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EVOLUTION OF FRUIT AND VEGETABLE DRYING TECHNOLOGIES: FROM TRADITIONAL DEHYDRATION TO AI-DRIVEN PRECISION PROCESSING AND CELLULAR STRESS RESPONSES AND MOLECULAR REGULATION

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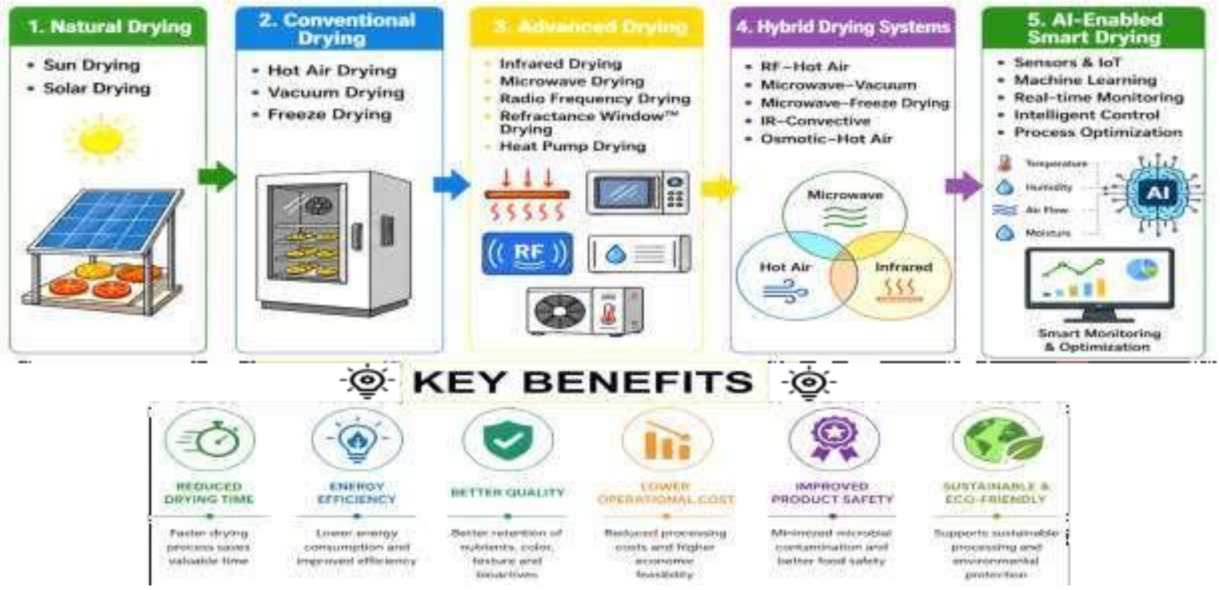
GRAPHICAL ABSTRACT



ABSTRACT

Drying of fruit and vegetables has become an important strategy of post-harvest handling in extending shelf-life, reducing storage and transport costs through decreasing moisture content and improving storability and portability of product. Beside a process of drying for removing water and changing mass transfer process of this material, Drying induces complex cellular, biochemical and molecular responses affecting nutritional quality, antioxidant capacity, structure and storability of food product. Some of these methods e.g. Sun drying, solar drying and hot air drying still widely used owing to the low operating cost and simplicity; However, there may lead to undesirable consequences including significant losses of nutrients, oxidatvie damages, collapse of structure and detrimental changes in quality. Advanced drying technologies such as infrared, microwave, radio frequency, Refractance Window, vacuum and heat-pump drying may enhance the retention of bioactive compounds by optimizing the rate of heat and mass transfer. Combining some complementary methods i.e. Hybrid drying technologies may reduce drying time and energy consumption. Artificial intelligence (AI), machine learning (ML), sensors technology and Industry 4.0 provide the means to monitor the drying process in real time and achieve intelligent adaptive optimization. Additionally, recent development on molecular and omics technologies will be promising for deciphering the genotype-specific drying behaviour, regulating stress responses and controlling secondary metabolites synthesis and metabolic pathways in the dehydration process of fruit and vegetable. The present review thus presents an integrated view of fruit and vegetable drying technologies, focusing on the intersection between the mechanisms of drying and the responses at the cellular, molecular and genotypic levels as well as intelligence of drying processes.

KEYWORDS: Dehydration, Hybrid drying, Smart drying systems, Post-harvest processing, Food processing systems, cellular stress responses, molecular regulation.

1. INTRODUCTION

Fruits and vegetables have a high nutritional value as they contain vitamins, minerals, dietary fiber and bioactive compounds. On the other hand, their high moisture content, which is in some cases more than 80%, renders them very vulnerable to microbial spoilage, enzymatic reactions and physicochemical deterioration. Dehydration is one of the most reliable and useful methods for post-harvest preservation, to reduce losses and prolong shelf life[1]. Conventional drying technologies such as sun drying, solar drying and hot-air drying decrease water activity and inhibit microbial growth, thereby increasing storage stability and reducing transportation costs[2].

Although various conventional methods of dehydration have used, there are some constraints exits. Sun drying is very weather sensitive and leaves products vulnerable to contamination by insects, dust, and microorganisms. Likewise, hot air drying might require longer processing times and consume significant energy. High temperatures can lead to loss of heat-sensitive nutrients (vitamin C, phenolic compounds, and carotenoids) and can have a negative impact on the colour, texture, flavour and rehydration properties[3]. Other frequently reported issues during conventional drying include structural collapse, shrinkage, case hardening, and moisture imbalance. These difficulties affect product quality and consumer acceptance, and indicate the need to develop more efficient and controlled drying technologies. However, dehydration does not only imply the physical elimination of water, at the cellular level the constant loss of water while drying means a strong abiotic factor which affects the membrane properties, cell shape, cellular metabolism and the redox balance. The process can bring about the modification of osmotic value, of the redox state of the cells, alteration of the cellular macromolecules; the presence of temperature can additionally induce alteration of proteins and membranes and the decrease of the stability of the active compounds[65].

1.1 Goals of Advanced Drying Technologies

The increasing demand for high quality dried fruits and vegetables has provided the impetus for the development of advanced dehydration technologies that address the limitations of traditional methods. Modern drying systems are designed for drying with a high degree of control the heat and mass transfer processes, without loss of quality. The main purposes are to minimize the drying time, optimize energy use, retain nutritional and sensory properties and retain the structural integrity of the final product[4].

The process performance of these drying methods can be significantly enhanced with the use of advanced drying methods, such as freeze-drying, microwave drying, radio frequency drying, infrared drying, reactance window drying, and heat pump drying. These technologies allow for quicker moisture removal and more even heat, maintaining colour, aroma, texture, vitamins and bioactive compounds. Additionally, numerous advanced systems are designed to work at lower temperatures or use volumetric heating methods, which can minimize heat damage and enhance the overall product quality[5]. Therefore, the application of advanced drying technologies is gaining increasing attention as sustainable technologies that can optimally combine productivity, product quality and energy consumption.

1.2 Overview of Smart Drying Systems

Recent technological developments have led to the idea of smart drying systems, which combine digital technology, sensors, automation, and artificial Intelligence with the drying process. Smart drying systems utilize real-time sensor networks to continuously measure and monitor important process variables such as temperature, humidity, airflow and moisture content. Collected data are analysed dynamically to optimize operating conditions to achieve efficient and consistent processes [6].

AI and machine learning methods have proven to be very effective in modelling of drying kinetics, forecasting moisture content and parameter optimization. Artificial neural networks (ANNs) and adaptive neuro-fuzzy inference systems (ANFISs), along with support vector machines (SVMs) and deep learning algorithms, can accurately predict drying behaviour with minimum energy usage. Smart control systems also allow for automated control of drying parameters according to product parameter changes, thus minimizing the risk of overdying, degradation of nutrients and loss of product quality[7].The incorporation of smart technologies is a key milestone in the path toward Industry 4.0-oriented data-driven, more efficient and sustainable food processing systems.

1.3 Omics and molecular technologies

Novel insights from molecular biology and omics technologies are emerging which will help to reveal how to improve the underlying biology of drying responses. For example, transcriptomics will identify genes that are regulated as a result of both dehydrative and heat stress whereas proteomics and metabolomics will enable identification of alterations in functional protein and metabolic signatures of nutritional quality and stress defence. Application of multi-omics approaches might, consequently, help to provide a systems biology overview of how drying procedures affect cellular pathways, the metabolism of antioxidants and secondary metabolites, and structural retention. Nevertheless, the integration of the molecular basis connecting the drying regimes to genotype dependent quality results are still lacking from many of the food dehydration technology reviews.[66]

1.4 Overview of Hybrid Drying Systems

While there are significant benefits to advanced drying technologies, there is no single technology available that can meet all industrial drying needs, including quality, energy efficiency, and processing speed. This has made hybrid drying systems interesting in recent years[8]. Hybrid drying is a combination of two or more drying technologies, taking advantage of certain strengths of the technologies and avoiding certain weaknesses.

