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Thermophysical Characterization of Cordyceps militaris in the Freeze-Drying Process: Focus on Primary Drying Stage

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Abstract: This paper presents a method for determining key thermophysical properties of *Cordyceps militaris* during the freeze-drying process, focusing on the variations in density, specific heat capacity, and thermal conductivity. In addition, the mass transfer characteristics of the dried region of *Cordyceps militaris* were investigated through the determination of the effective moisture diffusion coefficient. Experimental results revealed a significant reduction in bulk density, from 1020 kg/m³ to 277.08 kg/m³. Simultaneously, the specific heat capacity and thermal conductivity decreased from 2012 J/kg·K to 1850 J/kg·K, and from 1.073 W/m·K to 0.041 W/m·K, respectively. The effective moisture diffusion coefficient, determined based on the Knudsen diffusion mechanism, was found to be 0.00452 m²/s. These findings provide critical input parameters for modeling heat and mass transfer during freeze-drying and offer a scientific basis for the design and optimization of drying conditions for *Cordyceps militaris.*

Keywords: *Thermophysical Characterization; Cordyceps Militaris; Primary Drying Stage; Freeze-Drying.*

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I. INTRODUCTION

Cordyceps militaris is a valuable medicinal fungus, rich in bioactive compounds, and widely used in traditional medicine as well as in the production of functional foods. After harvesting, the product is typically dried to extend shelf life and facilitate storage and transportation. Among various drying methods, freeze-drying is the most highly regarded due to its ability to preserve key bioactive substances such as cordycepin, adenosine, polysaccharides, vitamins, and amino acids, while maintaining the natural shape and color of the product [1–5].

Despite its advantages, freeze-drying is a complex and energy-intensive process that is highly sensitive to operational parameters [6]. An inappropriate drying regime may compromise product quality, prolong the drying duration, and increase energy costs. Currently, studies on determining optimal freeze-drying regimes for *Cordyceps militaris* remain limited, especially in terms of theoretical modeling and experimental data, highlighting the need for more in-depth research in this area.

To develop an appropriate freeze-drying regime for *Cordyceps militaris*, it is essential to understand the heat and mass transfer mechanisms occurring within the material. Numerical methods have become effective tools for simulating and optimizing such processes, particularly for freeze-drying, which is inherently nonlinear and involves multiple interacting factors. However, accurate simulation requires comprehensive thermophysical data specific to the drying material. These properties are critical inputs that directly influence simulation outcomes and the determination of optimal drying conditions [6].

Although extensive thermophysical data exist for a variety of food materials, data for *Cordyceps militaris* are scarce or nonexistent. In our previous study, we investigated the changes in the thermophysical properties of *Cordyceps militaris*. However, that work focused solely on the determination of these properties during the freezing stage of the freeze-drying process [7]. The key parameters required include density, specific heat capacity, thermal conductivity, and porosity - essential inputs for solving heat and mass transfer equations in computational models.

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These properties can be determined using two main approaches: experimental measurement and mathematical prediction. Each has its strengths and limitations. While experimental methods offer high accuracy, they require sophisticated instrumentation and controlled laboratory conditions. Predictive methods, on the other hand, employ mathematical models based on the material's composition and structural characteristics [7-10].

Density can be obtained experimentally or estimated using models such as those proposed by Luikov, Choi & Okos [8–10], and Banu Koc [11], which take into account composition, moisture content, and sample volume.

Porosity significantly affects heat and mass transfer behavior. It can be determined through structural image analysis or calculated from bulk and true density, as in the models by Choi & Okos, and Mannapperuma & Singh [8–10].

Thermal conductivity reflects a material's capacity to conduct heat. Models by Luikov, Choi & Okos [12], Maxwell–Eucken, Carson [13], and Capozzi [14] are commonly used to estimate the effective thermal conductivity of porous materials based on their composition and porosity.

Specific heat capacity indicates the energy required to raise a material's temperature. It can be calculated based on chemical composition [12] and porosity, as in Capozzi's model [14].

Effective moisture diffusivity is a key parameter in drying processes, representing the rate of moisture migration within the material. It can be estimated using Fick's law [15], Arrhenius-type expressions [8, 16], or more detailed transport models (viscous flow, Knudsen diffusion, molecular diffusion) depending on the surrounding pressure [17–19].

