Review Article

Engineering Perspectives on Drying Technologies of Medicinal Plants: A Review on Kinetic Modelling and Bioactive Compounds Retention

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Abstract
Medicinal plants, an integral part of the Indian traditional medicinal practices, are a reservoir of bioactive molecules proven to have therapeutic effects against various ailments. The post-harvest losses of medicinal plants have been estimated to range between 10-40% in Asian countries, including India, mainly due to improper handling, storage and packaging. Drying is an important post-harvest operation of plant materials that can significantly impact the functional bioactive compounds. This review aims to shed light on the various drying methodologies of medicinal plants, weighing their merits and limitations, and highlighting the latest advancements and current research. The review summarizes the influence of drying parameters on the stability and retention of bioactive compounds in medicinal plants, as well as focuses on the drying kinetic models employed to comprehend their moisture transport mechanism. In conclusion, the authors intend to address the major challenges and research gaps to offer insights for advancing research in improving the herbal drug quality through optimized drying conditions.

Keywords: Bioactive compounds, Drying kinetics, Drying models, Medicinal plants, Statistical analysis

1 Introduction

Traditional herbal medicines are an integral part of the global health systems, addressing acute and chronic conditions with the least side effects. India, being a repository of medicinal plants, is considered a "living tradition" due to its diverse traditional medicinal practices [1]. The World Health Organization (WHO) has reported 21,000 medicinal plants of therapeutic significance, with about 2500 plants being used by traditional practitioners in rural areas for treating multiple diseases [2]. The Indian system of Medicine (ISM) promotes the utilization of medicinal plant-based formulations for the primary, secondary, and tertiary healthcare sectors [3]. The seasonal availability of medicinal plants and the effect of moisture on their shelf life necessitate proper drying and storage of medicinal plants for future use [4].

Drying, dehydration, or desiccation is the long-established physical preservation method, inhibiting enzyme and microorganism growth and activity by decreasing the water activity of plant materials, including leaves, stems, fruits, bark, and seeds with therapeutic significance [5]. The quality of the medicinal plants is influenced by heat and humidity, thereby demanding to be dried immediately after harvest. The drying regime has a significant influence on drug quality [6]. The drying air temperature is determined by the heat sensitivity of the active compound and the rate at which moisture migrates. Although higher drying temperatures accelerate the drying process and save time and energy, they can also degrade active compounds [4]. While natural methods such as open sun and shade drying involve unhygienic practices and larger drying areas, artificial drying methods, such as convective, fluidized bed, infrared (IR), microwave, osmotic, and heat pump drying, are effective in reducing drying time, improving quality, and controlling temperature, airflow, and relative humidity [7].

Drying kinetics investigation is critical for determining appropriate drying techniques for monitoring the process, analyzing moisture removal progress, and determining suitable drying conditions, as it signifies the inter-relationship between moisture removal and drying process variables [8]. The National Medicinal Plants Board (NMPB) coordinates efforts across ministries to promote the medicinal plants sector. It supports policy development, guides cultivation and supply chain processes, and enhances collaboration among stakeholders. It fosters research, quality control, and Intellectual Property Rights protection to boost product quality and global market presence. The prime focus of this review is to consolidate the findings related to different drying methodologies, drying kinetics investigation, mathematical modelling, and the influence of the drying process on the bioactive compounds of the prioritized medicinal plants most widely used in Indian traditional medicine formulations as listed by the National Medicinal Plants Board (NMPB) [9]. While existing reviews have explored various drying methodologies in general, recent studies have shifted towards herb-specific process optimization, applying drying kinetics and studying its impact on bioactive stability. For instance, Nguyen *et al*., [10] evaluated various drying technologies for *Phyllanthus amarus* and correlated their effect on total phenolic and total flavonoid content, whereas Padhiari *et al*., [11] studied how drying affects the saponin content in *Bacopa monnieri* (Brahmi leaves). These studies highlight the growing trend in correlating process parameters with retention of bioactive compounds and this review capitalizes on providing an extensive integration of kinetics, thermodynamics, and compound retention across prioritized Indian medicinal herbs.

2 Drying Methodologies for Medicinal Plants

Heat flows from drying air to moist material, causing surface moisture to evaporate, which leads to internal moisture diffusion to the material's surface until equilibrium is achieved. This complex movement incorporates liquid, vapour, surface diffusion, and hydrostatic pressure changes. The major factor that affects the herb quality is the drying methodology, the process parameters, which in turn affect the rate of drying, effective moisture diffusivity, activation energy, energy and exergy efficiency [12]. The initial moisture content of the material and the drying temperature are the major factors affecting drying time [13]. Drying methodologies of plant materials can be roughly classified as natural, convective, and advanced drying techniques, as described in Figure 1.

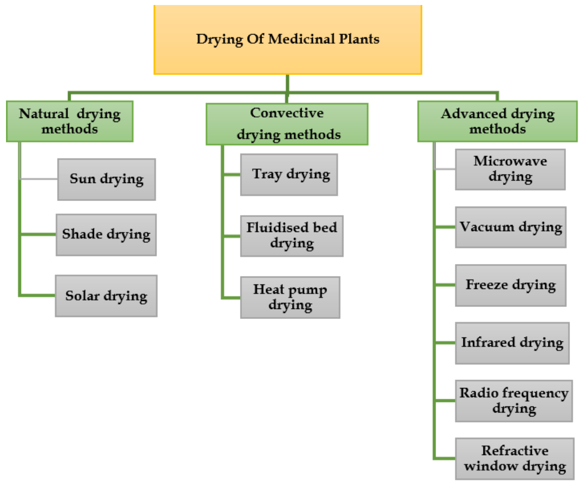

Figure 1: Different drying methodologies applied for medicinal plants dehydration.

2.1 *Natural drying methods*

In India, many farmers and agro-industries prefer to use solar drying methods to preserve plant materials due to the tropical climatic conditions, lower cost, renewable, and sustainable technology. Solar drying technology includes open-sun drying, shade drying and solar dryers. Open-sun drying and shade drying, though employed extensively, may result in inconsistent drying temperatures, which can result in poor quality herbs with great loss of bioactive compounds. In contrast to open-sun drying, solar dryers have better temperature regulation and lower drying time, thus resulting in better hygiene and quality. Based on the direction of airflow and its flow rate within the dryer, solar dryers are mainly classified as active and passive solar dryers. According to the effect of solar radiation on the product, solar dryers can be categorized as direct, indirect and mixed-mode solar dryers [14]. Hybrid solar dryers have a provision to augment the solar energy with biomass, heat pumps, or electrical heating has been developed [15]. Comparative studies highlight the constraints of natural drying. Open sun drying of *Garcinia indica* decreased anthocyanin content by almost 55% due to photo-oxidation [16]. In comparison, solar-assisted drying systems and shade drying provided enhanced compound stability, albeit with longer drying times.

This difference calls for process-specific optimization according to compound sensitivity.

2.2 *Convective drying methods*

Tray drying is a commonly used method in which plant materials are spread into thin layers on trays in a heated chamber. Hot air circulates for moisture evaporation under controlled drying conditions, retaining the quality of medicinal plants. Uneven air flow can lead to uneven drying. Modern tray dryers are fitted with optimized airflow systems to provide better uniformity and retention of bioactive compounds. This method is especially suitable for heat-sensitive herbs. Optimized airflow and heat recovery systems have shown energy savings nearing 87%, thus proving quite energy-efficient [17]. For medicinal plants such as *Ocimum sanctum Linn* (Tulsi), microwave-assisted tray drying at 45°C with 600W microwave pretreatment was particularly effective in preserving active compounds like volatile oil eugenol, an important bioactive compound.

Though tray drying poses certain limitations on the intensity of colour, it is still a cost-effective and efficient method for the treatment of aromatic traditional plants, as it aids in maintaining the key constituents within the plant [18]. Cabinet drying is similar to tray drying, except that a closed chamber carries the trays or shelves stacked in it. They provide better temperature control and protection from contamination, making it suitable for high-value herbs. Newer models have automatic temperature and humidity control to conserve bioactive compounds and reduce drying time [19]. Cabinet drying is an effective method for the preservation of bioactive compounds in *Azadirachta indica* (Neem), such as azadirachtin. This technique is best suited for high-value herbal commodities because of the controlled temperature and humidity, which ultimately improve dried materials' quality and shelf life [20]. Fluidized-bed drying is an advanced convective drying system that facilitates fluidization and uniform heating of individual particles due to an upward air flow stream, thus ensuring efficient drying with a high drying rate. It is most suitable for homogenous drying with advancements in designs and control systems to further improve energy efficiency and product quality. Drying *Moringa olifera* in a fluidized bed dryer at 50 °C has shown improved antioxidant activity and ascorbic acid content [21]. The fluidized bed drying offers significant advantages over traditional convective drying with a monolayer arrangement, such as 1) high heat and mass transfer rates, because of the large contact surface area between solid and gas phases, 2) uniform temperature and bulk moisture content of particles, because of the intensive particle mixing in the bed and solid thermal properties, 3) high drying capacity due to high air mass to product mass ratio [22]. The inclination towards renewable energy sources such as solar energy and innovations in high-efficiency systems has led to the progress of heat pump drying technology. Solar-assisted heat pumps and photovoltaic/thermal (PV/T) systems are currently merging heat absorption and renewable inputs for lower energy costs and carbon emissions.

