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# Refractance Window Dehydration Technology: A Novel Contact Drying Method

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**Refractance Window® (RW) system is a novel drying method for converting liquid foods and other related biomaterials into powders, flakes, or sheets with added value. In this system, purees or juices prepared from fruits, vegetables, or herbs dry in short times, typically 3–5 min, resulting in products with excellent color, vitamin, and antioxidant retention. The RW drying systems are simple and relatively inexpensive when compared with freeze drying, which usually needs large installations to be economical. In RW drying systems thermal energy is transferred from hot water to a film of puree or juice spread thinly on a plastic conveyor belt. These drying systems operate at atmospheric pressure and are used for commercial production of scrambled egg mix, avocado powder, high carotenoid-containing algae, herbal extracts and human nutrition supplements, and food ingredients, as well as dried fruits and vegetables. This article presents the principle of Refractance Window® drying and highlights some results that show its potential and how it compares with other dryers for processing fruits, vegetables, and other heat-sensitive products.**

**Keywords** Conveyor dryer; Drum dryer; Film dryer; Fruit and vegetable powders; Novel drying method; Nutraceutical; Quality

## INTRODUCTION

Drying is a unit operation where water is removed from products through application of heat, the end result being a solid. The final product may be in the form of sheets, flakes, film, powder, or granules. The drying process is distinguished from evaporation, where the final product is a liquid with a high concentration of dissolved solids. These two dehydration processes are very energy intensive yet have been used in the food industry for decades to provide microbial stability, reduce deteriorative chemical reactions, facilitate storage, and minimize transportation costs. Even though these objectives of drying as a unit operation are still relevant and important, today's consumers prefer more nutritious products with most of the health-promoting bioactive compounds retained. In response to this demand, recent development activities in the design of food dryers include product quality as a major criterion of dryer performance. Freeze drying has been used to produce dehydrated products with good retention of shape, flavor, color, vitamins, and rehydration ability. However, the cost of freeze drying is several times higher than spray drying[1,2] and air-drying.[3,4] Moreover, freeze-dried products tend to be porous and may rehydrate rapidly when exposed to a humid environment.[5,6] New drying techniques are emerging that provide certain significant advantages in terms of one or more of the following: energy consumption, product quality, safety, environmental impact, cost of dehydration, and productivity.[2]

Drying systems may be categorized as first, second, third, or fourth (the latest) generation based upon historical development.[7] Microwave, infrared, radiofrequency, refractance window, heat pump fluid bed drying, and the other hybrid drying systems described in Chou and Chua[1] are among the fourth-generation dryers that entail greater emphasis on retention of food quality. Apart from energy source, the temperature level (high or low), product residence times in dryer, and whether the heating medium should interact with material directly or indirectly are the other considerations in design for quality. It is also important to consider whether the heat is to be transferred to the wet material by convection, conduction, radiation, or a combination of those processes.[8] In most drying operations, energy is transferred from the surface to the center of the wet material with the exception of radiofrequency and microwave drying, where the energy supplied generates internal heat within the solid.[9] For additional information on classification of dryers, readers may refer to a recent review that also addresses the adaptation of classical drying processes to new technical developments and quality requirement by consumers.[10]

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The Refractance Window (RW™)[1] dryer discussed in this article is a relatively new development that falls within the contact, indirect, or film-drying techniques. In this drying method, thermal energy from hot water is transferred to wet material deposited as thin film on a plastic conveyor belt. The belt moves while in contact with the hot water and results in very rapid drying. The dry product is then scraped off the conveyor using a doctor blade that spans the full width of the belt. Unlike direct dryers, cross-contamination does not occur in indirect dryers such as RW system because the product does not contact the heat transfer medium. Other indirect or contact drying methods that closely relate to RW drying include drum and the solid steel belt or combined cylinder and belt (CBD) dryers. Most contact dryers use saturated steam, hot water, glycol solutions, or some commercially available heat transfer fluids for heating.[11] The heat transfer fluids do not make direct contact with the wet material but are used to transfer the energy indirectly via steel wall, plastic sheet, or steel belt. Recently, a unified approach to interpret the drying kinetics and modeling of convective drying process for suspensions, solutions, emulsions, and pastes under various conditions such as airflow, types of solid support, and initial concentration of suspension was presented.[12] The treatise includes examples of experimental drying and temperature curves for liquid dispersions of animal, vegetable, organic, and inorganic origin. This unified approach was expanded[13] to cover conductive drying of liquid dispersions and heat transfer on contact cylinders. The outcome of that unified approach has revealed an important phenomenon that has also been observed in RW drying. For cylinder temperatures lower than 100°C, a downturn of temperature of material occurs after the initial heating, followed by a stabilization of temperature due to large increase of thermal resistance of dried layer of material. Material processing involving conduction is advantageous because the heat transfer intensity is very high (ten times higher in comparison to a convective one), implementation is relatively simple, and directed variation of temperatures of heat transport medium allows the migration of dissolved substances to improve quality of processed material.[13] For better focus, the present discussion does not include the drying of suspensions in fluidized beds, spout beds, rotary drums, or paddle dryers with or without inert media,[14] nor does it cover the drying of thin films such as automobile paint, ink coating,[15] or coatings on thick webs.[16]

[1]RW™ is a trademark used exclusively for Refractance Window® drying and evaporation. Their mention in this paper is solely for correctness and does not imply endorsement of the technology over other systems performing similar function. Unless otherwise stated, RW will refer to Refractance Window® or RW™.