During freeze-drying, a sublimation front separates the material into two regions: a dry zone near the heat source and a frozen zone at the center. The dry zone, which shares the properties of the final product, is the focus of most simulations. As sublimation progresses inward, the dry region expands until the entire sample is dehydrated, marking the end of the primary drying stage. Therefore, accurate determination of the thermophysical properties of the dry zone is essential for reliable simulation [6].

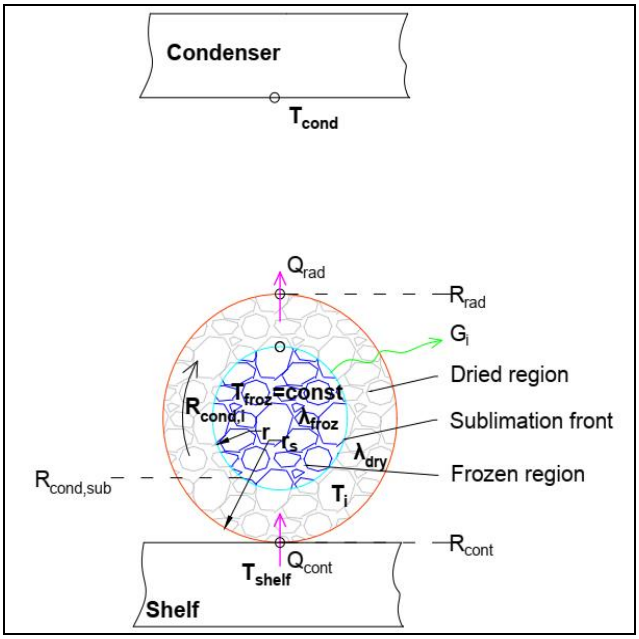

Fig 1: Heat Transfer Diagram of *Cordyceps militaris* Fiber in the Drying Tray [6]

From the above discussion, it is evident that accurate determination of thermophysical properties - particularly for the dry zone - is a prerequisite for numerical simulation and optimization of the freeze-drying process of *Cordyceps militaris*. In this study, key properties such as density, porosity, specific heat capacity, and thermal conductivity will be experimentally determined to serve as the foundation for modeling heat and mass transfer during freeze-drying..

II. MATERIALS AND RESEARCH METHODS

A. Research materials

The *Cordyceps militaris* samples used in this study were artificially cultivated at 4/4/A2 Vu Ngoc Nha Street, Vinh Ngoc Ward, Nha Trang City, Khanh Hoa Province, Vietnam. The fruiting bodies exhibited an orange color, with lengths ranging from 30 mm to 80 mm and diameters between 3 mm and 6 mm. After harvesting, the samples were preserved and transported to the laboratory at Nha Trang University. At the laboratory, the fresh *Cordyceps militaris* fruiting bodies were carefully separated from the cultivation substrate in preparation for the experiments.


Fig 2: Fresh Cordyceps militaris

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B. Method for Determining the Density of Cordyceps militaris

The density of *Cordyceps militaris* was determined as the ratio of the total mass to the total volume, including the mass and volume of solids, water, and gas present within the fibers of the sample [11, 20]:

$$\rho = \frac{m_t}{V_t}, \quad \left(\text{kg}/m^3\right) \tag{1}$$

where m_t is the mass (kg), and V_t is the total volume (m^3) of the *Cordyceps militaris* sample.

The experiments were conducted to measure the mass and volume of the samples in both fresh and dried states. These measurements were then used to calculate the density of *Cordyceps militaris* before and after the freeze-drying process. Specifically:

The mass of each sample was measured using an Ohaus PX224E precision electronic balance.

The volume of the sample was determined using the liquid displacement method, involving a graduated measuring cylinder and stainless steel beads (304 stainless steel, diameter: 0.1 mm) [21, 22].

C. Method for Determining the Porosity of Cordyceps militaris

The porosity of dried *Cordyceps militaris* was determined based on the relationship between the bulk density of the material and the mass fractions along with the true densities of its components [8, 9, 16, 23]:

$$\varepsilon = 1 - \rho \cdot \sum \frac{x_i}{\rho_i}, \tag{2}$$

Where:

ε is the porosity,
ρ is the bulk density of the material (kg/m³),
x_i is the mass fraction of the i-th component in the material,
ρ_i is the true density of the i-th component (kg/m³), calculated using the empirical formula proposed by Choi and Okos [8-10] (see Table 1).

This approach assumes that the total volume of the material includes both the solid matrix and the internal voids, and that the porosity represents the fraction of volume not occupied by solid matter.