These advancements allow for tighter control of drying parameters such as temperature and humidity, leading to improved energy efficiency and performance of the drying process. Modern heat pumps are quieter, more adaptable, and carry variable-speed compressors against the advanced backdrop of controls for precise operation. In a study, *Mentha spicata* was efficiently dried in a sustainable photovoltaic heat pump drying system with a thermal efficiency of 56.37% and an electrical efficiency of 12.27% [23].

2.3 *Advanced drying methods*

Microwave drying is a drying technology that involves electromagnetic waves in the bands of 915 MHz, 2450 MHz, and 5800 MHz, where 2450 MHz is widely used for food processing. With this method, internal heating of the material occurs due to the dielectric properties, leading to rapid and efficient volumetric heating. Combined convective-microwave drying at a microwave power level of 6 W/g, an air velocity of 1.5 m/s, and a temperature of 50 °C has been proven to be effective in extracting total alkaloids from Ashwagandha roots, making it an ideal choice for preserving both quality and bioactive compounds during drying [24]. Microwaves penetrate the sample and generate heat within it, leading to faster heating. Furthermore, the standing wave pattern of the microwave cavity can create hot spots, causing the sample to quickly heat to elevated temperatures and cause damage, specifically, charring [25]. Freeze-drying, also known as lyophilization, is the most reliable technology for preserving chlorophylls, carotenoids, and antioxidants in herbs like *Melissa officinalis* (Lemon balm) and *Urtica dioica* (stinging nettle). Freeze-dried samples of both herbs exhibited the highest content of chlorophyll a, chlorophyll b, carotenoids and anthocyanins.

Despite its higher cost, freeze-drying is recommended for its ability to retain functional pigments and maximize antioxidant properties, making it the most preferred drying method for high-quality herbal extracts [26]. Infrared (IR) radiation drying is an energy-efficient drying process and ensures high-quality food, and medicinal and aromatic plants. The electromagnetic spectrum includes infrared radiation, which is primarily responsible for the sun's heating effect [27]. The penetration depth is influenced by material thickness, its microstructure, moisture content, infrared power and the distance of the material from the IR source [28]. Far infrared (FIR) drying of *Stevia rebaudiana* leaves at 55°C has been shown to retain stevioside (7.88mg/g) and rebaudioside. A (8.58 mg/g) is better as the infrared treatment increases the micropores on the leaf surface and improves its quality [29]. Radiofrequency drying is a dielectric heating method that employs electromagnetic radiation with frequencies between 1 and 100 MHz to produce heat through direct volumetric coupling with food. This method has a more consistent electric field than microwave heating, enhancing heating rates and reducing thermal load. Radio-frequency vacuum drying has been found to maximally retain bioactives lobetyolin and syringing during dehydration of *Codonopsis pilosula* slices [30]. Refractive Window Drying (RWD) is a novel drying technology where mylar plates and hot water are used for rapid heat transfer, swift evaporation, and uniform drying with high retention of volatile aromatic compounds and therapeutic bioactive compounds [31]. RWD has lower energy consumption (28–38%), high thermal efficiency (55–72%) and reduced drying costs (30–50%). Researchers have identified that RWD effectively retains *Curcuma Longa* rhizome quality with moderate activation energy (47.05 kJ/mol) and thermodynamics confirming a controlled, non-spontaneous process for maximum bioactive compound retention [32]. Apart from drying, extraction of bioactive compounds is a crucial step in medicinal plants processing and the extraction methodologies such as Soxhlet, microwave-assisted, ultrasonic-assisted, and supercritical fluid can be applied not just to extract targeted bioactive compounds but also as effective pretreatment strategies for coventional drying methodologies to ensure better retention of thermo-labile compounds, such as sennosides and bacosides [33].

3 Mechanism of Drying and Drying Kinetics

Drying of plant material comprises mechanisms, such as surface diffusion, and liquid, and vapour diffusion that result from variations in moisture content and capillary action. When the equilibrium moisture content is reached, hygroscopic materials go through a constant rate phase followed by a falling rate phase. The first falling rate period, which is dominated by liquid diffusion driven by factors including temperature and moisture content, commences when surface moisture attains critical levels [34]. A second falling rate period that is mostly controlled by vapor diffusion follows. Diffusion is the primary driver of moisture movement in medicinal plants, and it is frequently modeled using moisture content reported on a dry basis for simplicity. In general, liquid and vapor diffusion mechanisms are important throughout the falling rate period [10], [29]. For process optimization, drying kinetics studies are crucial because they provide a cost-effective approach to identifying the best drying conditions. These investigations allow for accurate drying control by determining the best-fit kinetic model, which enhances productivity and product quality [13]. Drying curves are plotted between moisture content in a wet basis or dry basis versus time or between drying rate and moisture content. Moisture content wet basis and dry basis and drying rate are calculated using the Equations (1)–(3)

$$M_d = \frac{W_i - W_f}{W_d} \tag{1}$$

$$M_w = \frac{W_i - W_f}{W_i} \tag{2}$$

$$\text{Drying rate} = \frac{M_t - M_{t+dt}}{\mathrm{dt}} \tag{3}$$

where M_d, M_w are the moisture content on dry and wet basis in kg water/kg dry matter, W_i, W_f and W_d are initial, final and dry matter weights in kg, respectively. Drying rate is expressed as kg water/kg dry matter/hr, M_t is the moisture content at time t and dt refers to the time interval in hours [35]. Moisture ratio, a dimensionless parameter is effective in explaining the drying behaviour of materials since it normalizes the initial value as one. Moisture ratio is calculated using Equation (4)

$$\text{M.R} = \frac{M_t - M_e}{M_o - M_e} \tag{4}$$

where M_t is the instantaneous moisture content, $M_o$is the initial moisture content and M_e is the equilibrium moisture content, respectively. If $M_e$is relatively smaller than $M_t$andM_o, the MR is simplified as Equation (5) [36]

$$\text{M.R} = M_t/M_o \tag{5}$$

The effective moisture diffusivity is a major parameter when studying the drying kinetics of plant materials. It describes the moisture migration rate from the core (interior) to the surface. As most of the medicinal plant materials resemble thin-layer, resembling slab geometry, Fick's second law of diffusion is used to arrive at effective diffusivity. Assumptions include constant drying conditions, uniform moisture distribution, and negligible resistance to moisture diffusion. With reference to slab geometry, the equation is as follows Equation (6)

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 t D_{eff}}{4L^2}\right) \tag{6}$$

where, t is time in seconds, D_{eff} is the effective diffusivity in m^2/s and L is half thickness of the sample in m. This equation can be re-written by taking the natural logarithm on both sides as Equation (7)

$$D_{eff} = \frac{\ln\frac{8}{\pi^2} - \ln\text{MR}}{\left(\frac{t\pi^2}{4L_2}\right)} \tag{7}$$

Ln (MR) versus time is plotted and the slope (k_0) is calculated to determine the effective diffusivities at various temperatures Equation (8) [37]

$$k_0 = \left(\frac{-\pi^2 D_{\text{eff}}}{4L^2}\right) \tag{8}$$

Activation energy reflects the minimum energy required to facilitate moisture movement from the interior to the surface (moisture diffusion). Based on the Arrhenius equation, activation energy (E_a) is necessary for kinetic modelling of mass transfer during the drying process, Equation (9) [35].

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{9}$$

4 Drying Methodologies and Optimised Parameters of Medicinal Plants

In addition to drying methodologies such as sun, shade and convective tray drying, advanced technologies such as freeze drying, vacuum drying, microwave drying, infrared drying and hybrid drying methods such as hybrid solar drying and osmo-convective drying have been explored. It could be observed from the table that optimal drying temperature typically ranged between 50–70 °C and most drying occurred in the falling rate period. While tray drying has been more convenient and effective than sun and shade drying with shorter drying time [38], microwave drying is notable for better colour retention and rapid drying [39]. Freeze drying ensures maximum preservation of heat-sensitive compounds but is energy and time-intensive [11].

Blanching as a pre-treatment strategy is also found to lower the activation energy and improve moisture diffusivity [40]. Hybrid dryers improved the energy efficiency, thus leading to shorter payback time [36]. It has also been found that pre-treatment strategies like ultra-sonication, osmosis, and microwave radiation improve the drying efficiency by altering the organizational microstructure of the plant material, favoring the internal diffusion of water to the surface. Herbal materials are highly variable in thermal sensitivity, internal structure, and moisture diffusion characteristics, each of which plays an important role in determining how they react to drying conditions. Hence, factors like drying temperature, airspeed, relative humidity, and pretreatment protocols have to be adjusted to the individual plant specifications of each herb to maximize the retention of bioactive compounds [31]. Table 1 summarizes the research conducted on various drying methodologies of the most prioritised species of medicinal plants with high therapeutic significance.

