Refractance Window Drying: An Emerging Sustainable Drying Technology for Horticultural Crops

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ABSTRACT

Refractance Window Drying (RWD) is an emerging thin-film drying technology with promising applications in horticultural processing. It uses thermal energy from circulating hot water transferred through a transparent polymer film to rapidly remove moisture from fruits, vegetables and other heat-sensitive products. The combination of efficient heat transfer and evaporative cooling can reduce drying time while helping retain colour, nutrients, antioxidants and other quality attributes. Research on mango, banana, jackfruit and tomato demonstrates its potential for value addition and post-harvest loss reduction. Despite these advantages, challenges remain in process optimisation, uniform spreading, scale-up and industrial implementation. Recent hybrid systems offer further opportunities for sustainable processing.

INTRODUCTION:

Horticultural crops such as fruits, vegetables, herbs and other plant-based products are important sources of vitamins, minerals, dietary fibre, antioxidants and other bioactive compounds. However, their high moisture content and continued metabolic activity after harvest make them highly perishable, and inadequate

post-harvest handling, storage and transportation can result in considerable quantitative and qualitative losses. Drying is one of the oldest and most effective preservation methods because moisture removal inhibits microbial growth and slows chemical and enzymatic reactions while reducing product weight and volume. Nevertheless, conventional sun and hot-air drying may involve prolonged processing and excessive heat exposure, leading to deterioration of colour, flavour, texture, vitamins and other heat-sensitive components. Therefore, the development of rapid, efficient and quality-preserving drying technologies has become an important area of research in post-harvest horticulture and food processing (Hasan *et al*., 2019; Shende & Datta, 2019).

Among emerging drying technologies, Refractance Window Drying (RWD) has attracted considerable attention as a rapid thin-film method for fruits, vegetables and other heat-sensitive materials. It is particularly suitable for liquid and semi-liquid products such as fruit pulps, vegetable purees, juices, extracts and pastes, as well as selected thin-sliced products. In RWD, the food material is spread as a thin layer over a transparent polymer film positioned above circulating hot water, allowing thermal energy to transfer through the film while evaporative cooling helps limit product temperature (Raghavi *et al*., 2018; Shende & Datta, 2019; Mahanti *et al*., 2021). Recent research has expanded RWD towards hybrid systems involving infrared heating, vacuum and forced air to improve drying efficiency and product quality, while emerging approaches such as process modelling, machine vision, sensor-based monitoring and artificial intelligence are being explored for smart process control. Thus, RWD is increasingly being recognised as a promising technology for rapid, quality-oriented and sustainable processing of horticultural products.

What is Refractance Window Drying?

Refractance Window Drying (RWD) is an advanced thin-film dehydration technique in which liquid or semi-liquid food materials are spread as a thin, uniform layer over a transparent polymer film, commonly polyester or Mylar, positioned above circulating hot water. Heat is transferred from the hot water through the film to the food material, resulting in rapid moisture evaporation while evaporative cooling helps limit the product temperature. A typical RWD system consists of a hot-water reservoir, heating and circulation system, transparent polymer film, conveyor or supporting mechanism, product-spreading unit and air-exhaust system.

The technology is particularly suitable for fruits, vegetables, purees, pulps, juices, extracts and other heat-sensitive products because of its potential to retain colour, flavour, nutrients and bioactive compounds. Depending on the raw material and processing conditions, RWD can produce dried sheets, flakes, fruit leathers and powders with relatively short drying times and good quality retention (Raghavi *et al*., 2018; Shende & Datta, 2019; Mahanti *et al*., 2021).

Working Principle of Refractance Window Drying

Refractance Window Drying (RWD) works on the principle of simultaneous heat and mass transfer**,** in which thermal energy from circulating hot water is transferred through a thin transparent polymer film to the wet food material. The major heat-transfer mechanism is conduction**,** through which heat passes from the hot water across the polymer film to the product, while radiation contributes a smaller proportion of the total heat transfer (Abonyi *et al*., 2002; Zotarelli *et al*., 2015). As heat reaches the wet material, moisture moves towards the surface and evaporates; the energy required for evaporation produces evaporative

cooling, which helps maintain the product temperature considerably below the hot-water temperature during drying. Thus, the combined effects of conduction, limited radiation and evaporative cooling enable rapid moisture removal with reduced thermal exposure, supporting better retention of colour, nutrients, flavor and other heat-sensitive bioactive compounds.

