranoudis *et al.* (1997) applied mathematical modeling to optimize tunnel dryer designs for food dehydration, specifically that of raisins and currants. However, the potential loss of heat sensitive properties was not evaluated. It was noted that tunnel (convection) dryers are adaptable to the drying of almost any material that can be put in a tray.

Dr. Mohyuddin Mirza (Personal communication, 2005) described his experience with a portable, natural gas-fired tray dryer. The unit is approximately 8 by 12 feet, using stackable wooden tray frames to support herbs on a woven mesh. It was reported that Echinacea roots will dry in 3 days to 10 - 12% moisture with good uniformity. A major roadblock appears to be the time requirements in stacking the trays.

Re-circulating heat pump drying

Heat pumps can simultaneously raise the temperature from that of the waste heat stream and multiply the energy supplied to the heat pump (Zylla *et al.*, Part-I, 1982)

Computer simulation was used by Saensabai and Prasertsan (2003) to evaluate performances of five heat pump dryer (HPD) configurations based on component arrangement and ambient and drying conditions. Modeling equations are provided for low drying rates. It was noted that design for the low drying rate product must accommodate the continuous change of configurations with external condenser and cooler.

Pereira *et al.* (2004) justified the addition of a heat pump system to a convention re-circulating convection dryer. They found that heat pumps are able to deliver more energy than they consume. It was stated that the additional compressor energy required is counterbalanced by the energy savings if traditional (fossil fuel or electrical resistance) dryers were used instead.

Chua *et al.* (2002) discusses advantages and limitations of heat pump dryers as compared with conventional convection dryers. Increased efficiency, accurate control of drying conditions, wide range of drying conditions, better product quality, increased throughput, and reduced operational cost all provide a distinct advantage to heat pump dryers. However, increased maintenance, environmental issues (CFC's from refrigerant), and increased capital costs are a few drawbacks to the system.

Adapa *et al.* (Part-1, 2002) presented a simplified model for the performance of a low temperature heat pump dryer for specialty crops. Mathematical models for heat pumps and thin-layer dryers were combined to obtain a re-circulating heat pump dryer model.

Adapa *et al.* (Part-2, 2002) compared experimental results from a re-circulating heat pump cabinet dryer with results from the previously developed mathematical model. A good agreement between the two was found when drying alfalfa. It was found that the heat pump drying system was about 50% more efficient in recovering the latent heat from the dryer exhaust compared to the conventional dryers.

Adapa *et al.* (2002) studied the performance of a re-circulating cabinet dryer utilizing a dehumidifier loop while drying alfalfa. The effect of batch and continuous drying was also examined. Alfalfa chops required 5 hours in batch drying and in 4 hours in continuous drying to dry from 70% to 10% moisture content. The specific moisture extraction rate of the dryer ranged from 0.50 kg/kWh to 1.02 kg/kWh.

Adapa and Schoenau (2004) designed a re-circulating heat pump continuous bed dryer and dried alfalfa, catnip, wormwood, red clover, portulaca, dandelion and ginseng. It was reported that ginseng roots were dried below 10% moisture content (w.b.) in 5 days, using 190 kWh of energy. Under similar conditions, commercial dryers would require approximately 14 days and 244 kWh of energy to achieve similar results. The authors also reported that the re-circulating nature of the heat pump dryer made it 22% more energy efficient and resulted in 65% reduced drying time compared to conventional dryers incorporating electric coil heaters.

Microwave drying

Al-Duri and McIntyre (1992) compared the drying kinetics of skimmed milk, whole milk, casein powders, butter and fresh pasta using a fan-assisted convection oven, a microwave oven, and a combined microwave/convection oven. It was explained that because of the internal heat generation in microwave systems, vapor is rapidly generated within the material, establishing a large driving force. This forces the moisture to the surface, and results in very rapid drying without the need to overheat the atmosphere or suffer surface overheating effects. It was concluded that a uniformly dry product was obtained, which makes the microwave oven a suitable choice for materials with low moisture content or that are heat-sensitive, like pasta. Also, combining a hot air current with microwave power increases the drying rate.

Kowalski and Rybicki (2004) theoretically analyzed convective and microwave drying of saturated porous materials through the use of mathematical equations. Following modeling, they concluded that convective drying generates larger mechanical stresses in products than microwave drying, due to non-uniform drying. In this context, microwave drying has the predominance over the convective drying.

