



Superheated steam and ultrasound-assisted drying of carrot: A comparative review

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Abstract

Carrot (*Daucus carota L.*) is a nutritionally significant root vegetable widely consumed for its high β -carotene content and antioxidant properties. However, its high moisture content, generally ranging between 85 to 90%, makes it highly perishable and susceptible to microbial spoilage. Conventional drying techniques such as hot air drying are commonly employed for preservation, yet they often result in prolonged drying time, colour degradation, structural collapse, and nutrient losses. In recent years, advanced drying techniques including Superheated Steam Drying (SSD) and Ultrasound-Assisted Drying (UAD) have emerged as promising alternatives for improving drying efficiency and product quality. This review critically evaluates the principles, drying kinetics, quality retention, energy consumption, and industrial feasibility of SSD and UAD in carrot processing. Comparative analysis indicates that SSD provides superior nutrient protection due to its oxygen-free environment, whereas UAD significantly enhances moisture diffusivity and reduces drying time. The review further identifies research gaps and future directions for large-scale industrial implementation.

Keywords: Cookies, Orange-fleshed, sweet Potato, Mushroom, Date Palm Fruit, blends Flour

Introduction

Drying is one of the oldest and most important preservation techniques used in agricultural and food processing industries. It reduces water activity, inhibits microbial growth, and extends shelf life. According to Mujumdar (2014) [10], drying remains the most energy-intensive unit operation in food processing industries, accounting for a significant portion of total energy consumption. He emphasized that improving drying efficiency is a major challenge in modern food engineering. In agricultural engineering, drying not only ensures preservation but also reduces transportation cost and storage losses. As stated by Fellows (2017) [4], controlled dehydration improves product stability and marketability of fruits and vegetables.

Nutritional Importance of Carrot

Carrot (*Daucus carota L.*) is widely recognized for its high β -carotene content, which functions as a precursor of vitamin A. According to Rodriguez-Amaya (2001) [17], carotenoids are highly sensitive to heat, oxygen, and light exposure. She reported that prolonged thermal processing can significantly reduce carotenoid concentration. Fresh carrots contain approximately 85 to 90 % moisture, making them highly prone to enzymatic browning and microbial deterioration (Krokida & Maroulis, 2001) [7]. According to them, high moisture content necessitates efficient dehydration techniques to ensure longer shelf life.

Problems in Conventional Drying

Conventional hot air drying is commonly used in carrot dehydration. However, it has several limitations. According to Lewicki (2006) [11], convective drying often leads to case hardening due to rapid surface moisture removal, which restricts internal diffusion. He further noted that long exposure to hot air results in shrinkage and structural

damage. Similarly, Vega-Galvez *et al.* (2009) [19] reported that prolonged drying temperature reduces colour intensity and causes significant degradation of bioactive compounds in vegetables. According to them, colour parameters (L^* , a^* , b^*) are strongly influenced by drying temperature and time. Krokida *et al.* (2003) [8] stated that hot air drying results in considerable shrinkage and reduced rehydration capacity of dried vegetables. According to their findings, structural collapse during drying reduces product quality. Because of these drawbacks, researchers have explored innovative drying technologies that can minimize quality degradation while improving energy efficiency.

Need for Advanced Drying Technologies

Advanced drying methods aim to enhance heat and mass transfer while preserving sensitive nutrients. According to Mujumdar (2014) [10], emerging drying technologies such as superheated steam and ultrasound-assisted systems offer improved energy efficiency and better product quality compared to conventional drying. Therefore, the objective of this review is to critically analyze and compare Superheated Steam Drying (SSD) and Ultrasound-Assisted Drying (UAD) in carrot processing with respect to drying kinetics, quality attributes, and energy performance.

