EXPERIMENTAL DETERMINATION OF THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF UNFROZEN AND FROZEN *ABELMOSCHUS SAGITTIFOLIUS* (KURZ) MERR GINSENG

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ABSTRACT

The thermophysical properties of herbal materials play an essential role in the design and optimization of food processing technologies such as drying and freezing. However, quantitative thermophysical data for *Abelmoschus sagittifolius* (commonly known as Bo Chinh ginseng), a medicinal root widely used in functional foods and nutraceutical products, remain very limited. This experimental study aims to determine the thermal conductivity and thermal diffusivity of *A. sagittifolius* within the temperature range of -30℃ to 30℃. Experimental results obtained using the Transient Hot Wire method show that the thermal conductivity and thermal diffusivity increase significantly when the material temperature drops below 0℃. The experimental data were successfully modeled using second-order polynomial regression equations, demonstrating their suitability for integration into heat transfer simulation models. This study addresses a critical gap in the literature by providing the first standardized dataset of thermal properties for *A. sagittifolius*, thereby supporting improved thermal process modeling and optimization for this commercially valuable yet under-researched medicinal material.

Keywords: *Abelmoschus sagittifolius; thermal conductivity; thermal diffusivity; food freezing, transient hot wire.*

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1. INTRODUCTION

Abelmoschus sagittifolius (Kurz) Merr ginseng, also known as Bo Chinh ginseng or Tho Hao ginseng, is a medicinal herb grown in Vietnam. The roots of this plant contain many precious medicinal components. To study the freezing step in the freeze-drying process of this material, it is necessary to determine the thermal conductivity and thermal diffusivity of the material. These are two very important properties in determining the freezing time of materials. On the other hand, during the freezing process, water in the material will undergo phase transition from liquid to solid when the material temperature is lower than the initial freezing temperature, leading to significant changes in the thermal properties of the material. Therefore, in this study, the authors research experimental methods to determine the temperature-dependent thermal conductivity and thermal diffusivity of the material.

There are two main experimental methods for determining the thermal conductivity and thermal diffusivity of materials: steady-state methods and transient methods. Among them, the steady-state method can have a long measurement time depending on the size of the material for poorly conductive materials [1-4]. Therefore, this method is not suitable for determining the thermal conductivity of frozen materials because the ice in the frozen material is prolonged contact with a heat source, leading to the melting of the ice within the frozen material. Meanwhile, the transient technique is more suitable for measuring the thermal conductivity and thermal diffusivity of frozen materials due to its short experimental time and more accurate results [5]. In the transient method, the Transient Hot Wire technique is considered a highly reliable technique for

determining the thermal conductivity and thermal diffusivity of various materials, including gases, liquids, and solids. This method is also accurate, fast, and cost-effective [6-8].

Numerous studies have investigated the thermal conductivity and thermal diffusivity of fruits and food materials under frozen and unfrozen conditions, including stone fruits [9], mango and papaya [10], berberis [11], guava and passion fruits [12], and cranberries [13]. These studies primarily focus on common fruits and food products, while no quantitative thermophysical data have been reported for Abelmoschus sagittifolius or closely related medicinal roots. In particular, temperature-dependent thermal properties across the phase change region of medicinal plant roots remain largely unexplored. Therefore, the lack of standardized experimental data on the thermal conductivity and thermal diffusivity of Abelmoschus sagittifolius represents a clear gap in the current literature, which the present study aims to address.
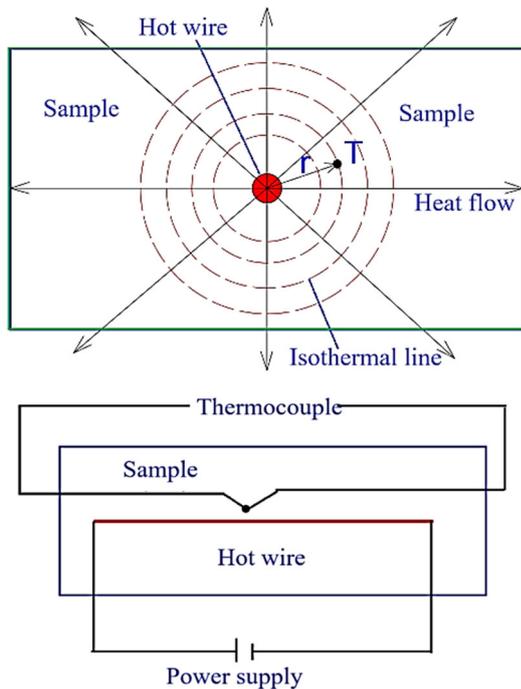
Transient hot wire method