In a simulation study on convection and microwave drying of potato and carrot slabs, Jia *et al.* (2003) determined that moisture diffusivity of the product increases from volumetric heating using microwaves.

Cui *et al.* (2003) examined the dehydration of garlic slices using a hybrid of microwave-vacuum and air drying. The sample was dried by microwave-vacuum until the moisture content reached 10% w.b., and then by conventional hot-air drying at a temperature of 45^{o}C to a final moisture content less than 5% w.b. The final product was then compared to slices dried by freeze-drying and conventional hot air drying. It was concluded that the quality of the hybrid microwave-vacuum and air dried products was close to that of freeze-dried products, and much better than that of conventional hot air drying.

Sunjka *et al.* (2004) compared a microwave-convection dryer to a microwave-vacuum dryer during the dehydration of cranberries. They concluded that the hybrid microwave-vacuum drying was superior in producing a better dehydrated product in terms of colour, texture, taste and overall appearance. It was noted that microwaves can be used as an additional energy source, therefore reducing the drying air temperature required.

Chou and Chua (2001) noted several advantages of hybrid microwave drying units over conventional units. Along with enhanced diffusion of heat and mass, microwave energy is able to increase drying rates without increasing surface temperature, thereby increasing product quality. However, higher capital investments and low energy efficiencies are significant disadvantages of microwave drying units.

It can be seen that literature related to microwave drying is limited, and articles concerning dryer design for herb drying do not exist. Additional research work in this area may be necessary before microwave energy can be applied to herb drying.

METHODS AND MATERIALS

Sample preparation

Fresh coriander foliage (leaves and stems) was obtained from a local grocery store and stored in a refrigerator at 5^{o}C (ambient relative humidity). Approximately 30 min prior to dehydration experiments, coriander was removed from the refrigerator and allowed to equilibrate with ambient conditions. Stems and leaves were not separated and thus dried together.

Moisture content

Moisture content measurement followed that of ASAE Standard S358: Moisture Measurement of Forages. For each fresh and dried sample, three replicates of at least 25 g were placed in an oven at 103^{o}C for 24 hrs. Prior to moisture content testing, the samples were allowed to equilibrate with ambient conditions for 30 min.

Colour measurement

An indicator of final dehydrated product quality is colour. Shears were used to cut fresh and dehydrated samples into approximately 10 mm pieces. Approximately 5 g of the chopped sample was placed in a 250 mL glass beaker from which the colour of the coriander was measured using a LabScan 6000 spectro-colorimeter (Hunter Associates Laboratory Inc., VA, USA). Colour calculations followed the same methodology as in Tabil *et al.* (2001), and thus color measurements were reported based on Hunter *L*, *a*, and *b* values. Three replicates of colour measurement were made for each sample, with six readings taken for each replicate. Following each replicate, the sample was mixed thoroughly in the beaker before a new set of readings were taken. The relative colour of the dried samples was compared using the index value ΔE (Equation 1).

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

Where $\Delta L = L - L_{base}$, $\Delta a = a - a_{base}$ and $\Delta b = b - b_{base}$. The base values of Hunter *L*, *a*, and *b* represent that of the fresh (un-dried) sample. The Hunter *L* value represents the lightness or darkness of a sample on a scale of 0 to 100 (100 being white and 0 being black). Hunter *a* value represents the greenness or redness of the sample (-50 being green and +50 being red). Hunter *b* value is also rated on a scale of -50 to +50, with -50 representing blue and +50 representing yellow.

Thin layer (convection) drying

Approximately 60 g of coriander was placed on the mesh trays within the thin layer drying unit. Initial coriander moisture content was determined to be 93.37%, w.b. for the first two trials, and 92.16%, w.b. for the final trial. Care was taken to ensure that the sample was distributed evenly across the trays, so that overlapping was minimized. Drying air temperature was set to 50^oC, while the relative humidity was maintained below 5%, and the air velocity was kept at 1.1 m/s. Three replicates were performed for this test. Figure 1 is a schematic diagram of the thin layer drying unit. Temperature, relative humidity, air-flow and product mass data were logged throughout the drying process using LABVIEW 6.0 (National Instruments, Austin, TX). Following dehydration, the dried samples were inserted into polyethylene bags and returned to the refrigerator set at 5^oC to be used for colour measurement.

