Comprehensive Reviews in Food Science and Food Safety

COMPREHENSIVE REVIEW

Modified Atmospheric Drying of Fruits and Vegetables: Equipment, Kinetics, and Feasibility

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ABSTRACT

Fruits and vegetables, with high moisture levels of 85%–95% and 75%–96%, respectively, are susceptible to enzymatic activity and external factors, leading to rapid degradation through oxidative reactions, microbial proliferation, and respiration mechanisms such as ethylene emission. Drying, a critical preservation method, relies on heat and mass transfer driven by temperature and vapor pressure gradients. However, excessive thermal exposure and oxygen interaction often deteriorate bioactive compounds. Removing oxygen during drying offers a promising strategy to mitigate degradation and enhance product stability. Modified atmospheric drying (MAD) is an advanced technique that replaces atmospheric oxygen with alternative gases such as CO_2, N_2, or H_2 to improve drying efficiency and product quality. This review represents the first comprehensive effort to systematically consolidate recent developments in MAD, providing insights into operational mechanisms, equipment design, drying kinetics, quality preservation, and industrial feasibility, with emphasis on potential to reduce oxidation, retain nutrients, and preserve structural integrity. Compared to traditional drying, MAD achieves up to 18% improvement in effective moisture diffusivity, a 17%–29% reduction in drying time, and up to 6% increase in rehydration potential. It also enhances retention of nutritional and bioactive compounds, with total phenolic content maintained at 15%–25% higher levels, ascorbic acid degradation reduced by up to 15%, and improved color stability reflected in a decrease in total color difference (ΔE) of up to 11%. CO_2 inhibits enzymes in aqueous and fatty matrices, whereas N_2 reduces oxidative and microbial deterioration. Overall, MAD improves product quality, shelf life, and energy efficiency, lowering production costs.

Abbreviations: CHPRD, closed-loop CO_2 heat pump with rotor dehumidification; CO_2, carbon dioxide; COP, coefficient of performance; FAO, Food and Agriculture Organization; H_2, hydrogen; HEPA, high-efficiency particulate air filter; IoT, Internet of Things; IR, infrared; ISO, International Organization for Standardization; MAD, modified atmospheric drying; N_2, nitrogen; NFPA, National Fire Protection Association; PID, proportional integral derivative; PPO, polyphenol oxidase; GWP, global warming potential; RAD, reduced atmospheric drying; SMER, specific moisture removal rate; WHO, World Health Organization; ΔE, total color difference.

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1 | Introduction

Fruits and vegetables represent cost-effective and nutritionally dense food sources, rich in essential micronutrients, including water- and fat-soluble vitamins and minerals, which are integral to physiological functions in humans (Mazzoni et al. 2021). According to the US Fruits and Vegetables Exports in 2024 report published by the United States Department of Agriculture (USDA) in 2025, Canada was the leading global exporter of fruits and vegetables, with an export valuation of approximately $5.65 billion in 2024, based on recorded trade data (USDA 2025). Additionally, all major exporting countries exhibited a progressive increase in export markets between 2015 and 2024. However, concurrent with the rise in production, the magnitude of processing losses and food waste has also escalated over the years. Fruits and vegetables, classified as highly perishable commodities, are inherently prone to spoilage due to their elevated moisture content, enzymatic degradation, and microbial activity (Sarkar et al. 2022). Postharvest losses of fruits and vegetables account for approximately 37% of total production, equivalent to 2.4 mt, primarily due to moisture-induced physicochemical reactions that accelerate spoilage. Contributing factors include inefficient storage, inadequate temperature control, poor packaging, and suboptimal transportation logistics, leading to significant economic losses (Gage et al. 2025).

Since antiquity, highly perishable food commodities, including fruits, vegetables, and meat products, have been preserved through thermal processing, solar dehydration, and canning (Llavata et al. 2020; Rajput et al. 2022; Sridhar et al. 2021). Among these methods, drying is a fundamental preservation technique aimed at reducing moisture content within the food matrix to enhance shelf stability (Jeevarathinam et al. 2025; Kamaleeswari et al. 2025). However, conventional preservation techniques are characterized by prolonged processing durations and have been associated with significant degradation in the nutritional profile, sensory attributes, and bioactive compounds of fruits and vegetables (Calín-Sánchez et al. 2020; Reis et al. 2022). The presence of oxygen during drying accelerates the degradation of food products, leading to lipid and protein oxidation, loss of bioactive compounds, and increased enzymatic and microbial activity (Liu, Wu, et al. 2014). To minimize these quality losses, various pretreatment strategies have been implemented prior to conventional preservation processes. These include osmotic dehydration, sulfiting, edible coatings, blanching (via hot water, microwave, or infrared (IR) treatment), ultraviolet irradiation, cold plasma application, and pulsed electric field treatment, all of which serve to preserve the structural integrity, biochemical composition, and overall quality of fruits and vegetables (Bassey et al. 2021; Chen et al. 2020; Gao et al. 2025; González-Pérez et al. 2021; Li et al. 2024; Madurangi and Marapana 2025; Malakar 2024; Zhou et al. 2020).

Osmotic dehydration is a pretreatment process where food is submerged in a hypertonic solution of sugar or salt, causing mass transfer due to concentration differences, leading to water loss and solute absorption (Turkiewicz et al. 2020). Blanching is one of the most widely applied pretreatment methods, primarily functioning to inactivate enzymes, enhance color stability, and accelerate drying kinetics (Llavata et al. 2020). Sulfiting, a preservation technique involving the immersion of cut fruits into sulfiting solutions, serves as both an anti-browning agent and a preservative, effectively extending shelf life for up to 1 year under ambient conditions (Khuwijitjaru et al. 2022). Non-thermal processing technologies are designed to ensure microbial safety while preserving sensory attributes and bioactive compounds, achieved through minimal or complete absence of heat application (Chacha et al. 2021). Despite their advantages, each of these pretreatment methods presents certain drawbacks. Extended exposure to hot water blanching results in significant loss of water-soluble nutrients (Mugo et al. 2024). Additionally, non-thermal processing techniques necessitate substantial installation costs and optimized processing conditions to achieve efficiency and may lead to undesirable cell wall degradation, ultimately affecting the nutritional profile of food products (Chacha et al. 2021). Furthermore, chemical preservation, particularly the use of sulfiting agents, such as sodium sulfite, sodium metabisulfite, and potassium metabisulfite, must be strictly regulated, as excessive intake can lead to adverse health effects, including nausea, respiratory hypersensitivity, hypotension, and potential DNA damage (Perumkulam Lakshmanan et al. 2025).

To mitigate these effects, modified atmospheric drying (MAD) using inert gases offers a cost-effective and efficient alternative to conventional pretreatments. This method prevents oxidation, preserves sensitive bioactive compounds, minimizes browning, increases product porosity, enhances drying kinetics, and extends shelf life. In MAD, the drying atmosphere is replaced with gases, which improve the physicochemical quality of dried products. The primary gases used in MAD are nitrogen (N_2), carbon dioxide (CO_2), and hydrogen (H_2) (Perumkulam Lakshmanan et al. 2025). These gases have a significantly greater impact on the bioactive retention in dried fruits and vegetables during MAD. The bioactive retention is supported to sustain sensory properties and promote longer shelf life of the food products. Maintaining the color of food in an oxygen-containing environment and preserving flavor compounds at the highest temperatures are the primary goals of using the MAD (Liang 2024). It had a significant impact on the drying kinetics of food products by enhancing the drying rate, porosity, and rehydration ratio while causing minimal structural damage to the food matrix (Liu, Miao, et al. 2014). MAD and reducing atmosphere drying (RAD) are distinct but related drying techniques. MAD refers to drying under a controlled gas composition, typically involving a reduction in oxygen levels and an increase in gases such as nitrogen or carbon dioxide (Melenciuc 2023; Wang et al. 2024). In contrast, RAD refers to drying in a closed system using a gas mixture containing a reducing gas, such as hydrogen (H_2), which acts as a reducing agent to inhibit oxidative reactions through chemical reduction (Alwazeer and Örs 2019; Perumkulam Lakshmanan et al. 2025). Given this, RAD is considered a specialized form of MAD that employs a reductive gas environment.

A bibliometric analysis was conducted to evaluate the growing research interest in the field of MAD over the period from 1997 to 2025, as part of a broader effort to justify the relevance and originality of this review. Figure 1a–d represents the distribution and classification of publications related to MAD. A systematic literature search was performed using Web of Science, Lens.org, and Google Scholar databases, employing key terms

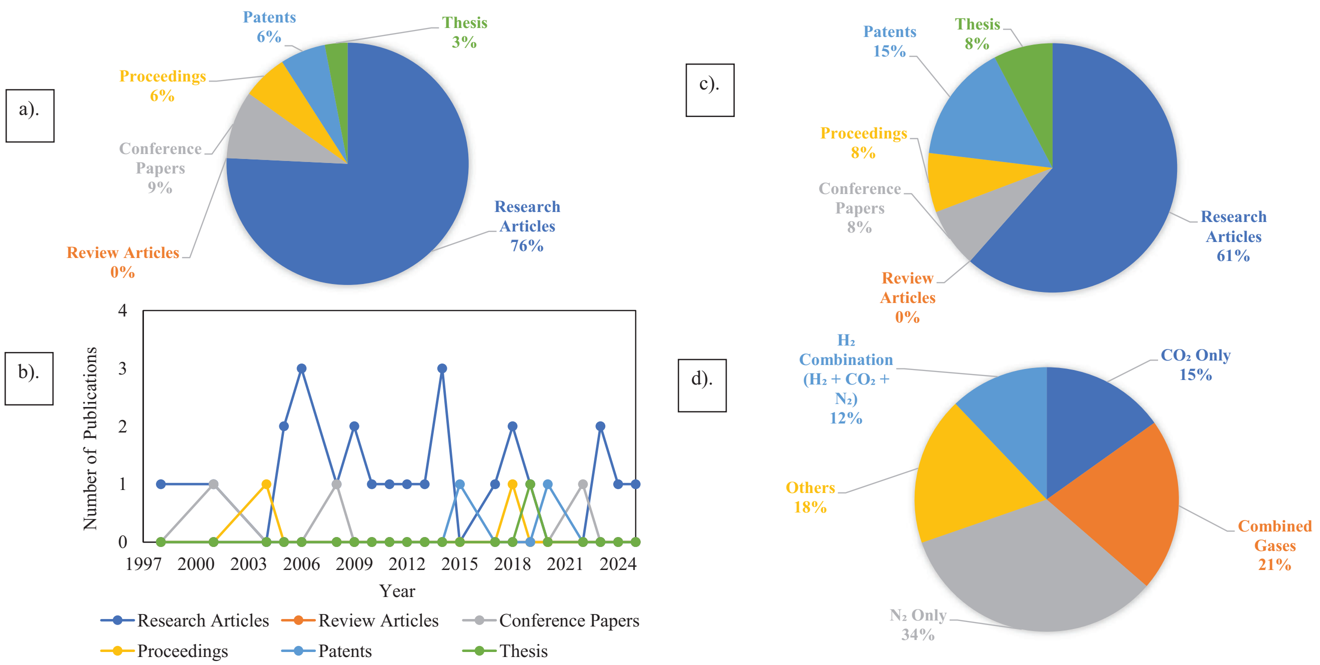

FIGURE 1 | Distribution and classification of publications related to modified atmospheric drying. (a) Overall publication-type distribution. (b) Year-wise publication trend from 1997 to 2025. (c) Publication-type distribution between 2015 and 2025. (d) Classification of studies based on the type of gas used in MAD systems.

such as "MAD" and "RAD." The inclusion criteria focused on peer-reviewed research articles, reviews, and conference proceedings that explicitly addressed MAD. The search revealed a limited literature directly related to this topic, comprising 25 research articles, 0 review articles, 3 conference papers, 2 proceeding papers, 1 thesis work, and 2 patents throughout the entire 1997–2025 timeframe. When the search was narrowed to the last decade, from 2014 to 2025, only 10 research articles, 2 conference papers, 1 proceeding paper, 1 thesis work, and 2 patents were identified. Notably, four of these were published between 2021 and 2025, indicating that this remains a growing yet still underexplored area within food drying technologies. This bibliometric evidence highlights the existing gap in comprehensive academic work on MAD and emphasizes the originality and necessity of the present review. Recent studies involving MAD techniques, such as hydrogen-based drying in apricot from Turkey (Alwazeer and Örs 2019), tomato from India (Perumkulam Lakshmanan et al. 2025), mango from China using carbon dioxide-based closed heat-pump drying combined with rotor dehumidification (Wang et al. 2024), and pear drying in carbon dioxide-modified atmospheres from the Republic of Moldova (Melenciuc 2023; Melenciuc et al. 2022), further demonstrate the growing global interest in this field.

The absence of a comprehensive review on MAD signifies a substantial gap in the current scientific literature. In this context, the present detailed and systematic review is vital to integrate research findings related to equipment design, drying kinetics, quality preservation, and industrial applications. Such an effort would provide a unified knowledge base to facilitate the development of advanced methodologies, address existing challenges, and promote sustainable applications for the drying of fruits and vegetables. Additionally, it would serve as a critical resource for guiding future research, fostering innovation, and enhancing industrial-scale implementation while ensuring the preservation of nutritional and sensory qualities in dried products. This review comprehensively examines MAD, emphasizing its mechanisms, drying kinetics, quality retention, and industrial viability. It explores how gas substitution mitigates oxidation, enhances moisture diffusivity, preserves nutrients, and improves product integrity. Additionally, this review also discusses the challenges in large-scale implementation of MAD and future research directions, including gas concentration optimization and integration with smart drying technologies for improved efficiency in food processing.

2 | Mechanisms of Gas Interaction With Food Matrices

The primary gases used in modified atmosphere systems are H_2, N_2, and CO_2. These gases, used individually or in combination, help to balance better quality food products. Additionally, other gases can be included to further optimize food preservation, enhancing both drying quality and longevity. The comparison between the conventional and MAD in terms of drying mechanism and quality attributes is illustrated in Figures 2 and 3.

2.1 | Carbon Dioxide

MAD is a non-conventional drying method where air is partially or entirely replaced by gases such as nitrogen (N_2) or carbon dioxide (CO_2). Among these, CO_2 has demonstrated considerable potential due to its distinct physical and chemical properties that influence drying behavior, product quality, and shelf life. Its application in drying processes can result in enhanced nutrient retention, reduced oxidative degradation, better color

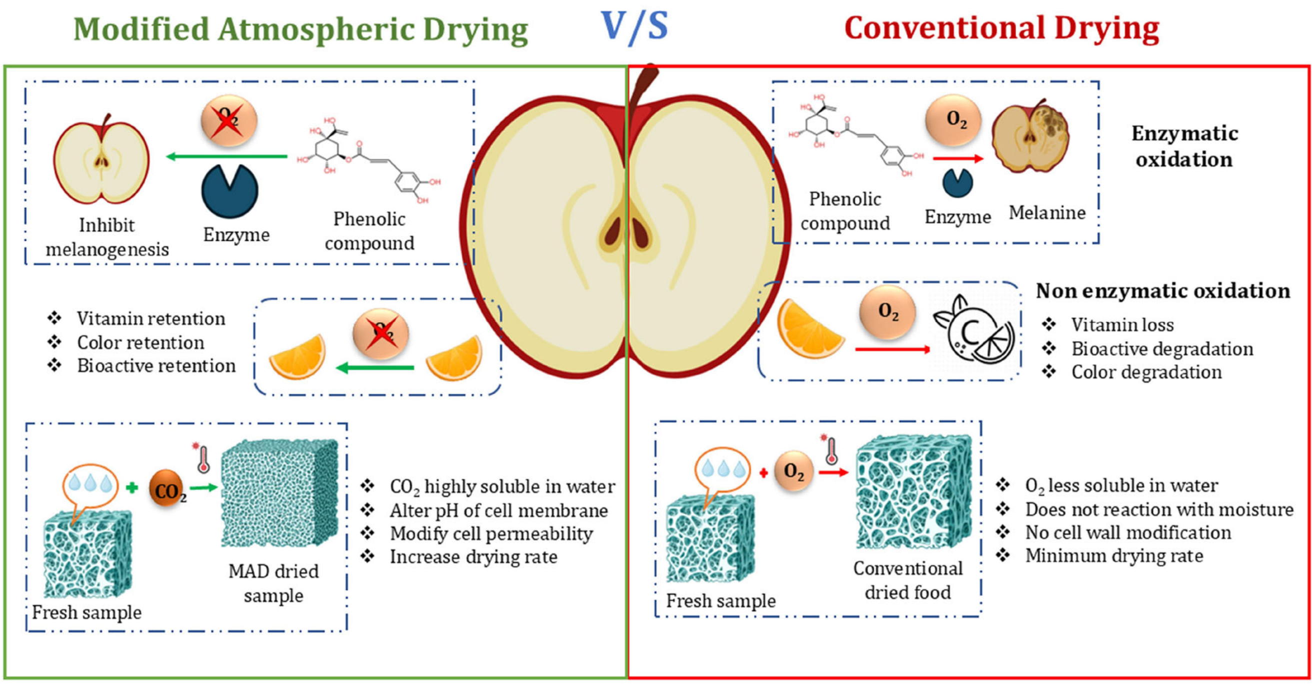

FIGURE 2 | Comparative mechanisms of modified atmospheric drying and conventional drying. MAD, modified atmospheric drying.