D. Method for Determining the Thermal Conductivity of Cordyceps militaris

The thermal conductivity of *Cordyceps militaris* was determined based on the effective thermal conductivity of porous materials. According to Luigi C. Capozzi, Antonello A. Barresi and Roberto Pisano [14], the effective thermal conductivity of the dry zone is calculated using the following equation:

$$k = k_{sol} \cdot \frac{2k_{sol} + k_{gas} - 2\varepsilon\left(k_{sol} - k_{gas}\right)}{2k_{sol} + k_{gas} + \varepsilon\left(k_{sol} - k_{gas}\right)}, \quad \left(\text{W}/(\text{m}\cdot\text{K})\right) \tag{3}$$

Where:

k_{gas} is the thermal conductivity of the vapor within the dry zone of *Cordyceps militaris* (W/(m·K)),
k_{sol} is the thermal conductivity of the solid phase (W/(m·K)),
ε is the porosity of *Cordyceps militaris* fiber.

The vapor thermal conductivity k_{gas} depends on temperature and pressure, or more specifically, on the concentration of water vapor.

The thermal conductivity of the solid phase λr is calculated using the following equation:

$$k_{sol} = \sum k_i . x_i^v, \quad \left(\text{W}/(\text{m}\cdot\text{K})\right) \tag{4}$$

Where:

k_i is the thermal conductivity of the i^{th} component in *Cordyceps militaris* (W/(m·K)), calculated using the empirical formula proposed by Choi and Okos [8–10] (see Table 1).
x^v_i is the volume fraction of the i-th component in *Cordyceps militaris*, which is determined by:

$$x_i^v = \frac{x_i}{\rho_i} \frac{1}{\sum \frac{x_i}{\rho_i}} \tag{5}$$

In which: x_i and ρ_i are the mass fraction and density of the i-th component, respectively.

E. Method for Determining the Specific Heat Capacity of Cordyceps militaris

The specific heat capacity of *Cordyceps militaris* is determined based on its effective specific heat capacity, taking into account the porosity of the material. According to Luigi C. Capozzi, Antonello A. Barresi and Roberto Pisano. [14], the effective specific heat capacity Cp,eff can be calculated using the following equation:

$$c_{p,eff} = c_{p,gas} \cdot \varepsilon + c_{p,sol} \cdot \left(1 - \varepsilon\right), \quad \left(\text{J}/(\text{kg}\cdot\text{K})\right) \tag{6}$$

Where:

$c_{p,gas}$ is the specific heat capacity of the vapor phase (J/(kg·K)), which depends on the temperature and pressure of the vapor,
$c_{p,sol}$ is the specific heat capacity of the solid phase in *Cordyceps militaris* (J/(kg·K)), calculated as:

$$c_{p,sol} = \sum x_i \, c_{p,i}, \quad \left(\text{J}/(\text{kg}\cdot\text{K})\right) \tag{7}$$

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Where:

$c_{p,i}$ is the specific heat capacity of the i-th component, calculated using the empirical formula proposed by Choi and Okos [8–10] (see Table 1).

F. Determination of the Effective Moisture Diffusion Coefficient

During the freeze-drying process of *Cordyceps militaris*, the chamber pressure typically ranges from 0.1 Pa to 100 Pa, placing it within the intermediate vacuum range. Under these conditions, moisture transport occurs predominantly via Knudsen diffusion. The effective moisture diffusion coefficient Deff is determined based on the Knudsen diffusion coefficient Dk , as follows [19, 23]:

$$D_{eff} = \frac{\varepsilon}{\tau} \cdot D_k, \quad \left(\mathrm{m^2/s}\right) \tag{8}$$

Where:

ε is the porosity,
τ is the tortuosity of the moisture migration path. For cylindrical objects, it can be estimated using:

$$\tau = 1 - \ln \varepsilon, \tag{9}$$

The Knudsen diffusion coefficient D_k [m²/s] is given by [19]:

$$D_K = \frac{1}{3} \cdot d_e \cdot \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M_w}}, \quad \left(\mathrm{m^2/s}\right) \tag{10}$$

Substituting Equations (2.54) and (2.55) into Equation (2.53), the effective moisture diffusion coefficient becomes:

$$D_{eff} = \frac{\varepsilon}{1 - \ln \varepsilon} \cdot \frac{1}{3} \cdot d_e \cdot \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M_w}}, \quad \left(\mathrm{m^2/s}\right) \tag{11}$$