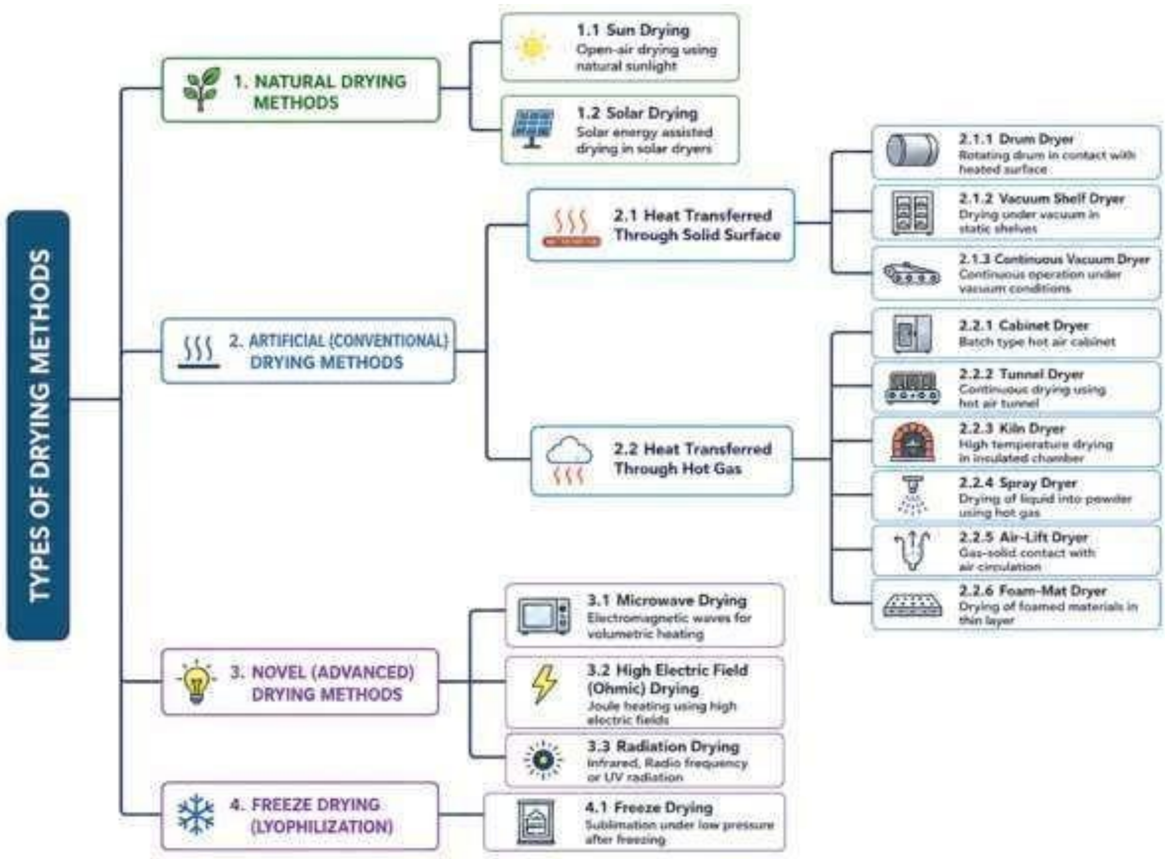
Some representative hybrid drying methods include radio frequency–hot air drying, microwave-assisted freeze-drying, infrared-convective drying, radio frequency–heat pump drying and osmotic dehydration–thermal drying. these systems tend to have synergistic effects; that is, the drying time is reduced, moisture uniformity is increased, nutrient content is also increased, and energy consumption is reduced compared to drying methods used separately[9,10]. The use of hybrid technologies is gaining more attraction as one of the most promising future lines of food dehydration systems, due to the fact that it is considered to be a compromise between product quality and operational efficiency.

This review traces the evolution of the fruit and vegetable dehydration technology from natural dehydration, conventional technology to advanced, hybrid and artificial intelligence (AI) based technologies. Special focus is given to drying mechanisms, quality preservation, energy efficiency and the new field of intelligent process control as a sustainable food processing tool[11]. The review covers an integrative view on different technologies of fruit and vegetable drying: classical, advanced, hybrid and AI-based technologies are linked with the cellular and molecular responses of the plant tissues during drying and thermal exposure. In addition, molecular information is reviewed in order to be combined with sensors and AI and machine learning to assist genotype-specific and precision drying system.

2. Natural Dehydration

The most primitive and common method for preserving fruits and vegetables is natural dehydration. These methods are generally based on natural heat and air movement to deplete the moisture content in agricultural products with minimum energy consumption from the outside. In the developing region, natural drying techniques are highly important because of their simplicity and low operation costs. Natural drying methods do not have economic benefits, but they are also associated with a number of drying limitations, such as drying efficiency, product quality, hygiene and weather dependence[11]. Dehydration methods such as sun drying, solar drying, shade drying, air drying and osmotic dehydration are the major natural methods[12](Fig.1).

Fig 1. Classification of fruit and vegetable drying technologies, including natural drying, conventional dehydration methods, advanced drying techniques, and emerging drying systems based on heat and mass transfer mechanisms.



2.1 Sun Drying

Sun drying, which uses sunlight to preserve food by exposing it directly to solar radiation was one of the earliest methods of food preservation. Sunlight heats up the product, causing moisture to evaporate from the product surface; and there is some natural airflow to remove moisture. Due to the simplicity and minimal capital investment, this method is widely used in drying grapes, figs, apricots, tomatoes and other vegetables[2].

Although sun drying is widely practised, it has several drawbacks. The drying process is very climate-sensitive and is influenced by climatic variations in temperature, humidity, precipitation and wind velocity. Dust, insects, birds and microorganisms are also sources of contamination for products and may affect food safety and quality. In addition, long dry periods can lead to unbalanced moisture distribution and nutrient loss, thereby affecting the overall quality of the product [3].

2.2 Solar Drying

To improve the efficiency of drying and protect products, solar drying was developed as an improvement over the traditional sun drying method. In solar drying systems, the products are placed in specially designed drying chambers that are used to harness the power of the sun and enhance the drying process while reducing exposure to environmental contaminants. There are two types of solar dryers: passive and active dryers. Passive solar dryers depend on the natural flow of air, whereas active dryers use fans or blowers to increase air movement and heat transfer [13.]

Computational fluid dynamics (CFD) has recently been used for optimising airflow patterns, temperature distributions and thermal performance in drying chambers in the development of solar dryers. These developments have helped increase drying uniformity, and shorten processing times. Compared with traditional sun drying, solar drying methods can dry with higher drying temperature and shorter drying times and retain color the colour and nutritional quality[13].In addition, the use of modern solar dryers with automated solar tracking and IoT technologies has improved energy efficiency and drying efficiency[6].

2.3 Shade Drying

Shade drying is a process of drying agricultural products in shaded areas where direct sunlight is excluded. This technique is especially appropriate for fruits, vegetables, herbs and medicinal plants with heat-sensitive pigments, volatile oils and bioactive compounds[14].Shade drying reduces the amount of photochemical degradation and helps maintain the natural colour, aromas, and antioxidant properties, unlike direct sun drying.

The main benefit of shade drying is that conserves the quality of sensitive produces. However, the less solar exposure there is, the more time is needed to dry the moisture, especially. Microbiological growth can be more likely with longer drying periods if control of the environment is not proper. Therefore, the shade drying method is typically used for high-value products where quality protection is a priority rather the processing rate[3].

2.4 Air Drying

Air drying, also called natural convective drying, is a process in which ambient or heated air is used to transfer moisture from food materials. Drying is affected by simultaneous heat and mass transfer between the product and surrounding air. Fruits and vegetables such as apples, bananas, potatoes and carrots are commonly air dried.

While air drying is a relatively easy and inexpensive process, it can result in considerable structural alternations in plant tissues. When moisture is removed from cellular structures, shrinkage, deterioration of texture, and decreased rehydration ability often occur[15]. In addition, longer drying periods may result in losses of heat-sensitive nutrients. However, owing to the scalability and versatility of this process in different agricultural products, air drying is one of the most common techniques used for dehydration[2].

2.5 Osmotic Dehydration (OD)

Osmotic dehydration is a peculiar natural dehydration procedure in which fruits and vegetables are immersed in hypertonic solutions that contain high concentrations of sugars or salts. When the osmotic pressure of the food tissue is different from that of the surrounding solution, water removes of the food tissue, and some of the solute molecules diffuse into the food tissue[16.]

Compared with the thermal drying process, osmotic dehydration can be performed at relatively low temperatures; this minimises the possibility of thermal damage and maintains sensory and nutritional quality. The process is able to enhance the texture, flavour, colour retention, and energy efficiency, as there is no phase change. Osmotic dehydration, however, is not enough for long-term preservation and is widely used as a pre-treatment to hot-air dehydration, freeze-drying or other dehydration techniques[17].

Recent studies have been directed towards the use of novel processes before the osmotic dehydration to improve mass transfer, including ultrasound-assisted osmotic dehydration (osmosonication), vacuum pulse treatment, pulsed electric field (PEF) technology and high hydrostatic pressure (HHP) processing. These methods increase the efficiency of water removal, reduce the processing time and increase the efficiency of the dehydration systems[16] (Table.1).

