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# A COMPREHENSIVE REVIEW ON DRYING TECHNOLOGIES FOR BEE PRODUCTS: IMPACTS ON QUALITY AND FUTURE RESEARCH DIRECTIONS

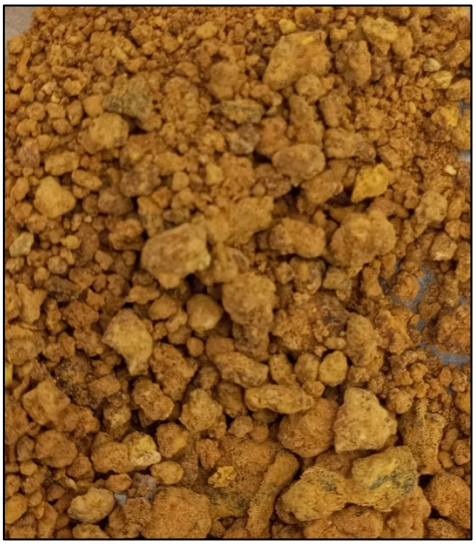
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## Graphical abstract



## Abstract

Bees generate a variety of valued natural products such as honey, royal jelly, bee bread and propolis, all of which hold commercial therapeutic, and nutritional importance. To maximize their use, numerous technologies have been implemented to preserve the value of these bee products for commercialization. Drying plays a huge role in processing bee products to ensure the preservation, stability and availability of their nutritional components upon consumption. This study presents an in-depth analysis of innovative drying techniques used in the drying of bee products compared to traditional drying. The review discusses the limitation of conventional methods, including hot air drying, oven drying, particularly regarding their dependence on weather conditions, slow drying rates, and potential nutritional degradation. It also addresses concerns about the volatile compound loss and the deterioration of heat sensitive nutrients. Advanced drying techniques such as freeze drying and spray drying, provides improved control, faster drying times, and superior preservation of product quality compared to traditional methods. Beekeepers, producers and researchers are working on optimizing drying strategies for bee products, thus necessitating a thorough understanding of the benefits associated with various dry processes. This review could aid in the reliable productions of dried high-quality bee products on meeting standards of the industries and satisfy consumer demands.

***Keywords*:** Bee products, Drying, Conventional drying, Advanced drying, Preservation

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## Abstrak

Lebah menghasilkan pelbagai produk seperti madu, royal jelly, roti lebah dan propolis, di mana kesemuanya mengandungi Kesan terapi dan kebaikan yang boleh dikomersialkan. Untuk memaksimakan kegunaanya, pelbagai technologi telah digunakan sebagai proses pengendalian untuk mengekalkan nutrisinya. Pengeringan memainkan peranan yang sangat penting dalam pemprosesan produk lebah bagi memastikan ia stabil dan masih mengangungi nutrisi baik. Kajian ini membentangkan analisis mendalam mengenaik Teknik pengeringan inovatif yang digunakan dalam pengeringan produk lebah berbanding kaedah tradisional, termasuk pengeringan udara panas dan pengeringan ketuhar, khusunya dari segi pergantungan terhadap keadaan cuaca, kadar pengeringan yang perlahan, serta potensi degradasi nutrisi. Ia juga menekankan kebimbangan tentang kehilangan sebatian meruap dan kemerosotan nutrient yang sensitive kepada haba. Teknik pengeringan maju seperti pengeringan beku dan pengeringan semburan menawarkan kawalan yang lebih baik, masa pengeringan yang lebih cepat, serta pemeliharaan kualiti produk yang lebih tinggi berbanding kaedah tradisional. Penternak lebah, pengeluar dan penyelidik sedang berusaha mengoptimumkan strategi pengeringan untuk produk lebah, sekali gus memerlukan pemahaman menyeluruh mengenaik manfaat yang dikaitkan dengan pelbagai proses pengeringan. Ulasan ini boleh membantu dalam penghasilan produk lebah kering yang berkualiti tinggi secara konsisten untuk memenuhi piawaian industry dan permintaan pengguna.


***Kata kunci*:** Produk lebah, pengeringan, pengeringan konvensional, pengeringan maju,

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## 1.0 INTRODUCTION

Since ancient times, bees have been regarded as a natural treasure, producing a diverse range of substances that are not only delicious and nutritious, but also hold immense therapeutic and commercial value [1]. Honey, the most renowned and widely consumed bee product, has been cherished throughout history for its rich flavour and numerous health benefits. Propolis is a sticky substance collected by bees from plants and plays a vital role in hive protection due to its antimicrobial properties [2]. Bee pollen, a nutrient-dense substance packed with proteins, vitamins, minerals, and antioxidants, is often recognized as a superfood and can be consumed directly [2]. Pollen collected by forager bees provides a well-rounded source of nutrition, especially when gathered from a diverse range of flowers throughout different seasons [3]. Meanwhile, beeswax is a natural secretion produced by worker bees, serves as the primary building material for honeycombs [1]. Due to its unique characteristics including hypoallergenic qualities, flexibility and water resistance, beeswax has become a vital component in cosmetics to pharmaceutical crafts [4]. Another valuable yet less explored bee product is bee bread. Bee bread is a fermented blend of bee pollen and honey, stored within the hive, and is rich in vitamins, protein, amino acids and minerals [5,6]. In addition to its nutritional value, bee bread has attracted considerable scientific interest due to its bioactive composition, particularly relating to health-promoting properties. Research indicates that the fermentation process carried out by lactic acid bacteria within the hive enhances the bioavailability of nutrients and contributes to its probiotic potential. As a result, bee bread is incresingly studied for its antioxidant, antimixrobial and anti-inflammatory activities, which supports its potential role in preventing chronic diseases and boosting overall immunity.

