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Simulation of Heat and Mass Transfer During Drying Processes

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Abstract

Drying is one of the core areas of both chemical engineering and food technology that involves both heat and mass transfer processes widely employed in various industries and households. Heat transfer, including temperature, air velocity, and drying time, in the drying process enables the diffusion of moisture from inside a material to its outer part by evaporation. The objective of this study is the simulation of the heat and mass transfer processes to examine moisture diffusion and heat conduction within solids. In the current research, the theoretical basis was employed as the methodology of the study based on Fourier's law of heat conduction and Fick's second law of mass diffusion. MATLAB simulations have been constructed to evaluate the moisture content of the material under specified drying time conditions. Based on the outcomes, there can be seen the exponential decrease of moisture content throughout the drying process up until reaching the equilibrium moisture content (EMC).

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1. Introduction

The initial works on drying processes started in the early 1920s with the research of W.K. Lewis. According to his research, he defined and described the drying process as the combination of evaporation of moisture content at the surface of porous material and the internal diffusion of moisture content from the interior to the exterior of the product (Tang, et al., 2026).

In late 1932, A.V. Luikvo was the first person to conduct an experiment to analyze the kinetics and dynamics behavior of the drying process. In his experiment, he proposed ``The Kinetics and Dynamics of the Process of Drying Moistening" (ElGamal, et al., 2023). Transportation of heat and mass has been an important mechanism in drying processes (removing water from materials) since before the 18th century. It has been one of the most ancient, popular, universal, and effective ways to prolong the use of products (e.g., food, wood, detergents, fertilizer, etc.) throughout human history (Tang, et al., 2026).

The drying process takes place when the material comes into contact with drying agents such as air velocity, temperature, and drying time. The thermal energy from these external sources is used to trigger moisture diffusion within the materials toward the surface (Hii, Chiang, & Putranto, 2023). The moisture from the substance is then removed through the process of evaporation until equilibrium moisture content is reached within the drying material or product. The drying agents that play important roles in transporting moisture from the core of the material to the surface are temperature, air velocity, and drying time. These factors significantly affect the drying rate of the product. However, temperature is considered the most dominant factor in the drying process (Kowalski & Pawłowski, 2025).

The need to understand the physical mechanisms that occur as solid materials dry is important for designing better dryers, saving energy, and maintaining high product quality. Consequently, various researchers have used numerical simulations to explore how heat and moisture are transported through materials. Vega et al. (2016) studied the peak surface temperature of fruits and vegetables during drying, which is an important factor in preserving food quality.

Modelling the transportation process of heat and mass during the drying of a material can take several approaches for analysis, including empirical/semi-empirical methods, theoretical methods, and reaction engineering approaches (REA). However, in this study, the focus is based on the theoretical method to simulate and model the drying process. Previous studies have shown that empirical methods are simple, but they lack theoretical proof and justification because moisture contents are predicted while temperature distribution is not (Metwally, et al., 2024; Popescu & others, 2024).

Moisture diffusion (transfer) in materials can occur in many ways, such as diffusion due to concentration gradients, thermal diffusion, and evaporation (Kowalski & Pawłowski, 2025). Among all moisture transfer mechanisms, diffusion is considered the most effective mode of transportation, in which Fick's second law is commonly applied (Simo-Tagne, Ndukwu, & others, 2026).

The relocation of moisture content in a mixture from an area of higher concentration to another area of lower concentration during drying is called mass transfer. Mass transfer takes place between two phases across the object interface. Consequently, the absorption of solute from gas to liquid requires transportation of dissolved substances through the gas phase until the gas-liquid boundary is satisfied, followed by partitioning across the boundary into the liquid phase.

The two basic fundamental processes of mass transportation are:

- Molecular diffusion, where molecules move freely without following a regular pattern in matter.
- Eddy (turbulent) diffusion, where fluid motion is irregular and flows non-uniformly.

Drying is an ancient, universal, and effective method that has long been used for the preservation of food, wood, and many other materials since before the 18th century (Stepanov & others, 2024).

1. Methods

According to the mathematical analysis of drying processes, there are two laws that govern this simultaneous coupled process of thermal energy and moisture diffusion. These two fundamental laws are described as Fourier's law for heat conduction and Fick's second law for mass diffusion.