5 Effects of Drying Methodology and Process Parameters on the Bioactive Compounds of Medicinal Plants

Wet material drying is a complicated, dynamic, unstable, extremely non-linear, and multivariable thermodynamic process, the mechanisms of which are not fully understood. The drying process's complexity is exacerbated by simultaneous transient coupled momentum, heat, and mass transfers, multiple phase transformations, time-dependent physical, chemical, and structural changes in the product being dried, significant biochemical and chemical reactions and erratic component migration [71]. Lower air-drying temperatures (~60 °C) lead to prolonged drying times and loss of phenolic components due to oxygen oxidation.

Table 1: Effect of drying methodologies and process parameters on the drying kinetics of medicinal plants.

No.	Botanical Name	Therapeutic Significance	Drying Method	Interpretation
1.	*Aegle marmelos linn. Corr (*Bael pulp*)*	Aids digestion. Exhibits antioxidant, anti-inflammatory and anti-diabetic properties	Sun, hot air, cabinet tray drying at 60, 70 °C	Cabinet drying at 70 °C exhibited a higher drying rate and shorter drying time (600 min) [41]
			Mechanical tray dryer at 55, 60, 65 °C	Drying occurred in the falling rate period, with 52.94% time reduction at 65 °C against 55 °C [42]
2.	*Aloe barbadensis* (Aloe vera leaves)	Anti-inflammatory, anti-ulcer activity and used to treat wounds, insect bites, eczema and psoriasis	Osmo-pretreated (10%NaCl) air drying at 55, 70 and 85 °C	Osmo convective drying at 85 °C results in higher effective moisture diffusivity [43]
			Hot air oven at 50, 60, 70, 80, 90 °C	Moisture diffusivity was maximum at 90°C with a minimum drying time of 200 min [44]
3.	*Alpinia galangai* (Sitraratha rhizomes)	Carminative, anti-diabetic, anti-oxidant, antispasmodic, antiphlogistic, and antibacterial properties	Solar dryer, natural sun drying	Solar drying at 30–55 °C showed less colour change and faster drying rate than sun drying [45]
			Tray drying with air velocities 0.25 and 0.5 m/s, temperature 45 and 75 °C, relative humidity at 15 and 70%RH	Convective drying of 2mm thick slices at 45 °C and 15% RH had better phytochemical retention drying time of 200 mins [46]
4.	*Andrographis paniculata (*Kalmegh Leaves and stem)	Exhibits anti-angiogenic, hepatoprotective, anti-platelet, and anti-diabetic potential	Vacuum drying at 40, 50, 60 °C, at absolute pressures of 10 and 30 kPa	Drying at 60 °C and 10kPa pressure was optimised. Effective diffusivity and active energy were 10–13 m^2/s and 33.4 kJ/mol [47]
			Tray dryer, de-humidified heat pump dryer (40-60 °C), freeze dryer, microwave dryer (270–720 W)	Hot water blanching for 15 s at 95 °C followed by de-humidified heat pump drying at 50 °C had the highest rehydration ratio [48]
			Shade, sun, solar, oven at 45 °C	Shade drying took 22 days to reach <10% moisture, while oven drying at 45 °C took 2 days [49]
5.	*Asparagus racemosus Willd. (*Shatavari Roots*)*	Anti-depressant, neuroprotective, immunomodulatory, anti-anxiety, cardio-protective, anti-diarrhoeal, anti-bacterial, antiparasitic, anti-epileptic, adaptogenic, antilithiatic, and anti-hepatotoxic activity	Vacuum, fluidised bed, solar, tray dryer at 40–70 °C	Vacuum drying at 50 °C exhibited maximum colour retention but high energy consumption (27kWh). Fluidised bed drying at 60 °C had the least energy consumption (4kWh) with a maximum rehydration ratio [5]
			Hybrid solar dryer and mechanical tray dryer at 50, 60, and 70 °C	The highest drying rate and least drying time of 20 h at 60 °C was observed for sliced and blanched roots than unblanched, split, or whole roots. Colour change was not significant [50]
6.	*Bacopa monnieri (L.) Pennell (*Brahmi plant)	Nerve tonic, memory enhancer, diuretic, carminative, and is prescribed for the treatment of asthma, epilepsy, and dementia	Microwave drying- 300, 600 W, hot air drying- 50, 70 °C, solar, and freeze-drying	Freeze drying showed better colour retention and the lowest water activity (0.15%) [11]
7.	*Cassia angustifolia Vahl (*Senna leaves)	A blood cleanser and diuretic used to relieve constipation and treat skin diseases	Sun, shade, LPG, cabinet dryer at 40, 50, 60 °C	LPG (CRIDA) drying is better [51]
			Shade drying and oven drying at 40, 50 and 60 °C	Oven drying of leaves and pods at 50 °C had a shorter drying time of 10 h [33]

Table 1: *(Continued)*

No.	Botanical Name	Therapeutic Significance	Drying Method	Interpretation
8.	*Chlorophytum borivilianum* (Safed Musli Roots)	Exhibits Aphrodisiac, anti-inflammatory, and immunomodulatory properties and is used to treat diabetes, arthritis, and postnatal problems	Shade (15–18°C), sun (25–30 °C), solar (40 °C) and cabinet drier (60–80°C)	Cabinet drying at 75 °C, air velocity 1.62 m/s showed maximum drying rate, minimum drying time (1.45 h) with significant retention of saponin content (0.743%) [52]
			Heat pump drying at 30, 35, 40 and 45 °C, hot air drying at 35, 40 and 45 °C	Heat pump drying at 30 °C with potassium metabisulphite was optimised based on colour retention, rehydration ratio and energy consumption [53]
9.	*Coleus barbatus* Root	Used to treat hypertension, congestive heart failure, eczema, colic, respiratory disorders, painful urination, insomnia, and convulsions	Rotary dryer (45, 55, 65 °C), Feed stock volume (50, 60, 70%)	Drying at 55 °C and 70% feedstock volume took a drying time of 450 min with effective moisture diffusivity $1.33x10^{-6} mm^2/s$ [54]
10.	*Crocus sativus Linn (*Saffron flowers)	Alleviates depression, aids digestion, improves cardiovascular health, helps treat neurodegenerative diseases, and manages menstrual cramps. The petals are effective in treating high blood pressure	Hot air oven at 55, 65, 75, 85 °C, Infra-red drying at 50–110 °C, microwave drying	Microwave drying at 1000 W optimised based on high safranal and picrocrocin content [55]
			Infra-red drying at 40, 50, 60 °C	Infrared drying at 60 °C and a distance of 10 cm from the IR source had the highest effective moisture diffusivity [56]
11.	*Garcinia indica Chois.(* Kokum rind)	Anti-inflammatory, anti-oxidant, anti-cancer potential used to treat skin ailments, ulcers and rheumatism	Open sun drying (30–35°C)	Drying time was found to be 38 h with an average convective heat transfer coefficient of 168.97 W/m^2 °C [16]
12.	*Gloriosa superba Linn (*Glory Lily beans)	Anti-inflammatory properties make it useful in treating rheumatism, arthritis, gout and various skin conditions.	Sun drying (30–45 °C) and 15–65% RH 4–6 mm thick bed	Drying happened in the falling rate period with a prolonged drying time of 2010 min [57]
13.	*Glycyrrhiza glabra Linn (*Liquorice roots)	Has anti-allergic, anti-viral, and immuno-modulatory effects and is used to treat gastric ulcers, asthma, bronchitis and arthritis	Carbon fibre assisted cabinet drying(CFACD) (50–60 °C), 46% RH, Infrared drying(ID) 362W, 185mm distance (50–60 °C)	ID had a shorter drying time(6380 min) than CFACD(7940 min), but the latter was found to be thrice as energy efficient and twice as exergy efficient as ID [58]
			Ultrasound pre-treated infrared drying (900W, 50 °C), 4 mm slice thickness	Ultrasound power of 60W, 40 kHz frequency, 30 min led to the formation of micropore channels(sponge effect), improved drying rate and reduced drying time by 18.2%. [59]
14.	*Gymnema sylvestre R. Br.(*Gudmar leaves*)*	Antioxidants, anti-diabetic, anti-inflammatory, anti-cancer, and anti-microbial properties offer a promising remedy for type I and type II diabetes mellitus	Shade drying at 25 ±5 °C, oven drying at 45 °C, freeze drying Far infrared at 125, 150, 175, 200 °C	Freeze-dried leaves showed better retention of phenolic compounds and superior antioxidant activity [60] Optimal drying condition achieved from the dissimilarity function was 200 °C for 8.4 min [61]
15.	*Emblica officinalis Gaertn (Amla fruit)*	Antioxidant, anti-diabetic, hypolipidemic and hepato-protective properties. Used to treat jaundice, malaria, hypertension and hepatitis B	Solar-assisted heat pump dryer at 35, 45, 50 °C	Heat pump drying at 50 °C improved ascorbic acid content by 88% and drying time reduced from 8 days to 18 h compared to open sun drying [38]
			Tray drying at 50, 60, 70 °C	Shorter drying time of 11 h at 70 °C and air velocity 1.5 m/s was observed. Drying happened in the falling rate period [62]
16.	*Nardostachys jatamansi DC. (*Jatamansi roots)	Exhibits antimalarial, antinociceptive, and cytotoxic activities.	Shade drying (22–34 °C) and oven drying(60 °C)	Shade drying was found to be economical and showed better retention of volatile compounds[63]