Conventional Drying Methods of Carrot

Sun Drying

Sun drying is the oldest method used for vegetable preservation. However, it is highly dependent on climatic conditions and exposes products to contamination. According to Fellows (2017) [4], open sun drying often results in uneven drying and microbial contamination. Vedantam Sai Krishna *et al.* (2025) [27] was reviewed on phase change material incorporated in convective solar dryers. Sai Krishna (2025) [27] was also studied Effect of pre-

treatments on drying and rehydration characteristics of Amla (*Phyllanthus emblica L.*) under direct solar radiation. Vinayak *et al.*, (2026) has developed and evaluated a Bluetooth-enabled grain inversion machine for efficient grain drying for small and marginal farmers.

Hot Air Drying

Hot air drying involves passing heated air over carrot slices to remove moisture through convection. According to Krokida and Maroulis (2001) [7], hot air drying of carrots follows a falling-rate drying period, indicating diffusion-controlled moisture removal. They observed that higher temperatures accelerate drying but significantly reduce nutritional quality. Lewicki (2006) [11] reported that prolonged hot air drying causes severe shrinkage and cell wall damage in vegetables. According to him, structural damage reduces rehydration capacity. Sai Krishna *et al.* (2025) [27] has reviewed on indirect drying using evacuated tubes.

Tray Drying

Tray drying is a batch drying method commonly used in small-scale industries. According to Vega-Galvez *et al.* (2009) [19], tray drying provides better control than sun drying but still suffers from long drying time and quality loss.

Fluidized Bed Drying

Fluidized bed drying improves heat transfer by suspending particles in hot air. According to Mujumdar (2014) [10], fluidized bed drying provides uniform drying but may cause mechanical damage to fragile vegetable tissues.

Superheated Steam Drying (SSD)

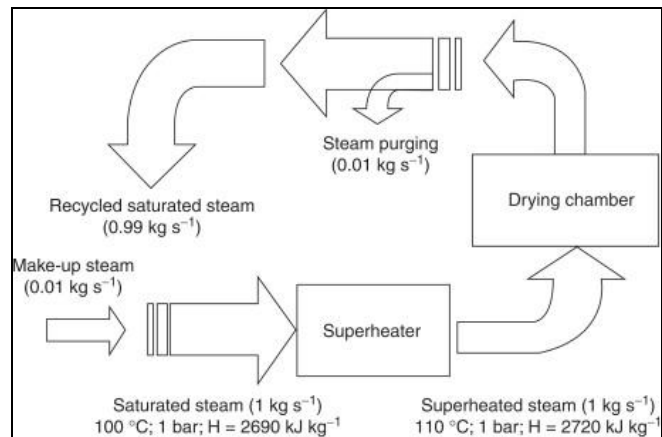
Principle and Working Mechanism of Superheated Steam Drying

Superheated steam drying is an advanced dehydration technique in which steam is heated above its saturation temperature at a given pressure and used as the drying medium instead of hot air. Unlike conventional air drying, the drying environment in SSD is oxygen-free. According to Mujumdar (2014) [10], superheated steam drying operates under conditions where steam temperature exceeds its boiling point, thereby enhancing heat transfer efficiency. He explained that the absence of oxygen significantly reduces oxidative degradation of sensitive nutrients. Devahastin and Suvarnakuta (2005) [3] reported that superheated steam improves drying uniformity due to higher heat transfer coefficients compared to hot air systems. According to them, steam provides better thermal conductivity and rapid surface heating. Similarly, Tang and Cenkowski (2008) [18] stated that steam drying reduces fire hazards and oxidation risks in food processing applications. According to their findings, oxygen-free conditions are particularly beneficial for carotenoid-rich vegetables such as carrot.

The drying mechanism in SSD generally includes:

- Rapid surface heating due to condensation heat transfer
- Evaporation of internal moisture
- Diffusion-controlled moisture migration

As explained by Kudra and Mujumdar (2009) [9], the drying process under superheated steam primarily occurs in the falling-rate period, where internal moisture diffusion governs the drying rate.