2.1 Assumptions

In regard to the two laws, the following governing assumptions have been made:

- Moisture content and homogeneous internal temperature are evenly spread within the material;
- There is no initial heat inside the wood;
- Both heat and mass in a material are equal and balanced across all sides of the material's geometry.
- Heat transfer was considered through conduction, while mass transfer was considered through diffusion.

- The surface of the material (product) has reached equilibrium during drying processes.
- Constant parameters like thermal conductivity (k), moisture content (D_e), heat capacity (CP), and density (ρ) are constant variables that can be found from previous sources.
- Coupling of heat and mass is not considerable and is solved independently instead of a connected system.
- The temperature and air velocity are constant throughout.

2.2 Heat Transfer Framework

Fourier's law states that the conductive heat transfer rate (q(x)), at which heat transfers through a material (product), is proportional to the material's thermal conductivity k and the temperature gradient $\frac{\mathrm{dT}}{\mathrm{dx}}$. The heat always travels from the region of hot concentration to the region of cold concentrations.

$$q_x = -k\frac{dT}{dx} \qquad (1)$$

where

q(x) is the heat flux.

k is the thermal conductivity.

$\frac{dT}{dx}$ is the temperature gradient.

Instead, we can also use the other Fourier equation for heat transfer, which can change at each time (t) on the cross-sectional area of material.

$$\rho C_p \cdot \frac{dT}{dt} = \frac{d}{dz}\left(k \cdot \frac{dT}{dz}\right) \qquad (2)$$

where

ρ: is the density (kg/m³).

Cp is the heat capacity (j/kg·˚C).

z is the distance (m).

T is the temperature (˚C).

2.3 Mass Transfer Framework

Fick's second law for mass transfer states that the amounts of particulates (solid, liquid, and gas) spread from the area of higher concentration to the area of low concentration (DAB) are proportional to the concentration gradient ($\frac{dC_A}{dx}$) through the diffusion process. The governing equation given below is for the steady state:

$$J_A = -D_{AB}\frac{dC_A}{dx} \qquad (3)$$

where;

JA is the molar flux of A.

DAB is the diffusion coefficient A.

CA is the molar concentration of A.

$\frac{dC_A}{dx}$ is the concentration gradient.

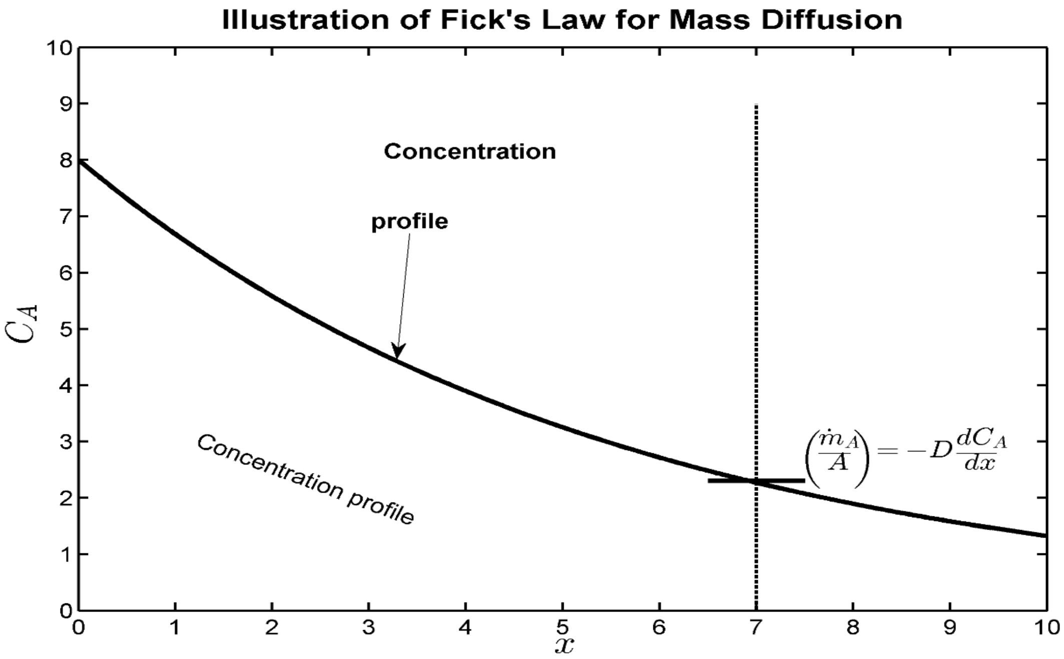

Figure 1: Illustration of Fick's law showing mass diffusion from a region of higher concentration to a region of lower concentration through a concentration gradient.