From an economic perspective, bee products are expanding in global market, driven by rising consumer demands for natural, functional and sustainable products. A part of their process includes drying, a common method applied after harvesting to remove moisture, enhance shelf-life and maintain product usability. Traditionally, drying methods such as sun drying and air drying have been used to preserve the usability of various products. While these techniques are able to properly dry a moistured product, it does not simply able to retain the original benefit of the product [7]. An efficient drying process also serves as a treatment in maintaining the quality, stability, and shelf-life of bee products, ensuring the benefit availability for both consumers and commercial purposes. Sun drying, the oldest and most conventional method, exposes bee products to direct sunlight [6]. Although it is simple and cost-effective, it is highly dependent on weather conditions, exposed to environmental factors and can be time-intensive. Air drying relies on natural airflow to remove moisture but tends to be slow and impractical for large scale

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production [8]. On the other hand, oven drying utilizes controlled heat to speed up the drying process. The high temperature involved could contribute to its efficiency in reducing drying time, but it can also lead to degradation of essential nutrients due to heat stress [6].

Advanced drying, such as hybrid technologies, have been developed to offer more efficient and controlled drying processes. One widely used technique is freeze drying, or lyophilization, which helps to preserve the quality and integrity of the bee products due to its low-temperature mechanics [9]. Meanwhile, spray drying utilizes drying of liquid feed in an atomized chamber and turns it into fine droplets while rapidly drying in a hot air stream, ensuring quick and effective moisture removal [10]. Vacuum drying uses a technique that operates under low pressure, reducing the boiling point of water, which would allow drying vacuum and minimizing heat-induced degradation and preserving essential nutrients [11].

This paper is a discussion about the overview of recently developed drying technology for bee products. It explores the fundamental principles, practical applications, along with the impact on the product's shelf-life and nutrition. Furthermore, it serves as a valuable resource for researchers and industry professionals, offering a thorough understanding of existing drying processes, their strengths, and drawbacks. The study also seeks to identify unexplored research areas and provide recommendations for future advancements in drying technologies.

## 2.0 CONVENTIONAL DRYING TECHNOLOGIES USED FOR BEE PRODUCTS

### 2.1 Hot Air Drying

Most of the frequently used conventional drying of foods includes the usage of heat convection and heat conduction. The hot air drying (HAD) process consists of thermal energy that travels from the surrounding environment to the material by convection. It is followed by heating the food interior through conduction, and eventually a stream of hot air is continuously blown over the material to facilitate moisture removal [12]. HAD is the most frequent convective drying technology used to dehydrate agricultural products because of its advantages in low cost and easy operation [13]. Several investigations on the effects of HAD on characteristics, physicochemical properties, morphological structure, effective diffusivity, and activation energy specifically for bee pollen preservation have been done. According to Isik et., (2019), bee pollen samples dried at HAD 40, 45, 50, 55 and 60℃ could affect its moisture diffusivity values resulting in range of $1.38 \times 10^{-10}$ $m^2/s$ to $4.00 \times 10^{-10}$ $m^2/s$ and the activation energy (Ea) was found to be around 42.96 kJ/mol [14]. In Isik's another study, HAD dried bee pollen samples that still had a high solubility index, but lower L* and b* colour values as compared with those of the fresh bee pollen. The lower colour index indicates that it has a darker and less yellow colour, as compared to the fresh ones. The total colour difference (ΔE) was the lowest for the bee pollen dried at 40℃. Bee pollen dried at this temperature retains the highest sensory scores and maintains its quality attributes as it has no significant difference in its morphology compared to samples dried at 45, 50, 55 and 60℃. Hot air drying at 40℃ is recommended for the drying of bee pollen [14].

A study by Bi et al. (2024) investigated the impact of varying drying temperature on the levels of a-dicarbonyl compounds (a-DCs), hydroxymethyl-furfural (5-HMF), and carotenoids in bee pollen in study shows a 65% increase of shortening period in the drying temperature from 40 to 70℃ [15]. According to the study, HAD had caused an elevated a*, lower L* and b* values in colour measurement. This result indicates a darker brown or more reddish colour, which is higher phenolic content due to fermentation period. The lutein and zeaxanthin decreased by 74% while the relative content of antheraxanthin increased 230% at 70℃, respectively, for each sample. The end results show 5-HMF content increased as well as the browning index with respect to the temperatures drying [16]. The 5-HMF is an indicator product created from the Maillard reaction during food heat processing in the early phases of the reaction, which may be used as a marker for pollen deterioration [17]. High amounts of 5-HMF from foods are reported to be poorly affecting human health, causing irritation to mucous membranes, skin, upper respiratory system, as well as contributing to neurodegenerative disease, cardiovascular systems and diabetes [17,18]. The colour of bee pollen deteriorates due to browning and pigment loss, including carotenoids. The natural pigment plants in pollens are carotenoids and anthocyanins, which can vary depending on botanical, season and geographic sources [3]. Based on Bi's results, the formation of antheraxanthin and a-DCs such as 3-DG, as well as lutein degradation, is indicated by a higher a* value, but lower L* and b* values [16].

A study by Borkovcova (2022), aims to evaluate the safety of bee drone brood in terms of the contamination risk with heavy metals, microbial contamination, and sensory acceptability by drying bee drone on a hot air oven (DBO) and lyophilization (DBL). Bee drone brood (DB) is made up of developing male honeybees (drones) that are taken from the hive when they are still larvae or pupae [19]. In some countries, drone brood is a culinary practice that is valued for its high protein content and other health benefits. Because of its abundance amino acids, vitamins, and minerals, it is sometimes used in traditional medicine and in cosmetics [19]. According to the study, there was no significant difference between dried DBO and freshly dried DBO after 30 days of storage in the results after undergoing microbial assay. Both samples contain microbial

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standard level limit and is a reliable source of zinc, calcium, and iron. For sensory evaluation, the drying methods had some effect at the end product's smell, appearance, and taste. The two samples had the same amount of sweetness, acidity, sharpness, and bitterness. Meanwhile, a sense of strong burnt, and intense nutty aroma lingered from the DBO sample [19]. Nonetheless, the elevated Pb levels detected in drone brood dry matter (2.1 µg/g) itself prevents DB from being regarded as a safe food ingredient [19].