## METHODS OF DRYING FRUIT AND VEGETABLE DISPERSIONS

The drying methods frequently used in the food industry to produce food powders, flakes, leathers, or sheets from juices, purees, pastes, or suspensions include drum, conveyor, and spray drying. Each of those methods has certain advantages as well as limitations that dictate their choice for handling a particular product and are briefly reviewed in this article for comparison with RW drying method. There are other drying methods for food powders not discussed here either because they are not commonly used or because their design is not as close to the Refractance Window drying system. Freeze drying is included because it has traditionally been regarded as the quality standard against which other drying systems have been compared in terms of producing dehydrated fruits and vegetables with the highest quality. For detailed information on drying methods for food powders, there are a number of excellent publications on this subject.[8,17–20]

### Drum Drying

Drum drying is the process where materials, usually in form of fluid, slurry, or paste, are dried by spreading as a thin layer on the surface of a revolving drum that is internally heated by steam. Product temperatures are usually in the range of 120–170°C. Since the layer is comparatively thin, the drying rate is not governed by the diffusion of the vapor through the product layer.[21] Drum drying is one of the most energy-efficient drying methods and is particularly effective for drying high-viscosity liquid or pureed foods. Energy efficiencies in drum drying could range from 70 to 90%, corresponding to steam consumption of 1.2–1.5 kg per kg of water evaporated.[19,22] Drum dryers may be dip or splash fed or equipped with applicator rolls. The latter is particularly effective for drying high-viscosity liquids or pasty materials such as mashed potatoes, applesauce, fruit-starch mixtures, gelatin, and various starches.[23]

Control of product quality under drum drying requires simulation of the drying kinetics as well as modeling of finished product quality by incorporating some thermal degradation index.[24] Nearly two decades ago, Vasseur and his research group[25] reported that the capacity of a drum dryer principally depends on the drying rate of the thin material and its degree of adherence to the drying surface. The amount of material adhering on the wall depends on the type of feeding device, steam pressure, and drum speed. The thickness of film calendered on a drum dryer has repeatedly come out as an important parameter that affects quality of drum-dried foods.[26] Condition of feed material such as viscosity, surface tension, and wettability are also important, but are generally fixed before the drying operation.[21] There is also the problem of non-condensable gases that accumulate inside the drum, thus affecting the drying process. Drum wall thermal inertia is also an important consideration in the control of drum dryers because the inertia decreases with reduction in wall thickness and drying rate.[27–29] Rodriquez and others[30,31] based their analysis of drum drying as a boiling phenomenon and modeled the change in moisture content of product by controlling the drum speed and steam pressure. Later, a two-region mathematical model was developed for drum drying of black liquor using superheated steam impinging jets as a convective drying medium. The entire liquor drying process occurred in the falling rate period.[32] Due to many operating variables and a wide variation of product characteristics, it is very difficult to accurately model a contact drying process such as drum drying. With its high thermal efficiency and reliability,[23] the incorporation of the mentioned models in design and control of drum dryers may make them more competitive again should energy costs continue to escalate. However, high temperatures in drum drying remain a concern because of severe quality loss in heat-sensitive products.[33] Although the drums can be enclosed in a vacuum chamber to achieve drying at lower temperatures,[19,21] high capital cost limits that approach to only special applications. The high cost of the exchange surface, which must be precisely manufactured to allow scraping, is another limitation of drum drying.[27]

### Conveyor Drying

A conveyor dryer removes moisture from a product by forcing air vertically through the product on a perforated conveyor belt. Due to processing requirements, a series of individual drying stages may be joined together in a straight line or stacked above each other to transfer products through several drying sections to achieve desired final moisture content in the product.[34] The material being dried can be in flake, crystalline, granular, cake, or extruded form. Since the material stays motionless relative to the conveyor belt, each particle has essentially the same residence time during drying and product degradation through impact or attrition is eliminated.[35,36] The flow of heated air in a conveyor dryer can be adjusted so that each area of the bed is exposed to the process conditions of air velocity, temperature, and humidity most suitable for that phase of the drying process.[19,35]

Solid steel belt dryers are closer to the conveyor dryers in design, but the belt is a continuous smooth solid strip of steel made endless by a riveted or welded joint. The belt is heated from the bottom and heat transfer to the product is wholly by conduction. The most common application for solid steel belt dryers is for slab, sheet, or film formation by converting a liquid (or semi-liquid) layer on the belt into a solid product.[37] A version of the belt dryer that uses a similar plastic material for the conveyor as RW dryer was recently developed for making casein films.[38] Some applications of steel belt dryers involve the evaporation of non-aqueous solvents such as casting of plastic films in which a plastic solvent solution is cast onto the steel belt and dried to a film before being stripped from the belt. Food gums are frequently produced with this method. Solid steel belt dryers have the following desirable characteristics: (a) they do not absorb liquids, flavors, or odors; (b) they can withstand a wide range of temperatures; (c) the belt does not stretch or shrink and is wear resistant; and (d) the belt has high thermal conductivity, high service life, is easy to keep sterile and clean, and can handle hot, sticky, oily, sharp, or aggressive materials. As with drum dryers, the inherent high temperatures in the system can compromise the quality of heat-sensitive products. Although steel belt dryers remove much moisture from products, sheet formation is usually the primary objective.

### Spray Drying

Spray drying is another method that is frequently used in single operation to transform pumpable fluids such as solutions, slurries, emulsions, gels, and colloidal suspensions into dried powders. The fluid is atomized using a rotating wheel or stationary nozzles, and the spray of single droplets comes immediately into contact with a flow of hot drying air.[39,40] The resulting rapid evaporation maintains a low droplet temperature corresponding to the wet bulb temperature of the air so that high drying air temperatures ($\sim$270°C as in drying of instant coffee) can be applied without affecting the product. The droplet drying time is very short. This combination of short drying time and low product temperature (90–110°C) allows the spray drying of heat-sensitive products at atmospheric pressure.[40] Other advantages of spray drying include effective control of product properties and continuous operation.[40] High initial investment on equipment, inflexibility to obtain different particle sizes with a given atomizer, and inability to produce high-bulk density product, if desired, are cited as the major disadvantages. The moisture content of raw material also needs to be very high to ensure that the feed can be atomized. The atomization and high air temperatures encountered in spray drying usually cause high volatile losses, although the temperature of most particles may remain at the wet bulb temperature of the air. High shear action during atomization may also make this technique unsuitable for products that are sensitive to mechanical damage.

## OBJECTIVE

The objectives of this article are to review results from evaluation of Refractance Window® drying method for producing high-value food products and compare the performances of RW systems with that of conventional drying systems commonly used in drying solid suspensions, juices, or purees.

FIG. 1. Model 5 Refractance Window® dryer.