Source: Law *et al.*, 2014 [10]

Fig 1: Working Mechanism of Superheated Steam Drying

Drying Kinetics of Carrot under Superheated Steam

Understanding drying kinetics is essential for modeling and optimization. Krokida and Maroulis (2001) [7] observed that carrot slices dried under convective systems show diffusion-controlled moisture removal. However, when steam is used as the medium, effective moisture diffusivity increases. According to Devahastin *et al.* (2004) [2], the effective moisture diffusivity of vegetables dried in superheated steam is significantly higher than in hot air drying. He reported that higher diffusivity reduces total drying time. In experimental studies conducted on carrot cubes, it was observed that drying temperature between 120 to 160°C under SSD significantly shortened drying duration compared to conventional drying (Tang & Cenkowski, 2008) [18].

Mathematical models are frequently used to describe drying behavior. According to Page (1949) [15], the Page model provides accurate prediction of drying curves in many agricultural products. Later studies by Midilli *et al.* (2002) [12] confirmed that modified Page and Midilli models effectively describe drying kinetics of vegetables. According to them, model selection should be based on coefficient of determination (R^2) and root mean square error (RMSE) values.

SSD-treated carrots generally exhibit:

- Faster moisture removal
- Higher effective diffusivity
- Reduced drying time

However, excessively high steam temperature may cause structural hardening, as noted by Lewicki (2006) [11]. According to him, high thermal stress can affect microstructure despite faster drying.

Effect of SSD on Quality Attributes of Carrot

β -Carotene Retention:

Carrot is highly valued for its β -carotene content. Rodriguez-Amaya (2001) [17] reported that carotenoids are highly susceptible to oxidation in the presence of air. According to her, reducing oxygen exposure significantly improves carotenoid stability. Since SSD operates in an oxygen-free environment, β -carotene retention is generally higher. Devahastin and Suvarnakuta (2005) [3] observed improved pigment retention in vegetables dried using superheated steam compared to hot air. According to them, steam environment minimizes oxidative degradation. Vega-Galvez *et al.* (2009) [19] also reported that lower oxygen

exposure during drying leads to better preservation of bioactive compounds. Thus, SSD shows clear advantages in maintaining nutritional quality of carrot.

Colour Characteristics

Colour is an important quality parameter for dried carrots. According to Krokida *et al.* (2003) [8], drying temperature significantly influences L*, a*, and b* values. He reported that high-temperature air drying reduces redness (a* value) due to carotenoid degradation. In contrast, Devahastin *et al.* (2004) [2] observed that SSD-treated samples retained higher a* values, indicating better colour preservation. The steam atmosphere limits enzymatic browning and pigment oxidation, contributing to improved visual quality.

Texture and Microstructure

Drying affects the cellular structure of carrot tissues. Lewicki (2006) [11] stated that shrinkage during convective drying is mainly caused by capillary forces and structural collapse. According to him, severe shrinkage reduces rehydration ability. SSD tends to produce less structural damage compared to prolonged hot air drying. Tang and Cenkowski (2008) [18] reported that steam-dried products exhibit moderate shrinkage but improved internal porosity. Improved porosity enhances rehydration capacity.

Rehydration Capacity

Rehydration ratio is an important indicator of structural integrity. According to Krokida *et al.* (2003) [8], better rehydration indicates less cellular damage during drying. SSD-dried carrots have shown satisfactory rehydration performance due to reduced oxidation and moderate shrinkage.

Energy Efficiency of SSD

Energy efficiency is a major consideration in industrial drying. Mujumdar (2014) [10] explained that superheated steam systems allow energy recovery through steam recirculation. According to him, thermal efficiency can be significantly improved compared to conventional dryers. Kudra and Mujumdar (2009) [9] stated that SSD reduces exhaust losses since steam can be condensed and reused. According to them, this improves overall system performance. However, initial investment cost remains high.