### 2.2 Oven Drying

Oven drying is a drying method typically used by directly transferring heat by conduction and radiation to products. The sample is positioned in a heated, enclosed space and exposed to high temperature [6]. A study from Isik (2021), said drying at low temperatures, such as 35℃ and 45℃, by oven does not affect the overall functional properties. However, it was observed that the carotene levels and vitamin C loss was higher in 45℃ when compared to 35℃ even though it has a shorter drying time and moisture content removal. On the other hand, the ash content, fiber, and protein were not affected by temperature difference [15]. A study by Minarti (2022) employed two drying techniques on pollen samples using sun drying and oven drying at 60℃ for 4 hours [6]. The results indicated that both drying methods significantly influence the quantities of proteins, lipids, and ash ($P<0.01$), hence concluding that the drying process affected nutrient composition [6]. The study concludes that the oven drying approach resulted in quicker reduced moisture levels, which prevents pollen decay, a higher amount of proteins, fats, and carbohydrates [6]. The higher ash level of the oven-dried pollen also signifies that its mineral content surpasses that of the sun-dried pollen.

Another investigation was conducted by De-Melo (2016) to examine the chemical, physical, and biological properties, as well as the microbiological quality, of pollen samples obtained from *Eucalyptus (Myrtaceae)* and *Eupatorium (Asteraceae* plants subjected to various drying methods [20]. Results show that the drying conditions of the samples affected the L*, a*, b* colour parameters and the biological value. In contrast to the protein and fat content, the levels of glucose and fructose remained unchanged. The vitamin E concentration (27.2 ± 0.3 µg/g, 27.5 ± 0.4 µg/g) in oven dehydrated samples with forced air circulation was substantially lower ($P<0.05$) than that in lyophilized samples (37.5 ± 0.2 g/100 g, 53.7 ± 3.9 g/100 g) [20]. A positive relationship existed between the colour parameters, where L* and b* indicate higher total phenolic contents, as well as between phenolic content and both antioxidant and antibacterial capacities. The results suggest that a lower temperature drying, such as freeze-drying, could serve as a feasible substitute for the existing technique to avoid further degradation due to temperature sensitivity [20].

## 3.0 EMERGING DRYING TECHNOLOGIES

Improved drying technologies for bee products aim to address the key limitations of traditional drying methods, such as prolonged drying times, loss of bioactive compounds, degradation of flavour and aroma, and vulnerability to microbial contamination. To overcome these issues, modern techniques integrate innovative approaches, such as hybrid or assisted drying, that significantly enhance efficiency, nutritional retention, and hygienic final product. Among the utmost promising advanced drying methods are the hybrid innovations, including microwave-assisted drying, vacuum, freeze drying, spray drying, infrared drying and others.

### 3.1 Microwave-assisted Drying

Microwave drying is a technology that uses electromagnetic waves in the frequency range of 300 MHz to 300 GHz to heat and dry materials [21]. The moisture in the material is heated and evaporated by the microwave energy, resulting in a reduction in the moisture content of the material.

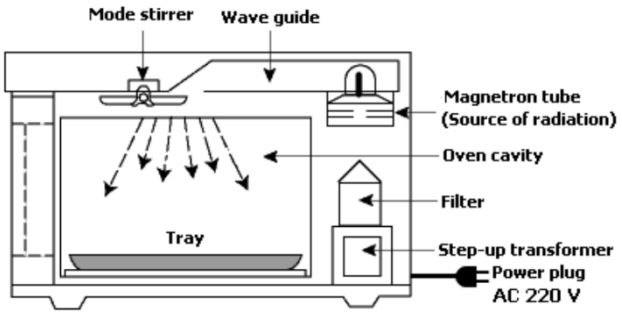



**Figure 1** Microwave oven dryer [11]

Figure 1 shows a schematic drawing of a microwave oven. Microwave drying works by creating an electromagnetic field that causes water molecules to oscillate and generate heat [22]. The heat generated by the water molecules is transferred to adjacent molecules, causing the material to heat up rapidly and evenly [3]. The rate of drying is determined by the power and frequency of the microwaves, the moisture content of the material, and the temperature of the surrounding environment. Microwaving is a commonly performed drying method at low temperatures with brief exposure duration to prevent the possibility of Maillard formation, especially when involved in sun and environment exposure [17]. Moreover, this drying method has been shown to adversely influence the

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level of antioxidants, including polyphenols and flavonoids [16].

Canale (2016) proposed microwave drying under vacuum as a different method for preserving the bioactive chemicals in bee pollen than the conventional approaches [23]. However, Conte (2017) found that the tocopherol levels in bee pollen had lowered values when subjected to microwave-assisted treatment specifically, after treatments of traditional drying, freeze drying, and microwave-assisted vacuum drying procedures [23]. Based on Kanar & Mazi (2019)'s data, a greater reduction was observed in the diastase number (DN) of samples subjected to microwave drying and microwave-assisted vacuum drying at 600W and 900W as compared to other drying treatments. There was an almost 72 to 76% reduction when using 900W power of microwave irradiation drying [18].

The power and temperature of the microwave are critical elements in the drying process as they directly influence, quality and preservation of bioactive substances in the final product. Increased power accelerates the drying rate while maintaining nutrients in material necessitating a careful balance of power and temperature [24]. Therefore, a modest microwave power level is advisable to facilitate adequate drying without causing overheating. According to Isik and colleagues (2019), using the microwave dried at 180W, 360W, 540W, 720W and 900W microwave power levels, the properties resulting from study would affect the moisture diffusivity [15]. The values ranged from $0.04 \times 10^{-8}$ $m^2/s$ to $1.14 \times 10^{-8}$ $m^2/s$ and the activation energy was found to be 71.68 W/g as drying time shortened by 94% when the microwave power level increased from 180W to 900W [15]. The protein, fat, total carbs, vitamin C, and color values of bee pollen were diminished as the microwave power level increased. The minimal ΔE value and maximal solubility (%) were achieved for bee pollen subjected to microwave drying at a power level of 180 W. Comparative analysis of the physicochemical properties and organoleptic characteristics of microwave-dried bee pollens revealed that the sample dried at a microwave power level of 180 W retained its quality attributes more successfully than the other samples [15].