## The Refractance Window Drying System

Refractance Window® (RW™) dehydration method was developed by MCD Technologies, Inc. (Tacoma, Washington) based on several years of R&D in novel water removing techniques. The company has since patented the drying system (Fig. 1) together with its counterpart evaporator. Besides its ability to handle a diverse range of liquid products, its practical application is to transform fruits, vegetables, herbs, and other related products into value-added powders and concentrates. The RW drying method has become attractive for applications in the food industry especially because the dried products are of high quality and the equipment is relatively inexpensive. The cost of Refractance Window drying equipment is approximately one third to one half that of a freeze dryer to dry a similar amount of product, while the energy costs to operate RW dryers are less than half of freeze dryers. Contact drying methods such as drum or combined cylinder and belt drying (CBD) are probably the closest to RW drying. Currently, RW drying technology is used to process products such as scrambled egg mix; avocado fruits for dips; high carotenoid-containing algae for treating macular degeneration and cancer; herbal extracts and nutritional supplements for human use; food ingredients such as herbs, spices, and vegetables; and nutritional supplements for shrimp farming.[41] For effective RW drying, the suspensions need to have the right consistency for ease of application and uniform spreading on the conveyor belt. A summary of the system's performance with regard to drying kinetics, retention of quality for various fruits and vegetables, energy use, and microbial reduction is reviewed in this article.

## Heat Transfer and Drying Kinetics

The Refractance Window drying system utilizes circulating hot water, usually at 95–97°C and at atmospheric pressure, to carry thermal energy to material to be dehydrated (Fig. 2). Thermal energy from circulating hot water is transferred to the wet product via a plastic interface that is relatively transparent to infrared radiation. The actual product temperature is usually below 70°C. Products, which include juice, purees, and suspensions, are spread on the transparent plastic conveyor belt that moves while its bottom surface is in contact with hot water circulating on shallow troughs. The heated water is recycled and reused, thereby improving the thermal efficiency of the system. The use of hot water as the heat transfer medium and at temperatures just below boiling is a design feature that is unique to this drying method.

During RW drying, the three modes of heat transfer, namely conduction ($q_{cond}$), convection ($q_{conv}$), and radiation ($q_{rad}$), are active. Figure 3 shows the process by which heat is transferred from circulating hot water to the product. The process water is heated by steam within an insulated tank and then circulated in shallow troughs to transfer thermal energy to the plastic conveyor. Since the plastic conveyor is very thin, it reaches the temperature of hot water flowing beneath it almost immediately. Thermal energy from the hot water is transmitted through the plastic conveyor by conduction and radiation. However, the precise contribution of each of these modes of heat

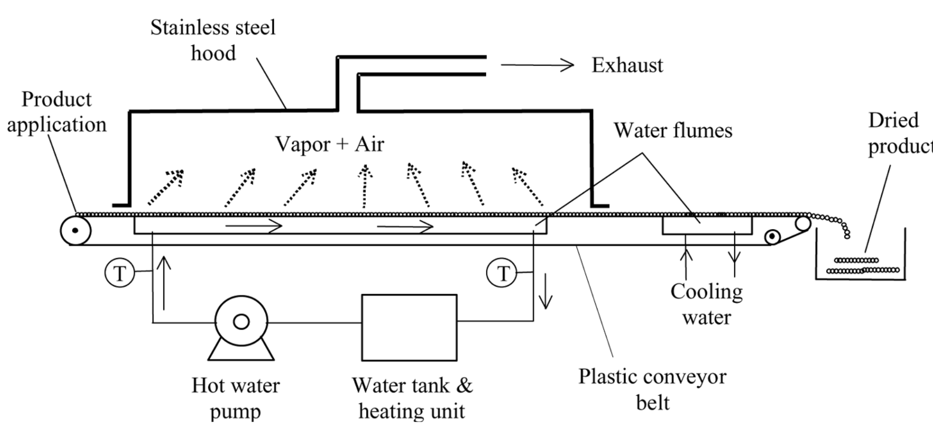


FIG. 2. Schematic diagram of Refractance Window® drying system (from Nindo et al.[47]).

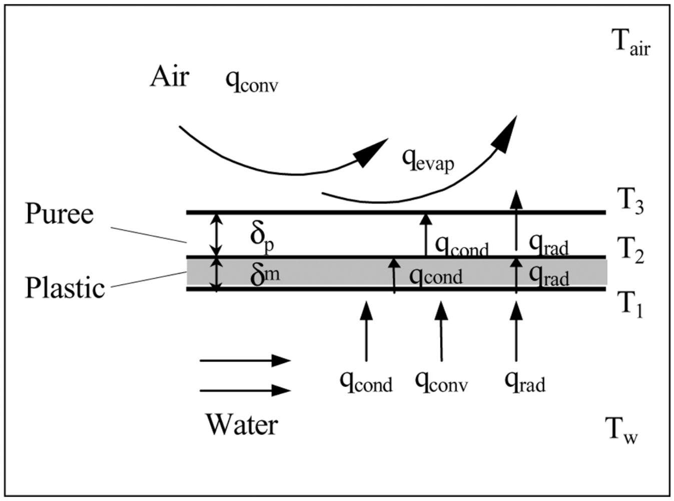


FIG. 3. Schematic diagram showing thermal energy transfer in RW drying system.

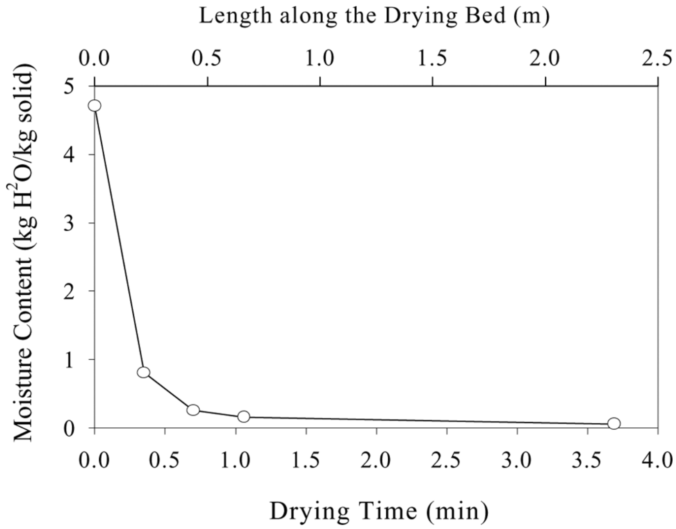


FIG. 4. Typical product residence time during RW drying of strawberry puree using process water temperature at 95°C and puree thickness of about 1.0 mm (From Ref. 46).