Table 1. Comparison of Natural Dehydration Methods and its Application

Method	Principle	Major Advantages	Major Limitations	Typical Applications	Reference
Sun Drying	Direct exposure to sunlight	Low cost, simple operation	Weather dependency, contamination risk	Grapes, tomatoes, figs	Sagar & Kumar (2010; Hasan et al. (2019)
Solar Drying	Enclosed drying using solar energy	Improved hygiene, faster drying	Higher initial cost	Fruits and vegetables	Barzigar et al. (2025)
Shade Drying	Drying under shaded conditions	Preserves colour and bioactive	Long drying time	Herbs, medicinal plants	Dhakal (2022)
Air Drying	Moisture removal through airflow	Scalable and versatile	Shrinkage and nutrient loss	Apples, bananas, potatoes	Hasan et al. (2019)
Osmotic Dehydration	Water removal using hypertonic solutions	Better quality retention, energy efficient	Usually requires secondary drying	Mangoes, apples, berries	Pandiselvam et al. (2022)

3. Molecular and Cellular Responses of Fruits and Vegetables During Drying

3.1 Cellular dehydration and water-stress responses

Cell dehydration due to drying leads to an increase in intracellular solutes and a decrease in intracellular water content, affecting intracellular water content, cell membrane integrity, osmotic adjustment, and metabolism of fruit and vegetable cells. Drought stress or osmotic stress due to intracellular dehydration stimulates molecular signalling pathways related to osmotic adjustment, active oxygen species (ROS), antioxidant defences, and stress response gene expression. The extent of stress response is determined by drying temperature, air relative humidity, drying velocity, tissue structure, and plant material status. In cellular dehydration, changes in the intracellular environment can cause changes in phase transition, loss of membrane stability, protein denaturation, damage to organelle structure and function.[67]

In the response to stress, activation of molecular signalling cascades related to stress-responsive pathways is initiated. For example, late embryogenesis abundant (LEA) proteins, dehydrins, heat-shock proteins and genes related to osmoprotectant metabolism might be activated, which protect plant cells by stabilizing membrane and proteins from damaging caused by dehydration. Stress responsive gene expression triggered by ABA, Ca+ dependent signalling, MAPKs, and transcription factors.[66]

3.2 Reactive oxygen species and antioxidant defence during drying

Water deficit and exposure to high temperatures disrupt the cellular redox balance and generate reactive oxygen species (ROS), which includes superoxide radicals, H_2O_2, and hydroxyl radicals. The accumulation of high levels of ROS can induce lipid peroxidation, protein oxidation, damage to membranes and decomposition of cellular structures. Oxidation intensity is dependent on the drying temperature, the presence of oxygen, duration of exposure and inherent antioxidant capacity of fruit and vegetables tissues. Plants possess enzymatic and non-enzymatic antioxidants to balance ROS levels.[68]

SOD, CAT, APX, GR, POD are the key enzymes, which participate in ROX Detoxification; Ascorbic acid, Glutathione, Carotenoids, Tocopherols, and Phenolic compounds represent the key non-enzymatic antioxidants which confer cell protection. The influence of drying parameters on the antioxidant related genes activity and expression. Mild stresses induced an increase in antioxidant defenses, and increased the amount of some phenolics due to the breaking of cell walls, which facilitates their extraction. High thermal stresses, however, lead to the irreversible breakdown of antioxidants and a decrease in enzymatic activity.

Therefore, the final amount of antioxidants in dried products depends on the sum of their cell biosynthesis, release and cellular distribution, the degradative actions of enzymes and their heat-induced destruction.[67]

3.3 Molecular regulation of phenolic compounds, flavonoids and carotenoids

Molecular Regulation of Secondary Biosynthesis As the level of various secondary metabolites determines the nutritional value of dried foods, regulation of biosynthesis pathway of such compounds by several genes plays crucial role. Phenolic compounds and flavonoids are produced mainly by the phenylpropanoid pathway in plants which is regulated by several key genes like Phenylalanine Ammonia-lyase (PAL), Cinnamate 4-hydroxylase (C4H) and 4-coumarate-CoA ligase (4CL). Follow-up enzyme's like Chalcone Synthase (CHS), Chalcone isomerase (CHI), Flavonoid 3-hydroxylase (F3H), Dihydroflavonol 4-reductase (DFR) etc., form various flavonoids and their derivatives.

Drying may affect gene expression of such enzymes and consequently accumulation and bioactivity of phenolic compounds.[68]

Moderate drying may also induce signal of stress, enhancing synthesis or extraction. But heat may promote oxidative degradation. The production of carotenoids is mainly controlled by gene PSY (phytoene synthase), PDS (phytoene desaturase), ZDS (ζ-carotene desaturase), lycopene cyclase's and Carotenoid cleavage dioxygenases (CCDs). Similarly, the expression of these genes under different drying processes is related with carotenoids retention.

Hence, it is desirable that the effect of drying on quality characteristics of dried fruits and vegetables be analyzed through chemical assessment along with their molecular control by the genes regulating their synthesis and degradation.[69]

4. Conventional Drying Techniques

In the fruit and vegetable processing industry, drying technologies constitute one of the most common processes for the preservation of products. The basic methods involved in removing water are essentially evaporation (using thermal energy), which consequently lowers water activity to improve shelf life. They are believed to offer easy operation, scalability and equipment costs that are comparatively low, which contribute to their widespread use in a variety of applications[18]. But, the long-term exposure to heat often leads to physicochemical changes such as shrinkage, discolouration, degradation of texture, loss of heat-sensitive nutrients (vitamin C and phenolic compounds)[2,3]. As a result, although the traditional drying process is still important in the industry, considerable research efforts focused on optimizing the efficiency of the traditional drying process and reducing quality deterioration (Table.2).

Table 2. Comparison of Conventional Drying Technologies

Drying Method	Operating Principle	Product Quality	Energy Requirement	Major Limitation	Reference
Hot Air Drying	Convective heat transfer	Moderate	Moderate–High	Shrinkage and nutrient loss	Li et al. (2023)
Vacuum Drying	Low-pressure evaporation	Good	High	Equipment cost	Belwal et al. (2022)
Vacuum Microwave Drying	Microwave heating under vacuum	Very Good	Moderate	Non-uniform heating	Yang et al. (2025)
Freeze-Drying	Sublimation under vacuum	Excellent	Very High	Long drying time and high cost	Bhatta et al. (2020)

4.1 Hot Air Drying

In industrial practice, hot air drying (HAD), the most commonly used drying technology for fruits and vegetables, is used. This is a process in which heated air is circulated across the surface of the product, and the thermal energy needed to evaporate moisture is supplied from the heated air. Moisture moves from the inside to the outside of the material, and shear flow reduces it[19].Moisture moves from the wet side to the dry side through the material and out with the air flow. Approximately two-thirds of the total drying time is consumed in the bound moisture removal period (called the falling rate period), which may be relatively slow and is considered energy intensive[4]. Although HAD is a simple heat treatment, it has significant drawbacks relating to shrinking, case hardening, and the loss of nutrients produced by exposure for extended periods to high temperatures. For example, drying temperatures of over 70°C have shown to greatly lower the vitamin C content and antioxidant activity in a few fruit products[3].

4.2 Air-Impingement Drying

Air-impingement drying is a method that enhances heat and mass transfer by forcing high-velocity air jet streams onto the product surface. The resulting turbulence causes the material's boundary layer resistance to decrease and the moisture to be drawn out from the material more rapidly. Rapid drying of cut fruits and vegetables has shown the greatest promise for this technique because nutrient losses are minimised[20].On the previous reports, vitamin C retention and shorter drying time were observed during hot-air drying, whereas hot-air drying with enhanced heat transfer efficiency resulted in better retention of vitamin C and shorter drying time. Previous studies reported greater heat transfer efficiency during the enhanced heat transfer drying process than in traditional hot-air drying, which led to increased vitamin C retention and faster drying times.

4.3 Fluidised Bed Drying

Granular and food materials that are particulate products can be dried by fluidised bed drying. During this process, hot air suspends the particles, resulting in a fluidized state of the particles, which facilitates uniform heat and mass transfer. The greater exposure time of the product to air causes the drying time to be shorter and the product to be more uniform[21]. They work particularly well with small food particles, and peas, diced vegetables, and grains are all of these types. Compared to fixed-bed drying systems, the drying time is reduced, and energy efficiency is increased for fluidised bed drying systems.