Functional foods such as pollens are recognized because of their substantial awareness of existing good bioactive substances, including vital amino acids, antioxidants, vitamins, and lipids. Many researchers have focused on proteins, antioxidants, and polyphenols present in pollen collected by forager honeybees, but its investigations is still limited on the lipid profile. Most studies on pollen lipids have focused on sterols due to their significance for honeybees [25]. According to Conte (2017) microwave-assisted treatment has been found to damage the antioxidant compounds (reduction of tocopherols) of non-bee bread samples, compared to freeze drying [26]. It was investigated that a-tocopherol contains 60% value, δ-tocopherol on 75%, and γ-tocopherol exhibited reductions of 90%, following freeze drying treatment. In contrast, microwave-assisted treatment led to the complete oxidation of all tocopherols. The results highlighted the role of tocopherols as antioxidants, especially under extreme stress conditions such as post-conditioning treatment. The findings suggested that microwave-assisted technique remarkably diminishes tocopherol levels, but freeze drying has a lesser impact on oxidative stress [26].

### 3.2 Vacuum Drying

The vacuum drying process involves placing the substance to be dried in chamber consists of zero vacuum, where reduced pressure is applied to a level below atmospheric pressure. The reduced pressure enables the moisture in the substance to evaporate at a temperature lower than that necessary under standard atmospheric pressure. The vaporized moisture is subsequently extracted from the vacuum chamber via a vacuum pump, which further decreases the chamber's pressure, resulting in further moisture being vaporized and eliminated [10]. Vacuum drying is a mild and effective drying technique commonly employed in the food and pharmaceutical sectors. This method is especially appropriate for drying heat-sensitive and fragile materials, as it facilitates drying at low temperatures, hence reducing the likelihood of damage to the material [8].

By using low temperatures and reduced pressure, vacuum drying can help to preserve the nutritional quality of products by removing moisture without exposing the material to high temperatures. This process helps retain the vitamins, minerals, and enzymes present in products. By reducing the water activity, it enhances storage stability and prevents spoilage over an extended period [27]. This can be especially important for bee products that are intended for long-term storage or export. Vacuum drying can potentially reduce the drying time of bee bread compared to other traditional drying methods such as sun drying [28]. This can be beneficial for large-scale product processing operations where rapid drying is required to meet production demands, hence it is important to note that the vacuum drying process (such as temperature, pressure, drying time) may need to be optimized for each individual product. The equipment and expertise required for vacuum drying can be expensive, which may limit its use for small-scale bee product producers.

A study conducted by Thakur & Nanda (2019) proposes to optimize and investigate bee pollen as a functional ingredient in milk powder through a response surface approach. The experimental design included process variables: bee pollen (5-15%), temperature (20-30℃), and pressure (15-25 inHg), to examine their impact on the physical characteristics and total phenolic content of the generated product [27]. Results demonstrated an enhancement in

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powder recovery (41.53-52.96%) associated with pollen, temperature, and pressure, while total phenolic content (12.35-22.65%) increased with pollen and pressure [27]. Solubility (74.86-83.73%) and bulk density (0.37-0.63 g $cm^3$) diminished with increasing pollen and temperature, whereas hygroscopicity (13.10-18.29%) escalated with pollen [27].

Drying is an essential stage that influences product quality and must be conducted under conditions that avoid irreversible alterations in the product, which may result in quality degradation. Kharchenko (2020) stated that these alterations are mostly linked to the denaturation of proteins and the inactivation of enzymes resulting from the heating of bee bread during drying at temperatures over 40°C [29]. Literature analysis indicates that bee bread is primarily dried using convection and vacuum drying, supplemented by infrared heating. The drawback of the convection drying method is its high energy intensity. The vacuum method's drawback is the substantial equipment expense, rendering it unsuitable for small enterprises [20]. Incorporating infrared heating into the primary drying processes can diminish both the drying duration and energy consumption of the operation. The study delineates the outcomes of modeling the combined use of convection and vacuum infrared-assisted drying techniques for bee bread within a device designed for small-scale industrial use. The resultant mathematical model facilitates the identification of parameters and modes for the drying process of bee bread while preserving product quality [29].

### 3.3 Spray Drying

Spray drying is a popular method for generating powdered food products, and numerous studies have examined its application for bee products [30]. This method converts liquid or slurry materials into dry powder by rapidly drying them in hot air by rapidly evaporating the liquid to turn into dry powder [31,9]. The principles of spray drying include atomization, drying, and powder collection [31]. The mechanism of spray drying is shown in Figure 2.

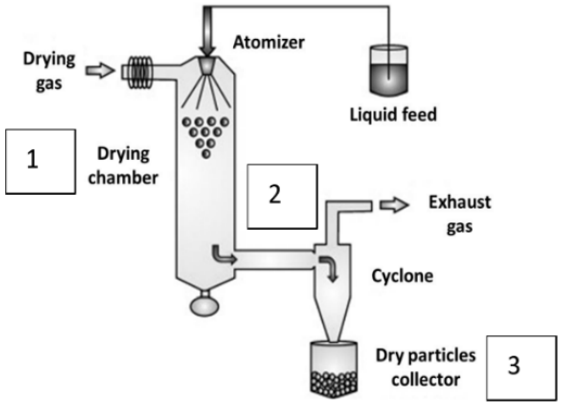



**Figure 2** Schematic representation of spray-drying mechanism. (1) Atomization. (2) Droplet-to-particle conversion. (3) Particle collection [32]

Atomization involves breaking up the liquid or slurry into small droplets, which increases the surface area and enhances drying. The drying process involves removing the moisture from the droplets, which is achieved by exposing them to hot air vacuumed through the tube to the atomizer, into the cyclone and then collecting the dried powder from the drying chamber [32]. This drying technique has lately been employed in the food and pharmaceutical sectors to manufacture powdered items. Spray drying is an efficient technique for conserving bioactive chemicals and antioxidant properties in fine powdered products, including baked goods, smoothies, and supplements.

