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# REHYDRATION KINETICS OF CONVECTIVELY DRIED MUSHROOM (*PLEUROTUS TUBER-REGIUM*): THEORETICAL AND EMPIRICAL MODELLING WITH SENSITIVITY ANALYSIS

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## ABSTRACT

*This study investigated the impact of rehydration temperature on the mass transfer kinetics of water into steam blanched convectively dried (70°C) mushrooms. The research employed both theoretical and empirical modelling approaches, supplemented with sensitivity analysis. The models were implemented using Matlab 2021 to provide a foundational understanding of the rehydration processes. Sensitivity analysis was conducted to identify the key factors influencing rehydration efficiency, using Monte Carlo Simulation to optimize drying protocols for enhanced rehydration performance. The results indicated a strong dependence of water rehydration on both temperature and time. The diffusivity of water into dried mushrooms ranged between 4.4569 E-10 to 6.3562 E-10* $m^2s^{-1}$*, increasing with higher temperatures. The activation energy was found to be 0.1388 kJ/mol, indicating uncomplicated moisture diffusivity. The Weibull model demonstrated superior performance with* $R^2$*, RMSE, and SSE values of 0.9985, 0.087, and 0.6665, respectively, compared to the Peleg model's performance. The rehydration process was found to* *be 74.1% dependent on time and 25.9% dependent on temperature. The study concluded that while drying is a complex and irreversible process, elevated rehydration temperatures can significantly improve the restoration of properties in dried mushrooms.*

**Keywords:** *Drying, rehydration, mushrooms, modelling, sensitivity analysis.*

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## 1. INTRODUCTION

Pleurotus tuber-regium is a significant tropical mushroom known for its unique taste and aroma, widely appreciated in Nigeria where it is called ‘Olu’ by the Yoruba and ‘Ero’ by the Igbo (Oranusi et al., 2014). It is recognized for its rich composition of bioactive polysaccharides, essential amino acids, dietary fiber, vitamins, and minerals (Lin et al., 2020). These components have been linked to health benefits such as anti-tumor, anti-hypercholesterolemic, and anti-oxidant properties, as well as potential for managing diabetes and obesity (Noshad et al., 2010). Moreover, Pleurotus tuber-regium can be cultivated on various agricultural wastes (Adedokun et al., 2002), making it a sustainable and efficient food source. However, the mushroom is highly perishable after harvest and faces seasonal scarcity during arid periods, necessitating preservation techniques to maximize its benefits.

Drying is a commonly used preservation method, contributing to global food security by extending the shelf life of agricultural products (Hu et al., 2021). Dried products are easier to store, transport, and rehydrate. However, high rehydration temperatures and extended times can damage the nutritional value and texture of dried foods, making rehydration optimization crucial. Rehydration process restores some quality attributes like texture, aroma, and nutritional content (García-Pascual et al., 2006), and kinetics studies help achieve the best product quality through careful optimization.

## 2. REVIEW OF LITERATURE

Rehydration process involves complex interactions between water and the food matrix, influenced by factors such as temperature, moisture content, and product properties (Noshad et al., 2010). The rehydration process stages include water absorption, product swelling, and leaching of soluble solids (Doymaz, 2012). Fick's second law of diffusion is often used to model the rehydration process in dried foods, describing changes in water concentration over time (Tran et al., 2020). Empirical models like Peleg's and Weibull models are also employed to capture rehydration kinetics (Vega-Gálvez et al., 2009), with sensitivity analysis identifying the most impactful parameters for optimization (Peter et al., 2021).

Several studies have modeled rehydration kinetics in biogenic materials. For instance, Vega-Gálvez et al. (2009) used multiple models to investigate the temperature's influence on Aloe vera slabs' rehydration, while Garc´ıa-Pascual et al. (2005) studied the rehydration of Boletus edulis mushrooms at various temperatures. These studies used both empirical and diffusion models to describe rehydration kinetics. However, sensitivity analysis of the rehydration process remains limited in the literature, representing a gap this study aims to address. By focusing on the time-temperature effects on the rehydration properties of pre-dried Pleurotus tuber-regium, this research seeks to model the process using theoretical and empirical models comparatively while examining the sensitivity of the rehydration indicators to process factors.