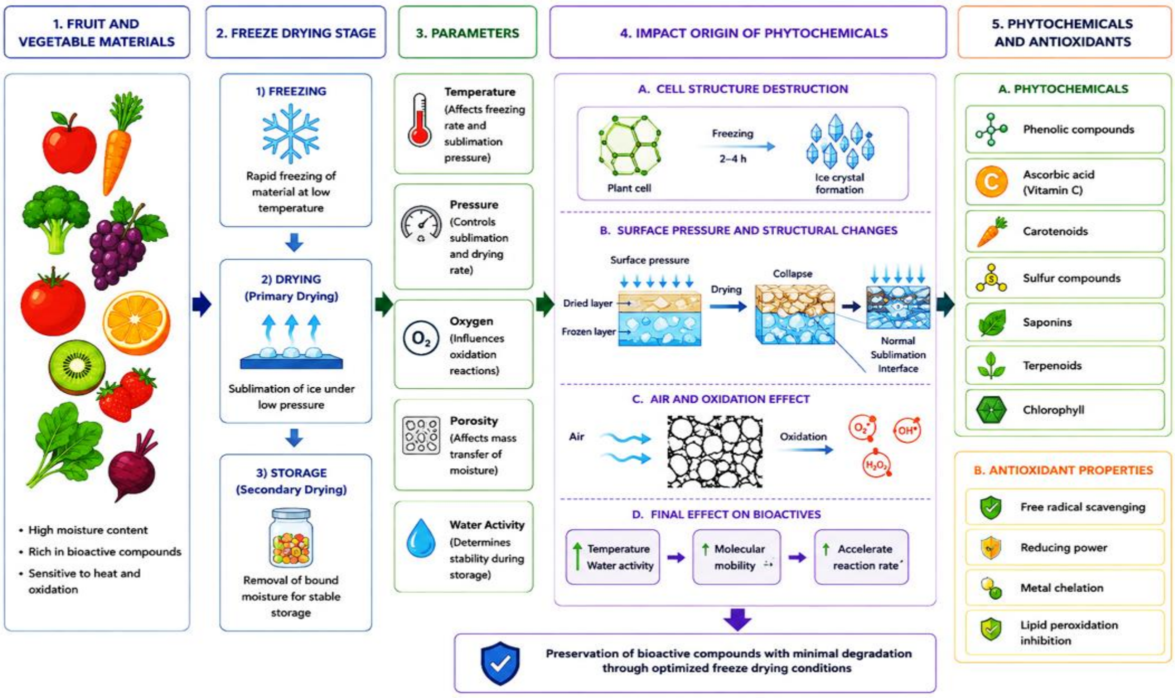
4.4 Low-Pressure Superheated Steam Drying (LPSSD)
The reduced pressure and superheated steam of LPSSD efficiently remove moisture. Oxygen concentration is low at drying conditions, thus reducing the oxidation reactions, resulting in better colour retention and nutrient preservation. In addition, this technology is more energy-efficient than conventional hot-air drying because energy recovery is accomplished by recycling steam[22]. However, due to its complexity and costs, LPSSD has not been widely adopted industrially.

4.5 Vacuum Drying
Unlike the standard drying process, vacuum drying is the process of drying under reduced pressure conditions, in which the water has a lower boiling point and can be removed at a lower temperature. The pressure gradient increases moisture migration from within the product, which increases the drying rate relative to conventional drying in atmosphere[23]. Owing to the reduced operating temperatures vacuum drying for heat-sensitive commodities such as fruits and vegetables.
The advantage of vacuum drying over hot-air drying is that the latter usually results in poor food colour, loss of physical quality and higher levels of oxidation, while the former may yield products of better nutrient quality. However, specialised equipment and the generation of a vacuum are necessary in a vacuum system, making operation and maintenance expensive. Therefore, it is generally considered to be an economically unhealthy method for large-scale industrial use and is often used along with other drying technologies to make it more efficient[4].

4.6 Vacuum Microwave Drying (VMD)
Vacuum microwave drying is a new drying technology that combines the characteristics of microwave drying with vacuum drying, resulting in the dehydration of samples with microwave high-speed and efficient microwave effect. The combination of microwave energy and the vacuum environment provide volumetric heating in the product and reduces the evaporation temperature of water[24]. This pairing can lead to much faster drying and decrease drying overall time.
The "puffing phenomenon", one of the most uncommon characteristics of VMD, may occur. VMD may exhibit one of the most unusual characteristics, the "puffing phenomenon." When drying, a very rapid inside build-up of vapour causes the cellular structure to collapse (porosity), which results in products with a high rehydration capacity Compared with the
convective drying technique, the. VMD operation is found to reduce the shrinkage and texture deterioration of the body. Studies have shown that the characteristics of vacuum microwave-dried products, including the length of drying time, colour, and porosity, are better than those of hot-air dried products[16].

4.7 Freeze-Drying
Lyophilization or freeze-drying, is considered the gold standard in product quality preservation technology. Freeze-drying is different from all the other evaporation-based processes in that ice is evaporated under low-pressure conditions, directly into a gas. The process involves three steps: the first step involves freezing, followed by primary drying (sublimation process) and lastly by secondary drying (desorption process)[10,25].
The process of freeze-drying is conducted at extremely low temperatures, providing an outstanding recovery of color, flavour, taste, vitamins, antioxidants and bioactive compounds. Several reports have indicated that retention of ascorbic acid and phenolics is much greater in fruits dried via the freeze-drying process than in those dried with hot air. For example, the content of ascorbic acid is approximately 86.6 mg/100 g dry weight in freeze-dried mulberry, but this content decreases to 10 mg/100 g dry weight in hot-air drying at 100°C[10].
These quality advantages, however, are very expensive. As one of the most energy-consuming procedures in dehydration, the freeze-drying process requires a long drying time, and it operates at relatively low temperatures and under low-vacuum pressure. Depending on the product properties, drying times are often in the range of eighteen to forty-eight hours. Conventional freeze drying for fermented cabbage takes approximately 18 hours, while microwave freeze drying only takes approximately 2 hours, and the quality attributes comparable[10]. Overall, traditional drying technologies still play a significant role in post harvesting conservation of fruits and vegetables. Hot-air drying, vacuum drying and even combination of hot-air and vacuum drying continue to be economically feasible for many industrial applications, but preservation of quality continues to be difficult. There are two other vacuum dryers, vacuum microwave drying and freeze-drying, which yield better product characteristics, but with higher capital investment and energy input[26]. These constraints have promoting developments of hybrid freeze drying technology to decrease energy expenditure and processing time (Fig.2).

Fig 2. Effects of freeze-drying process parameters on cellular structure, phytochemical retention, and antioxidant properties of fruits and vegetables during dehydration and storage.



This has prompted the evolution of new, complex, and hybrid drying technologies that aim to deliver an optimised product quality/drying efficiency and sustainability (Table.3).

Table 3. Comparison of Hot Air-Drying Sub-Methods, Application and its advantage

Method	**Principle**	**Advantages**	**Limitations**	**Typical Applications**	**Reference**
Conventional Hot Air Drying	Heated air removes moisture	Simple, low cost, scalable	Long drying time, shrinkage, nutrient loss	Fruits, vegetables	Hasan et al. (2019)
Air-Impingement Drying	High-velocity air jets	Faster drying, better vitamin retention	Higher equipment cost	Cut vegetables, fruit slices	Rashid et al. (2022)
Fluidised Bed Drying	Particles suspended in hot air	Uniform drying, high efficiency	Limited to particulate materials	Peas, grains, diced vegetables	Adegbite et al. (2023)
LPSSD	Superheated steam under low pressure	Reduced oxidation, energy recovery	Complex equipment	High-value food products	Mediani et al. (2022)

5. Advanced Drying Methods

Advanced drying technologies have emerged as an alternative and have attracted great interests over conventional method because they can increase the drying efficiency, decrease the energy demand of drying and maintain the quality of the product. Compared with conventional heat-based methods, advanced drying systems use innovative energy transfer methods such as electromagnetic radiation, dielectric heating, conductive heat transfer, and thermodynamic heat recovery. The conventional drying methods have many limitations, which are overcome by these technologies, such as long processing times, degradation of nutrients and poor product quality[27]. The use of advanced methods for drying thus has received much attention in the fruit and vegetable processing industry, especially for high-value and heat-sensitive products.

5.1 Infrared Radiation Drying

Infrared Drying (IR) uses infrared radiation as a direct energy transfer to food without a medium, preheating the food in between. IR waves pass through the product and are absorbed by the molecules of water and other components, causing internal vibrations and generating heat. This mechanism allows moisture removal in less time and better energy efficiency as compared to the traditional convective drying process[34]

A major benefit of infrared drying is that a good deal of reduction in the number of drying cycles can be achieved without greatly compromising the quality of the product. The heat losses due to the rise in the surrounding air are

low since energy is supplied directly to the product. Several studies have found infrared dried fruits and vegetables to have higher retention of vitamin C, phenolic compounds and natural pigments than did hot-air dried fruits and vegetables[28]. However, infrared-assisted drying of red dragon fruit resulted in a significant decrease in drying time of up to 42% than conventional drying methods for same produce, as improved color, antioxidant activity, and texture characteristics compared to conventional drying methods[10].
The other benefits of infrared drying involve better use of energy and its lower operating costs. But high intensities of infrared can lead to overheating of the surface, case hardening and water non-uniformity. Due to the above reasons, infrared drying is often used in conjunction with other techniques, including hot-air drying, vacuum drying and microwave drying to enhance the uniformity of the process and quality of the product.