But we can derive this Fick's equation in the above case to a non-steady state where the concentration changes over time (t).

$$\frac{dX}{dt} = \frac{d}{dz}\left(D_e \frac{dX}{dz}\right) \qquad (4)$$

where;

X is the moisture content,

T is the time (s),

D_e is moisture content diffusivity (m^2/s),

Z is the distance (m).

The constant parameters k, C_p, ρ, and D_e are values that can be obtained from other previous sources or literature.

2.4 Boundary condition

The environment in which the object and its drier interactions were defined was within the boundary condition that they were. The above equations are then simplified into these boundary condition equations. Consequently, solutions to these equations can be achieved by using refined surface boundary conditions of a drying material. The boundary conditions for mass and heat transfer are defined as below:

$$-D_e \frac{dX}{dz} = h_m(X - X_e) \qquad (5)$$

$$-k \frac{dT}{dz} = h_t(T - T_s) \qquad (6)$$

where;

X_e is the equilibrium moisture content,

h_m is the mass transfer coefficient,

h_t is the heat transfer coefficient.

Using the mass transfer boundary condition, we can generate the Moisture Ratio (MR) equation as follows:

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-(2n-1)^2\frac{\pi^2 Dt}{4L^2}\right) \quad (7)$$

The above moisture ratio equation is used to evaluate the desired drying state of the material by initializing the first term of the series (n=1). Then, by taking the natural log of it, the following decay equation can be defined as:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D}{4L^2}\right)t \quad (8)$$

It is the equation that turns the diffusion into a simple exponential decay. From the above equation, the linear relationship of the approximation of drying rate (k_d) against the moisture content at a given time (t) can be manipulated as

$$MR = \frac{X(t)-X_e}{X-X_e} \quad (9)$$

$$MR = e^{-kdt} \quad (10)$$

$$\frac{X_t-X_e}{X-X_e} = e^{-kdt} \quad (11)$$

$$X_t = X_e + (X - X_e)e^{-kdt} \quad (12)$$

Where

X(t) denotes moisture content at time t,

X denotes initial moisture content,

X_e denotes equilibrium moisture content,

k_e denotes the drying rate.

2. Results and Discussion

Table 1 below shows the evaluation of moisture and time on a solid material (e.g., wood) using EXCEL. This evolution is generated in respect to the given situation where, D_e= 6e-10kg water/kg, T=27˚C air, Xe = 9.2%, X = 75% (initial moisture content when), drying time t=3 days (6hrs/24hrs a day for diffusion time, which is 21600 seconds), and k = 4W/m.˚C.

Using the exponential decay equation given below, the following table was generated:

$$X\_t = X\_e + (X - X\_e)e\text{^}\{-kdt\} \quad (13)$$

For instance, at time t=0:

$X(t) = 9 + (75 - 9)\backslash times\ e\hat{}\{-4\backslash times0\}$ (14)

$X(t) = 75.00$ (15)

At time t=1.5:

$X(t) = 9 + (75 - 9)\backslash times\ e\hat{}\{-4\backslash times1.5\}$ (16)

$X(t) = 9.1635$ (17)

Table 1. Evaluation of moisture content over drying time using the exponential decay model.

Time t	e^{-kt}	**Moisture Content M(t) (%)**
0.00	1	75.00000000
0.25	0.3678794	33.28004312
0.50	0.1353353	17.93212869
0.75	0.0497871	12.28594651
1.00	0.0183156	10.20883217
1.25	0.0067379	9.444704502
1.50	0.0024788	9.163597644
1.75	0.0009119	9.060184210
2.00	0.0003355	9.022140533
2.25	0.0001234	9.008145047
2.50	4.54E−05	9.002996395
2.75	1.67E−05	9.001102312
3.00	6.144E−06	9.000405518

According to the table, at start when time t=0, the moisture content is 75% and the temperature is 27˚C, which is the maximum temperature at the surface. When the material was in direct contact with the open-air temperature, moisture content eventually started to decrease, meaning it was turning into vapor and moving out; meanwhile, the time also increases. By the time it reaches the required moisture content, the material has finish drying (this means that the moisture does not completely dry but partly dries since it's limit is 9% MC at equilibrium) and stabilized with the air.