## 3. MATERIALS AND METHODS

Fresh mushrooms were purchased in Iluju market in Ogbomoso township of Oyo state. The seller is a local farmer and identified the mushrooms specie as 'Ólu' which is the Yoruba name for *Pleurotus tuber-regium*. The harvested mushrooms were taking in a polymer packaging mesh to the laboratory for experimentation. Prior to experimentation in the laboratory, the mushrooms were washed thoroughly in distilled water to remove sand and dirt and afterwards air dried (29 – 31$^{O}$C) in the laboratory for 1 h.

### 3.1 Drying Process

The initial moisture content of the fresh mushroom was 76.04% w.b following the specifications of the Association of Official Analytical Chemists method (AOAC, 2005) using convective oven (SG-90526 - model, Stangas - company, Italy - country), at 105 $^{O}$C for 24 h (Oranusi et al., 2014).

The air dried mushrooms were pre-treated by steam blanching to aid drying and preserve product quality. For the blanching and drying process, a 600 g of whole mushroom (cap, gills and stalk with ~10 mm stalk thickness) samples were placed in single layer on a wire-mesh over a steam blancher at 100 $^{O}$C for 2 min in a closed system. Thereafter the mushrooms were removed from the blancher and air cooled for 30 min. The air cooled steam blanched mushroom were then dried in a convective dryer (SG-90526 - model, Stangas - company, Italy - country) at 70 $^{O}$C until constant weight (~8 h). The residual moisture content in the sun dried sample was 12 % w.b.

### 3.2 Rehydration Process

The water absorption was determined following the established standard protocol as widely used (Garcia-Pascual et al., 2005) where an ~100 g (cap, gills and stalk) dried mushroom sample was immersed in distilled water at sample to water ratio of 1:20 till saturation/equilibrium. Until saturation, the water gain by the samples was determined periodically by removing the sample from the water medium, blotted dry with tissue paper and weighed on a weighing balance (0.00 g accuracy). Replicated rehydration experiments were done and the mean of the replicate was utilized for further data analysis to enable statistical significance (Vega-Gálvez et al., 2008).

### 3.3 Theoretical Modeling

The effective moisture diffusivity of food and agricultural products are often determined with Fick's second law which after a long rehydration/drying time transforms (Doymaz, 2012) and simplify to Eqn. 1 (Zakipour and Hamidi, 2011).

$$\mathrm{Ln\ MR} = \mathrm{Ln}\left(\frac{M_t}{M_o}\right) = \mathrm{Ln}\left(\frac{8}{\pi^2}\right) - \frac{\mathrm{Deff}}{4\,\mathrm{L}^2}\pi^2 t \qquad (1)$$

Where, $D_{eff}$ is the effective moisture diffusivity ($m^2s^{-1}$), L is the half thickness of the product (m), and t is drying time (s). The effective moisture diffusivity is therefore the slope of the straight line obtained by plotting natural logarithm of moisture ratio against rehydration time.

In addition, the activation energy which refers to the energy required for the initiation of moisture migration from the sample's core to its surface before being evaporated to the environment and vice versa is often determined with Arrhenius equation given in Eq. (2) (Motevali et al., 2012).

$$\mathrm{D_{eff}} = \mathrm{D_o} \exp\left(-\frac{\mathrm{E_a}}{\mathrm{RT}}\right) \qquad (2)$$

Where, Ea represents the activation energy (kJ/mol), T represents the absolute temperature (K), R represents the universal gas constant (8.3 J/K.mol), and $D_O$ represents the Arrhenius equation's pre-exponential factor. Simply, Ln $\mathrm{D_{eff}}$ was plotted against the $T^{-1}$ to derive the activation energy.