5.2 Dielectric Drying

The interactions between the electromagnetic field and polar molecules in food materials generate heat: this is what dielectric drying technologies do. A difference between conventional heating and dielectric heating is that conventional heating has volumetric heating in the product starting from the outside inwards, while in dielectric heating, the product is heated volumetrically throughout the product[29].This property is very favourable for the removal of moisture and for drying.

5.3 Microwave Drying (MD)

Among the dielectric drying technologies, microwave drying has been the most extensively investigated. It usually works at 915 MHz (or 2450 MHz), a frequency where the energy of the EM field collides with the water molecules, causing their oscillation to be rapid and internal heat to be produced[16].
The first possible benefit of microwave drying is the quick drying-out rate. Compared with traditional moisture migration drying systems, migration is more efficient because energy is generated within the product. In several studies, it has been demonstrated that the drying time could be reduced by more than 50% by using MAD compared with the hot-air drying process with the same quality characteristics. Fruits and vegetables that contain high amounts of moisture are receptive to this technology, and microwave energy is absorbed by water molecules very efficiently[25].
However, there are several feasibility issues associated with microwave drying. A Hot spots or lack of uniformity of heating caused by nonuniform distribution of the magnetic field can cause nonuniform heating, which is a consequence of quality deterioration. Hence, usually microwave drying is usually used together with vacuum dryers, freeze-dryers or hot air dryers to obtain uniform heat and consistency of the product[30].

5.4 Radio Frequency Drying (RFD)

Radiofrequency drying works between frequencies of 3 to 300 MHz and alternating EFs are applied to obtain volumetric heating. The energy penetration depth of radio frequency energy is considerably greater than that of microwave energy, making it possible to heat the bulk of a product more uniformly in larger and thicker products than microwave energy[16].
Radio wave systems are especially useful for drying bulky agricultural products, cereals, fruits and vegetables because they can penetrate deeper than microwave systems can. This uniformity of heating results in less temperature variation within the product and fewer quality problems that arise in products from overheating[31]. Research has also shown that radio frequency drying can yield improved moisture extraction and produce a superior colour, texture and nutrition without sacrificing quality.
Another key benefit of the radio frequency drying technology is that it can minimize microbial contamination and insect infestation during the process. However, radio frequency equipment has significant capital costs and complex process control instrumentation[32]. Furthermore, product geometry and other product dielectric properties can impact the degree of heating, which requires optimisation attention to product operation parameters.

5.5 Refractance Window™ (RW) Drying

Refractance Window™ (RW) drying is a new method of drying that uses conductive, convective, and radiative heat transfer. Here, a thin layer of product is applied onto a transparent plastic film floating on the circulating hot water between temperatures of 70°C – 85°C[6].
The three modes of heat transfer are conduction from the film-heated surface, convection from the surrounding environment and IR radiation transmitted through the reflectance window. This specially designed combination allows for very quick drying and maintains relatively low temperatures of the products being dried. Consequently, nutrients, pigments, flavours and bioactive compounds that are sensitive to heat loss are better retained during drying by RW systems than by many conventional drying systems[33].
An RGU dryer is economically feasible, one of its biggest advantages. Investment costs for the capital investment in a plant designed for drying these products by a RW system have been found to be about 50-70% less than the investment for a plant built for drying the same product by freeze-drying, to obtain similar product quality in many food products[6]. Moreover, drying corresponds to much less drying time compared with freeze-drying, thus adding efficiency in the industrial realm.
Vitamin C, carotenoids, anthocyanins and antioxidants have been found to be very well retained when using the RW-drying method. For high-value foods, RW drying is gaining greater attention as a potential alternative to

freeze-drying because it has a good balance of quality food characteristics, energy efficiency and cost effectiveness[34].

5.6 Heat Pump (HP) Drying

Heat pump drying is an energy-efficient technology that operates via the reversed Carnot cycle. In heat pump drying technology, it is considered an energy-efficient technology and is based on the opposite Carnot refrigerator. Heat pump dryers can recover and recycle the heat of exhaust air, which avoids the loss of a large part of heat during the drying process, in contrast to dryers, which use only external heat sources[35].

One of the greatest benefits of a heat pump drying machine is that it can be operated without having to control either temperature or humidity, as they are kept separate. This feature can be used to optimise drying conditions for each fruit/vegetable species. The operating temperature is usually held at 20–60ºC, which makes heat pump drying a more suitable method for agricultural products that are sensitive to heat and may lose quality under conventional high-temperature drying[36].

Many studies indicate that heat pump-dried products have better colour stability, less shrinkage, better rehydration, and better vitamin and bioactive compound preservation. Besides, In addition, owning to efficient heat recovery and moisture removal techniques, energy savings of 30-60% are observed with respect to conventional hot-air systems[3].

These benefits do not come without additional expenses or complexity in equipment types when a heat pump drying system is used. Drying rates could also be lower than those attainable by microwave or infrared methods[37].Hence, configurations that combine heat pumps with radio frequency systems, microwave systems and infrared systems are increasingly explored to improve drying performance while maintain high energy efficiency.

The Advantages of the advanced drying technologies include great improvements with respect to conventional drying techniques, in terms of drying efficiency, a reduction in drying energy requirements and preservation of the quality of the dried products. Each technology has its merits on the basis of the product and drying needs; e.g, for any particular product, heat pump drying, IR/DiA Window™ may be its superior technology. The drying technologies receiving special attention are Refractance Window™ Drying and heat pump drying, which produce high quality products with high energy efficiency (Table.4). However, the restraints from single technologies have stimulated additional efforts to design hybrid drying systems that unite a series of drying methods into a single hybrid system to allow for the highest possible efficiency and product quality[38].

6. Combination (Hybrid) Drying Technology

Owing to the above, hybrid drying technologies have become effective ways to address the shortcomings of both drying technologies. Both traditional and novel drying systems have advantages and disadvantages; however, no single system can achieve the highest degree of energy savings, drying efficiency and product quality[39].A combination of different drying techniques is applied in a single process, called hybrid drying, which allows synergies and involves the combination or interaction of these techniques to improve heat and mass transfer and decrease the drying time and the operational cost. These methods can be categorized as: parallel combined drying with simultaneous operation of various drying techniques and tandem (sequential) combined drying, by following different drying technologies in different stages[10,3]

6.1 Parallel Combined Drying

A parallel hybrid drying system provides multiple energy sources simultaneously to achieve better moisture removal and quality drying. Multiple drying mechanisms can be applied simultaneously to speed drying up without substantially deteriorating of the drying quality.

6.1.1 Radio Frequency–Hot Air Drying (RFHAD)

Radio Frequency – hot air drying: Volumetric RF heating with conventional hot-air drying. The product is heated quickly by selective radio frequencies, and hot air completely de-moisturises the surface. This is a complementary mechanism which decreases the moisture gradients inside and helps in uniformity of drying.

Research has already proved that applying an RFHAD to hot-air drying could greatly reduce the drying time and also better distribute the moisture in the product[40]. The more uniform the heating is, the less likely the case hardening and too much shrinkage will occur, which is beneficial for the texture and rehydration properties of the product. In addition, RFHAD has been found to retain more bioactive compounds and colour in different fruits and vegetables than traditional drying techniques[6].

6.1.2 Radio Frequency–Heat Pump Drying (RFHPD)

RFHPD combines radio frequency heating and heat pump technology to efficiently remove moisture as it rapidly heats the interior. The heat pump controls temperature and humidity with accuracy, and radio frequency energy increases the speed of water volatilisation inside[41].

This combined system has proven to be effective in agriculture where products are sensitive to heat. Studies have shown that RFHPD reduces some of the colour degradation, cracking and damage to the structure that can be found in traditional drying systems. The mixture also decreases drying time without compromising the product quality and appearance[33]. These are qualities associated with RFHPD that have made it particularly suitable for high-quality fruits and vegetables.

6.2 Combined Microwave Drying

Drying using microwave is often used in conjunction with other drying methods to address the problem of non-uniform heating and localised overheating.

6.2.1 Microwave–Hot Air Drying

The purpose of microwave–hot air drying is to use microwave energy to accelerate the migration of moisture inside a product and hot air to eliminate moisture from the surface. This mixture results in a substantial reduction in drying time, as well as increased energy efficiency when hot-air drying is performed its own[42].

6.2.2 Microwave–Vacuum Drying

In the case of microwave - vacuum drying, the reduced pressure allows drying rapidly at a lowered temperature because of the decreased boiling point of water. This technology is used to manufacture very porous materials that have excellent conversion properties and less shrinkage[43].

6.2.3 Microwave–Freeze Drying

The application of freeze drying with microwaves has received immense attention because of its ability to increase the rate of sublimation. Treating fermented cabbage with microwave freeze-drying for 2 h resulted in better rehydration ability, probiotic viability, and sensory quality than 18 h with conventional freeze-drying methods[10]. Energy savings of more than 30% have been reported in similar studies compared to the conventional freeze-drying systems[34].