Table 1: *(Continued)*

No.	Botanical Name	Therapeutic Significance	Drying Method	Interpretation
17.	*Ocimum sanctum Linn.* (Tulsi leaves)	Antimicrobial, an antiviral, antioxidant used to treat acne, eczema, and other skin conditions.	Microwave drying at 136, 264, 440, 616W	Microwave power of 264W for 320 s reduces the drying time and improves energy efficiency [39]
			Freeze drying and Microwave drying at 300, 450, 600, 800W	Microwave drying at 800W had the highest drying rate, the least drying time (4.2 min) and moisture diffusion 1000 times that of freeze drying [64]
			Hybrid Solar Dryer at 40,50 and 60°C and bed thickness 2, 4 and 6 cm	Drying at 60 °C with a 2 cm bed thickness had a maximum drying rate of 0.27 kg/min and exergy efficiency of 65.75% [43]
18.	*Phyllanthus amarus* (*Bhumi amlaki* flowers, leaves and stem)	Aids in liver detoxification and has antioxidant, antiviral, and anti-inflammatory properties	Hot air drying at 50, 60, 70 °C	Increasing the drying temperature from 50 to 70 °C improved moisture diffusivity and reduced drying time by 57% [65]
			Hot-air HA (80, 100, 120 °C), low temperature-air LTA (25, 30, 35 °C), infrared IR (30, 35, 40 °C), microwave MW (200, 400, 600 W), sun (35.4 ± 1 °C) and vacuum drying VD (70, 80 °C)	MWD has the shortest drying time of 0.15 to 1.5 h, while LTAD at 25 °C takes the longest, at 23.75 hrs. LTAD at 35 °C gives the highest drying yield, while VD at 70 °C yields the lowest. IRD at 40 °C provides the highest extraction yield [10]
19.	*Piper longum Linn* (Fruit)	As a major ingredient in Trikatu, it is used to treat digestive issues, minor respiratory ailments, and bronchitis.	Sun drying (34–37 °C), Tray drying at 40, 50, 60 °C with 0.8 m/s air velocity	Drying occurred in a falling rate period and the maximum drying rate was observed when dried at 80 °C for 180 min [66]
20.	*Solanum nigrum Linn* (Makoy seeds).	Has hepatoprotective, anti-inflammatory, antipyretic and antioxidant properties	Solar-exhaust gas greenhouse dryer, 10–40% RH, Temperature 40–60 °C	A falling rate was observed with a drying time of 10 h for solar-exhaust gas mode and 11 hours for solar mode alone [67]
21.	*Tinospora cordifolia Miers (*Giloy stem)	Anti-inflammatory, anti-diabetic, hepatoprotective and immunomodulatory properties. Treat fever, jaundice, diabetes, urinary problems, and skin diseases	Convective tray drying at 40, 50, 60 °C and air flow rate of 1, 1.5 and 2 m/s	Maximum drying rate was achieved at 60 °C and 2 m/s air velocity, while the lowest was at 40 °C and 1 m/s air velocity [68]
22.	*Withania somnifera* (*Linn.*) *Dunal (*Ashwagandha root)	Ashwagandha roots are used to treat tumours, inflammation, arthritis, anaemia, breathing difficulties, insomnia, paralysis, and ulcers	Convective drying at 40, 50, 60 °C	Convective drying at 50 °C with 1.5m/s air velocity had better colour retention, rehydration ratio and alkaloid content 65.6% higher compared to sun drying [69]
			Tray drying at 45, 50, 55 °C	Tray drying at 45–55 °C is more efficient than shade drying and moisture removal occurs in falling rate period [70]

Higher air-drying temperatures (over 60 °C) reduced phenolic compound concentration due to thermal degradation [65]. Under certain drying circumstances, glandular trichomes—cells on the plant's surface that hold essential oils rupture and release the oils [72]. Observation of Table 1 indicates that freeze-drying always yields maximum compound retention for thermosensitive herbs such as *Bacopa monnieri* and *Gymnema sylvestre*. In contrast, in cases of herbs, such as *Aegle marmelos* and *Tinospora cordifolia*, convective tray drying at moderate temperatures (50–60 °C) strikes a balance between drying efficiency and phytochemical preservation. *Ocimum sanctum* exhibited inconsistent aromatic compound release between microwave and freeze-drying [52]. These inconsistencies are likely due to the differential microstructure and moisture diffusion properties inherent in plant structures such as roots, stems, and leaves. Hence, the choice of drying process must be customized to the anatomical and chemical makeup of the herb. It has also been studied that the integrity of the cell structure strictly influences the retention of active compounds. In a study, drying *Phyllanthus amarus* under multiple drying conditions showed that infrared drying at 30 °C despite having a higher dying time of 22 h, showed maximum retention of phenolic compounds (63.64 mg GAE/g), flavonoids (41.81 mg RE/g), pro-anthocyanidins (16.89 mg CE/g) and saponins (250.34 mgEE/g) compared to hot air, low temperature, microwave, solar and vacuum drying [10]. Freeze-drying was the most effective method for producing superior dried *B. monnieri*, yielding samples with the least overall color difference (11.415%), and the maximum content of triterpenoid saponins bacoside A (3.389%) as well as bacopaside I (0.620%) compared to microwave, solar and hot air drying [11]. Bacosides have renowned pharmacological activities, including neuroprotective, cognitive-enhancing properties [11]. Far-infrared drying at 200 °C for 15 min of *Gymnema sylvestre* had the maximum phenolic content (30.5 mg TAE/g) than lower temperatures such as 125, 150 and 175 °C. Although medicinal plant parts have high moisture content, it has been evident that most of them have no constant rate period and they usually dry in the falling rate period. In drying *Andrographis paniculata* it has been found that shade drying had the highest concentration of the diterpene lactone - andrographolide (2.18%), followed by sun drying (1.86%), and the least in oven-dried samples (1.74%) [49]. In another study, hot water blanching at 95–98 °C for 15 s followed by heat pump drying resulted in maximum retention of andrographolide [48]. In a study on *Chlorophytum borivilianum*, shade drying (15–18 °C) has shown maximum retention of saponin content (0.983%) while cabinet drying at 90 °C with air velocity 1.88m/s had the least saponin content (0.308%). In another study, microwave-dried tulsi leaves had exhibited better release of aromatic compounds carophyllene, β-Myrcene and (-)-calamenene, while in the case of freeze dried leaves eugenol, borneol and isoeugenol were released better [64]. Drying *Alpinia galangal* at lower temperature (45 °C) and 15% RH showed maximum retention of the active compound 1’-acetoxychavicol acetate [46]. It has been recorded that oven dried samples of *Cassia angustifolia* leaves and pods at 40 and 50 °C, respectively, possessed the highest content of the anthraquinone glycoside – sennosides [33]. Open sun drying of *Garcinia indica Chois*, for a drying time of 38 h, decreased the anthocyanin content by 54.8% due to thermal and photo-oxidation [16]. Carbon filter-assisted cabinet drying of *Glycyrrhiza glabra Linn.* (licorice) roots showed higher phenolic content (11.24 g/kg dry matter) than infrared drying (9.26 g/kg dry matter) [58]. In another study on ultrasound pre-treated infrared drying of licorice roots at 50 °C, it has been observed that ultrasound treatment time of 40 min increased the licorice glycosides by 50% while increasing the ultrasound power from 40 to 60W increased the glycyrrhetinic acid, rutin and liquiritin content compared to control without ultrasound pretreatment [59]. Oven-dried *Nardostachys jatamansi DC.* at 60 °C showed greater release of the essential oil compound patchouli alcohol while carophyllene oxide was present in higher concentration in shade dried samples [63]. In a study, rotary drying of *Coleus barbatus* roots of 2.5 mm thickness at 55 °C with 70% feedstock volume showed maximum retention of the active compound forskolin, a labdane triterpene used to treat conditions like high blood pressure [54].

6 Drying Kinetics Modelling of Medicinal Plants

Kinetic modelling is important in drying operations as it allows for the quantitative description of biological and physical interactions. It aids in the understanding of fundamental reaction mechanisms, which are necessary for quality modelling and control. Understanding thermodynamics and kinetics is critical for comprehending reaction progression since the rate of a reaction is governed by driving force and resistance [73].

Drying models are classified as first-generation, second-generation, third-generation, fourth-generation, and fifth-generation models. To reduce computing complexity, data-driven modelling, such as machine learning (ML), can be used in food drying applications. ML-based techniques can accurately simulate complex heat and mass transfer processes and forecast drying kinetics [74]. The generations and classification of drying models are represented in Figures 2 and 3. Although they lack a physical foundation, empirical models—which are solely based on experimental data—are straightforward and useful for creating drying kinetics. Whereas theoretical models are grounded in physics and are based on the concepts of mass and heat transport. The complex nature of agricultural products, the dynamic thermo-physical qualities involved, and the closely connected heat and mass transport processes during drying make developing theoretical models challenging [75].