Where:

d_e is the pore diameter (m), typically ranging from

Table 1: Mathematical models for Determining Thermophysical Properties of Ingredients in the Food According to Choi and Okos (1986) [8-10]

Thermal properties	Food component	Thermal property model
Density ρ, (kg/m^3)	Protein	$\rho = 1.3299 \times 10^3 - 5.1840 \times 10^{-1} t$
	Fat	$\rho = 9.2559 \times 10^2 - 4.1757 \times 10^{-1} t$
	Carbohydrate	$\rho = 1.5991 \times 10^3 - 3.1046 \times 10^{-1} t$
	Ash	$\rho = 2.4238 \times 10^3 - 2.8063 \times 10^{-1} t$
	Water	$\rho = 9.9718 \times 10^2 + 3.1439 \times 10^{-3} t - 3.7574 \times 10^{-3} t^2$
	Ice	$\rho = 9.1689 \times 10^2 - 1.3071 \times 10^{-1} t$
Specific heat c_p, (kJ/kg.K)	Protein	$C_p = 2.0082 + 1.2089 \times 10^{-3} t - 1.3129 \times 10^{-6} t^2$
	Fat	$C_p = 1.9842 + 1.4733 \times 10^{-3} t - 4.8008 \times 10^{-6} t^2$
	Carbohydrate	$C_p = 1.5488 + 1.9625 \times 10^{-3} t - 5.9399 \times 10^{-6} t^2$
	Ash	$C_p = 1.0926 + 1.8896 \times 10^{-3} t - 3.6817 \times 10^{-6} t^2$
	Water (0 ÷ 150 °C)	$C_p = 4.1289 - 9.0864 \times 10^{-5} t + 5.4731 \times 10^{-6} t^2$
	Water (-40 ÷ 0 °C)	$C_p = 4.1289 - 5.3062 \times 10^{-3} t + 9.9516 \times 10^{-4} t^2$
	Ice	$C_p = 2.0623 + 6.0769 \times 10^{-3} t$
Thermal conductivity k, (W/m.K)	Protein	$k = 1.7881 \times 10^{-1} + 1.1958 \times 10^{-3} t - 2.7178 \times 10^{-6} t^2$
	Fat	$k = 1.8071 \times 10^{-1} - 2.7604 \times 10^{-4} t - 1.7749 \times 10^{-7} t^2$
	Carbohydrate	$k = 2.0141 \times 10^{-1} + 1.3874 \times 10^{-3} t - 4.3312 \times 10^{-6} t^2$
	Ash	$k = 3.2962 \times 10^{-1} + 1.4011 \times 10^{-3} t - 2.9069 \times 10^{-6} t^2$
	Water	$k = 5.7109 \times 10^{-1} + 1.7625 \times 10^{-3} t - 6.7036 \times 10^{-6} t^2$
	Ice	$k = 2.2196 - 6.2489 \times 10^{-3} t + 1.0154 \times 10^{-4} t^2$

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- T is the temperature (K),
- R is the universal gas constant, (J/kmol.K)
- M_w is the molecular weight of water (kg/kmol).

To calculate the effective moisture diffusion coefficient of *Cordyceps militaris*, the pore diameter de must be determined. This can be achieved through structural image analysis of the material. This approach has been widely applied in several studies on material structure and porosity, including works in[24-28].

G. Experimental Research Equipment

➢ *Freezing Equipment*

The freezing stage is the initial phase of the freeze-drying process. During this stage, the temperature of the material is reduced below its crystallization point, causing the moisture within the material to solidify. In this study, a forced-air freezer installed at the Thermal Engineering Laboratory, Nha Trang University (Vietnam), was used to freeze *Cordyceps militaris* prior to the freeze-drying process.

This freezer allows adjustment of the freezing mode according to experimental requirements and has the following technical specifications [29]:

- Cooling capacity: 1 kW
- Freezing chamber volume: 50 liters
- Chamber dimensions: 430 mm × 280 mm × 420 mm
- Minimum achievable temperature: –50 °C
- Adjustable air velocity: up to 5 m/s

Fig 3: *Cordyceps militaris* Freezer used Prior to Freeze-Drying [29]

This device is used to freeze *Cordyceps militaris* to –40 °C before the freeze-drying process.