### 3.4 Empirical Modelling

The observed experimental data were represented mathematically and interpreted with Peleg and Weibull models. Empirical models are precursors to process management and control. In this study, Matlab 2021b was utilized to determine the parameters and constants of the two selected mathematical models regressively. The mathematical expressions for Peleg and Weibull model are specified in Eqn. 3 and 4, respectively.

$$\mathrm{M} = \mathrm{M_e} + \frac{\mathrm{t}}{\mathrm{k_1} + \mathrm{k_2 t}} \qquad (3)$$

$$\mathrm{M} = \mathrm{M_e} + (\mathrm{M_o} + \mathrm{M_e}) \exp\left[-\left(\frac{\mathrm{t}}{\mathrm{D}}\right)^{\mathrm{h}}\right] \qquad (4)$$

Where, $\mathrm{M}$ is the instantaneous moisture content (g water/g d.m), $\mathrm{M_o}$ is the initial moisture content (g water/g d.m), $\mathrm{M_e}$ is the equilibrium moisture content (g water/g d.m), t is time (s), $\mathrm{k}_1$ is kinetic constant [s (g dry matter $^*$ $\mathrm{g}^{-1}$)] and $\mathrm{k}_2$ is characteristics constant (g dry matter $^*\mathrm{g}^{-1}$). $\mathrm{D}$ is the scale parameter and $\mathrm{h}$ is dimensionless shape parameter.

### 3.5 Modelling Efficiency

The proficiency of the models utilized in this study was evaluated using statistical functions, including, sum of square error (SSE), root mean square error (RMSE) and coefficient of determination (R²). The mathematical structures of the functions are stated in Eqn. (5) – (7).

$$\text{SSE} = \sum(y_i - \hat{y}_i)^2 \qquad (5)$$

$$\text{RMSE} = \sqrt{\frac{SSE}{n}} \qquad (6)$$

$$\text{R}^2 = 1 - \frac{SSE}{SST} \qquad (7)$$

Where, Σ is the summation over all data points (i = 1 to n), $y_i$ actual value of the i-th data point, $\hat{y}_i$ is the predicted value of the i-th data point by the model.

## 4. RESULTS AND DISCUSSION

### 4.1 Effect of Temperature and Time on Rehydration

In this study, temperature and time are considered as the independent factors on which the rehydration moisture content depends. Figure 1 (a) and (b) illustrates the relationship between rehydration time and moisture content at the considered rehydration temperatures (30°C, 50°C, and 70°C).