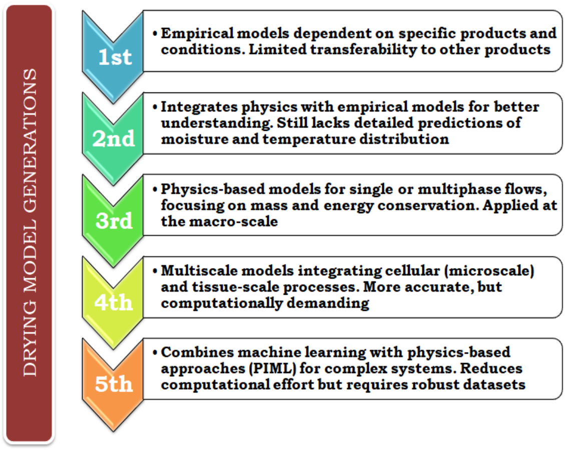

Figure 2: Different generations of drying models, its scope and limitations.

In order to evaluate and select the best-fit model for different drying methods under different drying conditions, statistical analysis plays a crucial role. The accuracy and reliability of a model depend on its fit to the observed experimental data. Thus, model evaluation involves the comparison of predicted outcomes against experimental data using defined statistical parameters. Table 2 presents the statistical measures that are employed in evaluating the fitted model [73].

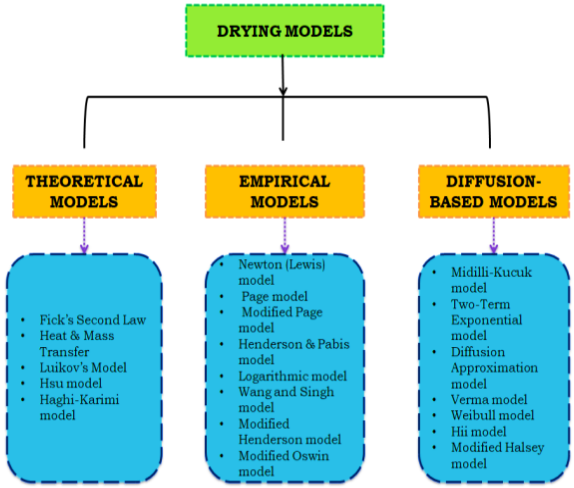

Figure 3: Classification of drying models based on the underlying principle as theoretical, empirical and diffusion-based.

Table 2: Statistical parameters for evaluation of drying models.

Parameter	Formulae	Range and Best fit Condition	Interpretation
Correlation coefficient (R)	$R = \frac{\sum_{i=1}^{N} (\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\exp,\mathrm{ave}})(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{pre,ave}})}{\sqrt{\sum_{i=1}^{N} (\mathrm{MR}_{\exp} - \mathrm{MR}_{\exp,\mathrm{ave}})^2 \sum_{i=1}^{n} (\mathrm{MR}_{\mathrm{pre}} - \mathrm{MR}_{\mathrm{pre,ave}})^2}}$	+1 to -1; If value is 1 indicates perfect positive correlation	Correlation or linear dependence between two variables
Coefficient of determination (R^2)	$R^2 = 1 - \frac{\sum (MR_{exp,i} - MR_{pred,i})^2}{\sum (MR_{exp,i} - \overline{M}R_{exp})^2}$	0 to 1; Value close to 1	Degree to which the model accounts for variability in dataset
Root mean square error	$RMSE = [\frac{1}{n}\sum_{i=1}^{N}(MR_{exp,i} - MR_{\mathrm{pred},i})^2]^{\frac{1}{2}}$	0 to ∞; Value close to 0	Average deviation between experimental and predicted values
Mean Bias Error	$MBE = \frac{\sum (MR_{exp,i} - MR_{pred,i})}{N}$	- ∞ to + ∞; Value close to 0	Average bias between observed and predicted values
Reduced Chi-Square	$\chi^2 = \frac{\sum (MR_{exp,i} - MR_{pred,i})^2}{N - n}$	0 to ∞; Value close to 0	Goodness of fit correlated with degrees of freedom
Model Efficiency	$\mathrm{EF} = \frac{\sum_{i=1}^{N} (\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\exp,\mathrm{ave}})^2 - \sum_{i=1}^{N} (\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\exp,i})^2}{\sum_{i=1}^{N} (\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\exp,\mathrm{ave}})^2}$	- ∞ to 1; Value close to 1	Relative accuracy in comparison to the mean prediction

In the kinetic modelling studies, drying methods and the drying parameters influence the moisture ratio [73]. Table 3 presents the kinetic modelling of medicinal plants showing specific drying behaviour due to the botanical characteristics and the drying technique applied. The models combined as Page, Henderson & Pabis, and modified models reflect the complexity involved in the mechanisms for the removal of moisture from the different materials found in a plant. Maximum application of the Page model, particularly of convective drying, suggests a good adequacy for describing an exponential decrease of moisture content [44], [62], [70]. Meanwhile, the Modified Halsey model for heat pump drying hints at some modifications that should be taken into account, special dynamics of moisture removal under different humidity conditions [48]. Surface diffusion is the critical diffusion mechanism for the early stages of drying. Liquid and vapour diffusion become more significant in later stages. It could also be observed that the plant material's microstructure also impacts the moisture diffusion dynamics. The Midlli model is most best fit for plant parts like roots, fruits and petals than leaves, suggesting that it can best reflect the complex mass diffusion patterns [53], [56], [66]. Novel drying methods like carbon fibre-assisted cabinet drying align with the Verma model that takes heat distribution into account [58].

Table 3: Best-fit models of medicinal plants and their relevant model equations.

S.No.	Botanical Name	Drying Method	Best Fit Model	Model Equation
1	*Emblica officinalis Gaertn* (Fruit)	Solar assisted heat pump drying	Henderson & Pabis model [38]	MR = e^{-kt}
		Convective tray drying	Page model [62]	MR = e^{-kt^n}
2	*Withania somnifera* (Root)	Convective tray drying	Modified page model [70]	MR = $e^{-(kt)^n}$
3	*Crocus sativus* (Petals)	Infra-red drying	Midilli model [56]	MR = $e^{-kt^n}+bt$
4	*Asparagus racemosus* (Roots)	Hybrid solar dryer	Page model [50]	MR = e^{-kt^n}
5	*Ocimum sanctum Linn* (Leaves)	Microwave drying	Hii model[39]	MR= a $e^{-k_1 t}$+ b$e^{-k_2 t}$
6	*Aloe barbadensis* (Leaves and gel)	Osmo convective drying	Logarithmic model [36]	MR = a $e^{-kt}+b$
		Convective tray drying	Page model [44]	MR = e^{-kt^n}
7	*Andrograophis paniculata* (Leaves and stem)	Vacuum drying	Two-term model [47]	MR = $a\, e^{-kt} + b\, e^{-k_0 t}$
		De-humidified heat pump dryer	Modified Halsey model [48]	MR = $e^{-(kt)^b}$
8	*Picrorhiza kurroa Benth ex Royle.* (Rhizomes)	Convective drying	Midilli model [76]	MR = $e^{-kt^n}+bt$
9	*Glorisa superba* (Beans)	Sun drying	Wang and Singh model [57]	MR= 1+ at+ bt^2
10	*Piper longum linn* (Fruit)	Tray drying	Midilli model [66]	MR = $e^{-kt^n}+bt$
11	*Chlorophytum borivilinum* (Roots)	Tray drying	Two-term model [53]	MR = $a\, e^{-kt} + b\, e^{-k_0 t}$
		Heat pump drying	Logarithmic model [53]	MR = a $e^{-kt}+b$
12	*Garcinia indica* (Rind)	Open sun drying	Henderson and Pabis model [16]	MR = e^{-kt}
13	*Glycrriha glabra linn* (Roots)	Carbon fiber assisted cabinet drying	Verma model [58]	MR = $a\, e^{-kt} + (1-a)\, e^{-gt}$
		Infrared drying	Page model [58]	MR = e^{-kt^n}
14	*Solanum nigrum* (Seeds)	Solar-exhaust gas drying	Logarithmic model [67]	MR = a $e^{-kt}+b$
		Microwave drying, Hot air drying	Modified Henderson and Pabis model [77]	MR= $a\, e^{-kt} + b\, e^{-gt} + c\, e^{-ht}$

Note: k- drying constant; n- model exponent; a, b, c- scaling factors; g, h –additional rate constant.