A common way for the usage of spray drying in food business is to dry out a lot of different kinds of food from liquid form. However, the main issue with spray drying sweet foods like honey is that they become sticky when exposed to high temperatures [33]. Honey is mostly made up of low-glass transition temperature (Tg) compositions, mostly glucose and fructose. These components may either stay as syrup powder or stick to the dryer room wall while the honey is drying and could result in low product yields and operational issues. To reduce these, high molecular weight additives such as maltodextrin can be added to the product before it is atomized to avoid sticking [9]. The quantity of maltodextrin and the temperature of the surrounding air significantly influence the spray-drying process to achieve optimal yield of bee honey powder. Cuevas (2017) asserts that process yield, volatiles retention, and 5-hydroxymethylfurfural (HMF)

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powder concentration are interrelated with increasing temperature. The powder yield, retention of volatiles, and solubility duration escalated with the augmentation of maltodextrin concentration. On the other hand, the moisture content, hygroscopicity and loose bulk density content decreased, showing that it still works well as a transport agent for the spray dryer [33].

A study by Pratami (2019) was conducted to determine the effect of spray drying to propolis microcapsules derived from *Tetragonula spp*. sample on the antioxidant activity (AA) and total phenolic content (TPC). The coating was made using maltodextrin and arabic gum as encapsulating agents for the microencapsulation and was then spray dried to achieve proper encapsulation technique. The results show a consistent number of high TPC number 237.33 mg GAE/g, moisture content of 6.32%, and water solubility of 98.48% [34]. These results show that the antioxidant properties and the phenolic compounds are preserved in the encapsulated form as well as enhancing their solubility index and physical appearance to finer particles.

Similar to other drying methods, spray drying could also significantly affect the physical and chemical properties of products. In Sari's (2024) study, bee bread from the stingless bee *Heterotrigona itama* was analyzed for its bioactive compounds and antioxidant activity, followed by encapsulation using a spray dryer to improve its stability. Phytochemical screening revealed there are still presence of multiple bioactive substances, including saponins, alkaloids, carbohydrates, quinones, flavonoids, tannins, phenols, glycosides, and ninhydrin compounds [35]. The process reduced the moisture content of the bee bread, changing its colour from brownish-yellow to golden tallow, which aids in preserving shelf-life by inhibiting microbial growth. However, the high inlet temperature of 160℃ during spray drying caused some evaporation of moisture, leading to particle hardening and the formation of an impenetrable layer. This phenomenon would decrease the solubility and dispersibility of the encapsulated bee powder [36]. It was also found that the antioxidant activity had reduced radical scavenging compared to raw extracts or pure compounds. The reduction is likely due to thermal degradation or interactions during drying, affecting the bioactive compound availability [37].

### 3.4 Freeze Drying

Freeze drying (FD) or lyophilization is a method for extracting water from a product through sublimation in a vacuum environment. The procedure comprises three principal phases, freezing, primary drying, and secondary drying [36]. In the freezing phase, the product is cooled to a temperature beneath the eutectic point, where solid and liquid phases exist in equilibrium [9, 36]. The freezing process transforms the water in the product from a liquid state to a solid state. During the primary drying phase, the pressure is diminished, and heat is introduced to the frozen product, resulting in the sublimation of ice into vapor. The vapor is subsequently eliminated using a vacuum pump or condenser. During the secondary drying phase, temperature and pressure are incrementally elevated to eliminate residual water molecules that failed to sublimate in the primary drying phase [36]. Freeze-drying is predicated on the principle that water molecules in a frozen condition can transition directly from solid to vapor, bypassing the liquid phase [10]. By decreasing the pressure and applying heat, the frozen water molecules can undergo sublimation and be eliminated, resulting in a dry product. Freeze-drying is frequently employed in the food, pharmaceutical, and biotechnology sectors to preserve items [10]. Figure 3 shows the image of LABOGENE freeze dryer taken at UTM, Skudai Malaysia.



**Figure 3** LABOGENE Freeze Drier

Recent studies into freeze-drying techniques have demonstrated their effectiveness for bee products. Nedic (2020) investigated a comparison of freeze drying, vacuum drying, and infrared drying procedures in examining the impacts on amino acid, alpha-dicarbonyl (a-DC), and volatile compounds of rape bee pollen [38]. Freeze-drying was the most effective drying method regarding total a-DCs content, which was generated significantly compared to the control (fresh bee pollen). Nedic's results shows that vacuum and freeze-drying procedures yielded dried products with comparable quality metrics and satisfied composition standards for honeybees [38]. Nevertheless, based on the conducted investigation using sunflower honey and acacia honey, there was a slight advantage in freeze-drying. In comparison to vacuum-dried honey, freeze-dried honey exhibited a better-preserved and less damaged structure at the end of the procedure in addition to shorter time consumption to fully dry. On the contrary, the thermal treatment of honey before the drying process significantly influences the undesirable elevation of HMF levels and diastase activity [38]. The energy efficiency of conducted

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processes will undoubtedly yield further insights into this issue and will be the focus of future research.

Freeze drying has the ability to preserve the original structure and colour, safeguard against chemical degradation, and exhibit superior rehydration properties [9]. However, due to the extended drying durations needed, freeze drying is an expensive and time-intensive process that produces minimal output while consuming significant energy. The expenses associated with freeze drying may be higher than those of hot air drying to attain equivalent moisture content, as indicated by the experimental study results [39]. In comparison to alternative drying techniques, freeze drying is the most effective way for removing moisture from heat-sensitive substances and producing higher-quality dehydrated food products. It is renowned for producing a superior product compared to other drying methods because to its low processing temperature and minimal oxygen involvement [38]. According to Bhattarchajee's (2024) study, advance hybrid technology can be combined with assisted technology, such as microwave infrared drying with freeze drying according to Figure 4 [10].