6.2.4 Microwave-Enhanced Spouted Bed Drying (MSBD)

Microwave enhanced spouted bed drying is a new combination of spouted bed drying (in which high velocity air streams suspend and circulate the particles) and microwave heating. The unending motion of particles allows for even microwave exposure and helps stop localised overheating.

The technology results in crispness, with a high porosity of the produce. Consequently, higher heat transfer rates and mass transfer rates yield more rapid drying rates and better energy efficiency. MSBD has, as such, become popular in the processing of snack foods, fruit chips and vegetable crisps[44].

6.2.5 Microwave Pulse-Spouted Bed Freeze-Drying (MPSFD)

Microwave pulse-spouted bed freeze-drying is another new development in freeze-drying technology. In this system, the particles flow continuously inside a spouted bed and pulsed microwave energy is applied during the freeze-drying process[45].

MPSFD, which is the result of research, has been found to accelerate the drying time by as much as 40% compared with conventional freeze drying without compromising the quality of the product. Owing to lower processing times, this technology also improves microbial safety and sensory properties are better retained. A shorter drying time means less energy will be used and is more economically viable when using products on an industrial scale[46].

6.2.6 Infrared-Combined Drying

Infrared dryers are often used in combination with convective, vacuum and microwave drying. Infrared radiation offers fast surface heating treatment, and drying by complementary mechanisms increases moisture transfer from the product inside.

As indicated, drying via IR convection reduces the drying time while ensuring good colour retention and good drying texture. Similarly, IR-vacuum systems reduce the transfer of moisture and the chances of oxidation and thermal degradation, whereas IR-microwave systems promote moisture removal and increase uniformity of moisture. The results of these studies always revealed better physicochemical quality, such as better retention of vitamins, antioxidants and natural pigments, than in the sole use of these drying technologies[16].

Tandem (Sequential) Combined Drying

Tandem hybrid drying technologies are a series of different drying methods. In this way, each method can focus on a specific moisture removal stage to optimise the overall moisture removal process.

6.2.7 Hot Air Followed by Microwave or Freeze-Drying

Hot-air drying followed by microwave or freeze-drying is a process usually used in tandem. In the first step, there is a significant amount of free moisture removed at relatively low cost by hot air. In the second step, more bound moisture is removed efficiently while maintaining product quality through the use of microwave energy or freeze-drying[47]

In this approach, a lot of energy is saved and the total drying time is a lot lower since the energy-consuming technology is used at the stage of dehydration only. These ‘staged' drying systems have been proven to be able to achieve processing costs which are significantly reduced without compromising product quality when compared to traditional freeze drying[48].

6.2.8 Osmotic Dehydration Followed by Hot Air Drying

One popular alternative to either of the above processes is a combination of osmotic dehydration and hot-air drying. Osmotic treatment removes a portion of water prior to the heating for thermal drying, thereby lowering the moisture content to be removed during the drying step[49].

The benefit of pretreatment is to retain colour, stability and flavour in the product, and minimise energy use in hot-air drying. Furthermore, osmotic dehydration will bring about less structural damage because of the lowered moisture gradients within the product. Thus, the process of drying fruits with hot-air and combined drying is often superior to the hot-air drying method alone in drying quality[50].

7. Heat-shock proteins and transcriptional responses to drying

The thermal drying process could mimic the conditions plants usually experience under heat and dehydration stress by inducing similar molecular responses as plant response to heat and dehydration. Molecular responses are shown by the heat shock proteins (HSPs) molecular chaperones, such as HSP70, HSP90, small heat-shock proteins to assist protein refolding and stop protein aggregation; small heat-shock proteins maintain protein structural integrity and also have the role to repair the damage that occurs by heat treatment, HSPs are induced by heat shock transcription factors (HSFs). The other big family of transcriptional factors involved in plant stress response by drought, osmotic stress, temperature stress and oxidative stress are dehydration-responsive element-binding proteins (DREBs), ABA-responsive element-binding factors (AREBs/ABFs), NAC transcription factors, basic leucine zipper (bZIP) proteins, WRKY transcription factors and others by regulating various cellular responses and coordination activities to adjust cell membranes integrity, osmotic potential and plant's adaptation to harsh conditions. By studying these networks' regulation, mechanistic explanations might be found why different drying methods cause varied effects in retained nutrients, antioxidant potential, tissue structures and during shelf life storage.[70, 71]

8. Omics-Based Approaches for Understanding Drying Responses

8.1 Transcriptomics and Proteomics

Using transcriptomics, such as with RNA sequencing (RNA-seq) offers a practical strategy for characterising genes and pathways which may respond to dehydration and thermal processing. Through comparisons of fresh with dehydrated tissues via transcriptomics, expression levels of genes related to oxidative stress, thermal response, carbohydrate metabolism, the phenylpropanoid pathway, cell-wall reconstruction and programmed cell death may be observed. RNA-seq comparisons between different drying technologies are possible to identify signature molecular patterns of excellent retention of nutrients. A comparison of transcripts of both hot-air-, freeze-drying, microwave and infrared-drying for instance, might shed light upon activation of diverse heat response pathways associated with technologies. Transcriptome does not necessarily directly correspond to protein functional activities; thus proteomic techniques are also crucial to identify changes in antioxidant enzymes, heat-shock proteins, metabolic enzymes and structural proteins upon drying. Quantitative proteomics can be employed to assess whether or not drying parameters affect protein abundances, modifications and degradations to protect cell damage and to assure nutritional quality of the products.[72, 70]

8.2 Multi-omics integration

The comprehensive view of changes in primary and secondary metabolites during drying: Utilizing Metabolomics An untargeted approach of metabolomics by LC-MS, GC-MS and NMR has the ability to uncover changes in phenolics, flavonoids, organic acids, sugars, amino acids and volatile compounds during the drying process. Metabolomic analysis could be correlated with the transcriptomic data to build relationships between gene expression and metabolite accumulation, demonstrating the impacts of different drying technologies on metabolic pathways and helping establish quality biomarkers. Systems biology approaches through integrating genomics, transcriptomics, proteomics and metabolomics could provide a global view on the multifaceted response of fruits and vegetables to drying. Multi-omics strategies are able to link the processing and environmental parameters to gene expression, protein contents, metabolites levels and product quality traits. Future multi-omics data could be incorporated with AI approaches to predict drying results from molecular profiles of fresh products. The obtained information may help designing tailored and genotype-specific drying protocols based on the molecular and biochemical profile of each specific cultivar.[71, 72, 73]

8.3 AI-Driven Molecular Prediction of Drying Quality

Intelligent drying strategies will be based on the integration of process data and the molecular and biological information of the drying materials. Today, mainstream artificial intelligent techniques consider solely temperature, humidity, air velocity, water content, drying duration and air humidity as input parameters. However, molecular descriptors, such as genetic characteristics, gene expression, metabolites, antioxidants content and chemical profiles can lead to a greater prediction efficiency. A molecularly informed AI platform could integrate:

Genotype → Gene expression → Protein activity → Metabolite profile → Drying response → Final product quality

It could also be used by machine learning algorithms to predict color loss, loss of texture, antioxidant content loss, nutritional value loss, shelf life, and loss of rehydration potential, which would be predicted using food ingredients' properties and dryer process equipment's parameters. Machine learning algorithms could guide the process design to make more control-exact dryers that adjust its parameter outputs depending on molecules found in specific cultivar.[74]

9. Mechanism and Benefits of Sequential Drying

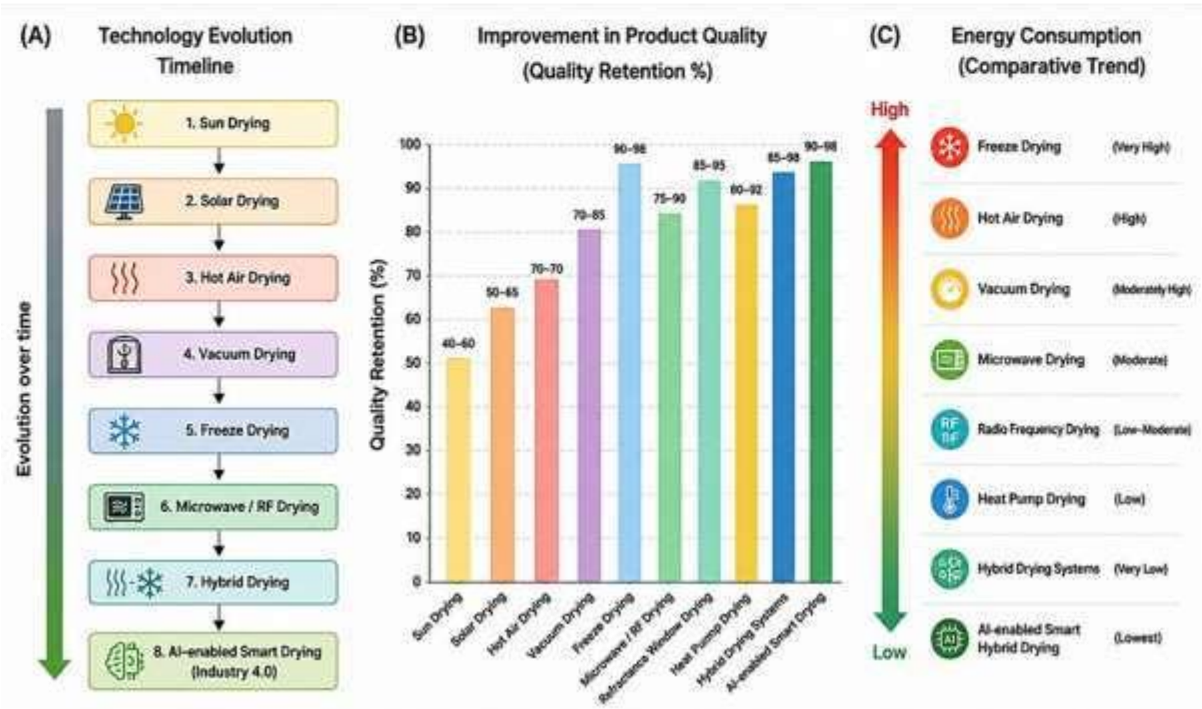
The main factor of tandem drying systems is the removal of various water forms sequentially. Efficient removal of free water; subsequent advanced drying technologies remove bound water that is more challenging to remove. This multi-stage process has benefits of improved drying time, decreased energy consumption and retained quality[51]