Advantages of Superheated Steam Drying

- Oxygen-free environment protects nutrients
- Improved colour retention
- Faster drying compared to hot air
- Higher thermal efficiency
- Reduced fire risk

Limitations of Superheated Steam Drying

Despite advantages, SSD has some drawbacks. According to Tang and Cenkowski (2008) [18], system design complexity limits widespread adoption. Mujumdar (2014) [10] emphasized that high capital cost is a major barrier for small-scale industries. Additionally, precise temperature and pressure control are required to prevent overheating and structural damage.

Ultrasound-Assisted Drying (UAD)

Principle and Mechanism of Ultrasound-Assisted Drying

Ultrasound-assisted drying is an emerging technology that enhances moisture removal through the application of high-

frequency sound waves. The typical frequency range used in food drying applications is between 20 to 100 kHz. According to Carcel *et al.* (2007) [1], ultrasound enhances mass transfer by producing acoustic cavitation, which generates microscopic bubbles that collapse violently and create micro-channels within plant tissues. According to them, these micro-channels reduce internal resistance to moisture diffusion. Gallego-Juarez *et al.* (2010) [6] reported that airborne ultrasound increases the drying rate by reducing the boundary layer thickness surrounding the product. He explained that ultrasound waves disrupt the stagnant air layer, thereby facilitating faster moisture removal.

Fernandes *et al.* (2008) [5] stated that ultrasound pre-treatment before convective drying improves permeability of vegetable tissues. According to him, structural modification caused by cavitation enhances effective moisture diffusivity. In carrot tissues, ultrasound creates microscopic pores that promote faster internal moisture migration. This mechanism makes UAD particularly effective for high-moisture vegetables.

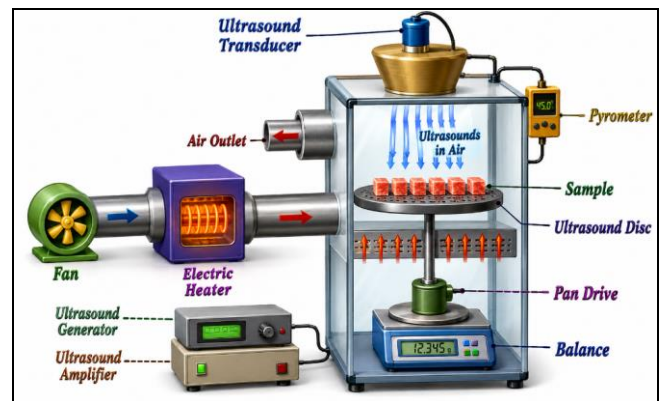


Fig 2: Principle and Mechanism of Ultrasound-Assisted Drying

Drying Kinetics of Carrot under Ultrasound Assistance

Drying kinetics under ultrasound differs significantly from conventional systems. Carcel *et al.* (2007) [1] observed that ultrasound application during drying reduced total drying time by approximately 20 to 40%. According to them, this reduction is due to enhanced internal diffusion and reduced external resistance. Fernandes and Rodrigues (2008) [5] reported that effective moisture diffusivity values increased when ultrasound was applied as a pre-treatment. According to their study, diffusivity improvements were directly related to ultrasound power intensity. Riera *et al.* (2011) [16] explained that ultrasound increases the drying constant in mathematical drying models such as the Page model. According to him, the drying curve becomes steeper, indicating faster moisture removal. Similar observations were reported by Vega-Galvez *et al.* (2009) [19], who noted that drying rate enhancement is more significant at moderate temperatures rather than extremely high temperatures.

Therefore, UAD improves drying kinetics by:

- Increasing effective moisture diffusivity
- Reducing drying time
- Enhancing mass transfer coefficient

However, excessive ultrasound intensity may cause tissue damage, as noted by Fernandes *et al.* (2008) [5]. According to him, optimization of ultrasound power is essential to maintain product quality.