Fig. 1. Principle of measuring thermal conductivity and thermal diffusivity of the Hot Wire method

There are many methods for measuring thermal conductivity and thermal diffusivity of materials, and one of the most widely used methods for determining the thermal conductivity of food is the transient hot wire technique [4, 8, 14]. According to Castán-Fernández et al. [15], this method is suitable for solid and granular

materials because the sensor is placed directly within the material, ensuring good thermal contact. The method has also been shown to be effective in measuring the thermal conductivity of porous solid materials such as geothermal grouting materials, and it can be applied in a similar manner to solid food materials to rapidly determine thermal conductivity with lower measurement errors compared to steady-state methods.

In this method, a hot wire is inserted along the center of an infinitely long, isotropic cylindrical sample with thermal diffusivity a independent of temperature and thermal conductivity k (Fig. 1). Initially (at time $t = 0$) in thermodynamic equilibrium with the hot wire at temperature T_0. Heat transfers from the heat source, then the heat flow is constant on a unit length q only thermal conduction (other heat transfer modes are negligible). Therefore, the temperature field around the hot wire heat source can be described by the following heat conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r} \right) \quad (1)$$

The above equation is solved with the following initial and boundary conditions:

- Initial condition: for $t = 0$, $T(r,0) = T_0$

- Boundary condition:

+ For $r = 0$, q = const $\quad (2)$

+ For $r \rightarrow \infty$, $T(\infty, t) = T_0$ $\quad (3)$

The above equation was analyzed by Carslaw and Jaeger [16] and proposed to determine the temperature rise over time t as follows:

$$\Delta T(r,t) = \frac{q}{4\pi k}\int_u^\infty \frac{e^{-u^2}}{y}du \quad (4)$$

From the general expression (4), it can be seen that the temperature rise at a point located at a distance r from the heat source is described by an integral of a first-order exponential form. This integral corresponds to the exponential integral function $E_1(u)$ where $u = \frac{r^2}{4at}$ is a dimensionless parameter that depends on the measurement position and time. Therefore, Eq. (4) can be rewritten in a more compact form as:

$$\Delta T(r_0,t) = \frac{q}{4\pi k}E_1\left(\frac{r^2}{4at} \right) \quad (5)$$

The exponential integral function $E_1(u)$ can be approximated by a Taylor series expansion for $u \ll 1$,

corresponding to measurement points located close to the heat source (i.e., small values of r), as follows:

$$E_1(u) = -\gamma - \ln u + u - \frac{u^2}{4} + ... \qquad (6)$$

Where $\gamma = 0.5772157$ is the Euler constant.

For $u << 1$, the terms u, u^2 and higher-order terms are negligible, and the ideal model for experimental analysis can therefore be expressed as follows:

$$\Delta T(r_0, t) = \frac{q}{4\pi k} \ln \frac{4at}{r_0^2 e^\gamma} \qquad (7)$$

The thermal conductivity of the material is determined by:

$$k = \frac{q}{4\pi \Delta T} \ln \frac{t_2}{t_1} \qquad (8)$$

To determine the thermal diffusivity, Nix *et al.* [1] proposed the following solution to equation (4):

$$\Delta T = \frac{q}{4\pi k} \left[-\gamma - \ln u + \frac{u^2}{2.1!} - \frac{u^4}{4.2!} + ... \right] \qquad (9)$$

Where: $u = \frac{r^2}{4at}$: dimensionless parameter

$\gamma = 0.57721$: Euler constant

The dimensionless parameter u is required to calculate thermal diffusivity a:

$$a = \frac{r^2}{4ut} \qquad (10)$$

As suggested by Nix *et al.* [1] if $u < 0.16$, only the first two terms in equation (9) need to be considered. Therefore, the expression used to determine u can be rewritten as follows:

$$\Delta T = \frac{q}{4\pi k} [-\gamma - \ln u] \qquad (11)$$

To determine u in equation (11), the author uses Goal Seek, a program in Microsoft Excel, to find the corresponding value.