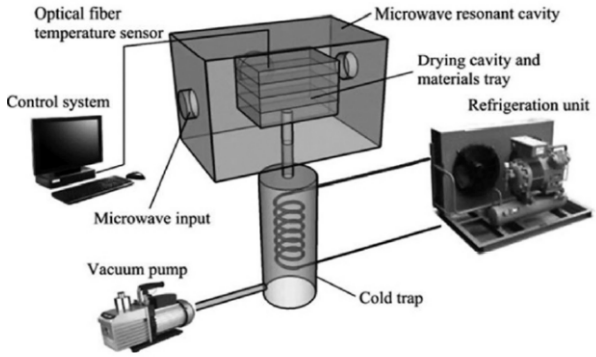



**Figure 4** Schematic diagram of microwave assisted freeze dryer [10]

Microwave aided freeze drying (MAFD) is a technology that uses microwave radiation in conjunction with freeze drying to overcome the constraints [10,11]. Since the water molecules quickly absorb energy for sublimation within the meal, the dry zone has no effect on MAFD. Thus, there is a great chance to speed up the drying process by microwave heating. Other benefits of MAFD over conventional freeze drying include longer drying times, quicker material energy dissipation, significant energy savings, and higher-quality products [18]. However, to preserve the product's quality during the drying process, the heat input amount in MFD needs to be controlled. According to the findings, the Freeze Dried-Microwave assisted (FDMVD) process's effective diffusivity (Deff) values were ten times higher than those of the standard FD process [38]. This suggests that FDMVD has a significantly higher mass transfer efficiency and significantly reduces the total drying time in comparison to the standard freeze-drying method [10]. The FDMVD technique is shown to be relevant in a number of industrial sectors. According to Conte (2017), the hybrid drying process shortened the drying time without sacrificing the dried product's quality [26]. Additionally, when compared to freeze-dried meals, food products dried utilizing a hybrid drying approach showed significantly better puffing and moisture absorption [26].

### 3.5 Infrared Drying

Most Infrared drying, also known as IRD, is a method of thermal dehydration that utilizes electromagnetic radiation in the infrared spectrum, which ranges from 0.78 to 1000 μm to aid the elimination of moisture [29]. Unlike conventional drying methods that rely primarily on convective heat transfer on hot air, IRD enables direct energy transfer to the product surface, resulting in faster and more energy-efficient drying [40]. Figure 5 shows that in IRD, heat is generated when infrared radiation is absorbed by the moisture present in the material, causing rapid surface heating and water evaporation [16]. The internal moisture subsequently diffuses to the surface, where it evaporates due to the sustained thermal gradient. There are a few studies that have employed IRD involving bee pollen and bee breads, and it was proven that it can help preserve bioactive compounds such as phenolic acids, flavonoids, and enzymes, while also retaining desirable sensory characteristics like colour and texture.

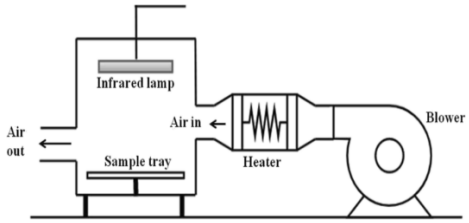



**Figure 5** Schematic diagram of infrared-assisted convective drying [48]

In Bi (2024)'s study, IRD demonstrates a balanced effect on the nutritional and aromatic qualities of rape bee pollen (RBP), serving as an intermediate between freeze drying and sun-drying methods [16]. It was conducted at 45℃ to minimize Maillard reaction products and thermal degradation, IRD was able to preserve the volatile compounds profile similar to FD, hot air drying (HAD), and pulsed vacuum drying (PFD), while differs notably from sun drying, which produces more new volatile substances. Furthermore, terpenes such as alpha-pinenes, associated with sensory properties and antibacterial activity, had a slight increase following IRD, contributing to RBP's characteristic flavour profile [16]. The principal component analysis positions IRD centrally among other drying methods, reflecting its moderate

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influence on volatile organic compounds, volatile organic compounds and amino acids, suggesting that IRD offers a practical compromise between nutrient preservation and drying efficiency. His findings suggest that IRD is an effective drying technique, balancing quality retention and processing feasibility [16].

A study from Borel and Lidja (2020), enforces infrared heating-assisted fluidized bed dryer to process bee pollen grains. The results demonstrated that the fluid dynamic characteristics of bee pollen in the fluidized bed dryer were favorable, with effective fluidization achieved as indicated by fluidization index values around 80% [53]. The bee pollen exhibited aggregative fluidization behavior under all tested conditions, with minimum fluidization velocity and pressure drop increasing linearly with bed mass. During drying, the application of infrared (IR) radiation significantly enhanced moisture removal rates, increasing the IR heat flux from 400 to 700 W/m² reduced drying time by 25%, while the fluidization air cooled the particle surfaces, preventing excessive temperature rises. This cooling effect was important in mitigating browning reactions commonly observed during IR drying without fluidization, where temperatures and browning indices were higher [54]. The hybrid IR heating-assisted fluidized bed drying preserved the color and quality of the pollen better than thin-layer IR drying alone. Kinetic modeling showed that browning during thin-layer IR drying followed zero or first-order kinetics depending on IR power, whereas browning was negligible in both conventional fluidized bed drying and the hybrid process. Importantly, the hybrid drying mode achieved about 30% higher effective moisture diffusivity and reduced specific energy consumption by 52% compared to conventional fluidized bed drying at 35 °C [53].

IRD involves the penetration of infrared radiation, which sends electromagnetic waves through the material for fast and uniform heating. Jun Wang (2022) suggests that Infrared Drying (IRD) has the highest drying rate and the shortest drying duration among the methods studied (Hot Air Drying, Freeze Drying, and Pulsed Vacuum Drying) while employing bee pollen samples [41]. However, despite its efficiency, IRD has caused serious lipid oxidation in the samples. The results of this lipidomic study demonstrate that IRD considerably reduces the amount of unsaturated fatty acids (UFAs) and the number of unsaturated triglycerides (TGs). As a consequence, these factors boost lipid oxidation during the process of inflammatory response disease (IRD) [41]. The free fatty acid (FFA) content also increases significantly after IRD, indicating lipid degradation. The levels of lipid oxidation markers, such as hydroperoxides and malondialdehyde, are higher in IRD-treated pollen than in pollen dried by FD or pulsed vacuum drying methods [41].