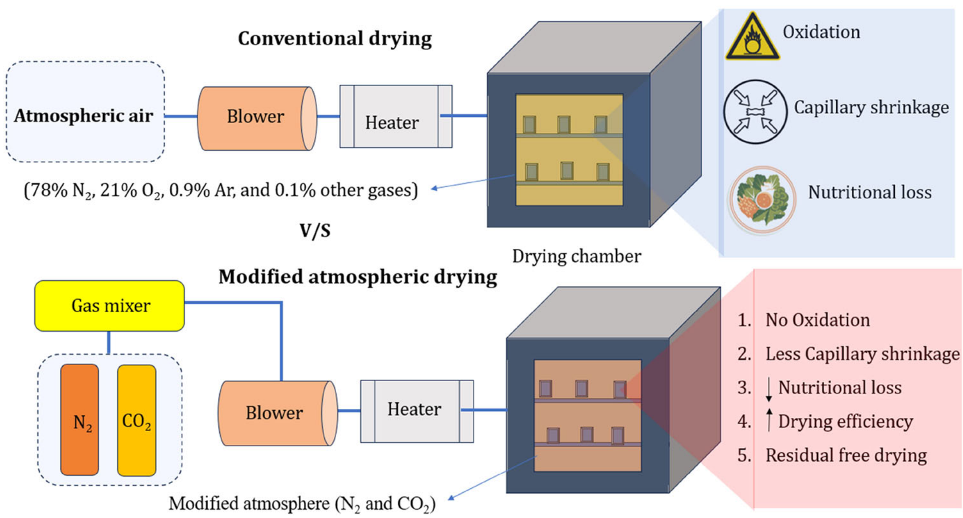

FIGURE 3 | Comparison of quality attributes in conventional drying and modified atmospheric drying.

preservation, and improved structural integrity in various food matrices. According to the European Commission project report (European Commission 2014), CO_2 drying enhances microbial inactivation by increasing the availability of free water in the food matrix during a pre-holding phase. This facilitates the penetration of CO_2 molecules into microbial cells, resulting in effective reduction or elimination of coliform bacteria, yeasts, and molds. This process achieves greater microbial kill rates compared to conventional freeze-drying methods. Due to its high solubility in both aqueous and fatty food matrices, CO_2 exhibits strong antimicrobial effects by disrupting cell membranes, lowering intracellular pH, and modifying protein structures. CO_2 permeates microbial membranes by interacting with phospholipids, disrupting membrane integrity. It also indirectly alters protein structures by shifting pH and ionization of amino acid side chains, disrupting hydrogen bonding and salt bridges. Additionally, CO_2 can directly form carbamates and complexes with amino groups, potentially affecting protein folding and enzyme activity.

Chakraborty and Mondal (2017) reported that intermittent CO_2 convection under far-IR radiation during vacuum drying of osmotically treated watermelon slices significantly enhanced internal moisture transport. This facilitated faster drying while reducing tissue collapse. Khanlari et al. (2014) observed slower drying rates of tomato pulp under CO_2-modified atmospheres, attributing this to the lower thermal conductivity of CO_2 compared to air. The more gradual moisture removal was advantageous for preserving heat-sensitive bioactive compounds, indicating a compromise between preserving quality and achieving faster drying. CO_2's role in nutrient preservation has been widely emphasized. Hawlader et al. (2006a) demonstrated superior retention of 6-gingerol in ginger when dried under CO_2 compared to air and nitrogen, indicating reduced thermal and oxidative degradation. Similarly, Erenturk et al. (2005) found that vitamin C loss in rosehip was significantly lower under air-CO_2 mixtures than in air alone, likely due to limited oxygen availability and reduced oxidative reactions. Sun (2019) reported significantly lower degradation of β-carotene under CO_2-modulated conditions in heat-pump assisted drying of carrot. These findings consistently show that CO_2 atmospheres help preserve thermolabile nutrients by creating less oxidative and milder thermal environments. CO_2 also aids in maintaining the visual and sensory properties of dried food. Melenciuc et al. (2022) compared CO_2 MAD with conventional air drying of pears and found better color preservation and fewer signs of enzymatic browning in the CO_2-treated samples. This was further supported by Melenciuc (2023), who reported that CO_2 drying helped maintain the natural appearance and flavor of pears. Hawlader et al. (2006b) observed similar results in guava and potato, with CO_2-treated samples exhibiting enhanced structural integrity and texture retention. Papaya dried under CO_2 also showed reduced shrinkage and better porosity compared to samples dried in air, emphasizing the structural benefits of using CO_2 (Hawlader, Perera, Tian, and Yeo 2006). The advantage of CO_2 in MAD is its contribution to microbiological stability and enzyme deactivation. CO_2 forms carbonic acid upon interaction with food moisture due to its inertness and slight solubility in water, leading to a localized drop in pH. This can inhibit microbial growth and suppress enzymatic activity such as polyphenol oxidase (PPO), which contributes to browning (Hawlader et al. 2004). This property is particularly valuable in low-temperature drying systems like heat-pump drying, where thermal inactivation of microbes and enzymes may be insufficient on its own. Gaseous CO_2 has been shown to contribute to microbial inhibition during drying through multiple mechanisms. Its ability to penetrate microbial membranes disrupts intracellular processes by reducing microbial viability. These effects are enhanced under low-oxygen conditions as CO_2 displaces oxygen and suppresses aerobic microbial growth (Hawlader et al. 2006b). Erenturk et al. (2005) noted a reduction in microbial activity and better nutrient preservation in rosehips dried in CO_2-enriched atmospheres. Similarly, studies involving guava, papaya, and pear drying under CO_2 (Hawlader, Perera, Tian, and Yeo 2006; Melenciuc et al. 2022; Melenciuc 2023) confirmed improvements in product stability and a lower risk of spoilage.

CO_2-MAD also improves moisture transfer through clear thermodynamic mechanisms besides its biochemical benefits. According to Dalton's Law of Partial Pressures, substituting air with CO_2 at constant total pressure reduces the partial pressures of O_2 and N_2, whereas the partial pressure of water is governed by the product's temperature and water activity, which remains unchanged. However, increasing the CO_2 molar fraction effectively lowers the relative humidity, which, in turn, steepens the vapor concentration gradient from the product surface into the surrounding atmosphere. The fundamental driving force for mass transfer during drying is the vapor pressure difference of water between the product surface and the drying gas, which governs the diffusion of moisture from the material into the surrounding atmosphere (Chakraborty and Mondal 2017). Altering the drying gas composition by specifically increasing CO_2 concentration can significantly modify this driving force by changing both the water vapor partial pressure and its diffusivity in the gas phase. Carbon dioxide, with distinct molecular characteristics compared to the other air components, reduces the effective partial pressure of water vapor in the drying environment by increasing the vapor pressure gradient that accelerates drying (Hawlader et al. 2006a; Melenciuc 2023).

Relative humidity is defined as the ratio of water vapor partial pressure to saturation vapor pressure at constant temperature. The increase of CO_2 lowers the mole fraction of water vapor relative to the total gas mixture without changing total pressure or water vapor partial pressure, effectively reducing relative humidity and enhancing moisture removal (Erenturk et al. 2005; Hawlader et al. 2006b). This interplay between gas composition and vapor pressure dynamics explains that CO_2-modified atmospheres improve drying rates and product quality by strengthening the thermodynamic driving force for mass transfer (Melenciuc et al. 2022; Khanlari et al. 2014). The understanding and control of the drying gas environment are paramount for optimizing drying efficiency and preserving food quality in industrial drying processes. Melenciuc (2023) focused on pear drying in a CO_2-modified atmosphere and found that CO_2 reduced relative humidity, leading to improved moisture transfer and faster drying kinetics. This study supports the broader understanding that CO_2 atmospheres can effectively manipulate relative humidity, which is essential for achieving higher drying efficiency and product quality. It underscores the critical role of CO_2 in lowering relative humidity and enhancing drying processes. The reduction in relative humidity increases the vapor concentration gradient, resulting in faster drying times and more effective microbial inactivation. Therefore, increasing CO_2 concentration in food processing atmospheres offers clear advantages in both product quality and safety. The study by Melenciuc (2023) provides experimental evidence that altering the gas composition, particularly increasing CO_2 concentration, can effectively lower the partial pressure of water vapor, reduce relative humidity, and steepen the vapor pressure gradient, ultimately improving the driving force for mass transfer during drying without changing total pressure or temperature. According to Fick's Law, this steeper gradient enhances moisture flux, thus accelerating drying (Hawlader et al. 2006b; Sarpong et al. 2018). These thermodynamic predictions have been confirmed in food studies. Wang et al. (2024) investigated mango drying using a CO_2-based heat pump with rotor dehumidification, showing increased drying rate, improved energy efficiency, and better retention of color and ascorbic acid, attributed to reduced oxidation. Thus, although CO_2 substitution does not change the partial pressure of water, it reduces relative humidity, intensifies moisture gradients, and promotes better internal moisture pathways, yielding significantly more efficient drying than air drying alone. This enhanced gradient promotes more efficient moisture diffusion. Moreover, CO_2 can dissolve in the water contained within plant tissues to form carbonic acid, leading to a mild drop in pH. This acidification can influence cell wall and membrane structures, making them more permeable and aiding in moisture release.

Melenciuc (2023) demonstrated that drying pears in CO_2-enriched atmospheres (30%–80%) better preserved color, ascorbic acid, and polyphenols compared to conventional air drying, primarily by enhancing mass transfer and reducing oxidation. CO_2 suppressed oxidative enzymes, reducing enzymatic browning by 38% and improving color stability by 20%, with only a slight decrease in drying time. Different gas mixtures showed specific benefits such as nitrogen and CO_2 preserving antioxidants and inhibiting spoilage and hydrogen improving drying rates and nutrient retention, whereas CO_2 alone provided mild protection against browning. This highlights that selecting the appropriate gas composition is crucial to optimizing drying efficiency and product quality. Overall, CO_2 serves not only as a quality-preserving drying medium but also as a mild, non-thermal microbial control agent in MAD systems. The inclusion of CO_2 in MAD systems offers numerous quality advantages over traditional air drying. The benefits in nutrient retention, color, texture preservation, and microbial stability make CO_2 a highly effective drying medium. It may slightly alter drying rates depending on the food matrix and drying configuration. Its application across diverse food products (including fruits and vegetables) demonstrates its versatility and potential for broader adoption in commercial food drying technologies.

2.2 | Nitrogen

Nitrogen gas (N_2) plays a pivotal role in MAD due to its inert and physically protective properties. It is commonly used to extend the shelf life of perishable foods like fruits and vegetables. Because N_2 is poorly soluble in aqueous and lipid matrices, it does not chemically interact with the plant tissue but rather limits oxygen availability, indirectly contributing to the preservation of sensory and nutritional quality. In nitrogen-based MAD, the central mechanism involves substituting the oxygen in the drying chamber with nitrogen, establishing an inert environment with minimal oxygen presence. This shift in gas composition is essential for limiting oxidative processes that would otherwise compromise delicate nutrients, natural pigments, and flavors in fruits and vegetables. Under nitrogen conditions, the drying time was further shortened compared to conventional drying methods. This reduction is attributed to the low oxygen levels and improved heat transfer efficiency (Perumkulam Lakshmanan et al. 2025). Elevated oxygen concentrations typically promote oxidation in food products, whereas nitrogen drying minimizes such reactions. A similar study conducted on ginger also found nitrogen drying to be more beneficial than traditional methods. This advantage was linked to the lower inlet relative humidity of nitrogen compared to air (Hawlader et al. 2006b). Although nitrogen does not actively enhance the rate of moisture loss, it stabilizes the thermal and chemical conditions of the drying process, allowing for a gentle dehydration. This controlled drying minimizes physical deterioration, such as structural collapse or excessive shrinkage, leading to a final product with superior texture, visual appeal, and nutrient preservation. In addition to its role in solid foods, nitrogen demonstrates utility in liquid and semi-solid systems under high pressure. High-pressure N_2 can diffuse into aqueous systems and damage microbial membranes, thereby enhancing food safety of fruits and vegetables without affecting sensory quality (Koseki and Itoh 2002). N_2 is especially useful in preserving firmness and slowing spoilage in low-moisture products, as demonstrated in studies comparing nitrogen and carbon dioxide under modified atmospheres. For fresh-cut vegetables like lettuce and cabbage, 100% nitrogen helps maintain appearance during cold storage by creating a favorable internal atmosphere over time low in oxygen and moderate in carbon dioxide. Even though microbial suppression is limited, the visual and textural quality of these products is well preserved. Overall, the application of nitrogen in MAD demonstrates superior preservation of bioactive compounds and structural integrity compared to CO_2 due to its inert nature and ability to minimize oxidative reactions. Furthermore, the integration of acidic electrolyzed water as a pretreatment enhances visual quality and pigment stability within nitrogen-rich environments, offering improved efficacy in maintaining the nutritional and sensory properties of dried products (Koseki and Itoh 2002).

Cam et al. (2018) designed a closed-cycle MAD system using high-purity nitrogen gas (>99.9%) and tested for drying strawberries. The system was specifically aimed at reducing oxygen concentration during drying, a crucial factor in preventing oxidation of bioactive compounds, enzymatic browning, and loss of nutritional quality. Their findings demonstrated that the N_2 atmosphere effectively preserved color, texture, and key nutrients such as vitamin C and anthocyanins. The nitrogen-based system substantially enhanced product quality and shelf life primarily due to the suppression of oxidative reactions that typically occur in oxygen-rich environments compared to traditional hot-air drying. A recent study by Homayounfar et al. (2023) introduced an advanced drying approach by integrating nitrogen gas injection with vacuum conditions in the drying of orange slices. This combined strategy further reinforced the protective effects of N_2 by lowering oxygen levels and enhancing mass transfer through reduced pressure. The results revealed significant improvements in drying rate, effective moisture diffusivity, and retention of quality attributes such as color brightness, phenolic content, and antioxidant capacity. The authors emphasized that the nitrogen-rich, low-pressure environment minimized thermal and oxidative stress, allowing for better preservation of heat-sensitive compounds. This dual approach of vacuum and nitrogen also supports shorter drying times, contributing to lower energy consumption and improved efficiency, making it attractive for industrial applications. These studies underscore the multifaceted benefits of nitrogen gas in MAD. N_2 contributes to improved process kinetics, higher energy efficiency, and superior product quality beyond serving as an oxygen displacer. It inhibits oxidation and microbial growth, unlike ambient air. Nitrogen provides a stable, inert environment that significantly extends the functional and sensory qualities of dried products. Moreover, these findings open pathways for the development of sustainable drying technologies where preserving bioactive compounds is critical, particularly in high-value fruit and vegetable products. In summary, the strategic use of nitrogen gas in MAD systems enhances product stability and nutritional integrity. It also aligns with industry goals of reducing processing losses and maximizing quality (Cam et al. 2018; Homayounfar et al. 2023).

2.3 | Hydrogen

Drying fruits and vegetables in a hydrogen (H_2) atmosphere is an emerging technique that is not yet widely adopted but is being studied for its distinct chemical characteristics, most notably, its strong reducing nature. The core mechanism relies on the removal of oxygen from the drying environment, creating a highly reductive and oxygen-free space that helps to preserve the oxidative stability and overall quality of the food (Alwazeer and Örs 2019). This oxygen elimination is similar to what occurs in other low-oxygen or inert gas drying processes. However, unlike gases such as nitrogen, hydrogen is not merely passive; it actively functions as a chemical reductant, capable of counteracting oxidation reactions. In terms of physical behavior, hydrogen's extremely low molecular weight allows it to diffuse quickly throughout the drying chamber, promoting consistent gas coverage and potentially leading to more uniform moisture loss. Although hydrogen does not actively drive moisture transfer the way carbon dioxide might, its key role is in sustaining a protective chemical environment that helps guard against the deterioration of nutritional and sensory qualities. Hydrogen (H_2) has been authorized by food regulatory agencies as a food additive under the propellant category, designated with the code E 949, and is used in applications like margarine production. Several studies have been conducted to assess the safety aspects of hydrogen usage. In air, hydrogen's flammability range spans from 4% to 75% by volume, with explosive limits under normal temperature and atmospheric pressure conditions falling between 18.3% and 59% by volume. Nevertheless, research indicated that when hydrogen is mixed with nitrogen, the normalized mass burning rate and flammability index decrease, significantly reducing the explosion risk (Tang et al. 2009). The use of hydrogen in industrial-scale MAD systems presents significant challenges, primarily due to its flammability and the need for explosion-proof infrastructure, continuous gas monitoring, and robust ventilation systems.