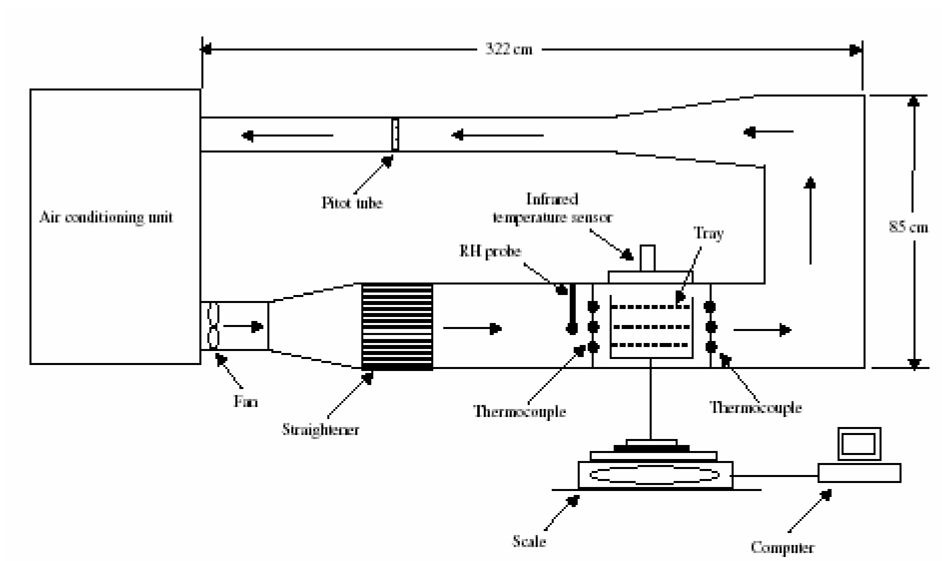

Figure 1. Schematic diagram of the thin layer (convection) dryer.

Microwave Drying

The Panasonic (Model NN-C980W), microwave unit used in experimentation was capable of both convective and microwave drying/heating, however, only microwave power was used for dehydration purposes. Technical specifications of the microwave unit can be found in Table 1. The desired drying temperature was unable to be preset; instead, an appropriate power setting was chosen (level 3) which maintained the average product temperature as close as possible to 50 ^oC. Ambient relative humidity was used in all three replicate tests. Temperature was logged using 4 fiber-optic probes connected to a 4 channel UMI Signal Controller (FISO Technologies Inc., Quebec, QB). Three of the fiber optic probes were placed on the product surface with each probe's spatial distance from the other two maximized. The fourth probe was laid on the floor of the microwave chamber to monitor ambient air temperature. Again, 60 g of coriander at 91.20%, w.b. was placed on a ceramic plate within the microwave chamber. The plate was not rotated during drying, but remained stationary throughout. On-line mass measurement was unavailable at the time of testing; therefore the tray was removed from the chamber and weighed at one minute intervals for the first test, and two minute intervals for the remaining two tests.

Table 1. Panasonic NN-C980W technical specifications.

Microwave Power Consumption	12.8 Amps, 1500 W
Heater Power Consumption	12.5 Amps, 1500 W
Microwave Output	1100 W
Heater Output	1400 W
Outside Dimensions	376 mm (H) x 606 mm (W) x 491 mm (D)
Oven Cavity Dimensions	242 mm (H) x 412 mm (W) x 426 mm (D)
Operating Frequency	2450 MHz

RESULTS AND DISCUSSION

Thin layer (convection) drying

Actual drying conditions differed slightly between the three replicate tests, as can be seen in Table 2. It can be seen that replicates 1 and 2 required 4 h and 27 min to dry approximately 60 g of coriander from 93.37% w.b. to approximately 12% w.b. While replicate 3 only required 3 h and 56 min to dry the coriander from 92.16% w.b. to approximately 12% w.b.

Table 2. Thin layer drying process conditions.

Trial	Initial Moisture Content (%, w.b.)	Final Moisture Content (%, w.b.)	Drying Time	Initial Mass (g)	Final Mass (g)	Mean Air Temperature (^oC)	Mean Relative Humidity (%)	Mean Air Velocity (m/s)
1	93.37	12.18	4h 27min	61.86	4.67	51.6	4.4	1.10
2	93.37	12.08	4h 27min	61.53	4.64	51.5	4.5	1.09
3	92.16	11.82	3h 56min	62.31	5.54	51.7	4.9	1.12

Upon removing the dried samples from the dryer, it could be seen that the leaves and stems were not dried uniformly. Some of the stems clearly retained moisture and were not friable as were the leaves. Instead, the moist stems were flaccid. Results from colour analysis of the dried material can be found in Table 3.