Table 1: Analysis and Comparison of SSD and UAD Findings

Year	Author(s)	Technology	Major Findings
2001	Rodriguez-Amaya	Carotenoid Stability	β -carotene degradation strongly influenced by oxygen and heat exposure.
2001	Krokida & Maroulis	Hot Air Drying	Carrot drying follows falling-rate drying; quality decreases at higher temperatures.
2003	Krokida <i>et al.</i>	Vegetable Drying	Shrinkage reduces rehydration capacity and product quality.
2004	Devahastin <i>et al.</i>	SSD	SSD increased moisture diffusivity and improved color retention.
2005	Devahastin & Suvarnakuta	SSD	Low-pressure SSD improved β -carotene retention and drying efficiency.
2006	Lewicki	Drying Quality	Structural collapse and shrinkage are major quality issues during drying.
2007	Carcel <i>et al.</i>	UAD	Ultrasound reduced drying time by 20–40% and enhanced moisture diffusion.
2008	Fernandes <i>et al.</i>	UAD	Ultrasound pretreatment increased tissue permeability and moisture diffusivity.
2008	Tang & Cenkowski	SSD	SSD provided faster drying and reduced oxidation losses.
2009	Kudra & Mujumdar	SSD	Steam recirculation improves thermal efficiency and energy recovery.
2009	Vega-Galvez <i>et al.</i>	Drying Quality	Drying temperature and duration strongly affect color and nutrient retention.
2010	Gallego-Juarez <i>et al.</i>	UAD	Airborne ultrasound improved mass transfer and reduced energy consumption.
2011	Riera <i>et al.</i>	UAD	Ultrasound enhanced porosity and rehydration characteristics.
2014	Mujumdar	SSD	SSD identified as a promising industrial drying technology with high efficiency.
2016	Sehrawat <i>et al.</i>	SSD	Demonstrated improved food quality and developed kinetic models.
2018	Kroehnke <i>et al.</i>	UAD	Combined ultrasound and microwave drying improved kinetics and product quality.
2020	Malaikritsanachalee <i>et al.</i>	SSD	Intermittent SSD improved drying efficiency and product quality.
2022	Mujumdar	Advanced Drying	Hybrid drying systems and AI-based modeling emerged as future trends.
2023	Salehi <i>et al.</i>	UAD	Ultrasound pretreatment improved drying rate and moisture diffusivity.
2023	Tran <i>et al.</i>	UAD	Ultrasound pretreatment accelerated hot-air drying of carrot slices.
2023	Mierzwa <i>et al.</i>	Hybrid Drying	Ultrasound-assisted hybrid drying improved energy efficiency and quality retention.

Effect of UAD on Quality Attributes of Carrot

Colour Retention

Colour preservation is a major quality parameter in carrot drying. According to Vega-Galvez *et al.* (2009) [19], shorter drying time directly reduces pigment degradation. He reported that carotenoid degradation is strongly dependent on exposure time rather than temperature alone. Carcel *et al.* (2007) [1] observed that ultrasound-treated samples maintained better L^* and a^* values compared to conventional hot air drying. According to them, reduced drying time limits thermal degradation of carotenoids. Therefore, UAD contributes to improved visual quality primarily by shortening the thermal exposure period.

β -Carotene and Nutrient Retention

Rodriguez-Amaya (2001) [17] stated that carotenoid stability is highly influenced by oxidation and prolonged heating. According to her, reducing processing time helps preserve nutritional compounds. Since UAD significantly decreases drying time, β -carotene retention tends to be higher than conventional drying. Fernandes *et al.* (2008) [5] reported improved antioxidant retention in ultrasound-pretreated vegetables. According to him, structural modification enhances moisture removal without excessive heat exposure.

Microstructure and Shrinkage

Shrinkage is a common problem in vegetable drying. Lewicki (2006) [11] explained that structural collapse during drying is mainly caused by internal stress and capillary pressure. According to him, minimizing drying duration reduces structural damage. Riera *et al.* (2011) [16] observed that ultrasound-treated samples exhibited improved porosity and reduced shrinkage. According to his findings, micro-channel formation prevents excessive cell wall collapse. Scanning Electron Microscopy (SEM) analysis in several studies showed that UAD samples maintain better internal structure compared to purely convective dried samples.