The integration of hydrogen into industrial-scale MAD systems presents significant engineering and safety challenges. The high flammability of hydrogen necessitates the use of explosion-proof infrastructure, including gas-tight drying chambers and intrinsically safe electrical components. Additional safety features must include real-time gas monitoring systems, hydrogen leak detectors, automated emergency shut-off mechanisms, and high-capacity ventilation systems to prevent gas accumulation within enclosed spaces (U.S. Department of Energy [DoE] 2023a). Furthermore, adherence to internationally recognized safety standards such as National Fire Protection Association (NFPA) code 2 and International Organization for Standardization (ISO) 22734 is essential (NFPA 2023). Personnel must receive specialized training on hydrogen handling protocols, and facilities should maintain detailed standard operating procedures that address leak detection, pressure control, and emergency response. These requirements increase both capital and operational costs and add layers of complexity that limit the technology's immediate scalability. In addition to safety concerns, the commercial application of hydrogen in MAD is currently constrained by supply chain and cost limitations. Hydrogen is typically stored in high-pressure gas cylinders, cryogenic tanks, or solid-state carriers such as metal hydrides, all of which require sophisticated infrastructure. The current high cost of hydrogen, especially when derived from renewable energy sources through water electrolysis, further restricts its economic feasibility for large-scale food processing applications (International Energy Agency [IEA] 2024; U.S. DoE 2023b; International Council on Clean Transportation [ICCT] 2024). According to projections, green hydrogen prices are expected to fall to approximately $2.50/kg by 2030 and $1.80/kg by 2040, but they remain above conventional energy costs in most regions today (North American Clean Energy 2023; European Hydrogen Observatory 2024). Despite these challenges, the outlook for hydrogen-assisted drying remains optimistic. Recent advances in hydrogen production, particularly in low-cost electrolysis technologies and on-site generation units, offer promising solutions (IEA 2024). Moreover, smart process control systems that incorporate sensor networks, machine learning, or Internet of Things (IoT) platforms can enhance operational safety and efficiency (U.S. DoE 2023a). The development of hybrid drying systems that combine hydrogen with inert gases could also provide a safer and more adaptable framework for commercial adoption. As technological and regulatory progress continues, hydrogen-assisted MAD may become a viable and sustainable option for the preservation of sensitive, high-value food materials in the near future.

3 | Comparison of Modified and RAD Techniques

RAD and MAD differ primarily in their purpose and gas composition. RAD uses gases like hydrogen or carbon monoxide to prevent oxidation and chemically reduce materials. In this case, hydrogen or carbon monoxide acts as a reducing agent, creating an environment that actively inhibits oxidative reactions through chemical reduction. Although RAD also involves modification of the drying atmosphere, its defining characteristic is the inclusion of an active reducing gas (Alwazeer and Örs 2019; Perumkulam Lakshmanan et al. 2025). In contrast, MAD is designed using gases like nitrogen and carbon dioxide. The primary goal of this environment is to minimize oxidation and preserve sensitive attributes of the material, including color, flavor, and nutritional quality. The drying process is usually conducted at atmospheric or slightly reduced pressure (Melenciuc et al. 2022; Melenciuc 2023; Wang et al. 2024). Although both methods aim to control oxidation, RAD involves active chemical reactions, whereas MAD relies on creating a stable, inert environment. Table 1 presents a comparative overview of MAD and RAD, focusing on operational aspects, safety considerations, and parameters related to industrial feasibility. RAD and MAD also present important limitations that affect their efficiency, safety, and applicability. RAD poses significant safety risks due to the use of flammable or toxic gases like hydrogen and carbon monoxide. It requires costly and complex equipment, limiting its use to specific industrial applications. MAD, while safer and more common in food processing, can suffer from inconsistent gas composition, limited suitability for certain products, and potential microbial growth if not properly controlled. Improvements for both methods could include the development of safer gas alternatives, advanced monitoring and sealing technologies, real-time control systems, and more energy-efficient or automated processes to enhance safety, reduce costs, and broaden their practical use. Considering technological feasibility and industrial applicability, MAD is the more widely recommended technique for food applications due

TABLE 1 | Comparative overview of modified atmospheric drying (MAD) and reducing atmospheric drying (RAD) based on operational, safety, and industrial feasibility parameters.

Parameter	MAD	RAD
Definition	Drying under a modified gas atmosphere (e.g., CO_2, N_2) to suppress oxidation	Drying under reducing gases (e.g., H_2) to actively inhibit oxidation through chemical reactions
Atmosphere composition	Carbon dioxide (CO_2), nitrogen (N_2)	Hydrogen (H_2), nitrogen (N_2), carbon dioxide (CO_2)
Safety risk	Low (non-oxidizing, food-safe)	High (H_2—flammable gas)
System complexity	Moderate (standard control systems)	High (requires advanced gas control and safety systems)
Scalability	High (widely adopted in food industry)	Limited (used in controlled environments)
Efficiency	Moderate to high (dependent on gas integrity and system sealing)	High for oxidation-sensitive materials, but generally low in food use
Control over product quality	Good (retains color, nutrients, and sensory attributes)	Excellent (minimizes oxidative degradation)
Cost of implementation	Moderate (relatively lower cost and easier integration)	High (specialized equipment and safety infrastructure required)

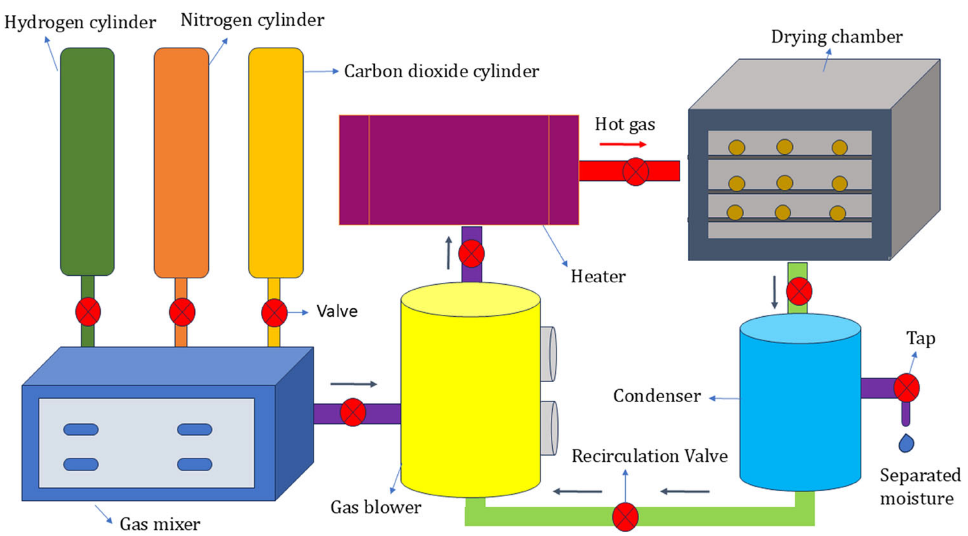

FIGURE 4 | Schematic diagram of reduced atmospheric drying.

to its operational safety, scalability, and broader industrial relevance. RAD, although highly effective in applications requiring strong oxidative control, is more suited to specific, controlled environments. In summary, although both methods have their merits, MAD presents a more feasible, safe, and sustainable solution for preserving sensitive food materials.

4 | Equipment Design, Configuration, and Applications

4.1 | Reducing Atmospheric Drying

RAD is a drying process where materials are exposed to heat in an environment with reduced oxygen levels. Figure 4 illustrates the schematic diagram of RAD. The purpose of this is to minimize oxidation reactions and preserve the quality and integrity of sensitive materials. RAD systems create an oxygen-deprived environment to prevent the degradation of heat-sensitive products, unlike traditional drying processes. RAD is particularly important in industries where the preservation of color, flavor, chemical properties, and structure is paramount. RAD is an essential process in various industries such as food processing, pharmaceuticals, and materials engineering. The controlled drying of sensitive materials under low oxygen environments is critical to preserve quality, enhance product shelf life, and prevent undesirable reactions like oxidation (Perumkulam Lakshmanan et al. 2025). RAD, particularly using hydrogen-enriched environments, has been shown to significantly preserve the nutritional and sensory qualities of dried foods. According to Alwazeer (2018), reducing the presence of oxygen during the drying process significantly limits enzymatic browning and pigment degradation that are major contributors to color loss. In conventional hot air drying, exposure to atmospheric oxygen at elevated temperatures accelerates oxidative reactions, leading to quality deterioration. RAD addresses this by replacing ambient air with inert or reducing gases such as nitrogen (N_2), carbon dioxide (CO_2), or molecular hydrogen (H_2) by creating an oxygen-depleted environment that slows down undesirable chemical reactions (Alwazeer and Örs 2019). The equipment design for RAD typically consists of a sealed stainless-steel drying chamber equipped with gas injection ports, temperature and humidity sensors, and air recirculation systems. The chamber must be airtight to maintain a stable gas atmosphere, and insulation is necessary to conserve energy and maintain uniform drying temperatures, generally between 40°C and 70°C. A critical component of the system is the gas mixing and control unit, which allows for precise regulation of the internal gas composition. Alwazeer et al. (2024) highlighted the role of molecular hydrogen as a promising reducing agent due to its antioxidant effects that can further enhance the preservation of sensitive food compounds. Though hydrogen is reactive, when used in low concentrations (typically 1%–5%) in combination with inert gases such as nitrogen, it contributes to a highly reductive drying atmosphere that significantly improves color stability and reduces nutrient degradation.

Moisture control within the RAD system is achieved through integrated dehumidifiers or desiccant units placed along the exhaust ports, ensuring efficient removal of water vapor while maintaining the desired gas balance. The airflow design may vary based on the drying mechanism, which could be a tray dryer for batch processes, a conveyor belt dryer for continuous drying, or a fluidized bed system for particulate materials. The air circulation system is typically closed-loop, minimizing gas loss and ensuring consistent environmental conditions. PID (proportional integral derivative) controllers are used to dynamically regulate temperature and humidity, responding to real-time sensor inputs to ensure optimal drying rates and product quality. Safety is a paramount concern in RAD systems, particularly when hydrogen is involved. Hydrogen detectors, explosion-proof motors, grounding systems, and emergency venting valves are integrated into the design to mitigate risks associated with flammable gases (Alwazeer 2018). Alwazeer et al. (2024) emphasized that although hydrogen introduces safety challenges, its benefits in enhancing food preservation through reduced oxidative stress justify its cautious use within properly engineered systems. Automated control systems with remote monitoring capabilities and data logging are increasingly being incorporated for industrial-scale applications to ensure process repeatability, traceability, and compliance with food safety regulations. Overall, the RAD technique, especially when integrated with emerging approaches such as reduced atmosphere assisted drying, represents a sustainable and technologically advanced method for improving the quality and shelf life of dried foods (Alvazeer and Betül 2020). The shift toward such controlled-atmosphere drying methods aligns with growing consumer demand for minimally processed, high-quality food products and supports efforts to reduce energy consumption and food waste in postharvest processing.

Alwazeer and Örs (2019) demonstrated that apricot slices dried under RAD_{MIX} (hydrogen + nitrogen) retained high antioxidant activity (76.3% DPPH inhibition vs. 83.5% in fresh), total phenolics (~259.5 mg GAE/100 g dm), and flavonoids (18.8 mg QE/100 g dm), closely resembling fresh and freeze-dried samples while outperforming hot air and vacuum methods in color and aroma retention. Similarly, Perumkulam Lakshmanan et al. (2025) applied a hydrogen-introduced drying atmosphere (4% H_2 + 5% CO_2 + 91% N_2) to tomato slices and found enhanced lycopene retention (94.28%, ~3.3 mg/100 g), minimal color change ($\Delta E = 10.1$), and superior rehydration ratio (4.67) compared to air or nitrogen-only atmospheres. The combination of RAD and mild chemical pretreatment (e.g., 1% potassium metabisulfite) further improved drying kinetics and structural integrity. These studies affirm that hydrogen-assisted RAD techniques can effectively reduce oxidative degradation, enhance nutrient retention, and improve the physical quality of dried fruits and vegetables. It offers a promising alternative to conventional drying methods. Over the past decade, RAD technology has evolved significantly, with improvements in equipment design and the configuration of drying chambers. These changes have been driven by the need to enhance energy efficiency, reduce processing times, and improve the uniformity and control of drying conditions.

4.1.1 | Design Considerations for RAD Equipment

The essential parameters to consider when designing RAD equipment include chamber design, atmosphere control, heat transfer mechanisms, energy efficiency, sustainability, automation, and monitoring. RAD requires carefully engineered equipment to maintain a controlled, low-oxygen or reducing gas environment, typically involving hydrogen, nitrogen, and carbon dioxide, to preserve food quality and bioactive compounds. Key design considerations include an airtight, corrosion-resistant drying chamber capable of safely handling flammable gases like hydrogen, along with precise gas mixing systems using mass flow controllers and integrated gas sensors for real-time monitoring. Uniform heat distribution (e.g., at 60°C) must be maintained without compromising the gas environment, whereas moisture removal systems must prevent the loss of the modified atmosphere. Additional elements such as food-grade perforated trays, purging systems to eliminate oxygen before drying, and automation with PID control and data logging ensure process consistency and safety. These technical elements were applied effectively in the drying of tomato slices using a hydrogen-enriched atmosphere, which significantly improved color retention, lycopene content, and rehydration behavior (Perumkulam Lakshmanan et al. 2025). A primary challenge in RAD systems is maintaining a consistent low-oxygen environment within the drying chamber. Future studies should investigate integrating high-efficiency sealed chambers equipped with advanced atmospheric control systems. Precise control of gas flow, pressure, and temperature is critical to achieving efficient drying while preventing oxidation of sensitive materials (Bhattacharjee et al. 2024). Heat transfer is another crucial design consideration. Recent trends in equipment design optimize both conductive and convective heat transfer mechanisms to reduce drying times. Current advancements include integrating high-conductivity materials for chamber walls and using more efficient heat exchangers. Improving heat transfer can significantly reduce overall energy consumption while enhancing system sustainability (Jimoh et al. 2023).

Equipment designs increasingly incorporate advanced sensors, control systems, and automation to monitor atmosphere, temperature, and moisture levels in real time. This allows precise control over the drying process and reduces the risk of product damage. A notable innovation is the use of predictive control systems, which employ historical data and machine learning algorithms to dynamically adjust parameters and optimize drying (Mishra et al. 2023). Optimizing RAD system configurations for performance and scalability remains a key research focus. Various configurations can be proposed based on material type, desired product characteristics, and process scale. Batch systems are traditionally used for smaller operations, whereas continuous RAD systems offer higher throughput and more consistent product quality. Continuous systems configured with multiple drying zones allow a more controlled drying process, reducing risks of uneven drying and product degradation. Recent studies have examined RAD systems for drying heat-sensitive products such as fruits and vegetables (Alwazeer and Örs 2019; Perumkulam Lakshmanan et al. 2025).

The design of RAD systems for fruit-drying can be optimized to minimize over-drying, which leads to nutrient and flavor loss. Implementing multi-stage drying systems is a notable trend, allowing staged moisture reduction particularly beneficial for temperature-sensitive products (Alvazeer and Betül 2020). Research by Gao et al. (2024) demonstrated that multi-stage drying improves product quality by preventing overheating and preserving structural integrity. One primary concern is the cost of implementing sophisticated atmosphere control systems. The integration of RAD with other drying technologies, such as spray drying, has potential to enhance drying efficiency and product quality (Alvazeer and Betül 2020). Hybrid systems could significantly reduce drying time and energy consumption. Further research into optimizing gas compositions, particularly with different inert gases, may offer additional improvements in quality and drying speed. Future advancements in RAD equipment design and configuration are expected to improve drying efficiency, product quality, and energy sustainability. The integration of advanced sensors, automated control systems, and innovative configurations will enable more precise, reliable, and scalable RAD systems. Ongoing research promises continued improvements in equipment design and application-specific configurations, making the future of RAD technology highly promising.

4.2 | Modified Atmospheric Drying

MAD involves the use of an altered atmospheric environment (typically reducing the oxygen content) to prevent oxidation and preserve the integrity of heat-sensitive materials during the drying process (Huang et al. 2018; Alwazeer 2018; Alwazeer and Örs 2019). Table 2 presents an overview of the different techniques, configurations, and key inferences related to MAD. Melenciuc (2023) investigated pear drying in a CO_2-modified atmosphere using varying CO_2 concentrations (30%–80%) at drying temperatures of 60–100°C. The CO_2-enriched environment preserved the sensory and nutritional qualities of pears, leading to better color retention and reduced losses of ascorbic acid and polyphenols. There were slightly shorter drying times compared to conventional air drying. A mathematical model for CO_2-based convective drying was developed along with a pilot-scale dryer featuring CO_2 recycling and demonstrating both the feasibility and environmental sustainability of this method. The use of CO_2 acted as an oxygen barrier, limiting oxidative damage and enhancing final product quality, particularly for oxidation-sensitive fruits. These studies illustrate how innovative drying approaches utilize advanced heat-pump integration with rotor dehumidification or CO_2-MADs. It can significantly improve drying efficiency and product quality. Melenciuc (2023) emphasized oxidative preservation and pilot-scale feasibility for pears. Both technologies represent scalable, energy-efficient solutions for preserving nutritional and sensory qualities in fruit-drying applications. Erenturk et al. (2005) demonstrated that drying medium significantly affects the retention of vitamin C in rosehip. Their study indicated that oxygen exposure during conventional air-drying leads to substantial degradation of vitamin C, a water-soluble and highly oxidative-sensitive compound. In contrast, modified atmospheres that reduce oxygen levels can minimize such degradation, underscoring the role of gas composition in preserving nutritional quality. Similarly, Melenciuc et al. (2022) compared CO_2-MAD with conventional air drying for pears and reported superior color and texture retention under CO_2 conditions. This suggests that CO_2 can slow oxidative browning and enzymatic reactions, leading to improved sensory attributes in fruits.