➢ *Freeze-Drying Equipment*

In this study, the FD-01 freeze dryer was used. The equipment is installed at the Thermal Engineering Laboratory, Nha Trang University, and has the following main technical specifications [30]:

- Power consumption: 2 kW
- Sublimation chamber volume: 38 liters, cylindrical shape (Ø 310 mm, length 500 mm)
- Refrigerant solution: 86% ethanol
- Heating element: 500 W resistor
- Vapor condenser plate temperature: down to –35 °C
- Sublimation chamber pressure: reduced to 20 Pa during operation

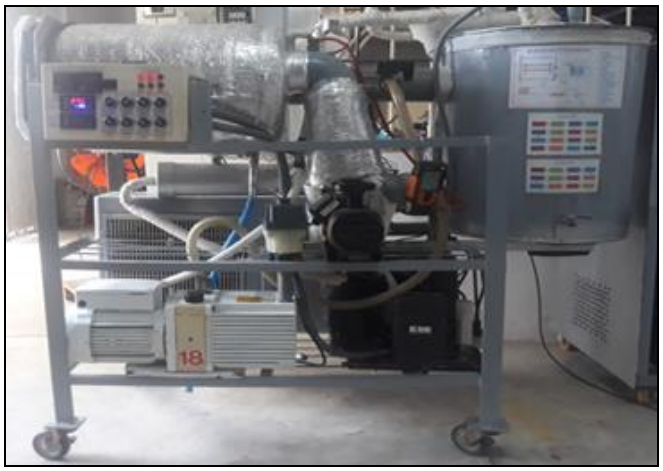

Fig 4: Image of the Freeze Dryer [30]

This equipment is used to dry *Cordyceps militaris* to a final moisture content of 7% (wet basis).

➢ *Measuring Devices Used in the Experimental Study*

A temperature-measuring device with 12 channels (Data Logger EXTECH TM500, Extech Instruments, Boston, Massachusetts, USA) was used in this study. The temperature probes were inserted into the surface of the *Cordyceps militaris* fibers placed on trays inside the drying chamber to record the temperature signal. The data logger recorded temperature values at 1-second intervals, and the measured values were stored automatically in the device's memory throughout the freeze-drying process.

An OHAUS PX224E 4-digit analytical balance was used to measure the mass of *Cordyceps militaris*. The measurements were used to determine the density of the material.

A volumetric measuring cylinder and 0.1 mm diameter 304 stainless steel beads were used to measure the volume of *Cordyceps militaris* fibers before and after drying. These measurements were also used in the calculation of material density.

An OHAUS MB120 moisture analyzer was used to determine the moisture content of the samples at various stages of the experiment.

III. RESEARCH RESULTS AND DISCUSSION

A. Composition Analysis of Cordyceps militaris

The basic composition of *Cordyceps militaris* is presented in Fig 5. Moisture accounted for the highest proportion at 78.56 %, followed by carbohydrates at 14.88 %. Protein constituted 4.08%, while ash and fat were present in the lowest proportions, at 1.43 % and 1.41 %, respectively.

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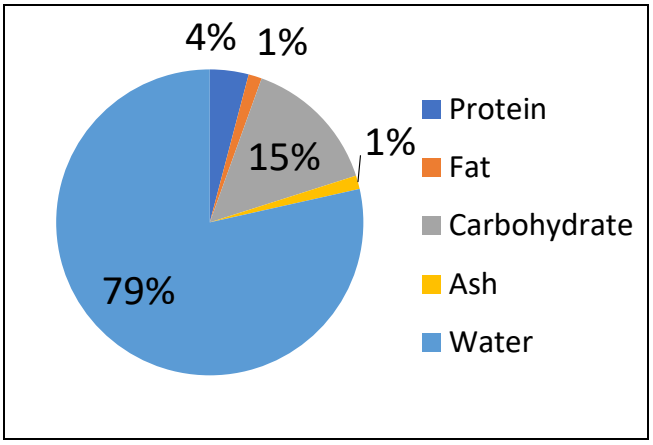