## 3.0 APPLICATION OF CURRENT DRYING TECHNOLOGY

Microwave drying has shown promise for the drying of bee bread due to its ability to provide rapid and efficient drying while preserving the nutritional content and sensory properties of the material. Some potential applications of microwave drying for bee bread as a rich source of nutrients and bioactive compounds, microwave drying can help to preserve these compounds by minimizing the exposure of the material to high temperatures. Microwave drying can result in a more uniform and consistent product, with less risk of overheating or damage to the material and significantly reduce the drying time for bee bread compared to conventional methods, which can help to increase productivity and reduce energy costs.

In response to the rising demand for high-quality dried food products, researchers are exploring and utilizing improved microwave-assisted drying techniques for more critical and sensitive products such as medicines. The impact of diverse microwave-assisted drying techniques, ambient temperatures, and preliminary treatments has been thoroughly investigated regarding the thermophysical and qualitative characteristics of dried products, such as color, nutritional value, and rehydration capacity [42]. The majority of findings in literature predominantly stem from laboratory dryers that were used intermittently. Innovative hybrid and combination microwave-assisted drying methods must be linked to laboratory research with commercial applications to realize their full potential and impose a more significant impact on the food processing sector [12].

However, there are some significant downsides to microwave drying. One of the most significant disadvantages is the high cost of the equipment. Microwave drying systems are generally more expensive than conventional drying equipment, thus the initial investment is essential for many organizations [43]. Furthermore, some compounds may react poorly to microwaves or heat unevenly, resulting in over-drying or under-drying in specific areas of the material [44]. This fluctuation can tamper the over-drying or under-drying process. Even though microwave drying normally offers uniform heat, there are several instances where it might create uneven drying, particularly in materials with varied densities or moisture content [45]. Uneven drying can be troublesome in some applications, resulting in quality inconsistencies.

Vacuum drying is essential for dehydrating heat-sensitive materials utilized in the pharmaceutical, chemical, food, and biotechnology sectors. Water evaporates more swiftly at reduced pressures, and low temperatures can be employed under vacuum for products that may discolor or disintegrate at elevated temperatures [46]. Vacuum drying requires more complex equipment than conventional methods and is a high-energy-consuming process. Hybrid drying

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technologies, such as air drying followed by microwave-vacuum processing, are becoming more common and have been used for producing dried puffed fruit and vegetable pieces. By using this method, the quality parameters for assessing dryers include physical aspects, vitamin and mineral levels and bioactive compound levels.

Hybrid drying processes build upon vacuum drying's advantages by adding other modalities like microwaves or fluidized beds, leading to faster drying, better energy efficiency, and sometimes lower manufacturing costs [29]. Adding a microwave system to a fluidized bed system combines the benefits offered by each technology as an optimal drying system should preserve quality, be cost-effective, minimize exposure to light and oxygen, and shorten the drying time [27].

Spray drying is a popular method utilized across multiple industries for its effectiveness in transforming liquid formulations into stable powdered products on a large scale. This method is particularly advantageous for encapsulating sensitive bioactive compounds by protecting them from environmental stressors during storage [9]. In the food industry, spray drying plays a crucial role in producing powdered food ingredients such as milk powders, coffee extracts, fruit juices, and flavors. The encapsulation of bioactive compounds such as vitamins, antioxidants, polyphenols, carotenoids, probiotics, and peptides helps in preserving their physicochemical properties and biological activity. Protein and peptides have emerged as effective carriers because of their functional properties, including film-forming ability, emulsifying capacity, and surface activity, which contribute to enhanced stability and controlled release of encapsulated compounds.

Pharmaceutical companies use spray drying to encapsulate medicines and peptide-based treatments to increase stability, prevent aggregation, and adjust release characteristics. This technique is beneficial for producing inhalable powders and enhancing oral bioavailability of active ingredients through effective microencapsulation in protein carriers. Despite its broad applicability, the spray drying process poses challenges such as shear and thermal stress during atomization and dehydration, which can compromise the stability of delicate bioactives. These drawbacks necessitate optimization of process parameters and the selection of appropriate carriers, with protein-based systems considered

Freeze drying is a widely acknowledged technique in the pharmaceutical sector, notably valued for its efficacy in processing heat-sensitive active pharmaceutical ingredients (APIs). The primary industrial application pertains to the stabilization and production of solid dispersions and drug nanocrystals, aimed at enhancing the solubility and oral bioavailability of poorly water-soluble drugs, predominantly classified as BCS class II (low aqueous solubility but high intestinal permeability) and class IV compounds (low aqueous solubility and low intestinal permeability) [46]. Freeze drying facilitates the production and solidification of nanocrystals in a singular manufacturing step, eliminating the need for further drying processes and thus enhancing the physical stability of pharmaceutical powders [47].

One distinct advantage of freeze drying is its capacity to preserve thermolabile materials, including biopharmaceuticals such as proteins, monoclonal antibodies, vaccines, and probiotics, which are particularly sensitive to heat and unsuitable for other drying methods that involve in elevated temperatures [46]. Furthermore, freeze-dried products typically exhibit enhanced flowability and mechanical robustness due to the porous matrix formed during ice sublimation, characteristics that are advantageous in pharmaceutical processing such as tableting milling [47].

Infrared technology involves the direct penetration of infrared radiation into food products, which converts into thermal energy, facilitating rapid moisture removal [41]. The capability of IRD to provide uniform heating and reduce drying times has motivated widespread application across various food sectors. The food processing industry has extensively applied infrared drying to various products, not limited to vegetables and fruits, but also other types of foods [48]. The usage of IRD has been particularly beneficial due to its higher drying efficiency and enhanced product worth compared to traditional methods. For example, IRD demonstrated an equal performance with rapid drying of moisture solids compared with freeze drying [48].