Liu, Miao, et al. (2014) further explored MAD using a heat-pump system for drying *Flos Lonicerae* (honeysuckle flowers), revealing that modified atmospheres enhanced color preservation and reduced structural damage. Their findings highlighted how the controlled environment reduced thermal stress and oxidative degradation, allowing better retention of active compounds and visual quality. This aligns with the conclusions of Hawlader and Khin (2008), who emphasized that inert environments such as those created with nitrogen or CO_2 significantly suppress oxidative reactions during drying. This inert condition helps retain volatile compounds and natural pigments that are often compromised in open-air drying. The studies involving tropical and high-moisture fruits also support the benefits of MAD. Hawlader, Perera, Tian, and Yeo (2006) showed that using nitrogen and carbon dioxide in drying guava and papaya resulted in improved retention of color and nutrients. Similarly, Khanlari et al. (2014) modeled drying kinetics of tomato pulp under varying modified atmospheres and found that both CO_2 and N_2 slowed down the drying rate but significantly improved product quality by reducing case hardening and shrinkage. Their experimental data also suggested a more uniform moisture distribution, which is critical for texture and shelf life. Ramesh et al. (2001) showed that nitrogen drying of paprika retained color and aroma better than air drying. O'Neill et al. (1998) observed similar outcomes in apple cubes, where nitrogen drying preserved color and density, crucial indicators of consumer acceptance. Morais and Silva (2011) also confirmed better aroma retention in nitrogen environments, attributing this to reduced volatilization and oxidative loss of aroma compounds. These results collectively affirm that nitrogen's inertness plays a crucial role in maintaining sensory attributes and chemical stability. Cam et al. (2018) developed a closed-cycle MAD system for strawberries using high-purity nitrogen (>99.9%). Their system not only reduced oxygen levels but also controlled humidity and temperature, leading to better moisture control and minimal quality degradation. This closed

TABLE 2 | Overview of modified atmosphere drying techniques, configurations, and inferences.

Drying technique	Atmosphere	Drying configuration	Inferences	References
Reduced atmosphere drying (RAD_{MIX})	• (4% H_2, 5% CO_2, 91% N_2)	• Reduced-air drying of tomato slices	• Preserves color, phenolic profile, and rehydration by minimizing oxidative damage and retaining nutritional quality	Perumkulam Lakshmanan et al. (2025)
			• Preserves texture and appearance more effectively than conventional drying	Alwazeer (2018)
			• Minimizes oxidation of sensitive compounds, ensuring higher sensory quality in dried products	Alwazeer and Örs (2019)
Modified atmospheric drying (CO_2)	• CO_2-enriched atmosphere	• Vacuum drying under CO_2 atmosphere, focusing on watermelon	• Intermittent CO_2 convection significantly improves drying efficiency by enhancing moisture removal rates while preserving the product's sensory and nutritional qualities	Chakraborty and Mondal (2017)
			• CO_2 enrichment can reduce oxidation and maintain fruit texture and color, leading to better product quality in dried watermelon	Melenciuc et al. (2022)
			• CO_2-enriched environments maintain more of the original water-soluble nutrients and enhance shelf life by reducing microbial activity	Melenciuc (2023)
Modified atmospheric drying (N_2)	• N_2-enriched atmosphere	• Heat-pump drying, various fruits and vegetables	• Increased drying efficiency with N_2 atmosphere, which lowers oxidation and preserves heat-sensitive nutrients like vitamin C and beta-carotene	Borompichaichartkul et al. (2013)
			• Lower oxidation rates under N_2-rich environments help maintain color and flavor in dried products like macadamia nuts and strawberries	Cam et al. (2018)
			• N_2-based drying systems provide a gentler drying process, reducing the formation of harmful compounds like acrylamide in dried fruits and vegetables	Homayounfar et al. (2023)
			• N_2 infusion prevents excessive cellular damage, enhancing the texture and rehydration capacity of dried produce	Liu, Miao, et al. (2014)
			• Drying under N_2 atmosphere helps retain higher antioxidant content in dried vegetables and fruits like carrots and apples	O'Neill et al. (1998)
			• Enhanced drying characteristics with N_2 allow for faster moisture removal and reduced drying times	Ramesh et al. (2001)
			• N_2-modified drying retains more vitamins and nutrients compared to conventional air-drying methods	Morais and Silva (2011)

(Continues)

TABLE 2 | (Continued)

Drying technique	Atmosphere	Drying configuration	Inferences	References
Modified atmosphere with combined gases	• Mixed gases ($N_2 + CO_2$)	• Heat-pump drying using gas mixture (N_2 and CO_2)	• Mixed gas atmospheres ($N_2 + CO_2$) improve the drying kinetics and enhance product quality by minimizing oxidative degradation while maintaining high nutritional value	Erenturk et al. (2005)
			• CO_2 and N_2 combination creates an inert drying environment, preserving volatile compounds and flavor while speeding up the drying process	Hawlader et al. (2006a)
			• The presence of CO_2 reduces microbial contamination, leading to better product shelf life and microbial safety	Hawlader et al. (2006b)
			• Combined gases improve both drying rates and the preservation of nutrients such as vitamin C and antioxidants in tropical fruits	Hawlader, Perera, Tian, and Yeo (2006)
			• The combination of N_2 and CO_2 gases enhances the physical characteristics of dried products, such as texture and rehydration ability	Khanlari et al. (2014)
			• Reduced oxygen exposure under $N_2 + CO_2$ conditions results in better color retention and a reduction in oxidative browning, especially in guava and papaya	Hawlader et al. (2004)
			• Modified atmosphere drying with $N_2 + CO_2$ is effective for preventing the loss of bioactive compounds and preserving the quality of dried fruits	Perera (2001)
Ethanol-induced modified atmosphere	• Ethanol-induced modified atmosphere	• Ethanol-modified convective dryers	• Ethanol-induced atmosphere reduces drying time by affecting moisture evaporation and helps maintain the integrity of heat-sensitive volatile compounds in dried pineapple	Braga et al. (2009)
			• The presence of ethanol can help reduce the formation of undesirable odors and off-flavors during drying	Braga et al. (2010)
			• Ethanol in the drying atmosphere significantly alters the volatile profile of dried banana and pineapple, enhancing flavor retention	Corrêa et al. (2012)
			• Ethanol-induced drying helps preserve aroma compounds, maintaining the quality of dried fruits like bananas even under reduced moisture levels	Santos and Silva (2009)
			• The ethanol-modified environment prevents the degradation of essential oils, providing a better sensory experience in dried products	Rahman et al. (2005)

system design demonstrates the potential of MAD not only in enhancing quality but also in energy efficiency and process control. In conclusion, MAD represents a promising direction in food processing that bridges the gap between traditional drying efficiency and modern demands for quality retention. This method minimizes oxidative damage, retains volatile and heat-sensitive compounds, and maintains product integrity by selectively introducing inert gases like nitrogen or carbon dioxide. The further innovation and optimization in MAD technologies will be essential for commercial scalability and broader adoption as consumer expectations for high-quality dried products grow.

Corrêa et al. (2012) introduced ethanol pretreatment as a drying aid for bananas, which acted similarly to CO_2 or N_2 by altering surface tension and reducing oxidative browning. This reinforces the concept that non-oxidizing or barrier environments, whether through chemical or gaseous means, can significantly improve drying performance and product outcomes. The use of ethanol vapors has shown significant effectiveness in preserving the nutritional, aromatic, and physicochemical qualities of sensitive food products such as pineapple. The studies by Braga et al. (2009, 2010) demonstrated that drying pineapple in an ethanol-induced modified atmosphere significantly improved the retention of volatile aroma compounds (especially esters and aldehydes) while minimizing the formation of off-flavors commonly caused by oxidation and thermal degradation. The complementary findings by Santos and Silva (2008, 2009) revealed that ascorbic acid degradation was substantially reduced under an ethanolic atmosphere, as ethanol displaced oxygen and acted as a protective barrier, slowing oxidative reactions and preserving nutritional quality. These protective effects were further supported by kinetic modeling of vitamin C degradation. Additionally, Rahman et al. (2005) found that MAD methods improved microbial stability and physicochemical properties such as texture and color in dried meat, reinforcing the broader applicability of modified atmospheres across food categories. Collectively, these studies highlight MAD as a promising technique for enhancing product quality, extending shelf life, and improving food safety during the drying of thermally sensitive products.

4.2.1 | Advances in Equipment Design

Recent trends in MAD system design show hybridization with other drying technologies such as heat-pump drying, vacuum drying, microwave drying, spray drying, and IR drying (Wefers 2015; Alvazeer and Betül 2020; Homayounfar et al. 2023). Table 3 represents different drying systems with modified atmosphere conditions and their efficiency. The studies have shown that combining heat-pump technology with MAD can offer superior performance in terms of drying time, energy consumption, and product quality (Wang et al. 2024). The microwave-assisted heat-pump drying systems can significantly shorten drying times by using microwaves to heat the product, whereas the heat pump regulates air temperature and humidity. This integration allows for energy recovery while maintaining a high degree of control over the drying environment. In particular, hybrid systems have been widely explored in food processing applications where maintaining flavor, texture, and nutritional content is vital. The combination of IR heating with a heat pump in the drying of fruits and vegetables has reduced drying time while preserving the natural color and taste of the produce (Chakraborty and Mondal 2017). The key goal is to improve heat transfer efficiency and the overall thermal management of the system. The recent studies have explored multi-stage drying chambers with improved airflow distribution. It ensures that the heat is evenly distributed and the air humidity is maintained at optimal levels for the material being dried. Advanced heat exchangers integrated into heat-pump systems allow for more efficient recovery of waste heat, reducing energy consumption. The researchers have introduced more compact, integrated systems that improve space utilization without compromising system performance. A common feature of these designs is the use of counterflow heat exchangers that facilitate better energy transfer between the air entering and exiting the drying chamber (Deymi-Dashtebayaz et al. 2024).

Energy efficiency is one of the focuses in recent research on heat-pump systems. The focus has shifted from just improving the heat pump's performance to designing systems that minimize energy input while maximizing drying output. The studies have proposed the use of multi-functional heat-pump systems that integrate both heating and cooling functions (Hu and Shen 2025). The continuous recovery and reuse of heat from the drying process in these systems can reduce the overall energy consumption by up to 50%. It makes them much more sustainable compared to conventional drying systems. The environmental considerations have pushed for the use of natural refrigerants (such as CO_2 or ammonia) in heat pumps, which have a lower global warming potential (GWP) than traditional refrigerants. The use of natural refrigerants not only decreases the carbon footprint of the drying process but can also improve the overall efficiency of the heat-pump system (Deymi-Dashtebayaz et al. 2024).

4.3 | Recent Developments in MAD Systems

4.3.1 | Integration of Microwave, IR, and Spray Drying Systems

The most significant advancements in MAD equipment design are the hybridization of traditional drying techniques with microwave, IR radiation, and spray drying, as shown in Figure 5a–c. These technologies work synergistically with modified atmospheric conditions to enhance the drying process. The recent studies have shown that incorporating microwave technology into MAD systems can drastically reduce drying times while improving energy efficiency (Wefers 2015). Microwaves provide rapid internal heating, ensuring more uniform moisture distribution within the material. It reduces the risk of external over-drying and preserves product quality (Cong et al. 2023). The coupling of microwave-assisted drying with a controlled atmosphere maintains the texture, color, and nutritional content of the product, which are often compromised by conventional drying methods. IR radiation provides efficient and fast heating by directly transferring heat to the material's surface, which is beneficial in the initial stages of drying. The current research has explored the use of IR in combination with modified atmospheric conditions, which can offer reduced drying times and improved moisture removal. This is especially advantageous in the food industry, where maintaining the flavor and nutritional quality of

TABLE 3 | Different drying systems with different atmospheric conditions and their efficiency.

Drying system	Drying environment and target product	Key findings vs. control	MAD configuration	Payback period and economic feasibility	Reference
Convective CO_2 dryer	Pears	• Better color and ascorbic acid retention than air-dried, with 20%–25% faster drying • Improved nutrient retention under CO_2	30%–80% CO_2	~4–5 years Marginal for local use and suitable for premium fruit-drying and export	Melenciuc (2023)
Heat-pump dryer under modified atmosphere	Guava, papaya	• 44% higher effective diffusivity in guava, 16% in papaya, less browning, faster rehydration, more vitamin C retention	N_2/CO_2 atmosphere	~3–4 years Energy efficient and higher quality retention	Hawlader, Perera, Tiang, and Yeo (2006)
	Apple, guava, potato	• Improved color preservation, better rehydration, more porous structure, lower shrinkage at 45°C, RH 10%–15%	N_2/CO_2 atmosphere		Hawlader et al. (2004)
Vacuum-assisted MAD	Orange slices	• Improved drying kinetics and product quality, reduced nutrient degradation	Vacuum + modified atmosphere	~4–5 years Suitable for heat-sensitive fruits and vegetables	Homayounfar et al. (2023)
Ethanol-modified convective drying	Pineapple	• Retained volatiles and aroma better, improved drying efficiency compared to control	Ethanol-modified atmosphere (0.5% ethanol v/v)	~3–4 years Ideal for products requiring aroma and color retention	Braga et al. (2009)
	Banana	• Ethanol improved volatile retention during drying	Ethanol-modified atmosphere		Corrêa et al. (2012)
Reducing atmosphere drying (RAD)	Apricots	• Enhanced preservation of color and nutrients under reducing atmosphere conditions	Gas mixture (O_2, N_2, H_2, and CO_2)	~2–3 years Suitable for quality-sensitive products	Alwazeer and Örs (2019)

Abbreviation: MAD, modified atmospheric drying.

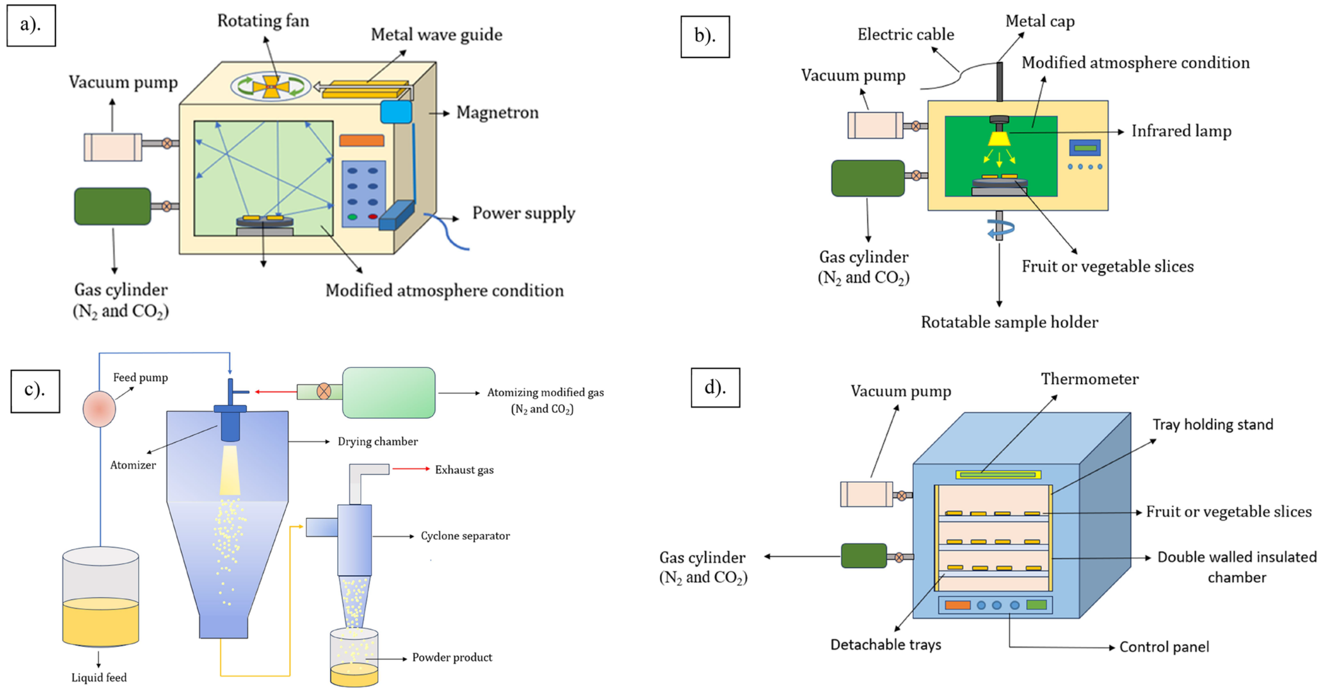

FIGURE 5 | Hybrid systems combining MAD with (a) microwave drying, (b) infrared drying, (c) spray drying, and (d) vacuum drying.

the product is crucial (Chakraborty and Mondal 2017). Hybrid systems that combine these techniques are increasingly seen as a way to overcome the limitations of each individual method.