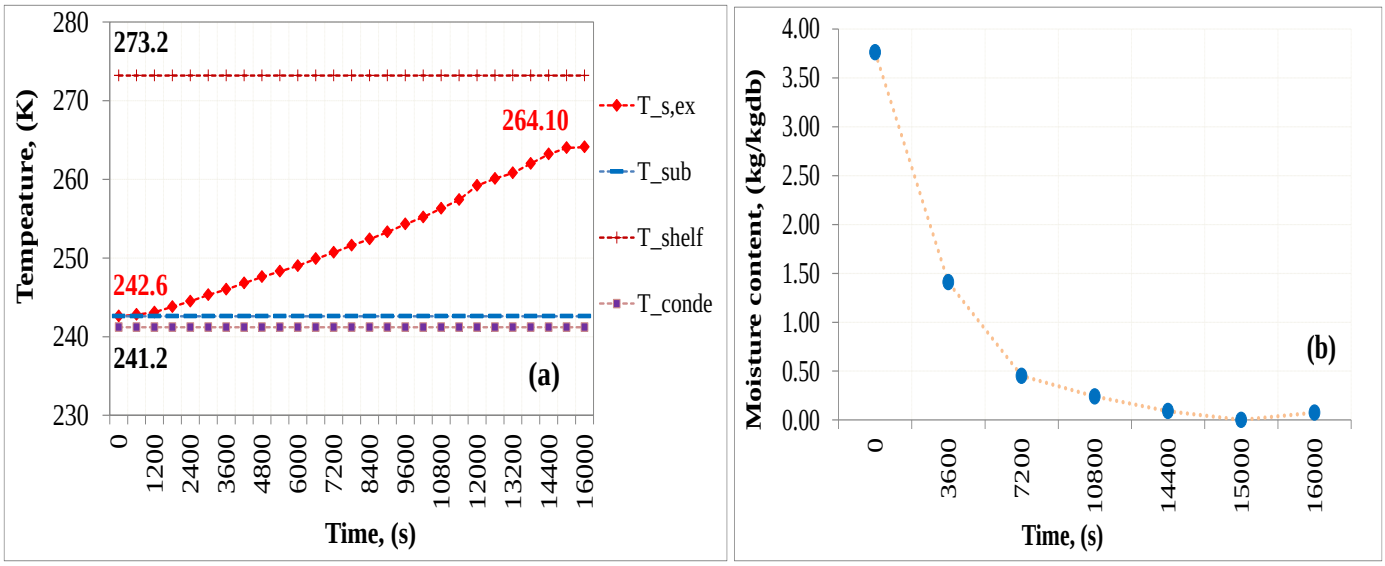
Fig 5: Composition of *Cordyceps militaris*

After the freezing process at -40 °C, approximately 93% of the moisture in *Cordyceps militaris* was frozen [7]. This frozen moisture is then removed entirely during the freeze-drying process. These results are used to determine the composition of *Cordyceps militaris* before and after freeze-drying.

B. Experimental Results of the Freeze-Drying Process

The freeze-drying experiment was conducted with a shelf temperature of T_{shelf} = 273.2 K, a condenser plate temperature of T_{conde} = 241.2 K, and a sublimation chamber pressure of P_{chamb} = 35 Pa.

Fig 6 shows the temperature and moisture content of *Cordyceps militaris* during the drying process. Under these conditions, it took approximately 16000 seconds for the moisture content to decrease from 79 % to 7 % (equivalent to 0.074 kg/kg dry basis). Simultaneously, the surface temperature of *Cordyceps militaris* fibers increased from 242.6 K to 263 K.



(a) (b)

Fig 6: Temperature (a) and Moisture Distribution (b) of *Cordyceps militaris* during the Freeze-Drying Process

These results provide essential input data for calculating the thermophysical properties of *Cordyceps militaris* during the freeze-drying process.

C. Results of Density Determination for Cordyceps militaris

Using the experimental method of weighing and measuring the volume of both fresh and dried *Cordyceps militaris* fibers, the density was determined according to (1). The average density values, based on ten samples (shown in Fig 7 and Table 2), were found to be 1020 kg/m³ for fresh and 277.08 kg/m³ for dried *Cordyceps militaris*.

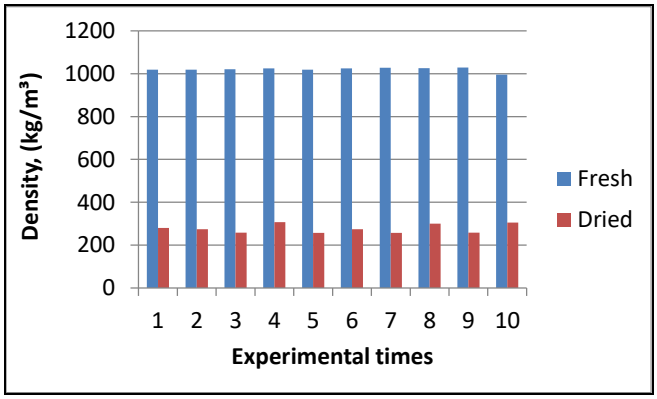


Fig 7: Experimental Determination of the Density of Fresh and dried *Cordyceps Militaris*

This indicates a significant reduction in density during the freeze-drying process. The reduction is primarily due to the sublimation of frozen water in the *Cordyceps militaris* structure, leading to a decrease in mass, while the overall

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volume of the material remains nearly unchanged. This results in a marked decrease in density.