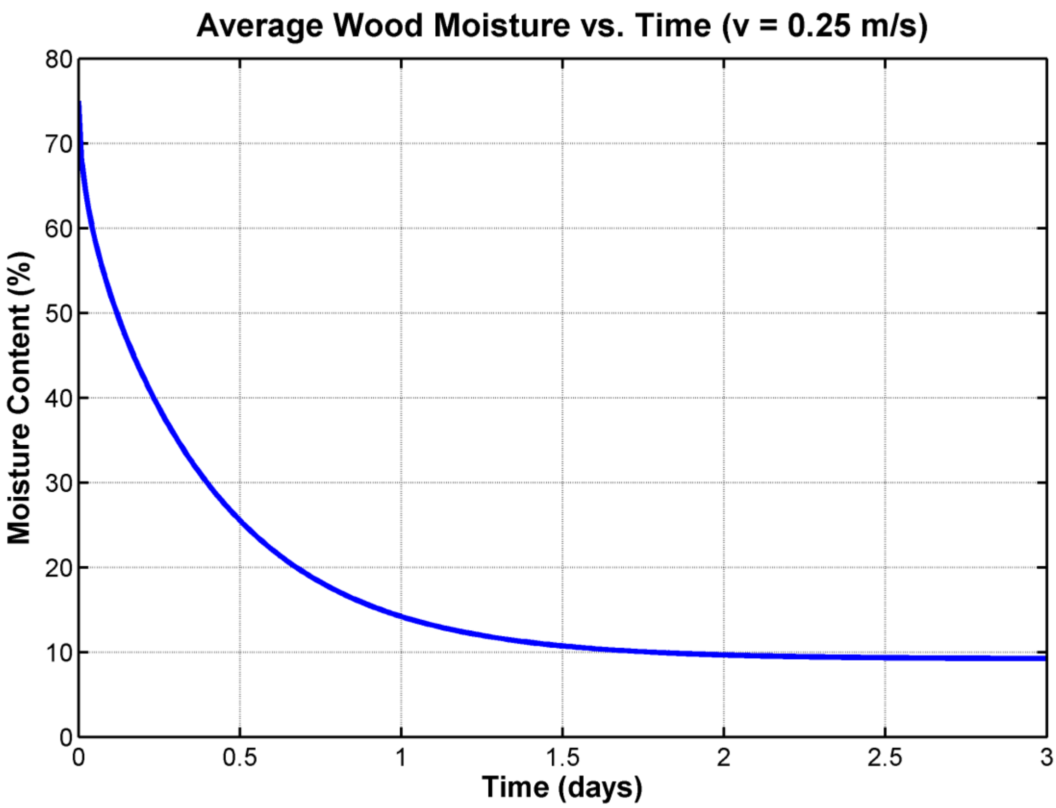

Figure 2: Graph of moisture content against time generated using MATLAB.

Figure 2 shows the average moisture content of a wood decreasing over time due to drying under constant airflow with a velocity of 0.25 m/s. By looking at the drying time of the wood it took only three days to dry, which means the wood is already half-dry, since it normally dries after 10 to 15 days. Furthermore, at the start (t=0), the wood contains 75% moisture content in the half-dry wood, which is remain as maximum level after certain days, and the curve exponentially decays quickly in the first two days because the moisture near the surface is evaporates faster. As the time continues to increase, the curve flattens to zero slope. Approximately after about 1.7 hours, the wood gets to the point where it has about 9% moisture, and therefore this slows down the wood drying rate. This shows that the wood has reached equilibrium moisture content (EMC) state. Thus, we can conclude from the graph that, for the past two days the wood has already reached its equilibrium state. However, for the next hour the moisture removal will still continue but in a rate that is much slower than the past two hours. The simulation was performed with $X = 1.0$kg liquid/kg, $X_e = 0.1$, $k = 0.5$, and $t = 3$days.