On the whole, the drying technology that combines the drying principles of both these methods, namely the hybrid drying technologies, is one of the most encouraging advances in the current food dehydration technologies. These multi-drying technology systems deliver benefits of multiple drying technologies directly – more efficient drying, quality of the product and lower operating costs than standalone technologies. Taking this into account, hybrid drying systems are likely to become one of the most important sustainable food processing systems in the future because of the increased demand for good dried fruits and vegetables[52].

9.1 AI-Enabled Drying Technology

The advent of Industry 4.0 has led to considerable transformation of the food processing industry, especially dehydration technologies. Energy usage in traditional dryers is often inefficient, product quality is inconsistent, processing speed is slow, and there is an inadequate degree of process control. Modern drying operations are now looking to artificial intelligence (AI), machine learning (ML), smart sensors and advanced automation systems as tools to overcome them. The advanced capabilities of AI-powered drying technologies, such as real-time data collection, predictive modelling, and intelligent control systems, enable the dynamic optimisation of drying conditions for high product quality and energy efficiency[53].Drying processes are complex in nature, and involve potential interactions among moisture migration, product properties, airflow, humidity, and temperature, all of which can be better understood and controlled with AI than with traditional control processes (Fig.3).

Fig 3. Evolution of fruit and vegetable drying technologies from traditional drying methods to advanced, hybrid, and intelligent drying systems, highlighting improvements in product quality, energy efficiency, and process sustainability.



9.2 Overview of AI-Enabled Drying Systems

The utilisation of AI for food drying is designed to address some of the significant challenges that traditional drying processes face, such as inefficient processes, uneven moisture distribution, high energy consumption, and degradation in product quality. Today's smart drying systems utilise sensor networks, data collection platforms and predictive algorithms to measure product conditions and production processes constantly [54].

Unlike traditional drying systems with fixed parameters found in certain drying systems, AI-based dryers can change operating parameters on the basis of current feedback. Factors such as drying temperature, air velocity, humidity, microwave power and drying time can be constantly adjusted during the process to ensure that product parameters are in line with the needs. Adaptive control has a significant effect on process stability, which minimises over drying and under drying, or the ability to see too much of one or the other, and both of these effects are consequential to poor product quality and energy use problems[6].

9.3 Advanced AI Techniques

9.3.1 Artificial Intelligence Algorithms

Multiple input/drying outcome relationships have been modelled with various AI algorithms for food drying systems. One of the most popular artificial intelligences (AI) technologies is Artificial Neural Networks (ANNs), which are used to learn the nonlinear relationship between experimental data. ANNs were able to predict drying kinetics, moisture ratios, drying rates and various quality parameters for a wide variety of fruit and vegetable products.

Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are based on the principles of fuzzy logic and can learn from neural networks to model very nonlinear drying processes with acceptable model interpretability. Likewise, several other algorithms have been applied to moisture content estimation and moisture drying time prediction, such as Support Vector Machines (SVMs), which have been proven to be of high predictive accuracy for the above mentioned applications.

The benefit of fuzzy logic is that a mathematical model is often not available, especially because the values of the variables fluctuate considerably, and a fuzzy logic controller can handle this easily. They imitate the human decision-making strategy, dealing with uncertain and imprecise process information[55]. Recently, to address the vast amount of sensor data generated and utilised in large-scale industrial drying systems, deep learning algorithms have been introduced, as well as decision-tree-based models.

10. Process Modelling and Prediction

Process modelling and prediction is one of the key use cases for AI in drying technology. The traditional mathematical drying models may have difficulty in actualising the complex phenomenon to express gas mixture heat, mass transfer and the complex characteristic physiological response to drying.

AI models are able to predict these drying curves with high accuracy, in addition to moisture content evolution, temperature profile, shrinkage behaviour, and quality changes. When ANN models are applied to drying kinetics analysis, there has been a report with prediction accuracy above 95% using ANN models. Knowing the behaviour of the drying process can define dryer conditions that will yield better results before processing starts, which decreases to some extent the trial-and-error operation to minimise the consumption of resources[56].

Additionally, AI-driven predictive models enable the creation of digital twins, which are virtual representations of drying systems that can simulate the behaviour of the system during the drying process and assist in making decisions during the real-time operation of the system (Table.5).

Table 5. Comparative Performance of Drying Technologies on Product Quality and Energy Efficiency

Drying Technology	Drying Time Reduction (%)	Vitamin Retention (%)	Colour Retention	Energy Efficiency	Industrial Scalability	Overall Performance Score	Reference
Sun Drying	Baseline	40–60	Low	High	High	Moderate	Sagar & Kumar (2010)
Hot Air Drying	20–30	50–70	Moderate	Moderate	Very High	Moderate	Hasan et al. (2019)
Vacuum Drying	35–50	70–85	Good	Moderate	Moderate	Good	Boateng (2024)
Freeze Drying	70–90	90–98	Excellent	Low	Moderate	Excellent	Chen et al. (2023)
Microwave Drying	60–80	75–90	Good	High	High	Very Good	Su et al. (2022)
Radio Frequency Drying	50–75	80–92	Very Good	High	High	Excellent	Gao et al. (2023)
Refractance Window Drying	65–85	85–95	Excellent	High	Moderate	Excellent	Gao et al. (2023)
Heat Pump Drying	40–70	80–90	Very Good	Very High	High	Excellent	Loemba et al. (2023)
Hybrid Drying Systems	70–95	85–98	Excellent	Very High	High	Outstanding	Sagar & Kumar (2010)

10.1 Intelligent Control Systems

Intelligent control systems with AI-based capabilities enable control of drying parameters in real time, via the use new sensor data. Smart dryers are not set at a specific value, but dynamically adjust process variables to ensure optimum drying conditions.

Advanced controllers that include a Nonlinear Autoregressive Moving Average-L2 (NARMA-L2) controller have demonstrated promising results in drying processes, and some of them have also demonstrated their ability to control this process. Through the use of neural network models, the NARMA-L2 controllers predict the behaviour of the system to adjust parameters for its operation automatically. These systems can keep the drying temperatures stable, control the moisture content, and minimise energy input variations in response to changes in product characteristics or ambient conditions. The continuous adaptability of operating conditions decreases process variations and provides better uniformity between production batches[57].

10.2 Multi-Objective Optimisation

There are numerous objectives of a food drying process That may be competing with one another, such as: minimise drying time, minimise energy use, maximise product quality, and minimise operational costs. Typical optimisation algorithms may not be capable of meeting them all at once.

Optimal trade-off solutions can be provided by using AI-based optimisation algorithms, which are effective in finding optimal trade-offs among multiple objectives. Optimisations based on techniques like a genetic algorithm, particle swarm optimisation, and optimisation with machine learning have been used to define optimal drying time, microwave power, airflow and temperature.

For instance, optimisation models offer the reduction of energy consumption in a scheme which considers the maximisation of vitamin retention and reduction of drying time. These characteristics are especially useful for large-scale production dryers, in which drying energy is a large component of the total production cost[58].

10.3 Sensor Integration and Data Fusion

Seeking to leverage the capabilities of an AI-backed drying system would largely involve actual data collection in need of real-time data. Common to all modern smart Dryers is the ability to employ several sensor technologies to ensure that the product quality and Process performance are controlled at all times.

Sensors that operate in the near-infrared light (NIR) can make quick non-destructive determinations of moisture and chemical composition. Low Field Nuclear Magnetic Resonance (LF-NMR) sensors can be used to accurately characterise water distribution and/or moisture movement in food products. During the drying process, computer vision can be used to assess colour differences, reduction and surface changes[59].

The idea of data fusion techniques is to fuse data from many sensors to create a comprehensive understanding of product conditions. This holistic approach enhances prediction performance and facilitates better process control than when considering a single-sensor system only.