7 Challenges and Future Directions

Drying is a critical post-harvest process for the preservation of medicinal plants by reducing the moisture content, preventing microbial growth and extending their shelf life. However, several challenges persist in drying and it is majorly concerned with sun drying. The color of the sun-dried amla was darker and the vitamin C content loss was greater. The microbial load was found to be higher in sun dried amla than heat pump dried one [38]. Another main factor is the temperature control, where the bioactive compounds of plants like Ashwagandha are sensitive to high temperatures, resulting in loss of bioactive compounds [70]. Similarly, the freeze-drying method used for the preservation of bioactive compounds in *Bacopa monnieri* was found to be effective but costly and time-consuming [11]. In addition to this, energy consumption remains a problem, which can be overcome by the application of techniques like FIR and microwave-assisted drying (MAD), but must be precisely controlled. The plant's initial moisture content and microstructure significantly affect microwave absorption and upcoming research must focus on energy-efficient technologies like vacuum-assisted microwave drying and its effect on the stability of heat-labile essential oils and bioactive compounds [6]. To overcome the challenges faced by existing drying techniques, several new energy-efficient systems are emerging. It has a wide potential application for the drying of medicinal plants. Electro-hydrodynamic drying that involves corona wind generated by high voltage electric current consumes less energy but delivers products of superior quality and radio frequency drying that involves electromagnetic field, which causes dielectric heating and ionic rotation, remains unexplored in terms of medicinal plants drying, are some examples [78]. Apart from these methods, new hybrid dehydration technologies are being developed. Novel drying technologies are needed to retain the high quality of the product and increase the efficiency of the process. Freeze drying can be modified by incorporating emerging drying techniques to produce ingredients for functional food development. Osmotic pre-treatment can be employed to overcome this. Combined techniques are advisable for high-quality retention [36]. Of the 32 prioritized species given by the National Medicinal Plant Board of India, there are limited to no insights on the drying methodology and kinetics of the following medicinal plants: *Saraca asoca (Roxb.) de Wilde, Aconitum heterophyllum Wall. ex Royle, Santalum album Linn, Swertia chirata Buch-Ham, Commiphora wightii (Arn.) Bhandari, Plantago ovata Forsk, Saussurea costus C. B. Clarke (S.lappa), Berberis aristata DC., Rauwolfia serpentina Benth. ex Kurz., Embelia ribes Burm. f., Aconitum ferox Wall.* This is a research gap that needs to be addressed to ensure that the correct drying methodology with optimized parameters that ensure maximum retention of the bioactive compounds of therapeutic significance is identified. Also, certain advanced drying strategies, such as refractive window drying and radio frequency drying and modelling techniques like integrating artificial neural networks in drying data analysis remain unexplored in the context of these medicinal plants.

8 Conclusions

This review highlights various drying techniques and kinetic modelling of the prioritized Indian medicinal plants. The effect of process parameters and drying methodology on the bioactive compounds based on their stability is focused on. It is found that the commonly used drying techniques are low-temperature convective drying, microwave drying and sun drying. Selection of an appropriate drying technique is crucial for proceeding with further processing conditions, which rely on consistent drying temperature and drying time, optimum moisture content and consistent drying rate. Novel drying techniques can significantly improve the quality and bioavailability of active compounds. However, it requires a high initial capital cost. Suitable drying kinetics are to be established in an industrial setup to perform drying operations in a continuous manner. Products with superior quality and market value can be produced by combining multiple drying techniques and studying the best-fit model to attain maximum energy efficiency and better retention of bioactive compounds. In conclusion, to improve process efficiency and product quality, future research should improve the existing models and investigate cutting-edge smart drying technologies that integrate real-time sensors and energy efficient hybrid drying technologies while taking bioactive compound retention and kinetic behaviour into account.

Author Contributions

K.S.: conceptualization, investigation, reviewing and editing; M.K.: investigation, methodology, writing an original draft; H.S.: research design, data analysis; V.K.: conceptualization, data curation, writing—reviewing and editing; V.T.: writing—reviewing and editing; N.D.G.: reviewing and administration. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] M. Prasathkumar, S. Anisha, C. Dhrisya, R. Becky, and S. Sadhasivam, "Therapeutic and pharmacological efficacy of selective Indian

medicinal plants – A review," *Phytomedicine Plus*, vol. 1, no. 2, May 2021, doi: 10.1016/j.phyplu.2021.100029.

[2] R. Panmei, P. R. Gajurel, and B. Singh, "Ethnobotany of medicinal plants used by the Zeliangrong ethnic group of Manipur, northeast India," *Journal of Ethnopharmacology*, vol. 235, pp. 164–182, May 2019, doi: 10.1016/j.jep.2019.02.009.

[3] B. R. Rao and D. Rajput, "Global Scenario of medicinal plants." csii.res.in. Accessed: Jan 10, 2025. [Online.] Available: http://www.csii.res.in

[4] T. S. S. B. Rao and S. Murugan, "Solar drying of medicinal herbs: A review," *Solar Energy*, vol. 223, pp. 415–436, Jul. 2021, doi: 10.1016/j.solener.2021.05.065.

[5] D. Kohli, P. S. Champawat, S. K. Jain, V. D. Mudgal, and N. C. Shahi, "Mathematical modelling for drying kinetics of asparagus roots (*Asparagus racemosus l.*) and determination of energy consumption," *Biointerface Research in Applied Chemistry*, vol. 12, no. 3, pp. 3572–3589, 2022, doi: 10.33263/BRIAC123.35723589.

[6] J. Müller and A. Heindl, "Drying of medicinal plants," in *Medicinal and Aromatic Plants: Agricultural, Commercial, Ecological, Legal, Pharmacological and Social Aspects*, New York: Springer, 2006, pp. 237–252.

[7] C. Kumar and M. A. Karim, "Microwave-convective drying of food materials: A critical review," *Critical Reviews in Food Science and Nutrition*, vol. 59, no. 3, pp. 379–394, 2019.

[8] S. V. Gupta and N. Patil, "Convective drying of osmo-dehydrated sapota slice," *International Journal of Agricultural and Food Science*, vol. 5, no. 3, pp. 219–226, 2014.

[9] A. Waman and P. Bohra, "Sustainable development of medicinal and aromatic plants sector in India: An overview," *Science and Culture*, vol. 82, pp. 245–250, Jan. 2016.

[10] V. T. Nguyen, Q. V. Vuong, M. C. Bowyer, I. A. V. Altena, and C. J. Scarlett, "Effects of different drying methods on bioactive compound yield and antioxidant capacity of *Phyllanthus amarus*," *Drying Technology*, vol. 33, no. 8, pp. 1006–1017, Jun. 2015, doi: 10.1080/07373937.2015.1013197.

[11] B. M. Padhiari, A. Ray, S. Jena, B. B. Champati, A. Sahoo, T. Halder, B. Ghosh, P. C. Panda, and S. Nayak, "Effect of different drying treatments on the physicochemical, functional, and antioxidant properties of *Bacopa monnieri*," *BioTechnologia*, vol. 102, no. 4, pp. 399–409, 2021, doi: 10.5114/bta.2021.111105.

[12] Z. Y. Gnativ, O. S. Ivashchuk, Y. M. Hrynchuk, V. V. Reutskyi, I. Z. Koval, and Y. Z. Vashkurak, "Modeling of internal diffusion mass transfer during filtration drying of capillary-porous material," *Mathematical Modeling and Computing*, vol. 7, no. 1, pp. 22–28, 2020, doi: 10.23939/mmc2020.01.022.

[13] F. H. C. Vera, A. N. Soriano, N. P. Dugos, and R. V. C. Rubi, "A comprehensive review on the drying kinetics of common tubers," *Applied Science and Engineering Progress*, vol. 14, no. 2, pp. 146–155, Apr. 2021, doi: 10.14416/j.asep.2021.03.003.

[14] A. Kamarulzaman, M. Hasanuzzaman, and N. A. Rahim, "Global advancement of solar drying technologies and its future prospects: A review," *Solar Energy*, vol. 221, pp. 559–582, Jun. 2021, doi: 10.1016/j.solener.2021.04.056.

[15] A. Jha and P. P. Tripathy, "Recent advancements in design, application, and simulation studies of hybrid solar drying technology," *Food Engineering Reviews*, vol. 13, no. 2, pp. 375–410, Jun. 2021, doi: 10.1007/s12393-020-09223-2.

[16] A. R. Hande, S. B. Swami, and N. J. Thakor, "Open-air sun drying of kokum (*Garcinia indica*) rind and its quality evaluation," *Agricultural Research*, vol. 5, no. 4, pp. 373–383, 2016.

[17] A. C. Iwansyah, T. D. Manh, Y. Andriana, M. A Hessan, F. Kormin, D. X. Cuong, N. X. Hoan, H. T. Ha, D. T. Yen, P. V. Thinh, and L. T. Hai, "Effects of various drying methods on selected physical and antioxidant properties of extracts from *Moringa oliefera* leaf waste," *Sustainability*, vol. 12, no. 20, pp. 8586–8586, Oct. 2020, doi: 10.3390/su12208586.

[18] L. Wiset, N. Poomsa-ad, H. Jindamol, A. Thongtip, K. Mosaleeyanon, T. Toojinda, C. T. Darwell, T. B. Saputro, and P. Chutimanukul, "Quality and bioactive compound accumulation in two holy basil cultivars as affected by microwave-assisted hot air drying at an industrial scale," *Frontiers in Sustainable Food Systems*, vol. 7, 2023, Art. no. 1219540, doi: 10.3389/fsufs.2023.1219540.

[19] A. Al-Hamdani, H. Jayasuriya, P. B. Pathare, and Z. Al-Attabi, "Drying characteristics and quality analysis of medicinal herbs dried by an indirect

solar dryer," *Foods*, vol. 11, no. 24, pp. 4103–4103, Dec. 2022, doi: 10.3390/foods11244103.