The hybrid drying systems that combine MAD with IR heating utilize complementary heat transfer mechanisms to address the limitations of single-mode drying technologies. Microwaves generate heat volumetrically by causing dipolar rotation and ionic conduction of water molecules inside the product matrix in MAD. This volumetric heating shortens drying time significantly compared to conventional surface heating as energy is delivered directly inside the material, accelerating moisture evaporation internally (Wefers 2015). Microwave drying alone often faces challenges such as uneven electromagnetic field distribution and heterogeneous dielectric properties within food materials that can cause localized overheating, surface burning, or case hardening. The integration of IR radiation in MAD addresses this by providing uniform surface heating through electromagnetic radiation typically in the near to far-IR spectrum that gently raises surface temperature to facilitate moisture migration without excessive thermal stress (Chakraborty and Mondal 2017). The combining of MAD and IR enables simultaneous volumetric and surface heating modes from a thermodynamic standpoint. This synergistic effect promotes rapid vapor diffusion by maintaining steeper moisture gradients and improves heat and mass transfer rates, significantly reducing total drying time. Chakraborty and Mondal (2017) showed that intermittent far-IR radiation during vacuum drying under CO_2 convection improved drying kinetics and product quality in osmo-dehydrated watermelon by enhancing heat penetration and moisture migration. Innovative hybrid drying devices, such as those patented by Wefers (2015), incorporate precise microwave power control combined with IR emitters enabling real-time modulation of drying intensity. These devices can induce puffing by rapidly vaporizing internal moisture via microwaves while maintaining surface integrity through IR radiation, producing expanded snack textures with minimal thermal degradation. The device also benefits from controlled atmospheres (e.g., vacuum or inert gases) to reduce boiling points and prevent oxidation, preserving product quality (Wefers 2015).

The optimization of drying parameters in hybrid microwave–IR systems involves balancing microwave power, IR intensity, drying temperature, vacuum level, and drying time. The incorporation of IR heating potentially lowers required microwave power, mitigating hotspots and further enhancing quality preservation (Cong et al. 2023; Alvi et al. 2023). Energy efficiency is a significant advantage of hybrid systems. Microwave energy directly converts electromagnetic energy into heat inside the product, minimizing heat losses to the surrounding environment. Meanwhile, IR radiation delivers targeted surface heat with minimal convective loss. Intermittent or pulsed IR application, as demonstrated by Chakraborty and Mondal (2017), reduces energy consumption by applying heat only when surface moisture levels demand it, preventing unnecessary energy expenditure. The challenges still remain, including achieving uniform electromagnetic field distribution, managing product geometry effects, and synchronizing microwave and IR power to avoid uneven drying or overheating. Advances in sensor technology, computational electromagnetic field modeling, and adaptive process control systems are critical to overcoming these issues and enabling industrial-scale adoption of hybrid drying (Alvazeer and Betül 2020; Wefers 2015).

The incorporation of MAD in spray drying can be effectively achieved using the system described in the patent by Alvazeer and Betül (2020) that introduces a reducing atmosphere spray dryer designed to protect oxidation-sensitive products. This system replaces the conventional hot air used in spray drying with a controlled mixture of reducing gases such as nitrogen, carbon dioxide, and hydrogen by significantly reducing the oxidative degradation of sensitive compounds like vitamins, pigments, enzymes, and unsaturated fatty acids. The drying process is carried out in a sealed, closed-loop system where the gas mixture is continuously recirculated through HEPA (high-efficiency particulate air filter) filters and a condenser to maintain a low-oxygen environment and ensure energy efficiency. This technology preserves the sensory, nutritional, and functional qualities of the dried product without relying on synthetic preservatives or antioxidants (Alvazeer and Betül 2020). In summary, hybrid MAD-IR drying systems leverage volumetric microwave heating and surface IR radiation to accelerate drying, improve uniformity, maintain nutritional and sensory quality, and reduce energy use. The available patents and studies reflect continuous innovation in device design and drying process optimization, highlighting the promise of hybrid drying as a transformative technology in food processing and preservation (Wefers 2015; Alvazeer and Betül 2020; Chakraborty and Mondal 2017).

4.3.2 | Vacuum Integration

Vacuum drying is another advanced technique that is being integrated with MAD to optimize the drying process. Vacuum-MAD systems, as shown in Figure 5d, lower the pressure within the drying chamber, which leads to a reduction in boiling point, allowing for drying at lower temperatures. This is beneficial for preventing thermal degradation of sensitive materials. The research has shown that vacuum drying, when combined with a reduced-oxygen atmosphere, can achieve higher drying rates while preserving the quality of the dried product (Homayounfar et al. 2023). In particular, vacuum-MAD systems have been found to be effective for drying fruits and vegetables, which are prone to oxidation. The combined effect of vacuum and reduced atmosphere helps minimize the loss of nutrients, color, and texture in the product. Vacuum-MAD systems can be further enhanced by incorporating temperature and humidity controls, improving the overall precision of the drying process. The combination of reduced pressure and modified atmosphere creates an ideal environment for drying heat-sensitive materials, making these systems increasingly popular in food and pharmaceutical applications.

Vacuum drying integrated with modified atmospheric conditions represents an advanced hybrid drying strategy that addresses key limitations of conventional thermal drying (such as prolonged drying times, high energy consumption, and degradation of sensitive quality attributes). This approach leverages the synergistic effects of low pressure and tailored gas atmospheres to enhance drying kinetics while minimizing thermal and oxidative damages, especially for high-moisture, heat-sensitive agricultural products such as fruit slices. Huang et al. (2018) investigated the drying characteristics and nutrient retention of fruit slices under vacuum-filling nitrogen drying. The application of vacuum substantially lowers the ambient pressure, thereby reducing the boiling point of water and facilitating faster moisture evaporation at relatively low temperatures. This accelerates the drying rate and preserves thermolabile nutrients (such as ascorbic acid, phenolic compounds, and pigments), which are otherwise susceptible to degradation under elevated temperatures and in the presence of oxygen. Homayounfar et al. (2023) developed a novel control atmosphere-vacuum (CAV) drying system that combines vacuum pressure with selective gas atmospheres specifically targeting orange slices. The drying chamber atmosphere is modified by introducing inert or semi-inert gases such as nitrogen (N_2) or carbon dioxide (CO_2), which replace ambient air (and thus oxygen) and reduce oxidative reactions during drying. Their results demonstrated that under optimized vacuum and atmospheric conditions, the drying time was significantly reduced and moisture diffusivity improved. The coupling of vacuum with an inert gas atmosphere led to superior retention of color, vitamin C, and total phenolic content compared to traditional vacuum or hot air drying alone. The study emphasized that gas composition and vacuum level were critical variables influencing both drying kinetics and final product quality.

The combined use of vacuum and modified atmosphere offers a highly controlled drying environment where mass and heat transfer can be fine-tuned to match the material properties and quality preservation targets. The lowered oxygen concentration inhibits enzymatic and non-enzymatic browning reactions, whereas the vacuum enhances moisture migration by increasing the vapor pressure gradient between the product surface and the surrounding environment. This dual mechanism significantly enhances drying efficiency while preserving critical quality parameters such as texture, color, aroma, and nutrient content (Huang et al. 2018; Homayounfar et al. 2023). In summary, vacuum drying within an MAD system represents a highly effective drying technique for heat-sensitive products, offering improvements in drying kinetics, energy efficiency, and product quality. The integration of vacuum and gas control provides a flexible platform for optimizing drying processes tailored to specific product characteristics and holds strong potential for industrial-scale applications in the drying of high-value food products.

4.3.3 | Heat-Pump Integration

MAD integrated with heat-pump systems represents a significant advancement in drying technologies widely applied in food processing. Figure 6 shows the schematic representation of an MAD system with heat-pump integration. The heat pump enhances energy efficiency, sustainability, and cost-effectiveness by precisely regulating temperature and humidity, ensuring uniform drying (Deymi-Dashtebayaz et al. 2024). Wang et al. (2024) analyzed a hybrid system combining a closed-loop CO_2 heat pump with rotor dehumidification (CHPRD) for low-temperature mango slice drying. Compared to conventional heat-pump dryers, the CHPRD system increased drying rates by up to 29%, improved specific moisture removal rate (SMER) by 14.2%, and coefficient of performance (COP) by 17.3%. It also enhanced product quality through better rehydration capacity, a 14%–15% increase in ascorbic acid content, and reduced color degradation. The two-term drying model best predicted drying kinetics, and the rotor dehumidification combined with CO_2 significantly boosted thermodynamic performance and final product quality, making it highly effective for heat-sensitive fruits like mango. This sustainable operation depends on proactive maintenance and operator safety measures. The regular inspection of key

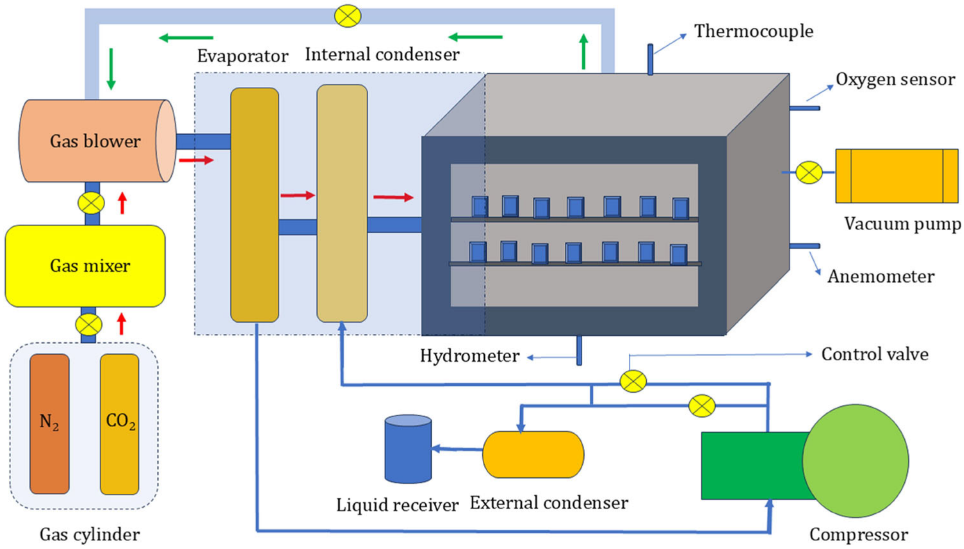

FIGURE 6 | Schematic diagram of modified atmospheric drying with heat-pump system.

components (such as the CO_2 loop and rotor dehumidifier) is essential to ensure efficiency and prevent wear. The maintenance of proper CO_2 pressure levels and prevention of system leakage also support both performance and environmental safety. Additionally, safeguarding operator health through training on safe handling of pressurized CO_2, electrical systems, and heat-resistant equipment is crucial. The commitment of efficient maintenance and safety protocols can operate the CHPRD system sustainably by maximizing its benefits for both energy conservation and the production of high-quality, heat-sensitive fruits like mango (Wang et al. 2024). In MAD, the drying atmosphere is modified by adjusting oxygen levels, relative humidity, and temperature (Melenciuc et al. 2022). The heat-pump recycles heat by transferring it from the drying environment to the refrigerant, efficiently controlling temperature, and dehumidifying the air by condensing moisture, thus optimizing moisture content in the product. This combination reduces oxidative degradation of sensitive compounds by introducing inert or CO_2-enriched gases (Hawlader et al. 2006a). Studies showed that integrating heat pump with MAD systems enhances preservation of color, vitamin C, and antioxidants by suppressing oxidation and enzymatic browning (Borompichaichartkul et al. 2013; Liu, Miao, et al. 2014; Wang et al. 2024).

MAD with heat-pump technology improves retention of bioactive compounds and nutrients. Hawlader et al. (2006a, 2006b) demonstrated that drying ginger under modified atmosphere heat-pump drying preserved higher levels of 6-gingerol compared to conventional methods, primarily due to the CO_2-modulated atmosphere limiting oxidation. Sun (2019) reported significant reduction of β-carotene degradation in carrot drying using CO_2 gas modulation with heat-pump drying. Zhu et al. (2025) highlighted that inert gases improve drying uniformity and color retention by minimizing enzymatic browning and oxidation. Borompichaichartkul et al. (2013) applied multi-stage heat-pump drying with modified atmospheres for macadamia nuts, observing enhanced drying rates and product quality. Hawlader et al. (2004) also noted that inert atmosphere heat-pump drying reduces energy consumption by optimizing moisture removal at low temperatures, protecting thermolabile compounds. Both batch and continuous drying systems incorporate heat-pump technology. Batch systems, suitable for small production volumes like herbs and pharmaceuticals, benefit from enhanced energy recovery and precise control of temperature and humidity. Continuous systems, designed for large-scale applications, utilize multi-stage heat-pump configurations with modular drying units adaptable for different volumes and materials, ensuring uniform drying and consistent quality (Hawlader et al. 2006a; Uthpala et al. 2020; Wang et al. 2024; Sun 2019). MAD systems provide sealed drying chambers with controlled atmospheres of inert gases such as nitrogen or CO_2, which reduce oxygen presence and oxidative reactions during drying, preserving sensitive compounds like β-carotene (Sun 2019). Heat pumps operate at low temperatures and dehumidify air to avoid thermal damage to heat-sensitive materials, including fruits, vegetables, nuts, and herbs (Zhu et al. 2025).

Studies by Hawlader et al. (2004, 2006a, 2006b) emphasize that reducing oxygen in drying chambers helps retain bioactive compounds such as 6-gingerol in ginger and improve rehydration characteristics by minimizing structural damage. Liu, Miao, et al. (2014) reported improved texture and reduced microbial spoilage in *Flos Lonicerae* when dried under modified atmosphere heat-pump conditions. Perera (2001) highlighted that MAD heat-pump drying can tailor product characteristics such as porosity and rehydration capacity, making it suitable for diverse food products. Typical MAD systems include heat-pump units for heating and dehumidification, gas supply systems for inert gases, airtight drying chambers with sensors to monitor temperature, humidity, and gas concentration, and control units to maintain optimal conditions (Perera 2001). Future research should focus on incorporating automation and advanced control strategies in MAD heat-pump systems. Real-time sensors monitoring drying chamber conditions allow precise heat-pump operation adjustments. Predictive algorithms can optimize drying time and energy use, whereas machine learning and AI can analyze past cycles for continuous operational improvements (Chakravartula et al. 2023). Despite benefits like energy efficiency and precise control, challenges remain in scaling, initial investment, and material variability (Lingayat et al. 2020). Innovations combining MAD heat-pump systems with microwave, IR, or freeze-drying technologies could further enhance efficiency and product quality.

4.4 | Advanced Configuration and Future Prospects of MAD Systems

Future developments in MAD system configurations can incorporate multi-zone and multi-stage drying chambers. These systems allow for the dynamic adjustment of temperature, humidity, and oxygen concentration across different stages of the drying process. The recent studies have shown that multi-stage systems can significantly improve drying efficiency and uniformity. These systems, each with specific environmental conditions, allow for better control over the drying process by dividing the drying chamber into multiple zones (Fernandes and Tavares 2024). One zone may operate under low oxygen conditions for the initial drying stages, whereas another zone may use a higher oxygen concentration for final moisture removal. These processes may be used in continuous MAD systems, involving multiple drying phases, each with optimized atmospheric conditions. The initial phase may involve a low-temperature, low-oxygen atmosphere to preserve volatile compounds, followed by a higher temperature phase to remove residual moisture. This staged approach reduces the risk of over-drying and preserves product quality (Baidhe et al. 2024). Advancements in sensor technology and control systems allow for real-time monitoring and management of the modified atmosphere during the drying process. These systems continuously track temperature, humidity, oxygen levels, and product moisture content, adjusting parameters to optimize drying conditions (Mao and Wang 2023). The recent research by Pang et al. (2021) has highlighted the benefits of integrating automated control systems with predictive algorithms to fine-tune the drying process and reduce energy usage. The use of IoT devices in MAD systems allows for the remote monitoring and control of drying operations. Sensors connected to cloud-based platforms can provide insights into process performance, allowing for adjustments in real time and improving the system's overall efficiency. Although significant progress has been made in the design and configuration of MAD systems, there are still several challenges to address.

Advanced MAD systems that combine multiple drying techniques (e.g., microwave, IR, heat pump) can be complex and costly to implement. Further research is needed to simplify the integration of these technologies while maintaining their benefits. MAD systems have shown promise in a variety of applications, and further research is required to fine-tune these systems for specific materials. Different materials may require unique atmospheric conditions, and the ideal configuration may vary. The energy-saving potential of heat pumps and other advanced techniques requires further research. The reduction in energy consumption and use of renewable energy sources will be critical for the continued success and adoption of MAD systems in industrial applications (Siddiqui et al. 2024). The recent studies have significantly advanced the design and configuration of MAD systems. Hybrid systems combining MAD with microwave, IR, and vacuum technologies offer substantial improvements in drying efficiency, product quality, and energy consumption (Sun 2019; Homayounfar et al. 2023; Alvazeer and Betül 2020; Chakraborty and Mondal 2017). The integration of heat pumps, modular equipment, and multi-stage drying configurations will provide further benefits, particularly in terms of sustainability and scalability. They are highly efficient, customizable, and environment-friendly solutions to industries that rely on drying processes as these systems continue to evolve. However, challenges related to system complexity, cost, and material-specific optimization remain, which will require continued innovation in the field.