Due to the short heating time and small characteristic thermal penetration depth, the measurements primarily reflect local thermophysical properties around the hot wire.

2. MATERIALS AND METHODS

2.1. Materials

Fresh ginseng roots used in the experiment were grown in Quang Binh province and supplied by SBC ROYAL CO., LTD. (Hue City). Ginseng was stored at 10°C in refrigerator..

To ensure sample homogeneity, fresh *Abelmoschus sagittifolius* roots with uniform diameters and initial moisture contents were carefully selected. The bulk density of the samples was determined using the Archimedes displacement method across a temperature range of -30°C to 30°C. The average density (ρ) was found to be approximately 998kg/m^3 in the frozen state ($T < 0$°C) and 1083kg/m^3 in the unfrozen state ($T > 0$°C). The initial moisture content of the fresh samples, measured using a halogen moisture analyzer (KETT FD-720, Japan), was 79% (wet basis).

2.2. Measuring equipment

Ni-Cr heating wire with a diameter of 0.2mm and a length of 10cm.

Copper-Nickel thermocouple with a diameter of 0.3mm

XY 6008 DC power- Senzooe (China): allows setting voltage and amperage. Power can be adjusted in the range of $5 \div 15$W/m.

FX1000 Yokogawa temperature recorder (Japan), the recorder can read temperature values from the thermocouple, measurement accuracy ± 0.15%.

The freezer used in the experiment was from AOBEISI (China).

2.3. Measurement procedure

The ginseng root has a long cylindrical shape. Using a paper knife to create a groove along the center line of the root. Insert the hot wire into the groove so that the wire is located at the center line. The thermocouple is placed close to the hot wire and in the middle of the cylinder as shown in Fig. 2.
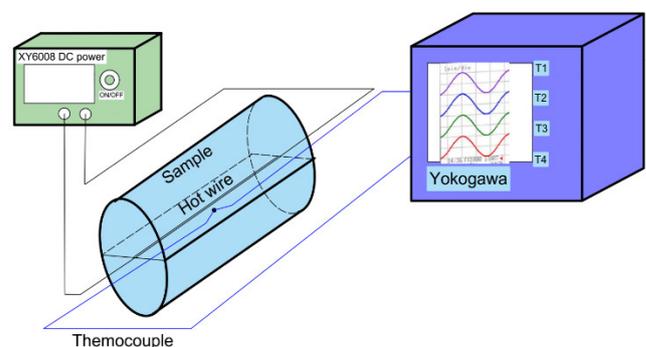

Fig. 2. Main component of apparatus

- The heating time and data recording in all experiments is 120 seconds.

- During data recording, the heating wire power is maintained constant through voltage and current settings on the power supply.

- At temperatures of $0 < T < 30°C$: The material is wrapped in plastic wrap and placed in an insulated glass of cold water. An additional thermocouple is arranged to measure the temperature of the cold water. When the core temperature of the material and the temperature of the cold water are equal. Proceed to supply power to the heating wire, the temperature recorder records the temperature of the material over time.

- At temperatures of $-30 \leq T \leq 0°C$: The material is placed in the freezer to cool to the required temperature. When the material reaches the required temperature, proceed to insulate the material and stop the freezer. When the material temperature is equal to the freezer temperature, proceed to heat the material and record the temperature of the material over time.

Each experiment was repeated three times, and the reported values represent the average results with corresponding standard deviations.

3. RESULTS AND DISCUSSION

3.1. Thermal conductivity

Using the Transient hot wire method, the authors conducted experiments to determine the thermal conductivity coefficient of Ginseng according to temperature, each experiment was repeated three times.

Table 1. Thermal conductivity of Ginseng (according to experimental results)

T (°C)	k_exp (W/m.K)	SD
-30	1.716	0.022
-25	1.684	0.021
-20	1.624	0.026
-15	1.614	0.001
-10	1.547	0.026
-5	1.495	0.036
0	0.718	0.023
5	0.733	0.012
10	0.758	0.018
15	0.76	0.007
20	0.768	0.012
25	0.777	0.013
30	0.796	0.004

Notes:

k_exp: thermal conductivity determined from experiment

SD: Standard Deviation

According to Table 1 and Fig. 3, in the temperature range below 0°C, water in the material crystallizes, leading to a significant increase in thermal conductivity due to the higher thermal conductivity of water in the solid phase than the thermal conductivity of water in the liquid phase.

