A review on mechanism, quality preservation and energy efficiency in Refractance Window drying: a conductive hydro-drying technique

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Received: June 12, 2018 | Published: June 21, 2018

Abstract

Thermal drying consumes up to 25% of the industrial energy consumption in developed countries. Refractance Window (RW) is a relatively new drying method that it is characterized by maintaining a relatively low temperature inside the food and short drying times. A RW dryer can produce high-quality products with retaining heat sensitive vitamins, color, phytochemicals content and antioxidant activity close to the freeze-dried products, while the cost of the RW equipment is less than 30 percent of the cost of a freeze-dryer and the energy consumption of RW is less than 50 percent of the energy consumption for a freeze-dryer.

Early understandings heat transfer mechanism in RW drying suggested that the moist material on a thin plastic sheet over hot water, creates a “window” for infrared radiation (IR) and as the material dries, the “window” gradually cuts off the radiation. Recently a conjugate heat and mass transfer model showed that a major portion of thermal energy is transferred via conduction; some of the researchers proposed the term “conductive hydro-drying” for the name of this technology. Another important parameter in RW drying is air convection. Forced air convection causes lower product temperature and higher moisture loss in comparison with natural convection.

Although many studies have been conducted on this technology, there are still many types of food materials for which RW drying and process optimization have not yet been investigated.

Keywords: Refractance Window drying, conductive hydro-drying, energy efficiency, product quality

Introduction

Dried vegetables, fruits and other food ingredients are widely used in prepared foods. Conservation of quality attributes such as aroma, color and nutrients has always been a challenge in dehydration of heat sensitive fruits and vegetables. Consumer demand for high quality dehydrated foods continually inspires efforts toward development of improved and innovative drying methods.¹,²

Thermal drying consumes 10–25% of the industrial energy in the developed countries. Drying energy consumption in the United States, United Kingdom and France were 1600×10⁹, 128×10⁹, 168×10⁹ MJ/year, respectively. With rapid industrialization of emerging global economies, the energy consumed for thermal dehydration and the resulting adverse environmental impact of the greenhouse gases will unavoidably increase over time.³

Refractance window drying

Refractance Window (RW) is a new film drying method and it is characterized by maintaining a relatively low temperature inside the food and by requiring shorter process times.⁴ To dry a similar amount of product, the cost of the RW equipment is about one-third of the cost of a freeze-dryer (FD); while energy consumption of RW is less than half of the energy consumption for a FD.⁵

RW drying system uses circulating water at 90 to 95°C as a means to convey thermal energy to materials to be dehydrated. A RW dryer can produce high-quality products with retaining heat sensitive vitamins, color, phytochemicals content and antioxidant activity close to the freeze-dried products.⁶ Early understandings heat transfer mechanism in RW drying suggested that the moist material on a thin plastic sheet over hot water, creates a “window” for infrared radiation (IR) and as the material dries, the “window” gradually cuts off the radiation. Recently a conjugate heat and mass transfer model showed that a major portion of thermal energy is transferred via conduction; some of the researchers proposed the term “conductive hydro-drying” for the name of this technology. Another important parameter in RW drying is air convection. Forced air convection causes lower product temperature and higher moisture loss in comparison with natural convection.⁷

Although many studies have been conducted on this technology, there are still many types of food materials for which RW drying and process optimization have not yet been investigated.
suggested that in this type of dryer, thermal energy from circulating hot water is transported to the wet product via a plastic interface which is relatively transparent to infrared radiation. Hot water’s thermal energy is transmitted through the thin Mylar conveyor belt via conduction and radiation. Water molecules show high absorption for IR with wavelengths of 3.0, 4.7, 6.0, and 15.3 µm. The IR transmission through the Mylar sheet is in this wavelength range, which results in quick drying. Moreover the IR transmission is stronger when the Mylar surface is in contact with water on one side and a moist material on the other side.5