[20] M. R. Wylie and D. S. Merrell, "The antimicrobial potential of the neem tree *Azadirachta indica*," *Frontiers in Pharmacology*, vol. 13, pp. 891535-891535, May 2022, doi: 10.3389/fphar.2022.891535.

[21] K. M. Manju, Rekha, Priyanka, and N. Kumar, "Effect of fluidized-bed and freeze-drying techniques on physicochemical, nutritional, thermal, and structural properties of *Moringa oleifera* flowers, leaves, and seeds," *Journal of Food Processing and Preservation*, vol. 45, no. 9, pp. 15719–15719, Sep. 2021, doi: 10.1111/jfpp.15719.

[22] A. Sozzi, M. Zambon, G. Mazza, and D. Salvatori, "Fluidized bed drying of blackberry wastes: Drying kinetics, particle characterization and nutritional value of the obtained granular solids," *Powder Technology*, vol. 385, pp. 37–49, Jun 2021.

[23] A. Korkmaz, E. Arslan, and M. Koşan, "Volatile compounds, bioactive properties and chlorophyll contents in dried spearmint (*Mentha spicata L.*) as affected by different drying methods," *Journal of Agricultural Sciences*, vol. 29, no. 2, pp. 604–617, 2023.

[24] A. K. Senapati, P. S. Rao, and S. Prasad, "Optimization of process parameters for convective-microwave drying of ashwagandha roots," *International Journal of Engineering Research and Applications,* vol. 4, pp. 168–189, 2014.

[25] D. Wray and H. S. Ramaswamy, "Novel concepts in microwave drying of foods," *Drying Technology*, vol. 33, no. 7, pp. 769–783, May 2015, doi: 10.1080/07373937.2014.985793.

[26] J. Branisa, K. Jomova, M. Porubska, V. Kollar, M. Simunkova, and M. Valko, "Effect of drying methods on the content of natural pigments and antioxidant capacity in extracts from medicinal plants: A spectroscopic study," *Chemical Papers*, vol. 71, no. 10, pp. 1993–2002, Oct. 2017, doi: 10.1007/s11696-017-0193-9.

[27] K. Ç. Selvi, A. Kabutey, G. A. K. Gürdil, D. Herak, Ş. Kurhan, and P. Klouček, "The effect of infrared drying on color, projected area, drying time, and total phenolic content of rose (*Rose electron*) petals," *Plants*, vol. 9, no. 2, pp. 236–236, Feb. 2020, doi: 10.3390/plants9020236.

[28] K. Krishnamurthy, H. K. Khurana, J. Soojin, J. Irudayaraj, and A. Demirci, "Infrared heating in food processing: An overview," *Comprehensive Reviews in Food Science and Food Safety*, vol. 7, no. 1, pp. 2–13, Jan. 2008, doi: 10.1111/j.1541-4337.2007.00024.x.

[29] X. Huang, W. Li, Y. Wang, and F. Wan, "Drying characteristics and quality of *Stevia rebaudiana* leaves by far-infrared radiation," *LWT*, vol. 140, 2021, Art. no. 110638.

[30] W. Ma, Z. Zang, B. Wu, G. Ma, F. Wan, Y. Xu, and X. Huang, "Effect of radio frequency vacuum drying on drying characteristics and physicochemical quality of *Codonopsis pilosula* slices," *Agriculture*, vol. 14, no. 9, pp. 1495, 2024.

[31] C. Acar, I. Dincer, and A. Mujumdar, "A comprehensive review of recent advances in renewable-based drying technologies for a sustainable future," *Drying Technology*, vol. 40, no. 6, pp. 1029–1050, 2022.

[32] N. Cunha, L. H. M. Silva, and A. M. C Rodrigues, "Drying of *Curcuma longa L.* slices by refractance window: Effect of temperature on thermodynamic properties and mass transfer parameters," *Heat and Mass Transfer*, vol. 60, no. 4, pp. 617–626, 2024.

[33] A. N. Kumar, A. Sneha, K. S. Srinivas, G. K. Babu, J. K. Kumar, M. V. Kumar, A. C. Jnanesha, and K. Vinutha,"Optimisation of harvesting time and drying techniques for higher sennosides in *Cassia angustifolia Vahl.* by RP-HPLC," *Industrial Crops and Products*, vol. 197, pp. 116591–116591, Jul. 2023, doi: 10.1016/j.indcrop.2023.116591.

[34] U. E. Inyang, I. O. Oboh, and B. R. Etuk, "Kinetic models for drying techniques—food materials," *Advances in Chemical Engineering and Science*, vol. 08, no. 02, pp. 27–48, 2018, doi: 10.4236/aces.2018.82003.

[35] D. S. A. Delfiya, K. Prashob, S. Murali, P. V. Alfiya, M. P. Samuel, and R. Pandiselvam, "Drying kinetics of food materials in infrared radiation drying: A review," *Journal of Food Process Engineering*, vol. 45, no. 6, pp. 13810-13810, Jun. 2022, doi: 10.1111/jfpe.13810.

[36] M. Moradi, M. Niakousari, and A. M. Khaneghah, "Kinetics and mathematical modeling of thin layer drying of osmo-treated aloe vera (*Aloe barbadensis*) gel slices," *Journal of Food Process Engineering*, vol. 42, no. 6, pp.

13180–13180, Oct. 2019, doi: 10.1111/jfpe. 13180.45.
[37] J. Crank, *The Mathematics of Diffusion*. Oxford, UK: Clarendon Press, 1975, p. 414.
[38] P. L. Singh and S. Singh, "Amla (*Emblica officinalis*) drying in solar-assisted heat pump dryer," *International Energy Journal*, vol. 12, no. 4, pp. 253–262, Dec. 2011.
[39] H. S. Kusuma, D. N. Izzah, and I. W. L. Linggajati, "Microwave-assisted drying of *Ocimum sanctum* leaves: Analysis of moisture content, drying kinetic model, and techno-economics," *Applied Food Research*, vol. 3, no. 2, Dec. 2023, Art. no. 100337, doi: 10.1016/j.afres. 2023.100337.
[40] N. B. Ma, T. T. H. Le, and N. L. Le, "Drying kinetics, rehydration behavior and morphological properties of pre-blanched thai basil leaves," *Applied Science and Engineering Progress*, vol. 15, no. 4, 2022, Art. no. 5557.
[41] V. Chaudhary, V. Kumar, B. R. Singh, J. Singh, N. Chauhan, and P. Kumar, "Drying characteristics of bael pulp using different drying methods and different varieties," *International Journal of Agricultural Engineering*, vol. 13, no. 1, pp. 19–30, Apr. 2020, doi: 10.15740/HAS/IJAE/ 13.1/19-30.
[42] A. Sharma, P. S. Champawat, S. Suman, K. Meghwal, and N. Prajapat, "Drying characteristics of bael fruit (*aegle marmelos*) pulp in mechanical tray dryer," *International Journal of Current Microbiology and Applied Sciences*, vol. 9, no. 8, pp. 922–935, Aug. 2020, doi: 10.20546/ijcmas.2020.908.100.
[43] Z. Parhizi, H. Karami, I. Golpour , M. Kaveh, M. Szymanek, A.M.B Marigorta, J. D. Marcos, E. Khalife, S. Skowron, N. A. Othman, and Y. Darvishi, "Modeling and optimization of energy and exergy parameters of a hybrid-solar dryer for basil leaf drying using RSM," *Sustainability*, vol. 14, no. 14, pp. 8839–8839, Jul. 2022, doi: 10.3390/su14148839.
[44] A. Vega, E. Uribe, R. Lemus, and M. Miranda, "Hot-air drying characteristics of aloe vera (*Aloe barbadensis Miller*) and influence of temperature on kinetic parameters," *LWT - Food Science and Technology*, vol. 40, no. 10, pp. 1698–1707, Dec. 2007, doi: 10.1016/j.lwt.2007. 01.001.
[45] P. Nimnuan and S. Nabnean, "Solar drying of galangal slices (*Alpinia Galangal (Linn.) Swartz.*) using household solar dryer," *Suranaree Journal of Science and Technology,* vol. 27, no. 4, pp. 1–8, Dec. 2020.
[46] A. Namkanisorn and S. Murathathunyaluk, "Sustainable drying of galangal through combination of low relative humidity, temperature and air velocity," *Energy Reports*, vol. 6, pp. 748–753, Feb. 2020, doi: 10.1016/ j.egyr.2019.11.150.
[47] Y. Y.Hee and G. H. Chong, "Drying behaviour of *Andrographis paniculata* in vacuum drying," *International Food Research Journal*, vol. 22, no. 1, p. 393, 2015
[48] C. Tummanichanont, S. Phoungchandang, and G. Srzednicki, "Effects of pretreatment and drying methods on drying characteristics and quality attributes of *Andrographis paniculata*," *Journal of Food Processing and Preservation*, vol. 41, no. 6, Dec. 2017, Art. no. e13310, doi: 10.1111/jfpp.13310.
[49] G. R. Smitha, N. A. Gajbhiye, and V. Tripathy, "Influence of drying methods and packaging materials on physico-chemical properties and phytochemical composition of Kalmegh [*Andrographis paniculata (Burm. f.) Wall. ex Nees]* for shelf life enhancement," *Medicinal Plants-International Journal of Phytomedicines and Related Industries*, vol. 12, no. 2, p. 227, 2020, doi: 10.5958/0975-6892.2020.00030.1.
[50] B. K. Bala, M. A. Hoque, M. A. Hossain, and M. B. Uddin, "Drying characteristics of asparagus roots (*Asparagus racemosus wild.*)," *Drying Technology*, vol. 28, no. 4, pp. 533–541, Apr. 2010, doi: 10.1080/07373931003618899.
[51] G. Pratibha, I. Srinivas, K. S. Rao, K. Swathi, and C. S. Rao, "Effect of different drying methods on quality and economics of senna (*Cassia angustifolia Vahl.*)," *Indian Journal of Dryland Agricultural Research and Development*, vol. 33, no. 2, pp. 50–50, 2018, doi: 10.5958/ 2231-6701.2018.00020.9.
[52] R. Agrawal, A. Upadhyay, and P. Sagar Nayak, "Drying characteristics of safed musli (*Chlorophytum borivilianum*) and its effect on colour and saponin content," *Journal of Pharmacognosy and Phytotherapy*, vol. 5, no. 8, pp. 142–147, Aug. 2013, doi: 10.5897/JPP11.051.
[53] S. R. Sakkalkar, P. H. Bakane, V. S. Sonone, and C. V. Dhumal, "Heat pump drying of safed musli (*Chlorophytum borivilianum*) roots," *International*