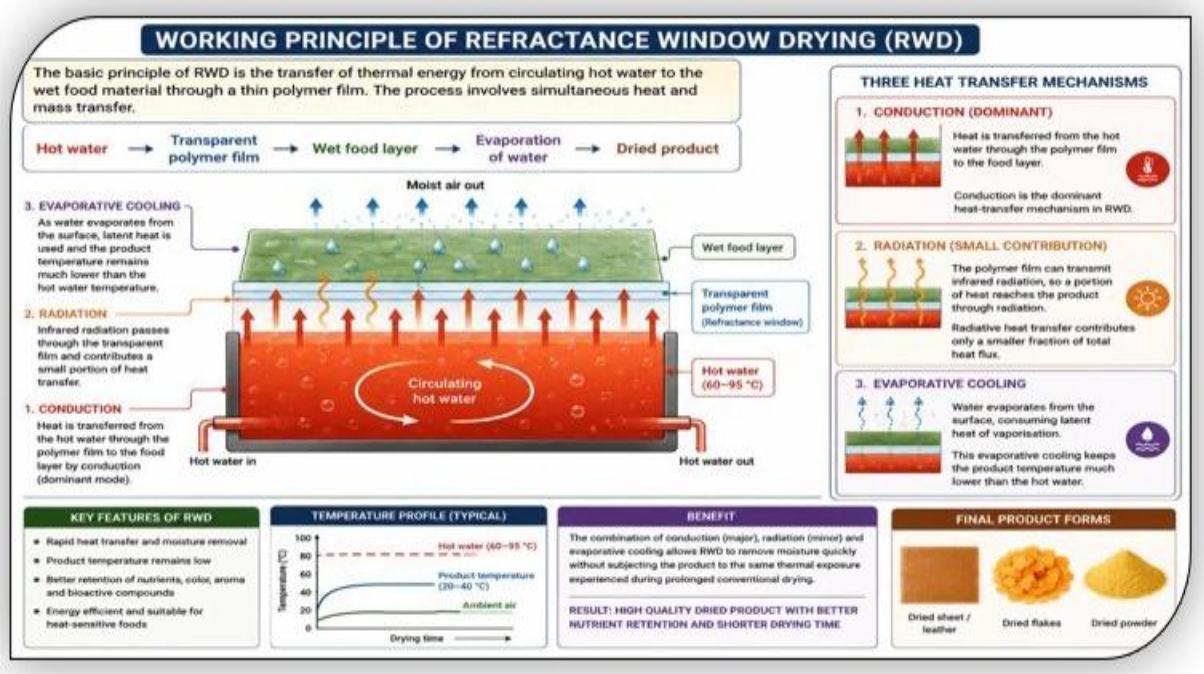


Figure 1. Schematic representation of the working principle of Refractance Window Drying (RWD)

Working Procedure of Refractance Window Drying

The working procedure of RWD begins with the selection and preparation of fresh horticultural material, followed by washing, peeling, deseeding and cutting as required. The material is then converted into puree, pulp, paste or thin slices and the RWD system is prepared by circulating hot water at the desired temperature, commonly around 85–95°C. The prepared material is uniformly spread as a thin layer over the transparent polymer film, where layer thickness influences the drying rate. Heat from the circulating hot water passes through the film to the wet product, causing moisture to migrate towards the surface and evaporate. The evaporated moisture is continuously removed by air movement, allowing drying to proceed rapidly. As moisture is removed, the material forms a dried sheet, leather or flakes, which are separated from the film and collected. If required, the dried material is milled and sieved into powder and packed in moisture-resistant packaging to maintain its quality during storage (Kaur *et al*., 2020).

Evidence from Horticultural Research

Horticultural crop	Research findings	Reference
Mango	RWD reduced the drying time of mango slices by approximately 4–8 times compared with tray drying, while maintaining favourable moisture and water activity. Studies on mango pulp also reported good retention of ascorbic acid and phenolic compounds under optimised conditions.	Ochoa-Martínez *et al.* (2012); Kaur *et al.* (2017, 2020)
Banana	RWD improved drying efficiency of banana puree and produced flour with favourable phenolic content, antioxidant activity and physicochemical properties.	Rajoriya *et al.* (2022); Mwaurah *et al.* (2022)

Jackfruit	Drying temperature and product thickness significantly influence the drying rate, nutrient retention and antioxidant properties of RWD-dried jackfruit.	Nansereko *et al.* (2022)
Tomato	Recent hybrid RWD systems using infrared, vacuum and forced air have improved drying efficiency while maintaining quality and, under suitable conditions, enhancing lycopene bioaccessibility.	Gunel *et al.* (2025)

Advantages of Refractance Window Drying

- **Rapid and efficient drying:** RWD provides fast moisture removal and reduces overall processing time.
- **Better quality retention:** The relatively low product temperature helps preserve colour, flavour, nutrients and bioactive compounds**.**
- **Versatile application:** It is suitable for fruit and vegetable purees, pulps, pastes and other heat-sensitive materials and can produce powders, flakes and fruit leathers**.**
- **Energy and cost benefits:** Hot-water recirculation and rapid drying offer potential for reduced energy consumption compared with some conventional drying methods.
- **Simple and adaptable technology:** RWD can be integrated with infrared, vacuum or forced-air systems for improved drying performance.

Limitations and Challenges

- **Uniform spreading:** The product must be spread at a consistent thickness to achieve uniform drying.
- **Product-specific optimisation:** Temperature, layer thickness and drying time must be optimised for each horticultural product.
- **Scale-up challenges:** Most studies are conducted at laboratory or pilot scale; industrial-scale throughput, automation, cleaning and film durability require further development.
- **Heat-transfer complexity:** Although RWD is commonly associated with the "refractance window," research indicates that conduction is the dominant heat-transfer mechanism**,** with radiation contributing less; therefore, further research is needed for accurate process modeling and industrial equipment design (Zotarelli *et al*., 2015).

CONCLUSION

Refractance Window Drying (RWD) is a promising and innovative drying technology for the sustainable processing and value addition of horticultural crops. Its rapid heat and mass transfer, combined with evaporative cooling, enables efficient moisture removal while helping preserve colour, nutrients, antioxidants and other quality attributes. Research on mango, banana, jackfruit and tomato has demonstrated its potential for producing high-quality dried products such as powders, flakes and fruit leathers. Although challenges related to uniform spreading, product-specific optimisation, scale-up and industrial application remain, recent developments in hybrid RWD systems using infrared, vacuum and forced air are improving its efficiency and versatility. With further research and technological development, RWD can contribute significantly to reducing post-harvest losses and promoting sustainable horticultural processing.

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