**Preservation of heat sensitive vitamins and phytochemicals**

**Ascorbic acid retention**

Ascorbic acid is an important vitamin and an essential nutrient for humans and some animal species. It is found in many fruits and vegetables but it is very sensitive to heat and oxidation. Several studies have shown that RW drying can preserve ascorbic acid content in the products. A study on drying strawberry purees showed that the retention of ascorbic acid was 94.0% after RW drying, which was very close to 93.6% in FD. Another study also showed that ascorbic acid retention in strawberry purees dried with RW system (93%) was comparable to FD products (94%). In dried asparagus using heated air, RW, and microwave assisted spouted bed, RW drying resulted in highest retention of total ascorbic acid.

**Anthocyanin retention**

Anthocyanins are valuable and nutritional phytochemicals, which are present in various plants. They are susceptible to drying processes. Research has shown that RW drying results in low anthocyanin losses. In a study, 45, 41, and 23% losses in total anthocyanins content were observed in colored potato flakes after FD, drum drying and RW drying, respectively. Haskap berry puree was dried using an RW dryer and more than 92% of anthocyanins were retained. RW dryer produced high-quality pomegranate juice powder with antioxidant activity, anthocyanins color and anthocyanins content close or higher than those of the FD or spray dried samples.

**Carotene retention**

Carotenes are colored pigments found in many fruits and vegetables. β-carotene is the most common form of carotene in plants. It can be used as a food coloring and it is a precursor to vitamin A. Carotenoids are also susceptible to heat and oxidation and their retention in dried products is imperative to achieve a high quality products. A study on quality retention of dried carrot puree showed that RW drying is a much better method than drum drying to dry carrot puree (Table 1). The color of the RW-dried carrot purees was comparable to fresh puree, and other studies on RW drying of carrots have demonstrated similar results.

**Table 1** Carotene losses in carrots samples dried by drum, freeze, and Refractance Window drying methods

| Dryer / Carotene Loss | Total carotene | α-carotene | β-carotene |
|-----------------------|---------------|------------|------------|
| Drum Dryer            | 56.0%         | 55.0%      | 57.1%      |
| RW Dryer              | 8.7%          | 7.4%       | 9.9%       |
| Freeze Dryer          | 4.0%          | 2.4%       | 5.4%       |

**Vitamin B retention**

Recently Nemzer et al studied physicochemical and physical property retention in blueberries, tart cherries, strawberries, and cranberries as affected by FD, RW and hot air drying methods. Their results showed that RW dried cranberry and strawberry samples had higher total vitamin B retention than FD and hot air dried products.
Microbial reduction

Although RW drying is comparable with freeze drying and other low temperature drying methods in terms of physiochemical quality retention, it can also reduce microbial load in its dried products. In a study on RW drying of pumpkin puree from 80% to 5% moisture content (wb) which was completed in about 5 minutes (with water at 95°C). RW drying of inoculated pumpkin purees resulted in 4.6, 6.1, 6.0, and 5.5 log reductions of total aerobic plate counts (APC), coliforms, *Escherichia coli*, and *Listeria innocua*, respectively. The RW dryer in this study demonstrated up to 70% energy efficiency.²

Case studies of drying fruits and vegetables

Green asparagus

In a study on drying of green asparagus using different methods, microwave assisted spouted bed (MWSB) drying was the fastest and resulted in highest retention of total antioxidant activity (TAA) among the methods where heated air was used. TAA of RW and freeze-dried asparagus was significantly higher than heated air-drying methods. The amount of ascorbic acid in the dried products were as follows RW>freeze-drying>MWSB >spouted bed drying.⁴

Paprika

RW drying method was used to dry paprika and the quality of the product was compared with FD and hotair drying methods(forced and natural convection drying methods). The reflected color characteristics of FD and RW dried paprika was better than hot air drying methods. Also, the browning index of FD and RW dried samples were not significantly different.²²,²³