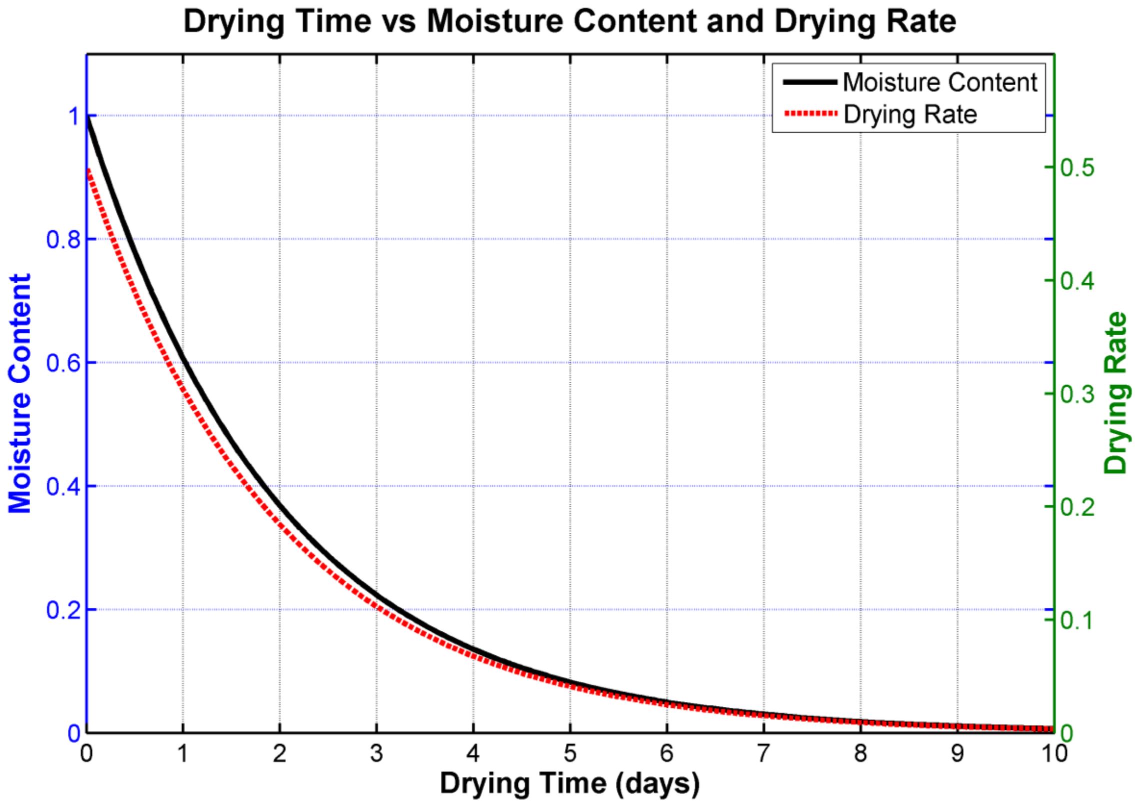

Figure 3: Graph of time against moisture content and drying rate generated using MATLAB.

At time t=0, the normalized moisture content is 1.0 and the drying rate is maximum at 0.5 as the wood is at its wettest according to the graph. However, as the day passed, the moisture started to evaporate and decrease; meanwhile, the drying rate also started to decrease exponentially along with the moisture content. By the time the moisture reaches the equilibrium state, it can be noticed from Figure 2 that the moisture content has reached its equilibrium moisture content (EMC). This means there is still a little more moisture content in the material, and it has not dried completely.

Effects of drying time on wood

The effect on drying time (Figure 2 and Figure 3) varies in different timelines. In Figure 2 the varied time is ¼ hours per day, which means every 6hours the moisture content drops each day from 0 to 72hours. However, it can be noticed from the graph that increasing the time from 0 to approximately 33hours resulted in a decrease in the percentage of moisture content from the wood sample. Furthermore, great moisture loss was observed within the first 12hours of drying (e.g., approximately 50% was lost).

3.2 Effects of air velocity on wood

Steady air movement across the surface of the wood has an effective effort on wood drying. The constant air has two important roles; firstly, it transfers the heat energy to evaporate the moisture through diffusion, and secondly, it vaporizes moisture away from the surface of the wood.

3.3 Effects of temperature on wood

Temperature is the main factor that has an impact on the drying efficiency of the wood. As per the given example the T=27˚C at an initial moisture content of 75%. According to the example, the initial temperature is 10˚C; when it increased to 25˚C, the moisture content increasingly was lost from the wood.