transfer still needs to be investigated. The use of process water at temperatures just below boiling and a thin plastic conveyor with infrared transmission in the wavelength range that matches the absorption spectrum for water[42] all work together to facilitate rapid drying. A thicker plastic material with low thermal conductivity, on the other hand, would provide higher resistance to transfer of thermal energy. Water has high absorption for infrared with wavelengths of 3.0, 4.7, 6.0, and 15.3 μm.[43] According to the inventors of RW drying system, the infrared transmission is stronger when the plastic interface is in intimate contact with water on one side and a moisture-laden material on the other side. When a pureed product with high moisture content is spread on top of the thin plastic conveyor, refraction at the plastic–puree interface is minimized, causing the radiant thermal energy to pass through the plastic into the product. The absorptivity of the puree is influenced by its thickness and moisture content.[44] The thermal energy transfer from the puree to the ambient air is primarily by convection and through evaporative cooling of the food material. This evaporation is very intense and constitutes a major part of energy consumption in RW drying. In the last stage of RW drying when the product is almost dry, heat transfer by conduction becomes predominant and the rate of heat transfer to the product slows as the product dries further. The cooling section at the discharge end of the RW dryer is intended to reduce the product temperature, preferably to below the glass transition temperature of the product, to facilitate product removal.

In an experiment with pureed strawberries (Fig. 4), the product dried in less than 5 min, contrary to several hours of tray or freeze-drying of the same quantities of the material. The superior quality retention capability demonstrated by RW drying is most likely due to the favorable combination of short drying times and relatively mild product temperatures (Fig. 5). The rapid mass transfer from wet product and the resulting high vapor saturation above the product limits product–oxygen interaction and helps to maintain the quality of product. For example, the residence time for RW drying of pureed asparagus from about 90% to 4% moisture content (wet basis) was only 4.5 min.[45] The capacity of the RW dryer varies with the condition of feed material but is typically in the same range as spray and drum dryers (Table 1). In drying experiments done with the belt moving (Fig. 5) and also with a stationary belt (Fig. 6) it was observed

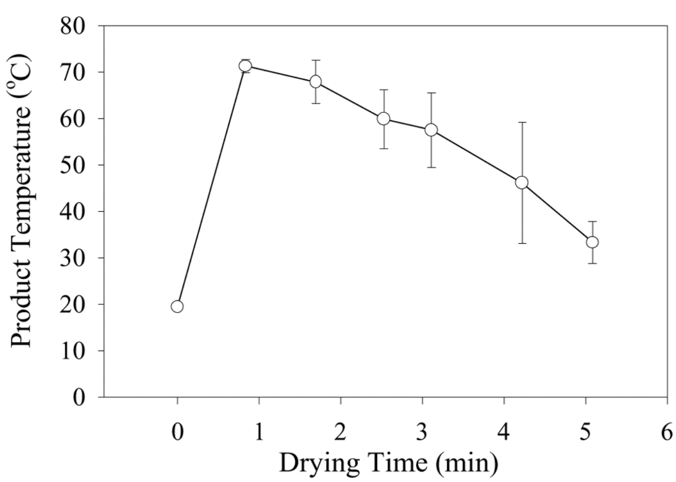


FIG. 5. Typical temperature profile for puree of thickness 0.7–1.0 mm during RW drying on a moving belt. Process water was regulated at 95°C (from Abonyi et al.[46]).

TABLE 1
Comparison of energy consumption of RW with other selected dryers[8,48]

| Dryer type | Typical capacity (kg/h) per $m^3$ or $m^2$ | Typical product temperature (°C) | Thermal efficiency (%) |
|---|---|---|---|
| Rotary dryer | 30–80 $m^{-3}$ | About 175 | 50–25 |
| Spray dryer | 1–30 $m^{-3}$ | 80–120 | 51–20 |
| Drum dryer (for pastes) | 6–20$m^{-2}$ | 120–130 | 78–35 |
| RW Dryer | 1–10 $m^{-2}$ | 60–70 | 77–52 |

in both cases that the product temperature does not reach the heating water temperature. This may be attributed to resistance to heat transfer and cooling that accompanies the intense evaporation.[46,47] The low product temperatures and short drying duration contributed to high retention of product quality, as will be discussed in a later section.

## Energy Consumption in Refractance Window Drying

The evaporation of water from the product at the air–puree interface constitutes a major part of energy consumption in RW drying. To determine the thermal efficiency of RW dryer, steam condensate was collected and a heat balance done by measuring process water and product temperatures at various points. Since process water from the dryer flows back into a reservoir and is reheated rather than wasted, RW drying demonstrates very good thermal efficiency when compared with other conventional dryers (Table 1). The dryer capacity data vary in a wide range because many factors influence the accuracy of energy audits[48]. In the case of RW system, the product thickness and consistency at deposition are very critical to the drying process. The product must spread thinly and adhere uniformly on the conveyor belt for the drying to be effective. Based on the latent heat of vaporization of water of about 2300 kJ/kg, thermal efficiency of RW drying (52–77%) is comparable to drum drying. Heated air-drying systems usually have lower efficiencies (20–40%) by comparison.[49] The capacity of conveyor dryers discussed earlier is about 2–15 $kg/m^2 h$ with a specific steam consumption of 1.8–2.0 kg/kg water.[34]

## Refractance Window Drying and Food Quality

The retention of food quality in a drying process rather than mere extension of shelf life has gained prominence

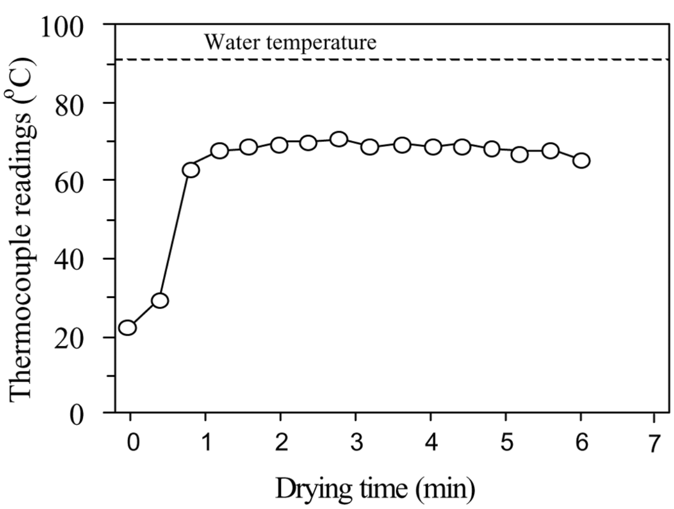


FIG. 6. Typical temperature profile for puree of thickness 0.7–1.0 mm during RW drying with the belt stationary (from Nindo et al.[47]).