Research has indicated that when infrared radiation substantially reduces drying time, energy consumption can decrease accordingly [49]. Despite this advantage, IRD alone may not be suitable for all food products, particularly those sensitive to heat. Hence, hybrid drying techniques combining IR radiation with hot air, vacuum, or microwave drying have been developed to harness synergistic effects. These combined methods enable drying rates, better control of drying conditions, and improved quality retention, making them favorable in industrial settings for processing heat-sensitive material drying.

### 3.2 Challenges and future impact of Drying Technologies

Looking ahead, the impact of innovative drying technologies is expected to be transformative across multiple dimensions. First, the preservation of quality and functionality will continue to advance, enabling the production of high-value foods, pharmaceuticals and nutraceutical products that align with consumer demand for minimally processed and nutrient-rich options. Second, the emphasis on energy efficiency and sustainability is anticipated to be enhanced as drying processes currently account for a considerable portion of industrial energy use.

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In this modern era, the digitalization of drying processes through artificial intelligence (AI), Internet of Things (IoT), and predictive modeling is expected to revolutionize process monitoring and control. A few examples that was newly integrated with AI were the Machine Learning and Multimodal Learning [50]. The emergence of 'smart dryers' are capable of real-time adjustment based on product characteristics will lead to greater consistency in quality, lower energy consumption and reduced operational costs. Such technology is able to monitor real-time capture of data on moisture, chemical composition and morphological characteristics during drying [51]. This allows for intelligent process monitoring and automated control, ensuring optimal drying conditions and thus better product quality. In parallel, the global economic implications are notable, as access to innovative and cost-effective drying systems will enable small and medium-sized enterprises, particularly in developing regions, to reduce postharvest losses and increase competitiveness in export markets.

Beyond the food sector, drying innovations have made substantial contributions to pharmaceuticals and biotechnology. Many bioactive compounds, enzymes, proteins and vaccines are inherently unstable under conventional drying conditions. Current techniques such as spray and freeze drying allows for stabilization and encapsulation of sensitive molecules and help support the development of controlled release drug delivery systems. Similarly, the agricultural sector, such as apiarists benefits from advanced drying through preservation of plant seeds, flower nectars and bee products with minimal energy input and reduced microbial risk [53]. Traditionally, many small-scale bee farmers rely on sun drying or uncontrolled ambient drying, which often leads to uneven moisture removal and microbial contamination. This not only reduces product quality but also limits their competitiveness in local and international markets where strict safety and quality standards are executed [54]. By employing assisted or hybrid drying technologies, farmers can stabilize bee products more effectively while minimizing energy input, making the process both cost-efficient and sustainable for rural communities with limited access to electricity.

Innovative drying technologies are positioned at the intersection of quality preservation, sustainability, and digital transformation. Their application extends far beyond traditional drying practices, influencing food production, pharmaceuticals, agriculture, and materials engineering. The future impact of these technologies will be characterized by the ability to meet the objectives of safeguarding product integrity and advancing sustainable industrial practices, thereby ensuring the relevance in addressing both market needs and global challenges.

### 3.2 Summary

Emerging drying technologies offer clear advantages over conventional methods by minimizing environmental exposure such as heat, oxidation and structural degradation. Table 1 shows the summary comparison table on drying technologies.

**Table 1** Comparison of drying technologies, their assessed properties, advantages and disadvantages

| Drying Method | Properties assessed | Advantages | Disadvantages |
|---|---|---|---|
| Hot air Drying | Moisture content, Colour, nutritional content, rehydration capacity | Low cost, easy operation, reduces drying time | Heat-sensitive, nutrient loss, colour changes, and slow operation |
| Oven Drying | Carotene content, Vitamin C content, Drying time, Microbial load | Controlled heat, accelerates drying | Loss of volatile compounds and nutrients due to heat loss |
| Vacuum Drying | Physical parameters, vitamin and mineral levels | Preserves heat-sensitive compounds, fast drying at low temperatures | High energy consumption, complex and costly equipment |
| Microwave-assisted Drying | Antioxidants, drying rate, and moisture content) | Faster drying, improves efficiency | Possible degradation of antioxidants, requires careful control of power and temperature, high initial cost |
| Spray Drying | Bioactive compound preservation, structure, nutritional value, and rehydration properties | Rapid drying, good for encapsulation, preserves bioactive | Thermal degradation due to high inlet temperature, particle hardening, causing decreased solubility |

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| | | | |
|---|---|---|---|
| Freeze Drying | Bioactive compound retention, antioxidant activity, preserves colour | Preserves flavour and aroma, Retention of heat-sensitive compound Longer shelf life and enhanced stability Suitable for large-scale production | Lengthy and energy-intensive drying process Expensive equipment and operating costs. Complex process requiring specialized knowledge, Equipment and maintenance costs |
| Infrared Drying | Drying rate, nutrient preservation, colour, lipid oxidation | Faster drying, energy efficient, preserves nutrition | Risk of lipid oxidation, possible uneven heating without hybrid techniques |

## 5.0 CONCLUSION

Emerging drying technologies represent significant advancements in the preservation of bioactive compounds in food and natural products. These modern approaches offer clear advantages over conventional methods by minimizing heat exposure, oxidation, and structural degradation. Among these technologies, freeze-drying stands out as one of the most effective techniques for preserving bioactive compounds, due to its low temperature, vacuum-based process that sublimates water without compromising nutritional or therapeutic value. Meanwhile, other innovative methods like vacuum drying, microwave-assisted drying, offer potential for broader industrial applications. Collectively, these emerging techniques not only enhance the shelf-life and safety of high-value products like bee bread, medicinal herbs, and nutraceuticals, but also support the development of premium, health-focused products with maximized bioactive retention. As research progresses, integrating these technologies with energy efficiency and scalability will be key to their adoption in commercial food and pharmaceutical industries.

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## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

## Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

## Ethics declaration

Formal ethical approval was not obtained for this study. However, the authors confirm that the research was conducted in accordance with established ethical principles and good research practices, with due consideration given to participant rights, informed consent, confidentiality, and responsible data handling.

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