Table 3. Coriander colour analysis from thin layer dryer.

Trial	L	a	b	ΔL	Δa	Δb	ΔE
1	30.29	-4.92	11.63	3.46	0.98	0.31	3.61
2	31.74	-5.14	11.93	4.91	0.75	0.61	5.01
3	33.36	-5.58	11.91	6.11	-0.06	1.03	6.20

All 3 dried samples were lighter than the fresh samples, however, only the samples from the first two trials retained a greener colour than the fresh coriander. The yellowness of the dried samples was also greater than that of the fresh coriander. Upon visual inspection, no appearance of browning could be seen. Ahmed *et al.* (2001) reports that Page's Equation (Equation 2) adequately described the convective drying of coriander leaves over a wide range of drying temperatures in the falling rate period. However, values for coriander equilibrium moisture content at the relative humidity values used in this study could not be found in literature. Following simple equilibrium moisture content experimentation, it is expected that convection drying of coriander can be modeled.

$$MR = \frac{m - m_e}{m_o - m_e} = \exp(-kt^n) \quad (2)$$

Where: MR = moisture ratio

m = product moisture at time t (%, dry basis)

m_e = equilibrium moisture content at the drying air temperature (%, dry basis)

m_o = initial moisture content (%, dry basis)

t = time (h)

k = rate constant coefficient (h^{-1})

n = dimensionless coefficient

Figure 2 depicts the moisture content of coriander as a function of drying time. Results appear to vary slightly towards the end of the drying cycle for the three trials. However, test results appear to be relatively reproducible.