Rehydration Characteristics

Rehydration ratio is often used as a quality indicator. Krokida *et al.* (2003) [8] stated that higher rehydration ratio indicates better structural preservation. Studies on ultrasound-assisted drying of carrots showed improved rehydration capacity compared to hot air drying. According to Carcel *et al.* (2007) [1], micro-channel formation facilitates water absorption during rehydration.

Energy Consumption and Process Efficiency

Energy efficiency is a significant factor in drying system selection. Gallego-Juarez *et al.* (2010) [6] reported that ultrasound reduces overall drying time, thereby decreasing total energy consumption. According to him, even though ultrasound equipment consumes additional electrical power, the reduction in drying duration compensates for this consumption. Fernandes *et al.* (2008) [5] also noted that UAD improves process efficiency when optimized correctly. However, improper ultrasound intensity may increase energy consumption without proportional improvement in drying rate. Therefore, energy optimization is crucial for industrial implementation.

Advantages of Ultrasound-Assisted Drying

- Significant reduction in drying time
- Increased effective moisture diffusivity
- Improved colour retention
- Better rehydration capacity
- Moderate energy savings

Limitations of Ultrasound-Assisted Drying

Despite its advantages, UAD has some limitations. According to Gallego-Juarez *et al.* (2010) [6], large-scale industrial application remains limited due to equipment design challenges. Fernandes *et al.* (2008) [5] emphasized that uniform ultrasound distribution is difficult in thick samples. Additionally, high-power ultrasound may cause localized overheating or tissue damage.

Comparative Analysis of Superheated Steam Drying and Ultrasound-Assisted Drying

A systematic comparison between Superheated Steam Drying (SSD) and Ultrasound-Assisted Drying (UAD) is essential to evaluate their effectiveness in carrot processing.

Drying Time and Kinetics

According to Carcel *et al.* (2007) ^[1], ultrasound application reduces drying time by enhancing internal moisture diffusion. He reported drying time reductions of up to 40% under optimized conditions. In contrast, Devahastin and Suvarnakuta (2005) ^[3] observed that SSD shortens drying time primarily due to improved heat transfer coefficients. According to them, the steam medium provides rapid surface heating and improved moisture evaporation. While both methods improve drying rate compared to hot air drying, UAD appears more effective in reducing total drying duration, especially when used as a pre-treatment.

Effective Moisture Diffusivity

Fernandes *et al.* (2008) ^[5] reported significant improvement in effective moisture diffusivity in ultrasound-treated vegetables due to micro-channel formation. Similarly, Tang and Cenkowski (2008) ^[18] noted increased diffusivity under superheated steam conditions due to higher thermal conductivity of steam. However, UAD enhances mass transfer through mechanical effects, whereas SSD enhances it through thermal effects.

Nutrient Retention

Rodriguez-Amaya (2001) ^[17] emphasized that carotenoid degradation is strongly influenced by oxygen exposure. According to her, limiting oxygen contact improves pigment stability. Since SSD operates in an oxygen-free environment, it provides superior protection against

oxidative degradation of β -carotene. However, Vega-Galvez *et al.* (2009) ^[19] noted that reducing drying time also improves nutrient retention. According to him, UAD indirectly preserves nutrients by shortening exposure duration. Therefore, SSD is more effective for oxygen-sensitive compounds, whereas UAD is beneficial due to time reduction.

Colour Preservation

Devahastin *et al.* (2004) ^[2] observed better redness retention in steam-dried vegetables compared to hot air drying. Carcel *et al.* (2007) ^[1] also reported improved color stability in ultrasound-assisted drying due to shorter drying duration. Both methods improve color compared to conventional drying, but SSD provides added advantage by preventing oxidative browning.