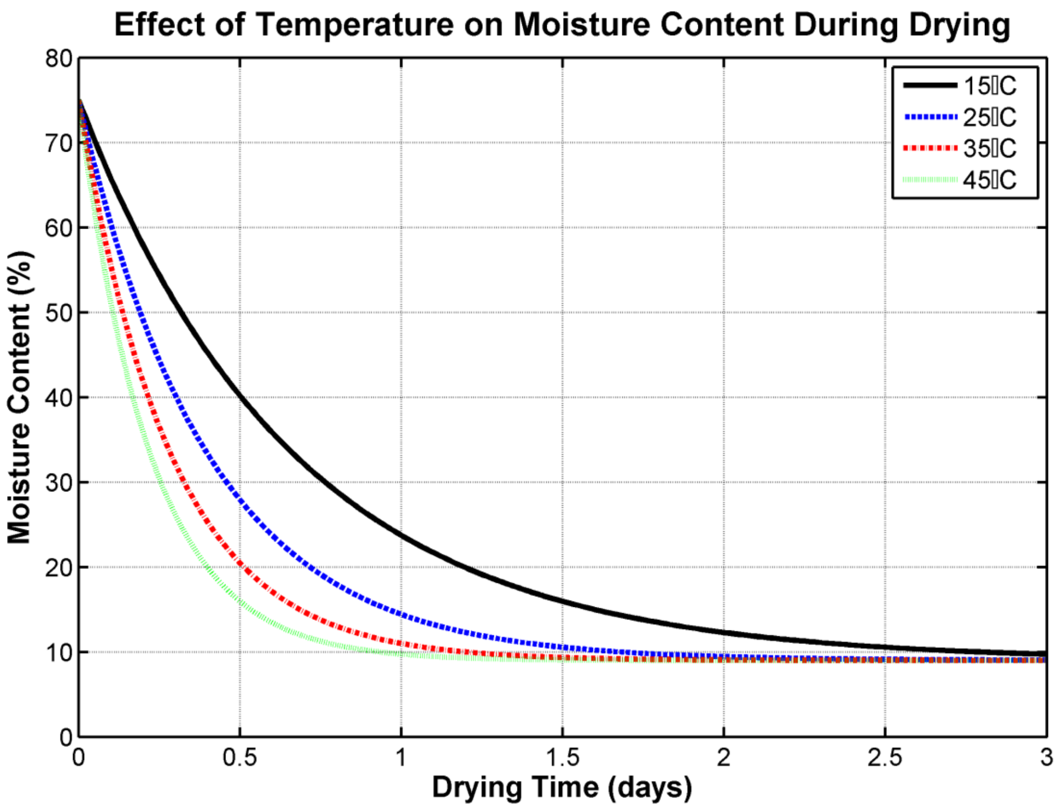

Figure 4: Effect of temperature on moisture content during drying under different temperature conditions.

3. Conclusion

This research conducted a theoretical analysis of heat and mass transfer in relation to drying in solid materials. The analysis involved the use of the principles of Fourier's law and Fick's second law which are concerned with heat conduction and mass diffusion respectively. Using the model generated from the application of these laws, an analysis was done to investigate the connection between drying time, moisture content, moisture diffusion, drying rate, and equilibrium moisture content in a solid material like wood.

The MATLAB analysis indicated that moisture content reduces exponentially with increase in drying time due to constant evaporation of moisture from the surface of the material. The analysis also indicated that the drying rate was high at the beginning of the drying process owing to the availability of much free moisture in the immediate surface of the material. However, as the drying process continued, the moisture content reduced until it reached the equilibrium moisture content (EMC), resulting in a reduction in the drying rate.

Also, the study revealed that temperature, drying duration, and air velocity play a significant role in the efficiency of the drying process. In all these variables, temperature played a vital role in influencing the process. From the graphical analysis, visualization was done on how the process occurred, what was the trend of moisture change in the process, and how the drying rates varied.

On the whole, from the theoretical analysis done, there is a basic way of approaching coupled heat and mass transfer in a drying process. The model created in the study will act as a stepping stone for further analysis in the future through more advanced drying processes that may involve simulations and experimentation. The future direction might include the use of empirical and semi-empirical drying models, reaction engineering approach (REA) models, varying thermal properties, and experimentation on drying.

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Conflicts of Interest

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

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