Although the material is biologically heterogeneous, the transient hot-wire method limits the impact of internal anisotropy on thermal property measurements through its localized approach and brief heating intervals. Therefore, the assumption of local isotropy is considered acceptable for the present measurements within the investigated temperature range.
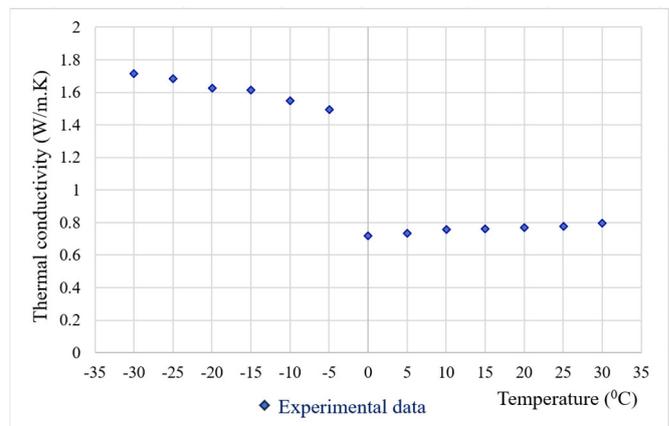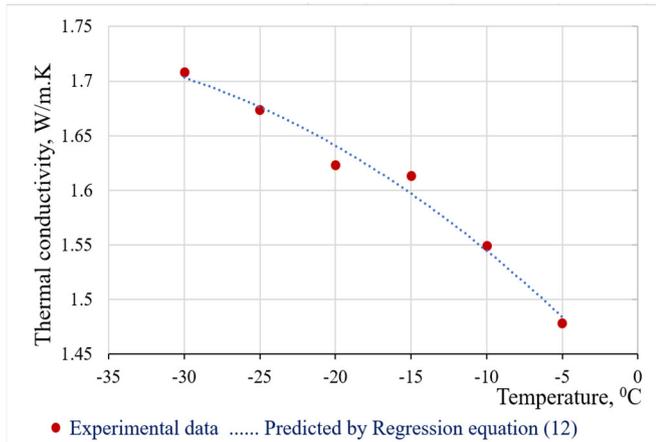
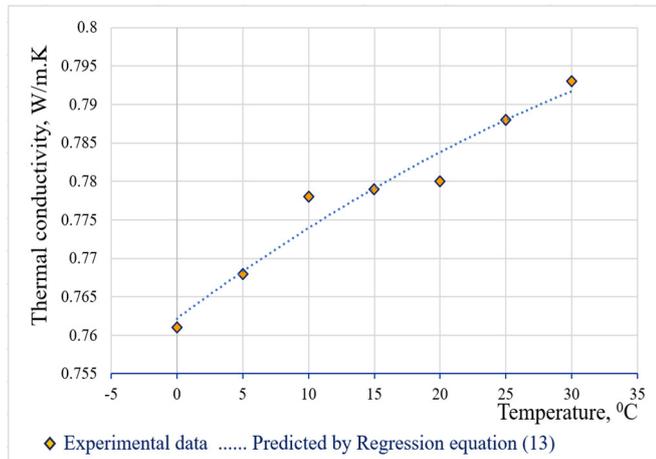Fig. 3. Thermal conductivity of ginseng at their respective temperatures

In this temperature range, a decrease in temperature results in a higher ice mass fraction, which consequently increases the thermal conductivity. In contrast, at temperatures above 0°C, the water within the material remains entirely in the liquid phase, and the thermal conductivity exhibits only minor variations. The relatively low proportion of other components causes negligible changes in the overall thermal conductivity of the material.

Due to the significant difference between the thermal conductivities of ice and liquid water, the thermal conductivity of frozen foods is highly temperature-dependent [10, 12]. Experimental studies on fruits have similarly shown that thermal conductivity increases as temperature decreases, particularly below the initial freezing temperature. Mukama et al. [4] synthesized experimental data on frozen materials and concluded that thermal conductivity increases with decreasing temperature below the initial freezing point. The present results are also consistent with the findings reported by Hoang et al. [17], based on both theoretical modeling and experimental data for various materials.