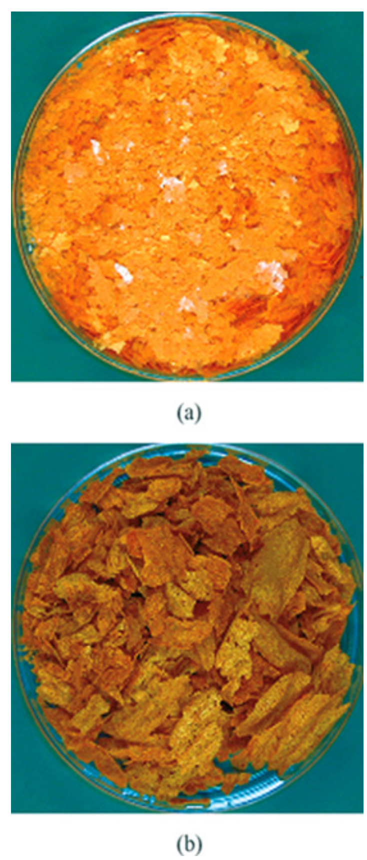


FIG. 7. Carrot flakes obtained from (a) Refractance Window dryer, and (b) drum dryer.

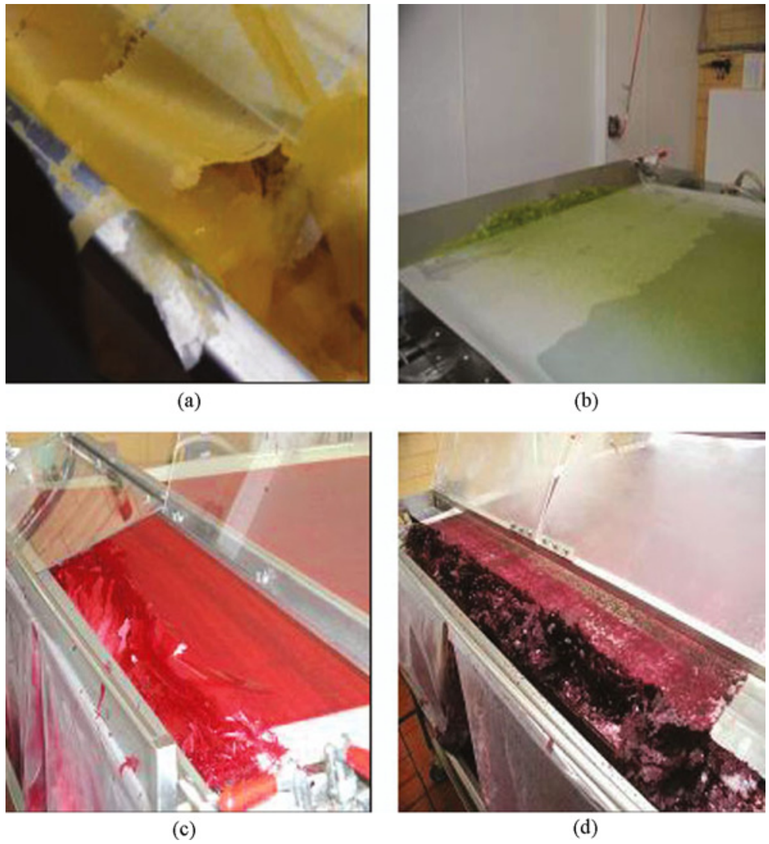

FIG. 8. Refractance Window drying of (a) squash, (b) asparagus soup mix, (c) lingonberry, and (d) blueberry.

recently because of consumers demand for more health-promoting foods. The importance of food quality retention in drying operations is evident from the increased research in this area.[50] In 2005, a special issue of *Drying Technology* (Vol. 23, #4) was dedicated to the subject of food quality. A compilation of literature that addresses the retention of nutritional and functionality quality during drying of fruits and vegetables was also presented recently to provide guidance to researchers and industry practitioners interested in this crucial area.[51] New dryers targeted for the food industry must go through several testing and improvement cycles to define some optimized conditions for retaining most heat labile compounds that are keys to quality retention in food. Several fruits and vegetables have been RW dried successfully with very good retention of quality. These include carrots, squash, asparagus, lingonberries, blueberries, strawberries, mangoes, and avocadoes, among others (Figs. 7 and 8).

TABLE 2
Color parameters of asparagus dried by five different methods

| Drying method | Temp (°C) | L | a* | b* | H | C |
|---|---|---|---|---|---|---|
| Tray drying | 50 | 24.8 ± 2.1 | −2.6 ± 0.7 | 20.6 ± 1.4 | 92.7 | 20.8 |
| | 60 | 14.4 ± 1.7 | −0.6 ± 0.1 | 12.2 ± 1.0 | 92.6 | 12.2 |
| MWSB | 50 | 17.9 ± 3.8 | −3.3 ± 0.7 | 14.7 ± 3.2 | 102.8 | 15.1 |
| | 60 | 26.8 ± 2.0 | −1.9 ± 0.5 | 17.6 ± 1.8 | 96.1 | 17.7 |
| RW | 95* | 18.3 ± 3.4 | −4.5 ± 0.4 | 15.6 ± 1.6 | 106.0 | 16.2 |
| Freeze drying | 20** | 37.7 ± 4.5 | −4.9 ± 0.7 | 20.7 ± 1.4 | 103.4 | 21.3 |
| Fresh asparagus | — | 40.2 ± 2.9 | −3.1 ± 0.7 | 11.7 ± 2.6 | 104.7 | 12.1 |

*Heating water temperature; **Plate temperature; RW: Refractance Window; MWSB: Combined microwave and spouted bed (from Nindo et al.[45]).