5 | Processing Parameters of MAD Systems

MAD is a specialized technique employed across various industries, particularly in food processing, pharmaceuticals, and materials science. The precise control over the drying environment is critical to maintaining product quality. The principle of MAD involves altering the atmospheric conditions (such as reducing oxygen levels, controlling humidity, or adjusting gas composition) during the drying process to minimize degradation and improve the efficiency of moisture removal (Huang et al. 2018). The integration of these modifications with advanced technological solutions like heat pumps, microwave assistance, or IR radiation. MAD systems have become more energy efficient, faster, and capable of preserving the quality of sensitive materials. The processing parameters, such as drying temperature, gas composition, and humidity, are fundamental to achieve optimal drying conditions. Table 4 emphasizes the impact of different processing parameters on MAD. These parameters influence the rate of drying, energy consumption, product texture, nutritional value, and overall quality. Studies have provided valuable insights into how these processing parameters can be fine-tuned and optimized in MAD systems to enhance performance (Melenciuc 2023; Khanlari et al. 2014).

5.1 | Drying Temperature in MAD Systems

Drying temperature is one of the most critical processing parameters that directly impact both the efficiency of the drying process and the final quality of the product. The relationship between drying temperature and product quality, especially in heat-sensitive materials like food and pharmaceuticals, is complex. If the temperature is too high, it can lead to undesirable effects such as over-drying, product shrinkage, loss of volatile compounds, and degradation of nutritional value. Conversely, if the temperature is too low, the drying process can become inefficient, prolonging drying times and increasing energy consumption (Rasul et al. 2022). Low-temperature drying is a significant advantage of MAD, as it helps preserve the texture, color, and nutritional value of heat-sensitive products. One of the advancements in this area is the integration of heat-pump drying systems (Wang et al. 2024). Heat pumps offer precise control over the drying temperature and can operate at lower temperatures without reducing drying efficiency. Studies have shown that using heat pumps in conjunction with modified atmospheric conditions can effectively dry materials like fruits, vegetables, and herbs while retaining their sensory attributes and bioactive compounds (Liu, Wu,

TABLE 4 | Impact of different processing parameters on modified atmospheric drying.

Processing parameter	Impact on drying efficiency	Impact on product quality	Key highlights	Reference
Gas composition (CO_2/N_2)	Accelerates drying by enhancing mass transfer, thereby increasing the drying rate and overall efficiency	Better color, higher vitamin C, and polyphenol retention	Modified gas composition enhances drying rate, reduces oxidative degradation, and preserves nutrient degradation	Melenciuc (2023), Hawlader, Perera, Tian, and Yeo (2006)
Drying method (heat pump, convective CO_2)	Reduced drying time, energy efficient, improved kinetics	Preserved antioxidants, flavor, and texture	Energy-saving and suitable for premium products	Hawlader et al. (2004), Hawlader, Perera, Tian, and Yeo (2006), Melenciuc (2023)
Temperature with CO_2 atmosphere	Moderate CO_2 temperatures shorten residence time	Retains heat-sensitive compounds	CO_2 reduces oxygen-mediated degradation	Melenciuc (2023), Alwazeer and Örs (2019)
System type (closed/heat pump, vacuum)	Closed-cycle + vacuum improves kinetics	Enhances aroma, volatile retention, microstructure	Ideal for high-moisture, sensitive products	Hawlader et al. (2004), Homayounfar et al. (2023)
Ethanol pretreatment	Increased drying rate and reduced drying time	Better retention of volatile compounds	Useful for aroma-sensitive crops	Braga et al. (2009), Corrêa et al. (2012)
Reducing atmosphere drying (RAD)	Maintains diffusion efficiency	Retains color and vitamins	Emerging technique for quality preservation	Alwazeer and Örs (2019)
Airflow/Pretreatment	Improved mass transfer and drying kinetics	Better nutrient retention	Supporting enhancements to MAD systems	Erenturk et al. (2005), Khanlari et al. (2014)

Abbreviation: MAD, modified atmospheric drying.

et al. 2014; Sun 2019). The recent research by Vega-Gálvez et al. (2022) on vacuum-assisted drying has demonstrated that reducing the pressure within the drying chamber allows for drying at lower temperatures. It further prevents the degradation of heat-sensitive products. This technique has shown promising results in drying delicate products like medicinal herbs, where preservation of active ingredients is crucial. A novel approach to temperature regulation in MAD systems is temperature cycling, where the drying temperature is periodically varied throughout the process. The recent studies have explored how alternating between higher and lower temperatures during drying can enhance moisture removal while reducing the risk of product damage. This method can improve drying efficiency, especially in multi-stage drying systems, by adapting the temperature to the product's moisture content at different stages of the drying process (Tang et al. 2025).

5.2 | Gas Composition in MAD

The composition of the atmosphere inside the drying chamber is another crucial processing parameter that significantly affects the drying rate and product quality. In conventional drying, the atmosphere typically consists of air, which contains around 21% oxygen. The oxygen level is deliberately reduced, and the concentration of other gases (such as nitrogen or inert gases like argon) is increased to create a modified environment that minimizes oxidation and degradation in MAD (Melenciuc et al. 2022). One of the most common modifications in MAD systems is the reduction of oxygen levels. Lowering the oxygen concentration helps reduce oxidation, which is particularly important in the drying of products like fruits, vegetables, and meats. Oxidation can lead to undesirable changes in color, flavor, and nutritional value. Reducing oxygen levels during the drying process can significantly improve the quality of products by preserving their vitamins, antioxidants, and other heat-sensitive nutrients (Alwazeer and Örs 2019; Hawlader et al. 2006a; Sun 2019). The current innovations have focused on optimizing the oxygen concentration during different stages of drying. For example, in the initial phase of drying, a low-oxygen environment may be maintained to preserve volatile compounds. The slightly higher oxygen levels can be introduced in the later stages to enhance moisture removal. These controlled fluctuations in gas composition help achieve faster drying while preventing quality degradation (Alwazeer 2018; Borompichaichartkul et al. 2013).

The composition of gases used in modified and RAD plays a crucial role in determining the efficiency of moisture removal and the preservation of food quality. Alwazeer and Örs (2019) introduced a reducing atmosphere composed primarily of nitrogen (N_2), hydrogen (H_2), and carbon dioxide (CO_2) with minimal oxygen (<1%), which effectively minimized oxidative degradation during drying. This composition led to 45%–60% higher antioxidant retention and 30% better color preservation compared to conventional air drying. Similarly, Perumkulam Lakshmanan et al. (2025) experimented with reduced atmosphere drying using gas composition of N_2, H_2, and CO_2 significantly altered the drying kinetics. The presence of hydrogen accelerated moisture diffusion, leading to a 25.3% reduction in drying time, and also enhanced the total phenolic retention by 18.6%, improving the rehydration ratio from 2.35 to 3.10, likely due to less structural collapse. Melenciuc (2023) utilized CO_2-enriched modified atmospheres during the drying of pears, taking advantage of CO_2's ability to suppress oxidative enzymes. This led to a 38% reduction in enzymatic browning and 20% better color stability, although the drying time was only 5%–7% shorter than in air. Comparatively, the gas composition in these studies reveals distinct functional benefits. The nitrogen and CO_2 mixtures are effective in preserving antioxidants and suppressing spoilage. The hydrogen enhances drying kinetics and nutrient retention, whereas CO_2 alone offers mild protection against browning and oxidative damage. The choice of gas thus directly influences both the rate of water removal and the nutritional and visual integrity of the dried product. It highlights the importance of tailoring gas atmospheres to the characteristics of each food type.

The utilization of nitrogen or other inert gases like argon is another method employed in MAD to reduce oxidation. Nitrogen is commonly used in food drying to replace oxygen and lower the risk of oxidative reactions. Nitrogen-enriched atmospheres, particularly when combined with low drying temperatures, can reduce the Maillard reaction (responsible for browning in food) and prevent undesirable changes in flavor and texture (Hawlader et al. 2006a, 2006b). Furthermore, these environments are ideal for preserving the structural integrity of delicate products like pharmaceutical tablets, where oxidation could impact the stability of active ingredients (Perera 2001). The recent developments in gas composition control systems have enabled the precise regulation of gas mixtures, allowing for more customized drying environments that are tailored to specific products. For example, some studies have shown that alternating between nitrogen can help optimize the drying of highly sensitive materials, improving drying efficiency and quality preservation (Doungporn et al. 2012; Cam et al. 2018; Homayounfar et al. 2023).

5.3 | Humidity Control and Moisture Content Regulation

Humidity is another vital parameter in MAD, as it influences both the rate of drying and the product's final quality. High humidity levels can slow down the evaporation of moisture from the material, whereas low humidity can result in faster drying. It also possibly leads to surface cracking or structural damage to the material (Zhang, Yang, et al. 2022). The recent research by Ai et al. (2023) on humidity control has led to innovations in equipment design to maintain the optimal relative humidity within the drying chamber. Advanced MAD systems can further incorporate dehumidifiers and humidity sensors to maintain an ideal balance between temperature, humidity, and oxygen levels. The goal is to ensure that the material retains moisture at the optimal rate without causing the product to shrink, crack, or lose its desired properties. One of the key advancements in advanced drying systems is the development of dynamic moisture control systems. These systems utilize real-time sensors to monitor the moisture content of the product during drying. It automatically adjusts the temperature, humidity, and airflow to optimize the drying rate (Kapoor et al. 2022). Studies have shown that this closed-loop control can significantly reduce drying time. It ensures that the product is not over-dried or under-dried, which is critical in maintaining the quality of high-value materials such as pharmaceutical products or fine food ingredients (Cam et al. 2018).

5.4 | Air Flow and Heat Distribution

Airflow within the drying chamber is another important parameter that influences the drying rate and the uniformity of the drying process. The current studies have highlighted the importance of even airflow distribution to avoid the creation of hot spots or areas of uneven moisture removal (El-Mesery et al. 2022). Future developments in MAD system design should focus on optimizing airflow to ensure uniform drying. Multi-zone systems, where different areas of the drying chamber are controlled independently for temperature, humidity, and gas composition, have been proposed to allow for more precise control of airflow. This design allows for greater flexibility, particularly in continuous drying systems, and helps achieve a more uniform drying rate across the entire material. Innovative designs for heat exchangers and heat transfer mechanisms can be introduced to enhance energy efficiency and improve heat distribution within MAD systems (Rashid et al. 2022). The research by Zhang, He, et al. (2022) has explored the use of fin-and-tube heat exchangers or plate heat exchangers in conjunction with heat-pump systems to improve the transfer of heat to the drying air. These designs have been shown to reduce energy consumption and provide a more consistent temperature throughout the drying process. The recent studies on processing parameters in MAD have made substantial advancements in optimizing drying temperature, gas composition, humidity, and airflow. The key developments in heat-pump systems, microwave and IR-assisted drying, and dynamic moisture control have improved the efficiency, quality, and sustainability of MAD processes (Wang et al. 2024; Chakraborty and Mondal 2017; Alvazeer and Betül 2020). The researchers can enhance drying speed, reduce energy consumption, and preserve the integrity of sensitive materials by fine-tuning these parameters. The challenges remain, particularly in optimizing these parameters for different types of materials and scaling up for industrial applications, whereas progress has been made (Ioannou Sartzi et al. 2024). The future research will likely focus on further refining these systems, integrating renewable energy sources, and improving the adaptability of MAD systems to various product-specific requirements.

6 | Influence of Gases on Drying Kinetics

6.1 | Moisture Diffusivity and Drying Rate

Effective diffusivity (diffusivity) serves as a comprehensive parameter to quantify the internal moisture migration within food matrices, regardless of the specific moisture transport mechanisms involved. It is a crucial factor in the modeling, simulation, and optimization of drying processes, as the rate of water vapor movement through the material is governed by internal diffusion toward the surface (Touil et al. 2014). Reported diffusivity values typically fall within the range of 10^{-12} to 10^{-8} m^2/s for food materials, with specific values observed between 1.36×10^{-9} and 3.45×10^{-9} m^2/s (Zogzas et al. 1996). Increased drying temperature significantly enhances diffusivity, whereas a reduction in oxygen (O_2) content results in a modest improvement. This trend reflects the influence of thermal and environmental conditions on heat and mass transfer mechanisms during drying. The presence of O_2 in the drying atmosphere may alter the surface structure of materials, potentially inducing microscopic capillary shrinkage and reducing porosity, thereby elevating resistance to moisture diffusion (Hawlader et al. 2006b). Consequently, lowering O_2 levels offers only a slight positive effect on diffusivity. Variations in O_2 concentration also modify the physical properties of the drying medium, such as density, viscosity, thermal conductivity, and specific heat capacity. These changes, in turn, affect heat and mass transfer behavior during hot-air drying, particularly in moisture-rich foods. As demonstrated in carrot drying, alterations in gas composition can result in shifts in drying rates and diffusivity, mirroring the observations reported by Ramesh et al. (1999, 2001) and Hawlader et al. (2006a).

In the study by Alwazeer et al. (2020), the role of molecular diffusivity was highlighted in the context of reducing atmosphere packaging for fresh cheese. The authors found that limiting oxygen diffusion through packaging materials significantly slowed microbial growth and oxidative reactions, thereby extending the cheese's shelf life. The reduced molecular diffusivity of oxygen helped to maintain a stable, low-oxygen environment, which preserved the freshness and texture of the product over a longer period compared to conventional packaging methods. The control of gas and moisture exchange indirectly contributed to moisture stability within the cheese, although drying rate was not a direct focus. Wang et al. (2024) investigated the performance of a heat-pump drying system combined with rotor dehumidification for drying mango slices at low temperatures. Their results showed that enhancing the drying rate through optimized humidity control and airflow significantly improved drying efficiency and product quality. The study reported that the combined system achieved up to 25.3% faster drying and better retention of color and nutrients compared to conventional heat-pump drying. Molecular diffusivity played a crucial role in moisture migration from the interior of the mango slices to the surface. It helped in maintaining a lower ambient humidity with increased vapor pressure gradient of the system, enhancing moisture diffusion. The both studies emphasize the importance of controlling molecular diffusivity and drying rate in food preservation, whether to minimize spoilage in cheese or to improve drying performance and product quality in dried fruits.

In MAD, lowering the oxygen concentration within the drying environment has been shown to slightly enhance the drying rate. This improvement is primarily attributed to the reduction in relative humidity of the drying medium and the resulting increase in the moisture diffusion gradient between the sample and its surrounding atmosphere. Such conditions promote faster moisture migration from the product surface. Ramesh et al. (2001) observed that the use of nitrogen improved both heat and mass transfer coefficients during the drying of spice paprika when compared to conventional hot air drying. This enhanced transfer capability translated into higher moisture diffusivity and accelerated drying. Similarly, Hawlader et al. (2006a) reported that replacing ambient air with an inert gas led to a noticeable increase in effective diffusivity and drying rate. In the drying of *Flos Lonicerae* under varying temperatures and oxygen concentrations, diffusivity values were reported to range from 5.034×10^{-11} to 16.660×10^{-11} m^2/s. As the drying temperature rose and oxygen levels dropped, diffusivity values increased significantly. Specifically, a reduction in oxygen content from 20.9% to 5.0%

resulted in a 4% to 5% rise in drying rate and a 15% to 18% increase in diffusivity. These findings suggest a moderate enhancement of mass transfer efficiency under oxygen-reduced conditions (Liu, Miao, et al. 2014).

However, the magnitude of this improvement varies across studies. Although Ramesh et al. (1999, 2001) reported approximately a 10% increase in drying rate for high-moisture foods like carrots and potatoes when using inert gases, Doungporn et al. (2012) found no significant difference in drying performance between inert gas and air during the drying. These discrepancies are likely due to variations in the initial moisture content and drying behavior of different materials. Products with high moisture content tend to exhibit a constant rate drying phase, during which the properties of the drying gas notably influence the drying rate (Hawlader et al. 2006a). In contrast, during the falling rate period, the moisture removal is more dependent on the intrinsic physical and chemical characteristics of the material, rendering the gas properties less impactful. Consequently, the changes in drying rate under modified atmospheres are less pronounced than in high-moisture materials but more substantial than in low-moisture products (Liu, Wu, et al. 2014). The diffusivity of regional wastes was evaluated under non-isothermal conditions, taking into account both inert and oxidative environments. At lower heating rates, effective diffusivity decreased, likely due to the hindered moisture movement within the particles. In contrast, drying in an oxidative atmosphere resulted in increased effective diffusivity values (Anabel et al. 2018). The gas velocity, a key parameter influencing the drying rate, was kept constant across all three atmospheric conditions. As a result, no significant differences were observed in the effective diffusivity values among the different gases (Doungporn et al. 2012; Khanlari et al. 2014). MAD effectively preserves ascorbic acid by operating at a controlled temperature of 60°C with a drying time under 120 min, significantly reducing thermal and oxidative degradation. The aerobic degradation pathway of ascorbic acid is notably suppressed in the low-oxygen environment of MAD, as it proceeds more rapidly than the anaerobic pathway. The latter becomes predominant only at elevated temperatures exceeding 120°C, underscoring the advantage of MAD in maintaining the integrity of heat-sensitive bioactive compounds within optimal processing conditions (Cam et al. 2018). Moisture diffusivity values under 100% nitrogen conditions were recorded as 6.17×10^{-8} and as 5.46×10^{-8} m^2/s under RAD_{MIX}, a gaseous mixture of 4% hydrogen, 5% carbon dioxide, and 91% nitrogen. Additionally, the Page model exhibited high reliability with R^2 values exceeding 0.98 across all dried samples, with the model constant (n) ranging between 2.412 and 2.575 for control and pretreated tomato slices. The Page model was identified as the most suitable model for predicting the drying behavior of tomato slices (Perumkulam Lakshmanan et al. 2025).