Mango

Drying process of mango was carried out using RW drying, freeze drying, drum drying, and spray drying. Results showed that the color of FD and RW dried mango powder and was close to reconstituted mango puree, but significantly lighter than drum dried, and darker than spray dried powders. In terms of bulk density, RW and drum dried mango powders had higher bulk density than freeze dried and spray dried samples. While solubility and hygroscopicity RW and freeze-dried powders were not significant different. The microstructure of RW-dried mango powder was smooth and flaky with uniform thickness.²⁴–²⁶

Aloe-vera

Aloe-vera extract was dried using spray drying, freeze drying, and RW drying methods. Reconstituted solutions from freeze dried and RW-dried samples had higher and nearly similar consistency while solutions of spray dried samples had the lowest viscosity. Also the activation energy for network formation of solutions reconstituted from freeze dried and RW dried samples was 24.6±0.3 and 24.7±0.4 kJ mol⁻¹ was slightly higher than activation energy for network formation of spray dried solutions.²⁷ Another study on RW drying of aloe-vera gel also showed that RW and freeze dried products are comparable.²⁸

Strawberry puree

RW-dried strawberries demonstrated color values close to that measured in freeze-dried samples. Total drying time for RW method was about 4 minutes (Figure 2) while freeze drying took 24 hours. In case of aromatic compounds, sample analysis showed that RW-dried strawberry purees had more heat-induced aldehydes and ketones and less alcohols and esters.¹³

Energy efficiency

Different studies on energy consumption and energy efficiency of RW drying have concluded that in comparison with different conventional drying methods, RW drying is a very energy efficient choice (Table 2,3).

Table 2 Comparison of energy consumption of RW with other selected dryers³

| Type of the dryer | Typical product temperature (°C) | Thermal efficiency (%) |
|-------------------|---------------------------------|------------------------|
| Rotary dryer      | About 175                       | 50-25                  |
| Spray dryer       | 80-120                          | 51-20                  |
| Drum dryer        | 120-130                         | 78-35                  |
| RW Dryer          | 60-70                           | 77-52                  |

Table 3 Overall energy efficiency of spray, freeze and RW dryers⁴

| Type of the dryer | Calculated energy needed for drying 1kg sample (kWh) | Energy consumption for drying 1kg sample (kWh) | Overall energy efficiency (%) |
|-------------------|------------------------------------------------------|-----------------------------------------------|------------------------------|
| Freeze dryer      | 1.46                                                 | 130.65                                        | 1.12                         |
| RW dryer          | 1.36                                                 | 4.31                                          | 31.56                        |
| Spray dryer       | 1.42                                                 | 11.01                                         | 12.92                        |

Future trends

- Investigating dehydration of different food materials including microorganisms (yeast, probiotics), leaf vegetables, meat and marine products.
- Investigating the effect of RW drying on starch granules.
Summary

Refractance Window is a relatively new film drying technique and it is characterized by high-quality products, short drying times, low cost, high energy efficiency and high evaporation capacity. RW drying can retaing product quality in terms of heat sensitive vitamins, color, phytochemicals content and antioxidant activity as compared to freeze-dried products.

Firstly, it was assumed that the main heat transfer mechanism of RW drying system was thermal radiation via the plastic sheet through a transparent window which was created by the contact of wet material on the surface of the sheet. Recently, a conjugate heat and mass transfer model developed to simulate the RW drying process showed that a major portion of thermal energy was transferred via conduction and development of a dried, thermally resistive layer at the base or development of air spaces between the product and the plastic sheet reduces the heat flux from the hot water, therefore reducing thermal damage and preserving the quality of the product. Another important parameter in a RW drying is air convection. Forced air convection in a RW dryer causes lower product temperature during the process and higher moisture loss values in comparison with natural convection.

Although many different drying experiments have been conducted on RW drying system, some areas including optimization of RW drying in terms of energy consumption and process design and investigating the effect of RW drying on starch granules and dehydration of microorganisms (yeast, probiotics), leaf vegetables, meat and marine products should be of interest to researchers.

Conflict of interest

The authors wish to declare no conflict of interest.

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