3.2. The thermal conductivity of Ginseng as a function of temperature

a) Thermal conductivity of frozen ginseng

b) Thermal conductivity of unfrozen ginseng

Fig. 4. Thermal conductivity of ginseng at their respective temperatures

Because determining the thermal conductivity of ginseng at temperatures above and below the freezing point by the theoretical models have too large errors compared to experimental data. The equations for the thermal conductivity with respect to the temperature of ginseng are determined through experimental data according to Fig. 4, equation (12) and equation (13). Equation (12) represents the thermal conductivity with respect to temperature with a temperature range smaller than the starting temperature of moisture crystallization with $R^2 = 0.9812$ and equation (13) is used to determine the thermal conductivity with a temperature greater than 0^oC with $R^2 = 0.9649$.

$$k = -0.0002 \times T^2 - 0.0147 \times T + 1.4145, T < 0^oC$$
$$(R^2 = 0.9812) \tag{12}$$

$$k = -10^{-5} \times T^2 + 0.0013 \times T + 0.7622, T \geq 0^oC$$
$$(R^2 = 0.9649) \tag{13}$$

The above equations ensure the accuracy standard used in engineering and they are used in calculating the freezing process of ginseng.

3.3. Experimental Thermal Diffusivity

Table 2. Thermal diffusivity of Ginseng (according to experimental results)

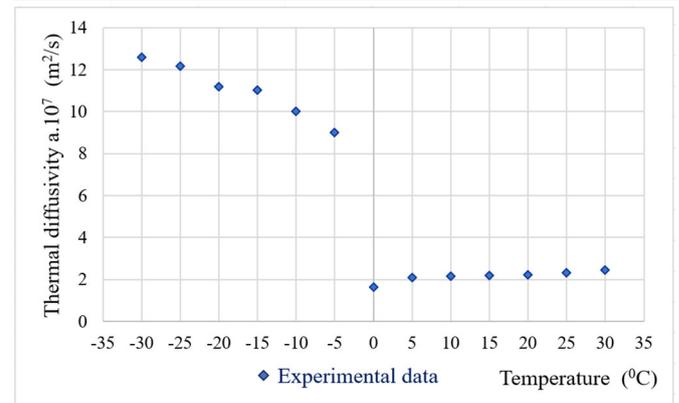| T (^oC)	a-exp $\times 10^7$	T (^oC)	a-exp $\times 10^7$
-30	12.59	5	2.08
-25	12.17	10	2.15
-20	11.17	15	2.19
-15	11.03	20	2.22
-10	10	25	2.32
-5	9.01	30	2.46
0	1.63		

Notes: a-exp: thermal diffusivity determined from experiment

Fig. 5. Thermal diffusivity of ginseng at their respective temperatures

At temperatures above 0^oC, the thermal diffusivity exhibits only a slight decrease with decreasing temperature, indicating a weak temperature dependence in the unfrozen state. When the temperature of the material drops below 0^oC, a sharp increase in thermal diffusivity is observed. This behavior is attributed to the onset of phase change, during which water within the material begins to crystallize, accompanied by the release of latent heat associated with the liquid-to-solid transition.

Specifically, in the temperature range from -5°C to 0°C, the thermal diffusivity increases markedly from 1.63×10^{-7}m²/s to 9.01×10^{-7}m²/s. At temperatures below -5°C, the thermal diffusivity continues to increase as the temperature decreases, corresponding to the increasing fraction of ice within the material. This trend indicates that the thermal diffusivity is governed by the combined effects of thermal conductivity, density, and specific heat capacity, particularly in the frozen state.

Although the specific heat capacity was not directly measured in this study, the observed increase in thermal diffusivity in the frozen region can be explained by well-established thermophysical behavior of high-moisture materials. During freezing, the thermal conductivity increases significantly due to ice formation, while the effective specific heat capacity decreases after the phase transition, whereas the density varies only slightly. As a result, the combined increase in thermal conductivity and decrease in effective heat capacity lead to a pronounced increase in thermal diffusivity in the frozen state.