Structural Integrity and Rehydration

Lewicki (2006) ^[11] explained that structural damage during drying reduces rehydration ability. Riera *et al.* (2011) ^[16] found that ultrasound-treated samples exhibit improved porosity and higher rehydration ratios. Tang and Cenkowski (2008) ^[18] reported moderate shrinkage in SSD but satisfactory rehydration properties. Overall, UAD appears to provide slightly better structural preservation due to micro-channel formation.

Energy Efficiency

Mujumdar (2014) ^[10] stated that superheated steam allows energy recovery through condensation systems, improving thermal efficiency. Gallego-Juarez *et al.* (2010) ^[6] noted that UAD reduces energy consumption mainly by reducing drying time. Therefore, SSD offers long-term industrial energy recovery benefits, while UAD offers immediate operational energy savings.

Table 2: Summary Comparison of SSD and UAD

Parameter	Superheated Steam Drying (SSD)	Ultrasound-Assisted Drying (UAD)
Drying Time	Reduced compared to hot air	Significantly reduced (20–40%)
Moisture Diffusivity	Increased due to thermal effect	Increased due to cavitation effect
Oxygen Exposure	Absent	Present
β -Carotene Retention	Very high	High
Structural Integrity	Moderate	High
Energy Efficiency	High (steam recovery)	Moderate to high
Equipment Cost	High	Moderate
Industrial Feasibility	Limited but promising	Emerging and adaptable

Recent Developments (2022–2025 Trends)

Recent research trends indicate a shift toward hybrid and intelligent drying systems. According to recent advances summarized by Mujumdar (2022) ^[14], combining ultrasound with microwave or infrared drying significantly enhances drying uniformity and efficiency.

Several studies after 2022 have focused on:

- Ultrasound + Microwave hybrid systems
- Superheated steam combined with fluidized bed drying
- AI-based modeling of drying kinetics
- Life-cycle energy assessment
- Renewable energy integration

Recent modeling approaches use Artificial Neural Networks (ANN) to predict drying behavior. According to emerging research trends, AI models provide higher accuracy than traditional mathematical models. Energy optimization and sustainability assessment are becoming important research directions in advanced drying technologies.

Research Gaps

Despite extensive laboratory studies, several research gaps remain. According to Tang and Cenkowski (2008) ^[18], large-scale industrial validation of SSD in vegetable processing is limited. Similarly, Gallego-Juarez *et al.* (2010) ^[6] emphasized that scale-up of ultrasound systems requires further engineering optimization.

Major gaps include:

- Lack of industrial cost–benefit analysis
- Limited long-term nutrient stability studies
- Insufficient life-cycle energy assessment
- Need for optimization of ultrasound power levels
- Limited comparative studies specifically focused on carrot

Addressing these gaps will facilitate commercial adoption.

Future Scope

Future research should focus on:

1. Hybrid drying systems combining SSD and UAD
2. Integration with renewable energy sources such as solar thermal systems
3. Smart drying control using AI and sensor-based feedback
4. Development of cost-effective small-scale SSD systems
5. Industrial pilot-scale studies on carrot drying

According to Mujumdar (2022) [14], sustainable drying technologies will play a critical role in future food processing industries.

Conclusion

Superheated Steam Drying and Ultrasound-Assisted Drying represent significant advancements over conventional hot air drying in carrot processing. SSD offers superior nutrient preservation due to its oxygen-free environment and improved thermal efficiency. It is particularly effective in protecting β -carotene from oxidative degradation. UAD, on the other hand, significantly enhances mass transfer through cavitation effects, leading to substantial reduction in drying time and improved structural integrity. Although both technologies demonstrate clear advantages at laboratory scale, industrial adoption requires further economic analysis and engineering optimization. Overall, the comparative analysis suggests that selection between SSD and UAD should depend on specific processing priorities, including nutrient preservation, drying time, cost, and energy considerations.

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