One of the key advantages of freeze-drying is its ability to preserve the structure, shape, and volume of the material - unlike conventional drying methods, where substantial volume shrinkage leads to an increase in density post-drying [20, 31-35].

D. Results of Porosity Determination for Cordyceps militaris

The porosity of fresh and dried *Cordyceps militaris* was determined using (2). The results showed that the initial porosity was approximately 0.10 and increased to 0.81 after the freeze-drying process. This dramatic rise highlights a major advantage of freeze-drying over other drying techniques [20, 31-34].

Due to the sublimation of moisture and minimal structural collapse, large voids are formed inside the material, significantly increasing porosity while maintaining volume. In contrast, conventional drying methods often induce considerable shrinkage, reducing the size and number of internal voids and, thus, decreasing porosity.

D. Setiady, J. Tang, F. Younce, B. A. Swanson, B. A. Rasco, C. D. Clary [35] compared the effects of three drying methods - Microwave Vacuum Drying, Hot Air Drying, and Freeze Drying - on the porosity, texture, and microstructure of potatoes. The results showed that Freeze Drying produced samples with the highest porosity (~80–85%) due to the preservation of the original tissue structure and minimal volume shrinkage. Microwave Vacuum Drying also resulted in relatively high porosity, attributed to the rapid evaporation rate that formed hollow structures within the core. In contrast, Hot Air Drying yielded the lowest porosity, as the slower evaporation rate led to significant volume shrinkage, increased material density, and reduced porosity.

Similarly, São Paulo [36] reported that the porosity of dried bananas decreased by approximately 10% compared to their initial porosity. This phenomenon was explained by the occurrence of heat and mass transfer processes within the porous structure, leading to capillary shrinkage, a reduction in average pore diameter, and thus, a decrease in overall porosity.

E. Results of Thermal Conductivity Determination for Cordyceps militaris

The thermal conductivity, calculated using (3), was found to decrease significantly after the freeze-drying process. The thermal conductivity of fresh *Cordyceps militaris* was 1.073 W/m·K, while that the average thermal conductivity values of the dried sample was 0.041 W/m·K (shown in Table 2).

This drop is attributed to the sublimation of ice within the material, which has a higher thermal conductivity than other food components and accounts for approximately 73% of the initial mass. Upon sublimation, the disappearance of ice leaves behind porous voids, resulting in a drastic reduction in thermal conductivity [8-10, 35, 37-42].

Additionally, during the freeze-drying process, a dry zone is gradually formed, and its temperature increases over time (as illustrated in Figure 6). This temperature rise leads to a slight increase in the thermal conductivity of both the vapor and the solid matrix within the dry zone, resulting in a gradual increase in the effective thermal conductivity of the dried Cordyceps militaris region. However, this increase is relatively minor (shown in Fig 8).

Therefore, it is crucial to consider the thermal conductivity of the dry layer formed during the drying process when modeling or designing freeze-drying systems.

F. Results of Specific Heat Capacity Determination for Cordyceps militaris

The specific heat capacity, determined by Equation (7), exhibited a notable decrease as a result of the freeze-drying process. For fresh Cordyceps militaris, it was 2012 J/kg·K, decreasing to an average of 1850 J/kg·K after drying (see Table 2).

This reduction is mainly due to the sublimation of ice, which possesses a relatively high specific heat capacity (second only to liquid water). Additionally, as the material temperature rises during drying, the specific heat capacity of unfrozen water decreases, further contributing to the overall reduction [8-10, 35, 37-42].

In addition, as the temperature of the dry region of Cordyceps militaris increases, the specific heat of the solid phase tends to decrease, while that of the vapor phase slightly increases. As a result, the effective specific heat capacity of the dry region gradually decreases. However, the overall change remains relatively small (see Figure 8).

The thermophysical properties of fresh and dried *Cordyceps militaris* are summarized in Table 2.