3.4. The thermal diffusivity of ginseng as a function of temperature
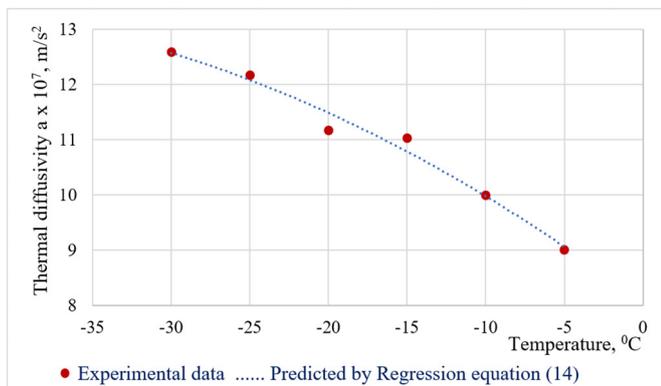
a) Thermal diffusivity of frozen ginseng
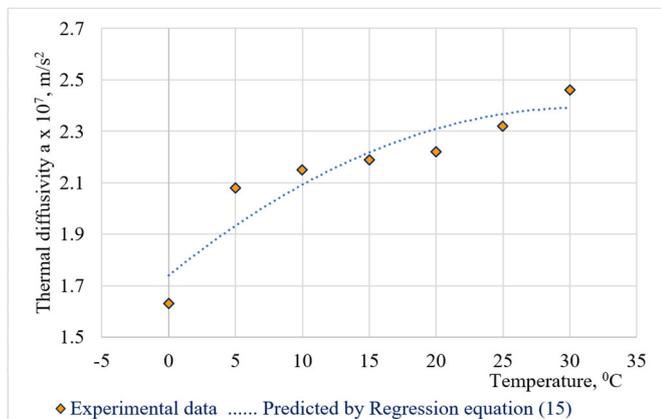
b) Thermal diffusivity of unfrozen ginseng

Fig. 6. Thermal diffusivity of ginseng at their respective temperatures

Thermal diffusivity is a function of temperature determined experimentally. Fig. 6a and equation (14) represent the thermal diffusivity as a function of temperature in the temperature range from -35°C to 0°C with $R^2 = 0.9807$. Fig. 6b and equation (15) represent the thermal diffusivity as a function of temperature in the temperature range greater than 0°C with $R^2 = 0.8704$.

$$a \times 10^7 = -0.0021 \times T^2 - 0.2145 \times T + 8.045,$$
$$T < 0°C \quad (R^2 = 0.9807) \tag{14}$$

$$a \times 10^7 = -0.0007 \times T^2 + 0.042 \times T + 1.7398,$$
$$T \geq 0°C \quad (R^2 = 0.8704) \tag{15}$$

The observed thermophysical behavior reflects the complex structural and phase transitions occurring within the root matrix during thermal processing. It should be noted that direct quantitative comparison with previously reported temperature-dependent thermal conductivity data is limited, as no prior studies have documented these properties for *Abelmoschus sagittifolius* or closely related medicinal roots under freezing conditions. Consequently, the present findings primarily serve as essential baseline data for future experimental investigations and modeling studies. By providing these missing parameters through the regression models developed in Equations (12), (13), (14) and (15), the data can be directly integrated into finite element software, such as COMSOL Multiphysics or ANSYS. This integration allows for the accurate prediction of temperature fields and freezing front propagation, ultimately supporting the industrial optimization of freeze-drying cycles and the preservation of bioactive compounds in medicinal plant processing.

It should be noted that the transient hot wire method has inherent limitations when applied in the phase change region. Latent heat effects, local heterogeneity of the biological material, and contact conditions between the hot wire and the sample may introduce additional uncertainty near 0°C. To minimize these effects, all measurements were conducted using a standardized procedure with identical conditions and repeated trials, and the reported values represent averaged results. Therefore, while the method provides reliable estimates outside the phase transition region, increased uncertainty near the freezing point should be considered when interpreting the results

4. CONCLUSIONS

This study is the first to provide detailed thermophysical data for Abelmoschus sagittifolius, an emerging medicinal root increasingly utilized in functional foods. The results demonstrate that temperature has a significant influence on the thermophysical properties of the material. Specifically, when the temperature falls below 0°C, thermal conductivity and thermal diffusivity increase sharply due to phase changes of moisture within the material. These findings are critical for developing accurate simulation models for freezing and thermal processing. The

regression models established in this work can be directly applied to numerical simulations in COMSOL or ANSYS, supporting improved process control and energy efficiency. Beyond its technical value, this study contributes original data to the limited thermal property literature on Southeast Asian medicinal plants. Future research should focus on extending these findings to dynamic thermal environments and integrating them into multi-physics simulations of freezing and freeze-drying systems.

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