7 | Comparative Drying Performance

The studies showed drying system operates effectively with air, nitrogen, or carbon dioxide. Adapting current commercial dryers for gas use may be impractical due to their large volume relative to drying capacity and the challenges associated with charging them with nitrogen (Ramesh et al. 1999). Drying time significantly decreased with an increase in atmospheric temperature. Despite the different gases used, the time required to reach the final moisture content was nearly identical for air, nitrogen, and carbon dioxide. This similarity is attributed to their comparable volumetric heat capacities (ρCp): nitrogen at 1.01 kJ/m^3°C, air at 1.00 kJ/m^3°C, and carbon dioxide at 1.3 kJ/m^3°C. Additionally, the gas velocity, one of the most critical factors influencing the drying rate, was maintained consistently across all three atmospheres (Khanlari et al. 2014).

The recent research into advanced drying methods reveals diverse impacts on drying efficiency and quality preservation depending on the drying atmosphere and system used. Alwazeer and Örs (2019) found that RAD led to 45%–60% higher antioxidant retention and 30% better color preservation than conventional hot air drying despite a 12%–15% longer drying time. Their subsequent study (Alwazeer et al. 2020) demonstrated that cheese stored in a reducing atmosphere maintained microbial stability for 21 days compared to 14 days in air-packaged samples, indicating extended shelf life. Perumkulam Lakshmanan et al. (2025) reported that hydrogen-introduced drying of tomato slices reduced drying time by 25.3%, while increasing total phenolic content by 18.6% and improving the rehydration ratio from 2.35 to 3.10, showing superior preservation of nutritional and structural quality. Melenciuc (2023), using CO_2-MAD for pears, achieved a 38% reduction in enzymatic browning and 20% better color retention, although the drying time improved only slightly (5%–7% faster than air drying). Wang et al. (2024) utilized a heat-pump drying system with rotor dehumidification for mango slices, resulting in 20% lower energy consumption, 87.2% retention of vitamin C (compared to 73.4% in traditional drying), and 18% less shrinkage, indicating efficient drying and excellent product quality. The comparison of these studies indicates that hydrogen and reducing atmosphere methods stand out for their impact on nutrient retention, drying speed, and rehydration behavior. The CO_2 atmosphere and rotor-assisted heat-pump systems excel in maintaining appearance, reducing oxidation, and energy efficiency. Therefore, the optimal drying method depends on the product type and the specific quality attributes desired for better nutritional content, color, texture, or energy conservation.

The thickness of sample also influences the drying performance under the different gases. The thin sample exhibits the better drying performance under CO_2 condition when compared with N_2 and other atmospheric condition. However, the N_2 looks more advantageous in higher thickness samples in terms of drying rate and drying time (Khanlari et al. 2014). The CO_2 atmosphere improves diffusivity when compared to N_2 gas during the drying phase. The drying performance was influenced by drying temperature but remained unaffected by the type of drying gas. At a constant drying temperature, the moisture content of fruits and vegetables remained consistent across different gases. Furthermore, the drying curves overlapped throughout the entire process, indicating that the type of drying gas had no significant impact on moisture reduction (Doungporn et al. 2012). The observed findings contrast with studies by Hawlader et al. (2006b) and Ramesh et al. (2001), who reported significant variations in moisture loss from high-moisture foods (such as guava, papaya, carrot, paprika, and potato) when dried under different gas atmospheres at the same temperature. These differences can be attributed to the high initial moisture content of these products, which leads to substantial surface water evaporation. This makes their drying behavior more sensitive to external factors like gas composition, which affects heat and mass transfer processes. In contrast, products with lower moisture content or denser structure may experience drying dominated by internal moisture diffusion, showing less sensitivity to the drying atmosphere. This suggests that the effectiveness of drying conditions, particularly gas atmosphere, should be evaluated based on the specific moisture content and structural characteristics of the product. Future studies should consider tailoring drying parameters to the physical and chemical properties of the material as a perfect approach, which may not yield consistent or optimal results across different food types. This evaporation increases humidity within the drying chamber, causing a drop in the drying gas temperature. Consequently, the heat capacity of each gas is affected, thereby influencing the moisture removal process. The varying oxygen levels by N_2 do not significantly influence the drying performance of strawberry slices. However, studies reported a slight increase in drying rate when certain vegetables were dried under an inert atmosphere (100% N_2) compared to air (Liu, Wu, et al. 2014). The N_2-based MAD system consumed 40% less energy compared to freeze-drying (Cam et al. 2018).

8 | Sulfiting and Other Pretreatments Prior to Conventional Drying

Fruits and vegetables are naturally high in moisture, which means they require extended drying times to reduce their water content, making the drying process energy intensive. Due to this reason, fruits and vegetables are typically subjected to physical or chemical pretreatments prior to drying to reduce drying times and preserve product quality, as well as to reduce energy consumption (Yu et al. 2017). The drying kinetics and the quality of the final product are highly dependent on the pretreatments performed before drying (Deng et al. 2019). Among the pretreatments, sulfiting is one the commonly used chemical techniques owing to the ease of use and the associated benefits. Sulfiting not only helps in maintaining color, preserves antioxidants, and inhibits enzymes, but it also has antimicrobial properties that aid in storage even after drying (Li et al. 2024). Although sulfites and different forms of sulfites (sodium sulfite, sodium metabisulfite, potassium metabisulfite, etc.) are listed as food additives in the Food and Agriculture Organization (FAO)/World Health Organization (WHO) Codex Alimentarius document, each country can decide either to approve or to decline its usage in dried food products. The maximum permissible limits of sulfites in dried fruits and vegetables as set by various regulatory bodies are given in Table 5. Besides these benefits that sulfiting offers to dry products, usage of sulfites beyond the recommended limits has severe impacts on human health such as nausea, hypotension, respiratory allergies, and even damage at the DNA level (Perumkulam Lakshmanan et al. 2025). This has led to the use of other physical or chemical pretreatments with maximum quality retention and minimal side effects on human health.

Physical pretreatments do not use any chemicals, thus making it one of the safest pretreatment techniques to utilize before drying. Physical pretreatments widely adapted in fruits and vegetables include water blanching, steam blanching, superheated steam impingement, freezing, ultrasonication, high pressure processing, and pulsed electric field (Deng et al. 2019). These pretreatments effectively reduce initial microbial load, inactivate browning enzymes like PPO, and enhance drying process by expelling intracellular air. Apart from these advantages, thermal pretreatments are often associated with nutrient leaching, color degradation, protein denaturation, cell membrane disruption, and loss of crisp texture and firmness. Thus, non-thermal physical pretreatments like freezing, ultrasonication, high pressure processing, and pulsed electric field are gaining interest for alleviating quality degradation (Ciurzyńska et al. 2021; Guo et al. 2023; Li et al. 2022). It is very important to emphasize on the optimized pretreatment conditions for non-thermal physical pretreatments, like intensity of electric pulses in pulsed electric field, frequency range in ultrasound, and range of pressure in high pressure processing, to yield desired results. One common mechanism of physical pretreatment is that they all operate based on cell wall degradation and result in depleting the quality and nutrient of the produce. Chemical pretreatments can effectively address the concerns of physical pretreatments that can not only aid in color and nutrient retention but also can effectively act as a preservative agent (Deng et al. 2019). Chemical pretreatments other than sulfiting include osmotic dehydration, acid dipping, alkaline dipping, edible coating, and even gaseous pretreatments like ozone and carbonic maceration. With consumers being more conscious about food composition, residues from these chemical pretreatments are becoming an area of concern. Table 6 represents the pros and cons of different pretreatments in fruits and vegetables.

Furthermore, disposal of the chemicals after pretreatments adds to the environmental pollution load. Hence, replacing pretreatments, especially sulfiting, is crucial, which has food quality and nutrient preservation properties. MAD can be a potential solution for preserving quality and nutrients without any residues. In the previous sections, the working mechanism of MAD (with nitrogen, carbon dioxide, and hydrogen gas mixtures) with food matrices was explained, and in the following section, the quality attributes of MA dried fruits and vegetables would be discussed.

9 | Effect of MAD on Quality Attributes

Quality attributes of dried fruits and vegetables play a crucial role in determining the final product acceptability. Table 7 represents the effect of MAD on quality parameters of fruits and vegetables. Certain parameters, such as color, texture, flavor, nutritional value, and rehydration ratio, are highly affected during the drying process. Moreover, the drying conditions (time and temperature) and the method of drying play a significant impact on the final dried product (Li et al. 2024). For example, flavor compounds may degrade when exposed to higher temperatures, and color may degrade when exposed to oxidation states (Liang 2024). With progress in drying methods like heat-pump drying, freeze-drying, low-temperature convective drying, refractance window drying, and microwave drying, nutritional properties as well as the sensitive compounds like color and flavor are preserved. Using this idea, the drying environment of conventional drying can be replaced with gases like nitrogen, carbon dioxide, and mixture of these gases, and even use of hydrogen at low levels is attempted in fruit and vegetable drying. The quality parameters of dried fruits and vegetables by MAD are given below.

TABLE 5 | Maximum permissible limits of sulfites in dried fruits and vegetables as per regulatory bodies.

Regulation body	Form of sulfite	Type of product	Maximum permissible limit	Reason for usage	Reference
Ministry of Health of the People's Republic of China	Sulfur dioxide, sodium metabisulfite, sodium sulfite, and potassium metabisulfite	Fresh fruits (surface treatment)	50 mg/kg	Microbial safety, color, and nutrient retention	HFPC (2014)
		Dried vegetables	200 mg/kg		
US Food and Drug Administration (FDA)	Sulfur dioxide, sodium bisulfite, potassium metabisulfite, sodium metabisulfite, potassium metabisulfite, and sodium sulfite	Dried food products	10 mg/kg	Preservation, color, and nutrient retention	USFDA (2011)
The Codex Alimentarius Commission	Sulfites	Fresh fruits (surface treatment)	50 mg/kg	Microbial safety, color, and nutrient retention	FAO/WHO (2011)
		Dried fruits	1000 mg/kg		
		Dried vegetables	500 mg/kg		
The European Union	Potassium metabisulfite, sodium sulfite, sulfur dioxide, sodium metabisulfite, sodium hydrogen sulfite, calcium sulfite, calcium hydrogen sulfite, potassium hydrogen sulfite	Dried fruits	50–2000 mg/kg	Maintain texture, color retention, and microbial safety	EFSA (2016)
		Dried vegetables	50–500 mg/kg		
Food Standards Australia New Zealand (FSANZ)	Sulfur dioxide, bisulfites, and metabisulfites	Dried fruits and vegetables	3000 mg/kg	Preservation, color, and nutrient retention	FSANZ (2016)
Health Canada	Sulfur dioxide, potassium metabisulfite, sodium bisulfite, sodium dithionite, sodium metabisulfite, sodium sulfite, or sulfurous acid	Dried fruits and vegetables	2500 ppm	Microbial safety, color, and nutrient retention	Health Canada (2023)

TABLE 6 | Pros and cons of different pretreatments in fruits and vegetables.

Pretreatment type	Name of pretreatment	Pros	Cons	Reference
Physical	Hot water blanching	• Straightforward process • Simple equipment needed • Ease of commercial application	• Large amounts of wastewater generation • Leaching of water-soluble nutrients • Can have negative impact on texture of sample	Mukherjee and Chattopadhyay (2007)
	Steam blanching	• Reduced nutrient losses (e.g., ascorbic acid) than hot water blanching • Enzyme inactivation effect as that of hot water blanching	• Lower heat transfer rate, thus requires longer exposure times • Blanching effect cannot be uniformly distributed to the products	Del Bo' et al. (2012)
	Superheated steam impingement blanching	• High heat transfer rate due to use if superheated steam • Rapid and efficient • Higher nutrient retention than hot water and steam blanching	• Concept still in infancy • Needs time for industrial application	Wang et al. (2017)
	Ohmic heat blanching	• Reduced treatment times (usually a few seconds) than other blanching methods • Electroporation on surface of fruits and vegetables enables rapid moisture transfer during drying (reduced drying times) • Environment-friendly compared to other blanching methods	• Efficiency is highly dependent on electrode material, field strength, voltage, and electric frequency • Generation of hydrogen and oxygen ions that may accelerate corrosion of electrodes • Difficult for temperature control • Non-uniform heat distribution in heterogenous food matrices	Varghese et al. (2014)
	Microwave blanching	• Faster blanching rates than hot water and steam blanching • Higher color retention (e.g., anthocyanin) than hot water and steam blanching • Uniform microstructure than hot water blanching	• Non-uniform heating resulting in hot spots and cold spots • No control over temperature • Highly dependent on frequency of microwave • Lower penetration depth for thick samples	Ruiz-Ojeda and Peñas (2013)
	Ultrasonication	• Can be done at ambient temperatures • Reduces drying time by micro cavitation • Increased porosity, reducing drying times and better rehydration ratio of dried products	• Needs optimized ultrasound frequency for each product • Needs media for propagation of ultrasound waves • Leaching of bioactive compounds in media • With increased distance from the probe, effect of ultrasound (and cavitation) decreases • Difficult for industrial scale-up	Tao and Sun (2015)

(Continues)

TABLE 6 | (Continued)

Pretreatment type	Name of pretreatment	Pros	Cons	Reference
	Freezing	• Creates porous structure during freezing, increases moisture transfer during drying • Maintain product quality	• Cannot inhibit browning enzymes, resulting in darker products • High cost of operation • May not suit all products (especially those susceptible to browning)	Ando et al. (2016)
	Pulsed electric field	• Non-thermal technique • Inactivates microorganisms and enzymes at ambient temperature • Very less times for pretreatment (10^{-4}–10^{-2} s) • Preserves color and quality attributes • Enhanced membrane permeability increasing mass transfer rate • Reduced drying times	• Highly dependent on electric field strength and exposure times • May cause cellular leakage • Applicable only to semi-solid and liquid foods • Cannot completely inactivate all microorganisms • Selective foods can react with electrode, corrode, and may produce toxins • High initial setup costs and tough to scale up for industrial use	Yu et al. (2017)
	High pressure processing	• Indirect contact with food, ensuring food hygiene • Increased cell permeability, reducing drying times	• Destruction in cell structure, tissue softening • Hazard of pressurized media entering foods • High initial setup costs	Jermann et al. (2015)
Chemical	Osmotic dehydration	• Removes about 70% water from food at room temperature • Decreases drying time • Less resource intensive, simple process • Retains color	• Loss of water-soluble pigments, vitamins, and minerals • Highly dependent on type and concentration of solute • Needs new hypertonic solution for each batch due to dilution from the previous batch • High volumes of disposal of hypertonic solutions	Ahmed et al. (2016)
	Alkaline dipping	• Highly suitable for fruits with natural wax coating (e.g., grapes, blueberries) • Increased membrane permeability, reducing drying time • Suppress polyphenol oxidase, thereby reducing browning	• Use of alkaline solutions may have residues that are toxic • Leaching of water-soluble compounds like vitamin C • Highly relied on type of alkali, pH, dipping time, and temperature of the dipping solution • May not be suitable for all fruits and vegetables • Disposal of used alkaline solutions causes environmental pollution	Corona et al. (2016)

(Continues)

TABLE 6 | (Continued)

Pretreatment type	Name of pretreatment	Pros	Cons	Reference
	Acid dipping	• Inactivation of polyphenol oxidase, thereby reducing browning • Enhances certain pigment stability like anthocyanin and betalain • Can soften thick peels of fruits (e.g., lemon) • High drying rates	• Leaching of water-soluble nutrients and pigments (e.g., chlorophyll, carotenoids) • Disposal of used acid solutions causes environmental pollution • May not suit all fruits and vegetables	Hiranvarachat et al. (2011)
	Sulfiting	• Prevents enzymatic and non-enzymatic browning even at very low concentrations • Increased cell permeability, enhanced drying rates, reduced drying times • Antimicrobial activity • Preserves quality attributes (e.g., color)	• Sulfite residues are often hazardous • Strict legislation for sulfite limits in various countries • Gaseous forms of sulfites may have diffusivity issues	Deng et al. (2019)

9.1 | Color

Color is one of the most important quality parameters as it can significantly affect the acceptability of foods. With conventional air drying, the combination of air and heat accelerates enzymatic and non-enzymatic browning, thus causing color degradation (Süfer et al. 2024). Hue angle is an indicator of browning, more the hue angle, lesser the browning. When apples were cubed and subject to air and nitrogen drying, the hue angle increased to the maximum value between temperatures 55 and 65°C for air drying but reached highest hue value at 50°C for nitrogen drying. This may be due to the decrease in the presence of oxygen (0.4% v/v) in the nitrogen drying atmosphere, thus maintaining color even at lower temperatures than air drying (O'Neill et al. 1998). Similar findings were reported when apple, potato, and guava were dried in 100% air, 100% nitrogen, and 100% carbon dioxide atmospheres (Hawlader et al. 2004). When the products were dried for longer times like 18 h (in comparison to 4 or 8 h), the color values L^* increased, and a^* and b^* values decreased, indicating the color retention of the final dried products. It was also observed that there were no significant differences in the color values between 100% nitrogen and 100% carbon dioxide drying atmospheres, which was again justified by the lower concentration of oxygen in the drying environment. Likewise, Hawlader, Perera, Tian, and Yeo (2006) also reported small ΔE values when guava and papaya were dried in 100% nitrogen and 100% carbon dioxide than conventional air drying.