TABLE 3
Color value L, a*, b*; chroma, and hue for carrot puree[46]

| Treatment | L | a* | b* | H | C |
|---|---|---|---|---|---|
| Fresh puree | $54.3 \pm 0.8^{d}$ | $28.7 \pm 0.2^{b}$ | $44.0 \pm 1.0^{a}$ | $56.8^{b}$ | $52.5^{c}$ |
| Drum dried | $67.5 \pm 0.6^{c}$ | $20.8 \pm 0.4^{d}$ | $39.4 \pm 1.7^{b}$ | $62.1^{c}$ | $44.6^{a}$ |
| RW dried | $72.0 \pm 0.3^{b}$ | $34.1 \pm 0.5^{a}$ | $45.1 \pm 0.8^{a}$ | $52.8^{\mathrm{a}}$ | $56.5^{\mathrm{d}}$ |
| Freeze dried | $77.6 \pm 0.4^{a}$ | $27.1 \pm 1.2^{c}$ | $44.1 \pm 0.4^{a}$ | $58.5^{b}$ | $51.8^{b}$ |

L: lightness, a*: redness, b*: blueness, Chroma, $C = (a^{*2} + b^{*2})^{1/2}$, H: $\tan^{-1}(b^*/a^*)$.
[abcd]Different letters in the same column indicate significant difference ($p \leq 0.05$).

TABLE 4
Color parameters L, a*, b*, chroma, and hue values for strawberry puree*[46]

| Treatment | L | a* | b* | H | C |
|---|---|---|---|---|---|
| Fresh puree | $45.3 \pm 1.6^{d}$ | $27.0 \pm 1.7^{b}$ | $22.0 \pm 1.9^{a}$ | $39.2^{a}$ | $34.8^{a}$ |
| Spray dried | $77.8 \pm 0.7^{a}$ | $23.9 \pm 0.6^{c}$ | $16.8 \pm 0.5^{c}$ | $35.1^{b}$ | $29.2^{b}$ |
| RW dried | $63.2 \pm 0.5^{c}$ | $29.3 \pm 0.6^{a}$ | $20.2 \pm 0.5^{b}$ | $34.6^{b}$ | $35.6^{a}$ |
| Freeze dried | $71.5 \pm 0.5^{b}$ | $25.6 \pm 0.8^{b}$ | $16.6 \pm 0.6^{c}$ | $33.0^{c}$ | $30.5^{b}$ |

[abcd]Different letters in the same column indicate a significant difference ($p \leq 0.05$).
*With maltodextrin.

TABLE 5
Carotene losses in carrots after drum, Refractance Window, and freeze-drying[46]

| | Total carotene | | α Carotene | | β Carotene | |
|---|---|---|---|---|---|---|
| Sample | g/g Solid | Loss (%) | g/g Solid | Loss (%) | g/g Solid | Loss (%) |
| Control | $1.77 \pm 0.0^{a}$ | | $0.85 \pm 0.04^{a}$ | | $0.92 \pm 0.0^{a}$ | |
| Drum dried | $0.78 \pm 0.1^{b}$ | $56.0 \pm 1.2$ | $0.38 \pm 0.09^{b}$ | $55.0 \pm 1.1$ | $0.39 \pm 0.0^{b}$ | $57.1 \pm 1.3$ |
| RW dried | $1.62 \pm 0.3^{a}$ | $8.7 \pm 2.0$ | $0.79 \pm 0.16^{a}$ | $7.4 \pm 2.2$ | $0.83 \pm 0.1^{a}$ | $9.9 \pm 1.8$ |
| Freeze dried | $1.70 \pm 0.0^{a}$ | $4.0 \pm 3.6$ | $0.83 \pm 0.03^{a}$ | $2.4 \pm 3.7$ | $0.87 \pm 0.0^{a}$ | $5.4 \pm 3.5$ |

The results are average of three replicates.
[ab]Different letters in the same column indicate a significant difference ($p \leq 0.05$).

TABLE 6
Total antioxidant activities of green asparagus portions after drying by various methods*

| | | Asparagus spear portion | | | |
|---|---|---|---|---|---|
| Drying method/condition | Temp. (°C) | Tip | Middle | Basal | Whole spear |
| Freeze drying | 20 (plate) | $98.4 \pm 3.7^{a}$ | $74.5 \pm 4.1^{a}$ | $55.7 \pm 3.5^{a}$ | $76.2 \pm 3.8^{a}$ |
| RW™ | 95 (water) | $88.2 \pm 6.2^{a}$ | $75.2 \pm 2.6^{a}$ | $56.2 \pm 1.4^{a}$ | $73.2 \pm 3.4^{a}$ |
| Tray drying | 60 (air) | $67.1 \pm 4.8^{b}$ | $45.7 \pm 3.3^{b}$ | $40.6 \pm 1.7^{b}$ | $51.1 \pm 3.3^{b}$ |
| Spouted bed | 60 (air) | $49.1 \pm 2.1^{c}$ | $42.6 \pm 1.4^{b}$ | $40.9 \pm 2.7^{b}$ | $44.2 \pm 2.1^{d}$ |
| MWSB | | | | | |
| 2 W/g | 60 (air) | $55.8 \pm 4.1^{bc}$ | $42.4 \pm 2.9^{b}$ | $37.1 \pm 1.8^{b}$ | $45.1 \pm 2.9^{cd}$ |
| 4 W/g | 60 (air) | $56.9 \pm 6.1^{bc}$ | $55.2 \pm 3.2^{c}$ | $37.5 \pm 3.7^{b}$ | $49.9 \pm 4.3^{bc}$ |

*Tukey HSD test. Same letter in same column means there is no difference between treatments. The units of antioxidant activity are in Trolox equivalents, μmol/g (from Nindo et al.[45]).