Journal of Agricultural Engineering, vol 7, no. 1, pp. 86–92, Apr. 2014.

[54] V. Chandrasekar, V. E. Nambi, and S. Shahir, "Effect of drying parameters on drying Characteristics and forskolin content of rotary dried coleus," *Journal of Agricultural Engineering (India)*, vol. 59, no. 1, pp. 86–96, Dec. 2023, doi: 10.52151/jae2022591.1767.

[55] V. Maghsoodi, K. Akhtar, and A. Ebrahim, "Effect of different drying methods on saffron (*Crocus sativus L*) quality," *Iranian Journal of Chemistry and Chemical Engineering*, vol. 31, no. 2, pp. 85–89, 2012.

[56] F. Sharifian, Z. R. Gharkhloo, A. A. Yamchi, and M. Kaveh, "Infrared and hot drying of saffron petal (*Crocus sativus L.*): Effect on drying, energy, color, and rehydration," *Journal of Food Process Engineering*, vol. 46, no. 7, Art. no. 14342, Jul. 2023, doi: 10.1111/jfpe.14342.

[57] P. Suganya, R. Kailappan, and S. Parveen, "Thin layer sun drying kinetics of glory lily beans (*Gloriosa superba L.*)," *International Journal of Engineering Science and Technology*, vol. 5, no. 9, p. 1688, 2013.

[58] F. Icier, D. Ozmen, M. Cevik, and O. F. Cokgezme, "Drying of licorice root by novel radiative methods," *Journal of Food Processing and Preservation*, vol. 45, no. 3, Mar. 2021, Art. no. e15214, doi: 10.1111/jfpp.15214.

[59] J. Shang, Q. Zhang, T. Wang, Y. Xu, Z. Zang, F. Wan, Y. Yue, and X. Huang, "Effect of ultrasonic pretreatment on the far-infrared drying process and quality characteristics of licorice," *Foods*, vol. 12, no. 12, pp. 2414–2414, Jun. 2023, doi: 10.3390/foods12122414.

[60] C. M. Peries, S. Navarthne, J. Wijesinghe, A. P. Henagamage, and R. Coorey, "Effect of different drying methods on antioxidant activity and availability of phytochemicals in leaves of *Costus speciosus*, *Coccinia grandis* and *Gymnema sylvestre*," *Asian Journal of Engineering and Applied Technology*, vol. 11, no. 1, pp. 29–35, Jun. 2022, doi: 10.51983/ajeat-2022.11.1.3310.

[61] G. Abhiram, A. Briyangari, and R. Eeswaran, "Drying of *Gymnema sylvestre* using far-infrared radiation: antioxidant activity and optimization of drying conditions," *Agri Engineering*, vol. 5, no. 1, pp. 611–622, 2023.

[62] K. Lavanya, "A study on drying kinetics of indian gooseberry–aonla (*Phyllanthus emblica* Linn.)," *International Journal of Agricultural Sciences*, vol. 8, no. 52, pp. 2446–2449, 2016.

[63] R. S. Chauhan, M. C. Nautiyal, G. Figueredo, and V. S. Rana, "Effect of post harvest drying methods on the essential oil composition of *Nardostachys jatamansi* DC.," *Journal of Essential Oil Bearing Plants*, vol. 20, no. 4, pp. 1090–1096, Jul. 2017, doi: 10.1080/0972060X.2017.1363001.

[64] T. Imaizumi, P. Jitareerat, N. Laohakunjit, and N. Kaisangsri, "Effect of microwave drying on drying characteristics, volatile compounds and color of holy basil (*Ocimum tenuiflorum L.*)," *Agriculture and Natural Resources*, vol. 55, no. 1, pp. 1–6, Jan. 2021, doi: 10.34044/j.anres.2021.55.1.01.

[65] A. D. Sousa, P. R. Ribeiro, K. M. Canuto, G. J. Zocolo, R. D. Pereira, F. A. Fernandes, and E. S. Brito, "Drying kinetics and effect of air-drying temperature on chemical composition of *Phyllanthus amarus* and *Phyllanthus niruri*," *Drying Technology*, vol. 36, no. 5, pp. 609–616, Apr. 2018, doi: 10.1080/07373937.2017.1351454.

[66] P. Bhagyashree, B. Vanita, and D. Sneha, "Thin layer drying of long pepper (*Piper longum L.*)," *Journal of Spices and Aromatic Crops*, vol. 22, no. 1, pp. 31–37, 2013.

[67] G. O. Orido, E. K. Ronoh, P. O. Ajwang, and B. B. Gathitu, "Evaluation of thin layer models for simulating drying kinetics of black nightshade seeds in a solar-exhaust gas greenhouse dryer," *Bioprocess Engineering*, vol. 7, no. 1, pp. 10–31, May 2023, doi: 10.11648/j.be.20230701.12.

[68] A. Jaiswal, P. S. Champawat, and S. K. Jain, "Studies on drying characteristics of (*Tinospora cordifolia*) giloy stem," *Journal of Pharmacognosy and Phytochemistry*, vol. 10, no. 1, pp. 2357–2359, 2021.

[69] A. K. Senapati, P. S. Rao, S. S. Mahanand, L. Bal, and S. Prasad, "Optimization of process parameters for convective drying of ashwagandha (*Withania somnifera*) roots," *Research in Environment and Life Sciences*, vol. 10, no. 2, pp. 173–177, 2017.

[70] P. Kumar, M. Bala, R. Singh, and M. D, "Modelling the drying characteristics of ashwagandha (*Withania somnifera*) roots," *International Journal of Chemical Studies*, vol. 8, no. 4, pp. 207–212, Jul. 2020, doi: 10.22271/chemi.2020.v8.i4c.9690.

[71] M. Aghbashlo, S. Hosseinpour, and A. S. Mujumdar, "Application of artificial neural networks (ANNs) in drying technology: A comprehensive review," *Drying Technology*, vol. 33, no. 12, pp. 1397–1462, 2015.
[72] C. Nurhaslina, S. A. Bacho, and A. Mustapa, "Review on drying methods for herbal plants," *Materials Today: Proceedings*, vol. 63, pp. S122–S139, 2022.
[73] C. Ertekin and M. Z. Firat, "A comprehensive review of thin-layer drying models used in agricultural products," *Critical Reviews in Food Science and Nutrition*, vol. 57, no. 4, pp. 701–717, Mar. 2017, doi: 10.1080/10408398.2014.910493.
[74] M. I. H. Khan, C. P. B. Gamage, M. A. Karim, and Y. Gu, "Fundamental understanding of heat and mass transfer processes for physics-informed machine learning-based drying modelling," *Energies*, vol. 15, no. 24, p. 9347, Dec. 2022, doi: 10.3390/en15249347.
[75] A. Halder, A. K. Datta, and R. M. Spanswick, "Water transport in cellular tissues during thermal processing," *AIChE Journal*, vol. 57, no. 9, pp. 2574–2588, 2011.
[76] R. Joshi, V. Agnihotri, and S. K. Nandi, "Modeling of thin layer drying kinetics of *Picrorhiza kurroa* under different drying conditions," *Nonlinear Studies*, vol. 24, no.1, p. 79, Jan. 2017.
[77] J. K. Sugumar and P. Guha, "Evaluation of the changes in physicochemical and functional characteristics of *Solanum nigrum* under different drying methods" *Measurement: Food*, vol 17, 2025, Art. no. 100211, doi 10.1016/j.meafoo.2024.100211.
[78] T. Anukiruthika, J. Moses, and C. Anandharamakrishnan, "Electrohydrodynamic drying of foods: Principle, applications, and prospects," *Journal of Food Engineering*, vol. 295, 2021, Art. no. 110449.