Table 2: Thermal Conductivity, Specific Heat, and Density of Fresh and Dried *Cordyceps militaris*

State	Density (kg/m^3)	Porosity -	Thermal conductivity (W/m.K)	Specific heat Capacity (J/kg.K)
Fresh	1020	0.10	1.073	2012
Dried	277.08	0.81	0.041	1850

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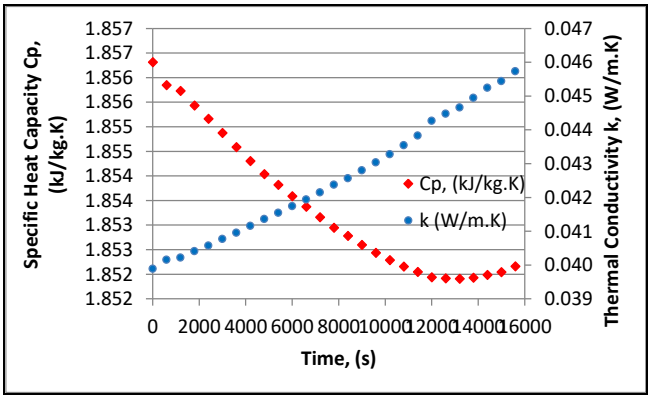

Fig 8: Variation in Thermal Conductivity and Specific Heat Capacity of the Dry Region of *Cordyceps militaris* during Freeze-Drying

G. Results of Effective Moisture Diffusion Coefficient Determination for Cordyceps militaris

In this study, freeze-drying was conducted at a sublimation chamber pressure of 35 Pa. At this pressure, moisture transport occurs primarily via Knudsen diffusion.

To determine the effective moisture diffusion coefficient, it was necessary to estimate the pore diameter (d_e) of *Cordyceps militaris*. This was accomplished through structural image analysis of the cell tissue, following the methods described in references [24–28]. Microscopic images of the cell tissue structure are presented in Fig 9.

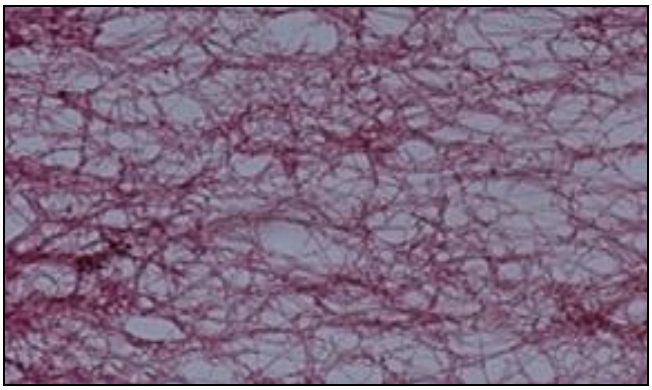

Fig 9: Microstructure of Freeze-Dried *Cordyceps militaris* Observed with a Nikon E200 Optical Microscope at 100× Magnification

Image analysis using ImageJ software revealed that the average pore diameter (d_e) in the structure of dryed *Cordyceps militaris* was 3.8×10^{-5} m. Based on (8), with porosity $\varepsilon = 0.81$, average temperature $T = 253$ K, and $d_e = 3.8 \times 10^{-5}$ m, the effective moisture diffusion coefficient (D_{eff}) was determined to be 0.00452 m²/s. This value falls within the expected theoretical range and is consistent with the modeling assumptions for vacuum drying processes of porous materials [43, 44].

This coefficient is a critical parameter for simulating the internal moisture diffusion process within the dried region of *Cordyceps militaris* fibers during freeze-drying.

IV. CONCLUSION

Based on experimental methods combined with theoretical models developed in previous studies, this research has determined key thermophysical properties of *Cordyceps militaris* before and after freeze-drying.

Notably, the density of *Cordyceps militaris* decreased significantly from 1020 kg/m³ to 277.08 kg/m³, corresponding to an increase in porosity from 0.1 to 0.81. This demonstrates the preservation of the structural integrity and original shape of *Cordyceps militaris* throughout the freeze-drying process.

In addition, thermal conductivity and specific heat capacity decreased markedly—from 1.073 to 0.041 W/m·K and from 2012 to 1850 J/kg·K, respectively—due to ice removal and the formation of internal voids during sublimation. In contrast, in the dry region of Cordyceps militaris, the specific heat capacity slightly decreased, while thermal conductivity exhibited a minor increase.

The average effective moisture diffusion coefficient was calculated to be 0.00452 m²/s, providing essential input for modeling heat and mass transfer phenomena during the freeze-drying of *Cordyceps militaris*.

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