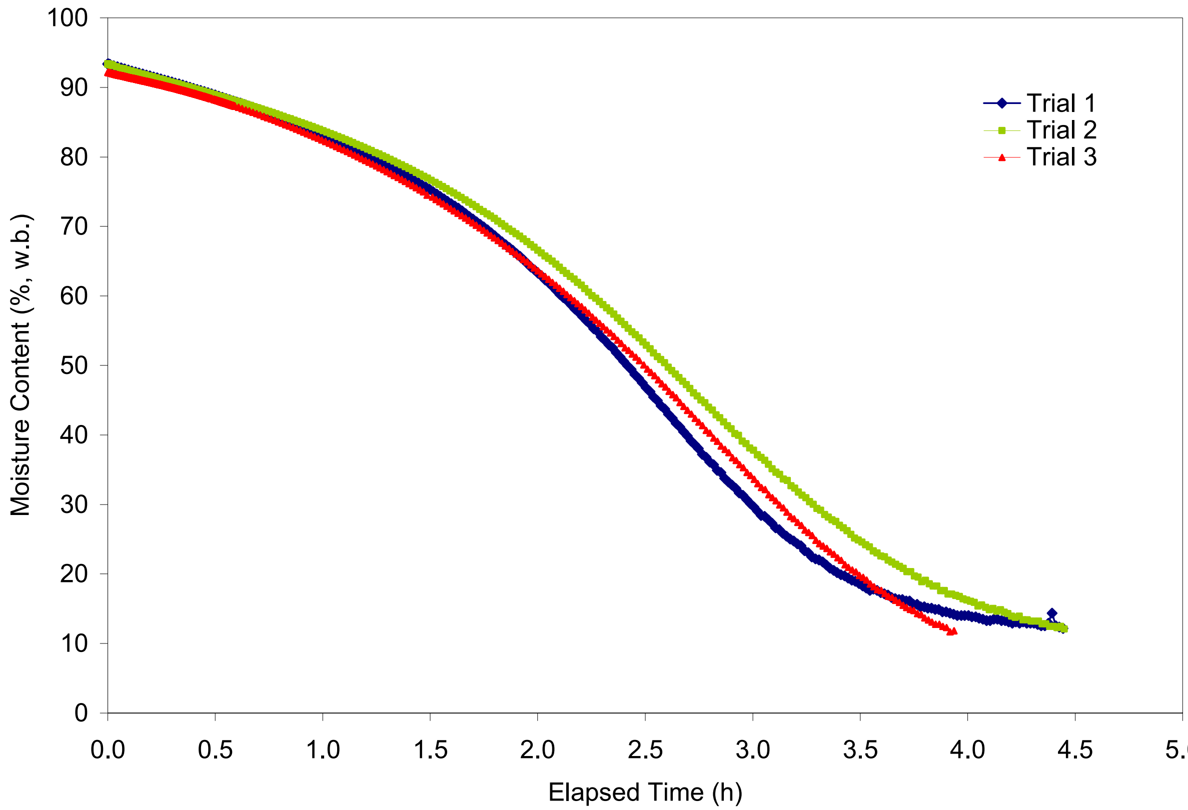

Figure 2. Coriander dehydration in thin layer dryer.

Microwave drying

Microwave drying process conditions and results can be found for the three replicates in Table 4. Results from microwave drying are highly variable as compared with thin layer drying data. Microwave power was able to reduce the coriander moisture content to at least the 12%, w.b. target in 21 min in trial 1, and 22 min for trials 2 and 3. The mean air temperature in trial 1 was calculated as 53.2°C, close to the desired 50 °C, and lower than the 61.9 °C and 62.5 °C in trials 2 and 3, respectively. The reason for this being the fact that the microwave chamber door was opened for mass measurements in trial 1 every minute, and every second minute in trials 2 and 3. Every time the microwave begins a new cycle, it took some time to heat the product. Therefore, more time was spent raising the product to the desired temperature in trial 1.

However, it can be seen that the maximum temperatures achieved were 86.9°C, 102.5°C, and 98.6°C for trials 1, 2, and 3, respectively. These values were significantly higher than desired and would cause significant losses in valuable heat sensitive properties. However, uniform temperature control is difficult to achieve in microwave chambers, as "hot" and "cold" zones develop due the standing wave pattern achieved in the chamber by the microwaves.

Table 4. Microwave drying process conditions.

Trial	Initial Moisture Content (%, w.b.)	Final Moisture Content (%, w.b.)	Drying Time	Initial Mass (g)	Final Mass (g)	Mean Air Temperature (°C)	Min Temperature (°C)	Max Temperature (°C)
1	91.20	11.49	21 min	60.95	6.06	53.2	16.6	86.9
2	91.20	12.07	22 min	60.15	6.02	61.9	17.6	102.5
3	91.20	9.63	22 min	60.28	5.87	62.5	24.4	98.6

Colour analysis results in Table 5 show that microwave dried samples are lighter in colour than the fresh samples. Dried coriander from trials 1 and 2 had higher greenness and yellowness values than the fresh coriander; however, the opposite was true for trial 3 coriander. Also, slight browning could be seen in small areas in all three trials. This is most likely due to the aforementioned "hot" zones which develop inside the microwave chamber.