10.4 Impact on Product Quality and Energy Efficiency

The application of technologies with AI has a major impact on the preservation of product quality and improvement of energy efficiency. AI systems continuously adjust process parameters to maintain the frequency of the desired colour, texture, flavour, vitamin content, and retention of bioactive compounds[60].

Dynamic parameter adjustment keeps common quality defects like case hardening, excessive shrinkage and uneven moisture from happening. With moisture gradient monitoring, for example, AI systems can adjust airflow or temperature before deterioration becomes an issue.

Beyond improvements in quality, AI can also result in significant energy savings by preventing wasted energy from being used and by optimising the use of already available resources. The use of renewable energy systems like solar dryers and wind-assisted drying further increases sustainability. AI can also help to manage thermal energy storage (TES) systems, which store excess renewable energy when production is high and when energy is needed later in the process, thereby optimising the overall process[61].

10.5 AI in Pretreatment and Hybrid Drying Systems

AI-driven drying solutions are not limited to drying systems and involve optimisation processes that are used in pretreatment and hybrid drying solutions. Cold plasma processing, ultrasound-assisted dehydration process and subjected pulsed electric fields processing are new technologies involves interactions of several parameters, and these are hard to configure with traditional optimisation methods.

Large databases of experiments can be used to train machine learning models that characterise the optimal conditions for pretreatment to enhance drying performance and product quality[62]. The AI algorithms, for instance, can determine the optimum microwave power and hot-air temperature for hybrid microwave-hot air dryers or optimise the interaction between the radio frequency and heat pump in the radio frequency-hot-air-pump (RFHPD) systems. This is a very clever arrangement of the coordination which maximises efficiency of the drying, yet preserves the quality of the product.

Likewise, AI powers up hybrid drying by managing multiple energy sources and drying mechanisms at a time (Table.6) and (Fig.4).

Fig 4. Conceptual framework of an AI-enabled smart hybrid drying platform integrating sensor networks and real-time process optimization for high-quality and sustainable food dehydration.

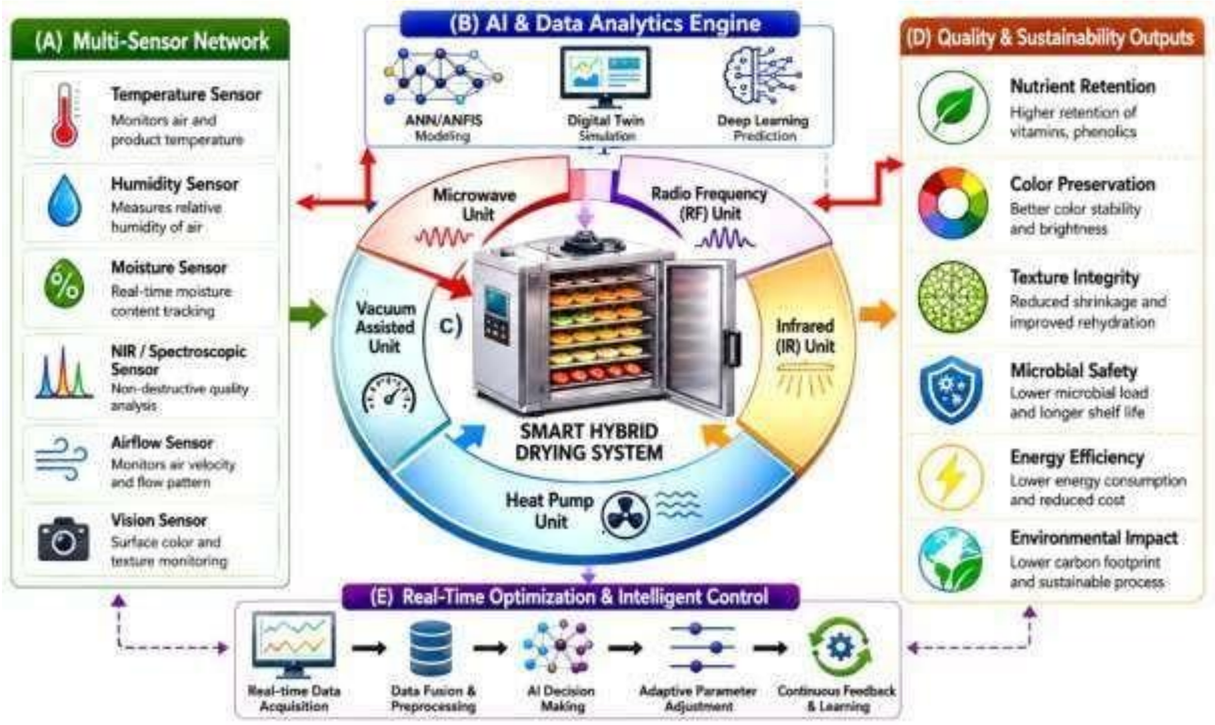


Table 6. AI Applications in Smart Drying Systems

AI Technique	Drying Application	Input Parameters	Output Prediction	Benefits	Reference
ANN	Drying kinetics modelling	Temperature, RH, airflow	Moisture ratio	High prediction accuracy	Đaković et al. (2023)
ANFIS	Process optimization	Drying conditions	Drying time	Handles nonlinear data	Fernando (2025)
SVM	Quality prediction	Moisture and temperature	Product quality	Robust prediction	da Silva Ferreira et al. (2025)
Deep Learning	Real-time monitoring	Sensor datasets	Process behaviour	Self-learning capability	da Silva Ferreira et al. (2025)
Genetic Algorithm	Multi-objective optimization	Energy and quality parameters	Optimal settings	Energy saving	Fernando (2025)
Digital Twin	Virtual dryer simulation	Real-time sensor data	Process control	Industry 4.0 integration	Hassoun et al. (2024)

11. Future Directions and Challenges

Although many developments and improvements since then, a number of obstacles lie ahead before it becomes a commercially viable industrial product with AI drying processes. A big problem is the generalizability of the models. Although machine learning systems are trained for a specific fruit or vegetable, they are not always able to accurately apply their model to other varieties because of the differences in the physical structure, moisture distribution and chemical composition.

Another challenge remains: interpretability. There are many machine learning models out there that are working as something akin to a "black box", which becomes hard for operators and regulators to interpret. Regulatory approval and industrial adoption will require greater transparency and AI that can be predicted[63].

Other obstacles are the integration of Industry 4.0 infrastructure, high price of sensors, cybersecurity issues, and the importance of achieving reliable real-time data acquisition. Further study is needed to build a strong AI model that can be adapted to further agricultural products, as well as the development of additional sensors and intelligent control systems.

Overall, the drying technologies with the help of AI are the next-generation food dehydration technologies. These technologies have the potential to make significant contributions to drying efficiency, energy savings and product quality through their use of advanced modelling, predictive analytics, intelligent control and sensor integration. With the ongoing development of Industry 4.0 technologies, AI will play a crucial role in future sustainable and intelligent fruit and vegetable processing systems[64].

12. CONCLUSION

Preserving fruits and vegetables is still a major problem because of the high moisture contents in fruits and vegetables and their predisposition for postproduction degradation. The use of natural drying systems such as sun, solar, shade and air drying is still appealing due to their minimal energy consumption and low capital costs. The production of high-quality and hygienic products, however, is limited because of their dependency on environmental conditions, limited process control and sensitivity to contamination. Traditional drying methods like hot-air drying, vacuum drying, and vacuum microwave drying have markedly enhanced material drying speed and stability. The drying speed and stability of materials have been greatly improved with the use of traditional drying technology, such as hot-air drying, vacuum drying, and vacuum microwave drying. However, these processes come at a price, with compromises in product quality, production processing times, and operational costs. Although it achieves excellent colour, texture, vitamin and bioactive retention, its energy consumption and production time have not enabled it to become a cost-effective process for large-scale applications. Also, hot air drying is economical but may often lead to losses in nutrient quality (degradation), shrinkage, and nutritional loss. With advanced drying technologies, especially dielectric technologies such as microwave and radio frequency, drying with Refractance Window™, that significant improvement in drying efficiency can be achieved, preserving valuable nutritional and sensory properties of the product. They can be used to fast-track the water extraction, eliminate the need for thermal damage and present a potential solution to traditional methods. When reviewing the technologies, hybrid drying systems seem to be the most effective solution for energy efficiency, drying rate and product quality. Hybrid approaches, utilising the complementary drying mechanisms, have a very superior overall performance, overcoming many limitations arising from the use of single technologies.

In the future, AI is poised to play a significant role in driving innovations in drying technology by means of predictive modelling, intelligent process control (ICP) and real-time optimisation. High costs, sensor integration, model interpretation and adaptability with various crop varieties are, however, the challenges that need to be overcome for smart drying systems to be widely industrially implemented.

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Credit authorship contribution statement

HB: Conceptualization, Original draft writing, Methodology, Statistical analysis, Project administration, Resources, Validation, Visualization and Original draft writing. **ST**: Validation, Review, Conceptualization and Supervision. **IC, GP and AR:** Resources, Validation, Review, Supervision.

Data Availability: All related data are presented fully within the paper, and available upon reasonable request to the lead author and the corresponding author

Declarations

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