As oxygen is one of the substrates required for enzymatic browning, lower the availability of oxygen in the drying environment, lower the browning process, and higher the color retention. Moreover, when macadamia nuts were dried in a heat-pump dryer with air and nitrogen drying atmospheres, L^* for the internal side remained high, but the external color was darker (Borompichaichartkul et al. 2013). The least color degradation was observed for macadamia nuts in nitrogen drying atmosphere at 40°C. It did not alter the whiteness of internal side of the kernels as L^* remained high, and there was no significant difference between treatments. However, external side was darker than internal side. Although the impact of drying medium and temperature on external color was small, the best condition was achieved using nitrogen in the first stage at 40°C. A novel idea of introducing a reducing gas like hydrogen in drying atmosphere along with nitrogen and carbon dioxide (4% H_2, 5% CO_2, 91% N_2—gas mix drying) was experimented by Alwazeer and Örs (2019). When apricots were dried in this atmosphere with reducing gas, minimum color change ΔE was observed for 100% nitrogen and gas mix drying than hot air and vacuum drying. The overall color values of nitrogen gas drying and gas mix drying were similar to that of fresh apricots, indicating good color retention. When similar experimentation was carried out in tomato slices, there were significant differences ($p < 0.05$) between the drying methods on the color of the sample (Perumkulam Lakshmanan et al. 2025). However, the results of gas mix drying and nitrogen drying yielded the best color retention in tomato slices, supporting the previous results in apricots. The MAD products tend to positive effect on the color of products that is possibly due to the reduction of oxygen present in the drying environment that would otherwise cause enzymic and nonenzymic browning.

TABLE 7 | Effect of modified atmospheric drying (MAD) on quality parameters of fruits and vegetables.

Fruit/Vegetable dried	MAD gases	Gas composition	Drying parameters	Effect on quality parameters	Reference
Apple	Nitrogen	—	50°C	• Hue angle increased • Increase in open pore and total porosity	O'Neill et al. (1998)
	Oxygen	0.4% (v/v)			
Apple, potato, and guava	Nitrogen	100%	50°C for 18 h	• Color improvement with longer hours of drying • Rehydration ratio follows a curve for apple and guava • Steady rehydration ratio for potato	Hawlader et al. (2004)
	Carbon dioxide	100%	50°C for 18 h		
Guava and papaya	Nitrogen	100%	45°C for 8 h	• Reduced ΔE values than hot air drying • Higher vitamin C retention than hot air drying • Increased porosity, less firmness of the dried product	Hawlader, Perera, Tian, and Yeo (2006)
	Carbon dioxide	100%			
Ginger	Nitrogen	100%	45°C for 8 h	• Higher 6-gingerol retention in nitrogen (43.5%) and carbon dioxide drying (45.4%) than hot air drying	Hawlader et al. (2006a)
	Carbon dioxide	100%			
Apricot	Nitrogen	91%	70°C for 8 h	• Minimum color change ΔE compared to hot air and vacuum drying • DPPH scavenging activity similar to fresh apricots	Alwazeer and Örs (2019)
	Carbon dioxide	5%			
	Hydrogen	4%			
Tomato	Nitrogen	91%	60°C	• Minimum color change ΔE compared to hot air drying • Lycopene and ascorbic acid retention than hot air drying • Increased rehydration ratio than 100% nitrogen drying	Perumkulam Lakshmanan et al. (2025)
	Carbon dioxide	5%			
	Hydrogen	4%			
Orange slices	Vacuum + nitrogen	N_2 gas was injected from 20 to 40 kPa	80°C and 40 kPa (vacuum)	• Improved drying kinetics, faster drying, and reduced nutrient degradation compared to vacuum/conventional hot-air drying	Homayounfar et al. (2023)
Strawberry	Nitrogen	N_2 gas was used to lower oxygen level to 9.47%	60°C, drying, and 3 m/s air/gas velocity	• Closed-cycle MAD resulted in lower ascorbic acid and anthocyanin degradation than hot-air drying	Cam et al. (2018)
Pineapple	Ethanol	0.5% ethanol (9.0 mL/min)	40°C and 0.42 m/s air velocity	• Ethanol in the drying atmosphere promoted faster evaporation and improved volatile retention	Braga et al. (2009), Santos and Silva (2009)
Carrots	Nitrogen	N_2 gas was flushed until 5% O_2 content	40–70°C	• Improved drying characteristics and quality (color and rehydration ratio) compared to conventional drying	Liu, Wu, et al. (2014)

9.2 | Nutritional Content, Bioactive, and Flavor Compounds

Dried fruits and vegetables act as a concentrated source of nutrients like fiber, vitamins, minerals, and antioxidants. Although drying helps preserve many nutrients, heat-liable compounds, like vitamin C, certain B vitamins, flavonoids, polyphenols, and carotenoids, may degrade during the drying process (Bassey et al. 2021). However, with MAD, nutrients and flavor compounds of fruits and vegetables are expected to be maintained than conventional drying techniques. Regier et al. (2005) experimented the hot air drying of carrot by replacing air with nitrogen. It was reported that drying using nitrogen did not have a huge impact on the stability of lycopene and β-carotene at a temperature of 70°C. Similar results were reported by Rahman et al. (2009) on allicin retention in garlic, where the drying atmospheres, namely, air drying, vacuum drying, and nitrogen drying, did not have any significant difference. In nitrogen drying, the loss of allicin was very fast in the initial stages, followed by a slow decrease at later stages. Hence, when fruits or vegetables are dried using nitrogen gas, it should be done at shorter drying times to reduce the loss of bioactive compounds.

On the other hand, Hawlader et al. (2006a) compared the retention of 6-gingerol in ginger by different methods of drying. In comparison to hot air drying, the incremental of 6-gingerol for nitrogen drying and carbon dioxide drying was 43.5% and 45.4%, respectively. MAD had better flavor notes than hot air drying, on par with vacuum drying and freeze-drying. Another study by Hawlader, Perera, Tian, and Yeo (2006) observed higher retention of vitamin C in nitrogen drying and carbon dioxide drying in papaya (80% and 82%) and guava (39% and 41%) than hot air drying. Among the MAD, carbon dioxide drying slightly retained more vitamin C than nitrogen drying due to the lower drying times required for carbon dioxide drying environment. In gas mix drying atmosphere (4% H_2, 5% CO_2, 91% N_2—gas mix drying) by Alwazeer and Örs (2019), the DPPH scavenging activity of apricots was similar to that of fresh samples. The total flavonoids of the apricots did not have a significant difference between the drying methods, though gas mix drying had better flavonoid retention than nitrogen drying and air drying. This was explained by the reducing property of hydrogen gas that may have protected the oxygen-sensitive bioactive compounds from degradation. When the same drying conditions were applied to tomato slices, the lycopene retention in gas mix drying was almost similar to that of fresh tomato (Perumkulam Lakshmanan et al. 2025). Although there was a decrease in the ascorbic acid content due to drying, gas mix drying retained the most ascorbic acid in tomato slices, followed by sulfite pretreated tomato slices subjected to nitrogen drying. The beta carotene content increased from 0.39 mg/100 g to 12.16 mg/100 g owing to the higher temperature and the gas mix drying environment. MAD can have a positive impact on nutrient and flavor compound retention, based on the gases used in the drying environment, along with the exposure time of the dried product.

9.3 | Porosity and Rehydration Ratio

The overall open structure of product after drying is known as porosity and is highly dependent on the initial moisture content, drying conditions, and the drying methods (Liu et al. 2022). During drying, the structure of the food collapses from its initial form, leading to change in porosity, thereby texture. As a result, porosity, texture, and rehydration ratio are all interconnected and greatly influence the organoleptic characteristics of a dried product. To experiment with the relationship product structure and MAD, O'Neill et al. (1998) subjected apple cubes to hot air drying, nitrogen gas drying, and vacuum drying. Among the drying methods, vacuum drying had the most porous structures, followed by nitrogen drying. However, the MAD product had the highest open pores (open pore porosity) and was expected to rehydrate more quickly and perhaps more efficiently than other drying methods. Likewise, Hawlader et al. (2004) observed more open pores on apple and guava samples by MAD, vacuum, and freeze-drying than hot air drying. The rehydration rate of these products almost followed a curve, defining the increase in capillary water uptake by the open pores caused by the drying methods. Due to the increased porous structure (more air in the solid structure) of MAD products, the firmness of the MAD samples was less than that of air-dried samples. Interestingly, similar results were reported when papaya was dried under different drying environments (Hawlader, Perera, Tian, and Yeo 2006). Among the drying methods, freeze-dried papaya had the most porous structure, followed by MAD products and vacuum dried products. This phenomenon was explained by the intricate relationship between wound response and hypoxia in MAD atmosphere. Although the lycopene and β-carotene content of carrots was not significantly affected by the drying method, the storage of air-dried carrots with nitrogen gas was found to maintain lycopene without degradation (Regier et al. 2005). On the other hand, when tomato slices were dried by gas mix drying and MAD (with nitrogen), the rehydration ratios of the former samples were more than the latter (Perumkulam Lakshmanan et al. 2025). The possible reason could be the increase in the number of closed pores that hindered capillary action and reduced rehydration ratio (Thibault et al. 2024). Thus, with MAD, dried fruits and vegetables could reproduce the real fresh produce due to high porosity and rehydration ratio. The type of pores (open or closed) developed on the structure would depend on and influence the initial nature of the product. Meanwhile, the package and transportation of MAD products (with more open pores) should be handled with care as these products tend to be less firm than conventionally air-dried products, leading to easier disintegration under stress/load.

10 | Challenges and Potential Solutions

MAD is an advanced dehydration technique that controls the atmospheric composition surrounding the material to optimize moisture removal while minimizing thermal damage (Liu, Wu, et al. 2014). This method is particularly valuable for drying heat-sensitive substances such as fruits and vegetables. Although MAD presents significant advantages over conventional drying methods, several technical, economic, and environmental challenges must be addressed to improve its feasibility and efficiency. One primary challenge of MAD is its high energy consumption (Borompichaichartkul et al. 2013). The continuous regulation of gas composition, humidity, and temperature necessitates sophisticated equipment and significant power input. Conventional drying methods rely solely on thermal energy, whereas

MAD requires additional energy for gas circulation, humidity regulation, and precise environmental control (Perumkulam Lakshmanan et al. 2025). Reducing energy demand while maintaining drying efficiency is critical for its commercial viability. The complexity of equipment is another significant barrier. MAD systems require specialized drying chambers equipped with gas delivery systems, sensors, and climate control mechanisms, leading to high capital investment and maintenance costs. Furthermore, achieving uniform drying is challenging, as heterogeneities in moisture content can lead to inconsistent drying rates, affecting product texture, color, and stability. The gas composition also influences drying kinetics and product quality (Pragalyaashree et al. 2017; Wyrwisz et al. 2025). Common gases such as nitrogen and carbon dioxide help mitigate oxidation and microbial growth, but their availability, cost, and handling requirements pose logistical issues, particularly for large-scale applications. Another critical concern is environmental sustainability. The extensive use of gases can contribute to greenhouse emissions and resource depletion if not managed responsibly. Understanding the long-term environmental footprint of MAD is essential for its integration into sustainable industrial practices.

Several strategic solutions have been proposed to overcome these challenges. Innovative drying chamber designs, such as multi-stage and fluidized bed systems, improve heat and mass transfer, resulting in faster and more uniform drying (Jafari and Malekjani 2023; Muhlbauer and Muller 2020). Sustainable gas utilization strategies, including gas recycling systems, help mitigate environmental impact by minimizing gas wastage and reducing overall operational costs (Nolan and Anderson 2015). The application of IoT-based sensors enables continuous monitoring and real-time adjustments in gas concentration, enhancing precision in drying parameters. AI-driven predictive modeling further facilitates optimization by considering food-specific characteristics and environmental conditions, leading to reduced energy consumption and improved process reliability (Dash et al. 2023). Additionally, computational modeling and predictive simulations can refine drying parameters for different materials, ensuring reproducibility and improving product quality (Parrish et al. 2023). Furthermore, integrating MAD with renewable energy sources such as solar power enhances sustainability by reducing fossil fuel dependency, preventing environmental pollution, and supporting eco-friendly preservation methods (Villagran et al. 2024). The adoption of solar-powered MAD systems not only minimizes carbon footprints but also eliminates residue formation, ensuring clean and efficient drying practices. Evaluating interactions between MAD-treated food products and packaging materials with controlled gas permeability will further optimize storage stability and minimize post-processing quality losses (Pola et al. 2021). Overall, MAD offers immense potential for enhancing product stability and extending shelf life while maintaining structural integrity. However, optimizing its energy efficiency, addressing equipment complexity, achieving drying uniformity, improving gas utilization, and mitigating environmental impact require continuous advancements in engineering, material science, and computational modeling. By integrating these solutions, MAD can evolve into a widely accepted drying method across various industries, contributing to improved product preservation and sustainability.

11 | Conclusion and Future Prospects

Ensuring food preservation methods are efficient, sustainable, and environmentally safe is essential for advancing modern drying technologies. MAD offers an innovative approach to fruit and vegetable preservation by minimizing oxidation, enzymatic browning, and bioactive compound degradation (Perumkulam Lakshmanan et al. 2025). This is achieved through reducing oxygen availability and substituting the drying atmosphere with precisely controlled inert gases such as carbon dioxide (CO_2) and nitrogen (N_2), which enhance structural integrity, improve rehydration properties, and prevent capillary shrinkage within food matrices (Hawlader et al. 2006b; Liu, Wu, et al. 2014). Additionally, hydrogen gas (H_2) presents potential benefits as a drying medium due to its unique physicochemical properties; however, its flammability at concentrations ranging from 4% to 75% requires stringent monitoring of gas mixtures, ensuring proper containment and leak-proof operation within drying chambers. Real-time gas sensors integrated with IoT technology and artificial intelligence (AI) enable the detection of gas leakage and optimization of drying conditions, enhancing both safety and operational control (Dadhaneeya et al. 2023; Khan 2020). MAD can be effectively combined with advanced drying techniques such as freeze-drying, spray drying, IR drying, and microwave-assisted drying, thereby improving energy efficiency, accelerating drying kinetics, and maintaining superior product quality (Raghavan 2020). These hybrid techniques can yield synergistic effects, enhancing moisture diffusivity, functional compound retention, and extended shelf life. However, key processing parameters, including optimal gas composition, precise temperature control, and humidity regulation, are crucial in maximizing both product integrity and drying performance (Jha and Tripathy 2021). Future advancements in MAD will focus on refining gas mixture optimization to improve enzymatic activity suppression and microbial inhibition while ensuring food safety during drying.

Moreover, energy recovery mechanisms can improve thermal efficiency and reduce overall power consumption without compromising food quality. Establishing hydrogen safety standards in MAD applications is critical to mitigating its flammability risks, necessitating advanced gas containment, leak-proof drying systems, and real-time monitoring solutions (Russell et al. 2024). Regulatory frameworks should define acceptable gas composition thresholds to ensure food safety, microbial stability, and compliance with global preservation standards. However, most of the available data are based on lab-scale research and are qualitative, thereby limiting the scope of comprehensive techno-economic evaluations. The availability of techno-economic data in the future can aid in addressing scalability and cost-effectiveness for adapting MAD in industrial scale. Long-term research should investigate the stability of vitamins, antioxidants, and bioactive compounds in MAD-treated food products to extend shelf life and enhance potential health benefits (Roslan et al. 2020). Studies on texture preservation and rehydration properties under MAD conditions will further optimize drying parameters for superior consumer acceptance and product functionality. Additionally, scaling MAD technology for large-scale food processing industries demands strategic optimization of gas usage, drying chamber designs, and automation to ensure cost efficiency. The economic viability of MAD versus conventional drying methods must be thoroughly examined to encourage industry adoption and investment in sustainable food processing. In addition to these parameters, MAD can be a technology for more resilient and sustainable global food systems, especially for regions with high postharvest losses. Finally, investigating microbial stability and oxidative resistance in MAD-treated foods during long-term storage will provide insights into packaging innovations and preservation strategies. Besides, through selecting the appropriate gas and lower temperature drying, MAD would be a climate-adaptive drying solution that mitigates the energy consumption and carbon footprint. In conclusion, by integrating MAD with smart drying technologies and sustainable energy sources, the food industry can significantly enhance drying efficiency, improve product longevity, and reduce environmental impact.

Author Contributions

S. Ganga Kishore: conceptualization, methodology, investigation, writing – original draft, validation. **Meenakshi P. L.**: conceptualization, writing – original draft. **K. Kamaleeswari**: formal analysis, writing – review and editing. **Rahul R.**: writing – original draft. **J. Deepa**: writing – original draft, formal analysis, investigation. **G. Jeevarathinam**: conceptualization, supervision, formal analysis, writing – original draft, writing – review and editing. **Madhuresh Dwivedi**: methodology, writing – review and editing. **Punit Singh**: writing – original draft. **Sarvesh Rustagi**: writing – original draft. **Syed Mohammed Basheeruddin Asdaq**: writing – original draft.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No data were used for the research described in the article.

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