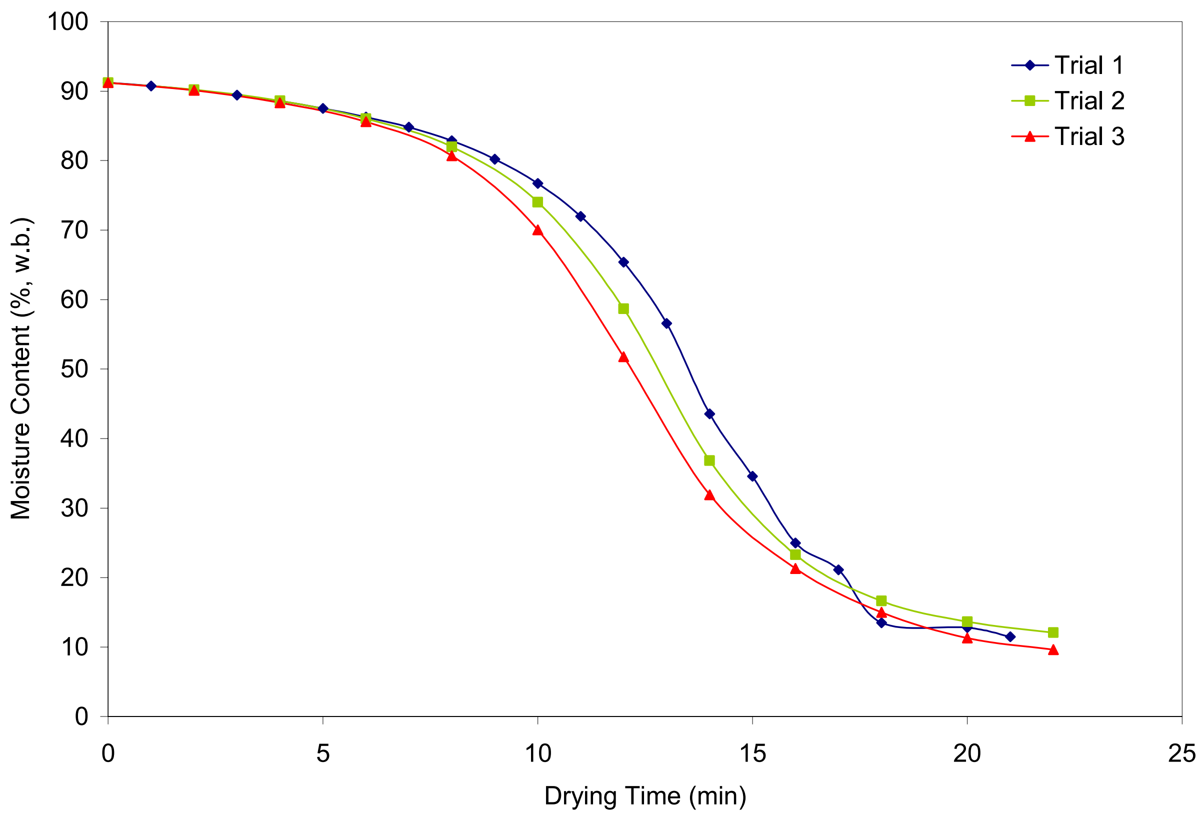

Figure 3. Coriander dehydration in microwave dryer.

Table 5. Coriander colour analysis from microwave dryer.

Trial	*L*	*a*	*b*	Δ*L*	Δ*a*	Δ*b*	Δ*E*
1	27.38	-3.75	10.03	0.13	1.77	-0.85	1.97
2	28.91	-5.19	10.34	1.67	0.33	-0.54	1.78
3	30.08	-5.90	11.49	2.83	-0.38	0.62	2.92

Figure 3 illustrates the coriander moisture content as a function of drying time. It can be seen that drying coriander in the microwave was 11 to 14 times faster than the thin layer dryer. Thin layer dried samples were lighter and had higher yellow values than those dried in the microwave. Differences in greenness were so small, that no accurate comparison could be made.

CONCLUSIONS AND RECCOMMENDATIONS

Of the three dryer types studied in literature and the two experimentally tested, the following conclusions can be drawn:

1. Additional literature is required on herb properties and herb dryer design; for example, moisture measurement standards for herbs and spices.

2. Convection dryers have the simplest construction and operational characteristics, translating into lower capital and operational costs. However, this results in a trade-off in terms of final dried product. Non-uniform drying was found to be present in coriander drying tests, and is also reported in literature. Experimentation showed that thin layer dried coriander were lighter and more yellow than those dehydrated in the microwave unit.

3. Microwave drying has the distinct advantage of being able to reduce the product moisture content to desired levels in a very short period of time. A problem inherent with microwave units is their inability to produce a constant amount of product volumetric heating at all locations within the oven cavity. This may result in samples that have areas of thermal damage (and subsequent losses of heat sensitive properties) and other areas which are not completely dehydrated. Microwave units are also more complex to construct. Also, temperature control is generally not a feature associated with these units, it is generally adjusted by power input to the system. The power level selected in experimentation was not able to ensure constant product temperature at all locations, causing concentrations of high temperatures which could lead to losses of heat sensitive properties.

4. Convection dryers equipped with re-circulating heat pumps have the ability to reduce drying times and increase overall system thermal efficiency as compared with conventional convection dryers. This comes with the increased capital and maintenance costs associated with the heat pump unit.

5. It is possible to use two or more dryer varieties in a hybrid unit to utilize the desirable characteristics of each unit. Another viable option may be to use a particular drying method intermittently (only when needed) to dehydrate products without overheating, preserving heat sensitive properties.

6. Process management is a vital part of herb dehydration. Components of specialty crops with differing drying kinetics should be separated prior to dehydration. This can be aided by effective design.

It is recommended that a subsequent study be conducted, incorporating a re-circulating heat pump dryer. Heat sensitive properties should also be monitored, as colour alone is not always an accurate indicator of product quality.

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