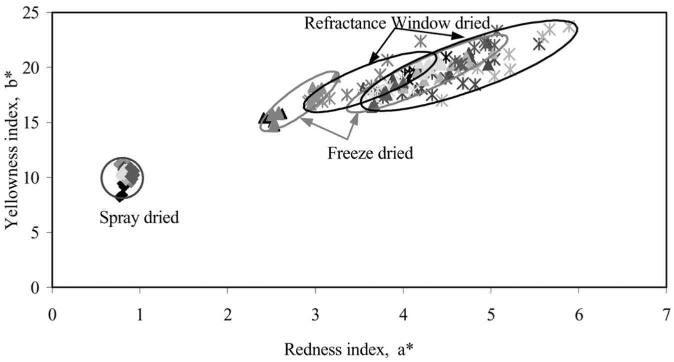


FIG. 9. Color of Refractance Window-dried (∗), freeze-dried (△), and spray-dried (◇) aloe vera during 7 weeks of storage at 35°C.

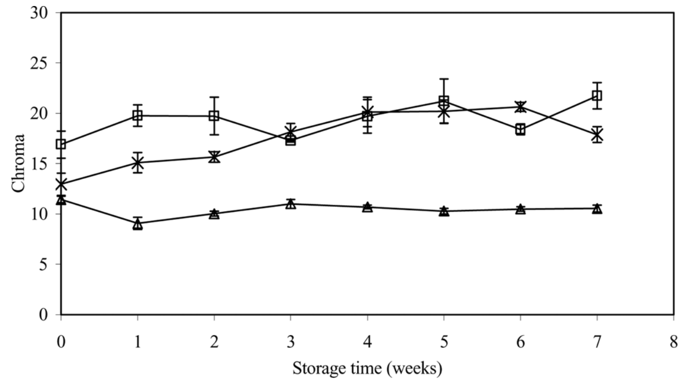


FIG. 11. Chroma $[\sqrt{(a^{*2} + b^{*2})}]$ of spray- (△), freeze- (∗), and Refractance Window- (□) dried aloe powder during 7 weeks of storage at 35°C.

*Asparagus, Carrots, and Strawberries*

The color of food is important to their acceptability, and instrumental techniques are frequently used to obtain objective color evaluation.[52] Table 2 shows color of green asparagus (*Asparagus officinalis* L.) after tray (TD), microwave spouted bed (MWSB), Refractance Window (RW), and freeze drying (FD). The greenness ($a^*$) of asparagus after FD and RW drying are little different, though FD material showed more yellowness ($b^* = 20.7$). The hue angle (H) of both freeze and RW dried asparagus was very close to the freshly blanched asparagus. However, the chroma value (C), which is a measure of color saturation of materials that have similar hue and lightness, indicates that RW-dried asparagus is closer to the fresh material.

Table 3 shows the influence of RW, freeze drying, and drum drying on color of carrots, while Table 4 compares color of strawberries after freeze drying, RW, and spray drying. As commonly practiced in the industry, about 23.3% (w/v) of maltodextrin with dextrose equivalency of 10 was added to strawberry puree before spray drying to prevent the product from sticking on the wall of the spray dryer. No maltodextrin was added to strawberry puree with other drying methods. The drum-dried carrot was darker (higher hue) compared to RW- and freeze-dried counterparts. For strawberry puree with added maltodextrin, RW drying was closest to freeze drying in terms of chroma followed by spray drying, although the hue angle for spray and RW dried were very similar (Table 4). RW-dried carrots and strawberries generally retained their appealing color, while drum-dried carrots suffered severe heat damage, as demonstrated by their brown color and burnt aroma.

The retention of vitamins in carrots and total antioxidants in asparagus after drying by different methods, including RW drying, was also investigated (Tables 5 and 6). The loss of carotenes in carrots under drum drying was much larger compared to the losses under freeze or RW drying, which were low and of comparable magnitude, although freeze drying consistently showed the highest retention (Table 5). Freeze drying contributed to 5.4% loss of β carotene, followed by RW drying (9.9%) and drum drying (57.1%). The total antioxidants in dried asparagus were evaluated using a synthetic vitamin E analog (Trolox) as reference standard. Out of the five different drying

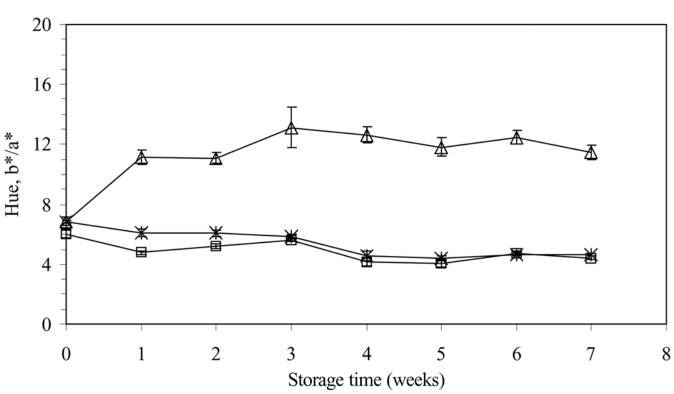


FIG. 10. Change in hue of spray- (△), freeze- (∗), and Refractance Window- (□) dried aloe powder during 7 weeks of storage at 35°C.

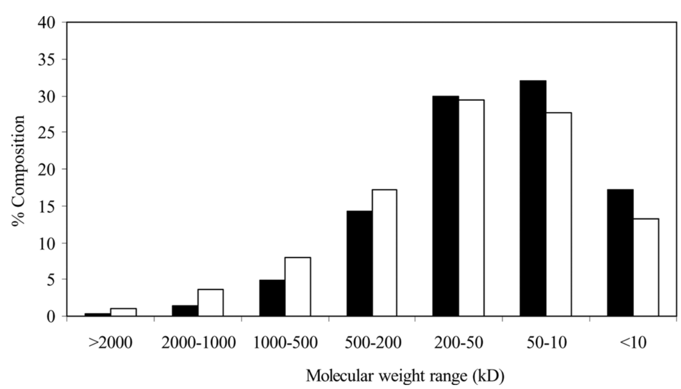


FIG. 12. Molecular weight distribution of freeze-dried (■) and RW-dried (□) aloe.

TABLE 7
Microbial counts in LogCFU/mL as affected by Refractance Window drying*[47]

| | APC | | Coliforms | | *Escherichia coli* | | *Listeria innocua* | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Control | 7.17 | 0.12 | 6.78 | 0.09 | 6.73 | 0.14 | 6.14 | 0.11 |
| Treated | 2.54 | 0.26 | < 0.69 | NA | < 0.69 | NA | < 0.69 | NA |
| Log reduction | 4.63 | | 6.09 | | 6.04 | | 5.45 | |

*Process water temperature was 95°C. Data are means of three replicated tests for each group of microorganisms.

methods investigated, freeze and RW drying methods showed higher and comparable retention of total antioxidants. Tray drying, spouted bed, and a combination of microwave spouted bed drying treatments did not reveal any significant differences in each of the spear portions (Table 6).

*Aloe Vera—A Cosmetic and Herbal Product*

There is growing interest in producing high quality dried aloe vera (*Aloe barbadensis* L.). Aloe vera is a plant from the lily family that possesses therapeutic and antioxidant properties.[53] Extracts or gels from aloe vera are widely used in skin care products and, lately, as health supplement for humans. Aloe vera polysaccharides possess antioxidative properties that may be lost through thermal processing.[54] The suitability of the new Refractance Window method for dewatering heat-sensitive herbal products such as aloe vera was investigated and comparisons made with freeze and spray drying. The resulting dried materials were examined for changes in color and molecular weight distribution of polysaccharides.

Both the RW- and freeze-dried (FD) aloe vera had a light cream color compared to the whiter (higher lightness value) spray-dried powder (Fig. 9). During 7 weeks of storage at 35°C, the yellowness ($b^*$) and redness ($a^*$) of both RW- and freeze-dried aloe increased slightly and in proportion to the overall hue ($b^*/a^*$) that ranged between 4 and 6 (Fig. 10). The hue of spray-dried aloe increased slightly during the first 3 weeks of storage then stabilized around 12 for the remaining period of storage. The chroma or color saturation (Fig. 11) of aloe powders dried by the three methods was not significantly changed. These data indicate that freeze-dried and RW-dried aloe powder stored under accelerated storage conditions maintain a similar color.

Subjecting polysaccharide products to heat over time may cause depolymerization and shifts in molecular weight distribution (MWD), especially if the process occurs in the presence of $H^+$ or enzymes.[55] Such breakdown may affect the usefulness of aloe vera powders by reducing the shelf life and biological activity. Figure 12 shows the MWD of polysaccharides in aloe after RW and freeze drying. It is evident that MWD is not greatly affected by the drying methods investigated. However, molecular weights of aloe polysaccharides in the ranges >2000 kD, 2000–1000 kD, 1000–500 kD, and 500–200 kD were higher for RW- than for freeze-dried aloe. The percentage composition of polysaccharides within the 200 to 50 kD range (normally considered to possess more functional properties) was nearly the same for the two drying methods. The freeze-drying process retained more of the aloe polysaccharides with molecular weights of less than 50 kD.

## Microbial Reduction in Refractance Window Drying

Table 7 summarizes the microbial reductions achieved when drying pumpkin puree pre-inoculated with coliforms, *Escherichia coli*, and *Listeria innocua*. *Listeria innocua* is often used as a surrogate for the heat-tolerant human pathogen *E. Coli* O157:H7 and *Listeria monocytogenes* because of the similarity in their thermal resistance. It can be seen that the microbial count after RW drying was greatly reduced for all the microorganisms. For the inoculated samples, the test microorganisms were reduced to the minimum detection limit of < 5 CFU/mL, which corresponds to a microbial reduction of at least 6.1, 6.0, and 5.5 log CFU/mL for coliforms, *Escherichia coli*, and *Listeria innocua*, respectively. The reduction of inoculated populations ($10^6$ CFU/ mL) of coliforms and *E. coli* to an undetectable level is significant because it indicates that RW drying can produce safe products. The initial total aerobic count (APC) in non-inoculated pumpkin puree was 7.17 log CFU/mL and after drying the APC was reduced to 2.54 log CFU/mL, a 4.6-log reduction.

## SUMMARY

Studies conducted on the Refractance Window drying technology show that the system demonstrates high retention of product quality (color, vitamins, and antioxidants) when compared with other conventional drying methods. Only 9.9% loss of beta-carotene in carrots occurred with RW drying compared to 5.4 and 57% in freeze and drum drying, respectively. Both freeze-dried and RW-dried asparagus showed color hues not significantly different from the fresh material. Freeze-dried and RW-dried aloe vera showed similar pattern of color change during storage. The molecular weight distribution of aloe polysaccharides was unaltered after drying by the two methods. The RW drying system produces high-quality dehydrated foods and herbs because most of the nutritional and sensory attributes in the end products are maintained. The quality of the dried products is comparable to those obtained by freeze drying, yet the cost of the equipment is several times smaller than freeze drying. Concerning microbial reduction ability, Refractance Window achieved at least 4.6-, 6.1-, 6.0-, and 5.5-log reductions for total aerobic counts, coliforms, *E. coli*, and *L. innocua*, respectively, with the latter three being reduced to undetectable levels. A number of foods that are difficult to spray dry without the addition of non-sugar carriers have also been handled successfully in the RW dryer. These attributes of RW drying make it suitable for processing of high-value foods, nutraceuticals, and food supplements where high standards of quality and safety are required. Additionally, RW drying technology has potential for use in parts of the world where effective drying methods such as freeze drying have been difficult to implement due to cost. The assembled scientific data are also useful for those in the food, nutraceutical, cosmetic, and biotechnological industries for selecting appropriate drying methods for their applications.

## NOMENCLATURE

| | |
|---|---|
| C | Chroma value |
| CBD | Combined cylinder and belt dryer |
| CFU | Colony forming units |
| FD | Freeze drying |
| H | Hue value |
| MWD | Molecular weight distribution (kD) |
| MWSB | Microwave spouted bed drying |
| q | Heat transfer rate (J/s) |
| RW | Refractance Window® or RW™ |
| T | Temperature (°C) |
| TD | Tray drying |

### Greek Symbols

| | |
|---|---|
| $\delta$ | Material thickness (mm) |

### Subcripts

| | |
|---|---|
| w | Bulk water |
| 1 | Bottom surface of plastic |
| 2 | Plastic-puree interface |
| 3 | Puree surface |
| cond | Conduction |
| conv | Convection |
| evap | Evaporation |
| m | Plastic conveyor |
| p | Puree |
| rad | Radiation |

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