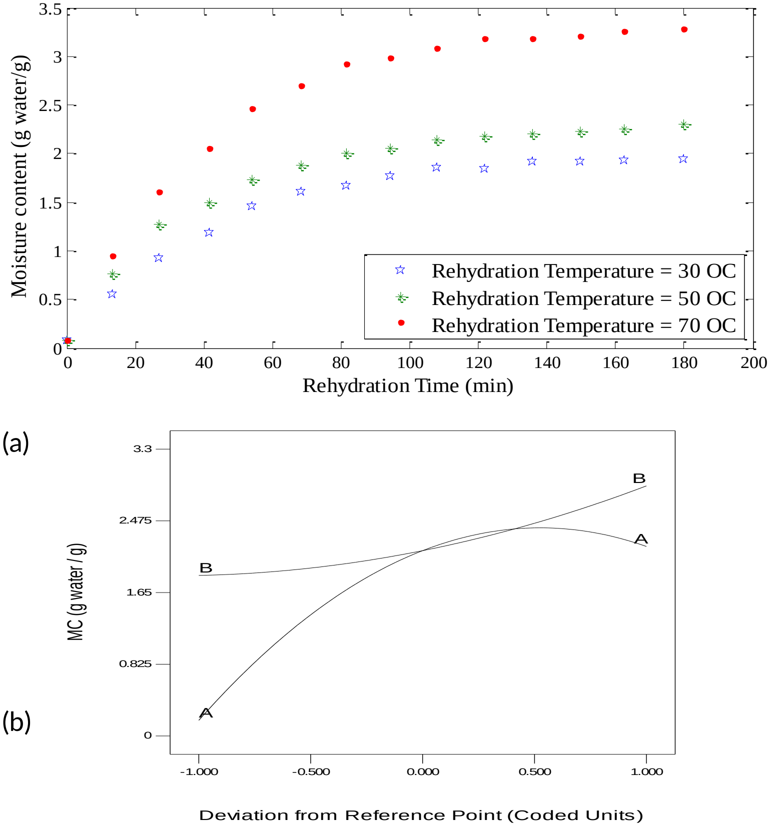


Figure 1. Effect of rehydration process on rehydration moisture content

The y-axis represents the moisture content in grams of water per gram of dry matter (g water/g), while the x-axis represents the rehydration time in minutes (min).

Figure. 1 (a) showed that moisture content increases with rehydration time for all the three temperatures considered. Initially, the increase is rapid (up to about 60 min), followed by a slower rate of increase as time progresses, eventually approaching an equilibrium moisture content. Higher rehydration temperatures result in higher equilibrium moisture contents. This is because elevated temperatures provide more energy for the water molecules, increasing their mobility and the rate of absorption. The difference in moisture content among the three temperatures becomes more pronounced as the rehydration time increases. At shorter rehydration times, the differences are smaller, but they grow larger with time. The plateau observed at longer rehydration times indicates that the material has reached its maximum moisture-holding capacity at each respective temperature, known as the equilibrium moisture content. The differences in equilibrium moisture content at different temperatures suggest that the material's ability to retain water is enhanced at higher temperatures, due to changes in the material's structure or increased solubility of water in the material matrix at elevated temperatures.

In Figure. 1 (b) lines A (time variation) and B (temperature variation) showed the change in water content when each factor deviates from its reference point while the other factor is held constant at its reference level. The line labelled A and B showed how water content changes as the individual factor deviates from its reference point relative to the other. The steepness and direction of these lines indicate the sensitivity and nature (positive or negative) of the effect of the factor on water content. The steeper the slope of the line, the more sensitive the water content is to changes in that factor. If the line is relatively flat, the factor has little impact on water content. Also, if the line slopes upward, it indicates that increasing the factor increases the water content. If it slopes downward, increasing the factor decreases the water content. Bearing those explanations in mind, it is observed that the moisture content absorbed during rehydration is more sensitive to time compared to temperature. The characteristics of the lines also meant that increasing temperature will increase water absorption while increasing time will certainly not because the material has already reached equilibrium. It therefore means that the process can be hastened with increasing the temperature; however, elevated temperature could be disastrous to product quality. The crossing of the two lines signifies interaction between the two factors. Close results have also been reported by many authors including Garc´ıa-Pascual et al., (2005), Vega-Gálveza et al., (2009) and Doymaz (2012).

In essence, several factors that affect the rehydration dried mushrooms may include the drying, drying temperature and time, mushroom variety, pre-treatment, amongst others. For instance, convective oven drying generally results in better rehydration characteristics compared to sun drying due to more controlled drying conditions and reduced damage to the mushroom structure (Hu et al., 2021).

Different drying methods impact the rehydration quality. For instance, Hu et al., (2021) reported that convective oven drying resulted in better rehydration characteristics compared to sun drying due to more controlled drying conditions and reduced damage to the mushroom structure. Calín-Sánchez et al., (2020) reported that button mushrooms and shiitake mushrooms exhibit different rehydration kinetics. Hu et al., (2021) reported that Pre-treatments such as blanching or using additives can enhance the rehydration capacity by modifying the tissue structure and improving water absorption. Therefore, understanding these factors assists in selecting the appropriate drying method and conditions to achieve high-quality rehydrated mushrooms, thereby ensuring consumer satisfaction and nutritional value.

### 4.2 Theoretical Modelling

The effectiveness and rate of rehydration depend on several factors, including the material's properties and environmental conditions such as temperature. The effective diffusivity in this study is represented in Table 1. Effective diffusivity (Deff) is a parameter that quantifies the rate at which water molecules diffuse into the dried material during rehydration. It is influenced by temperature and the intrinsic properties of the material while the activation energy is the minimum amount of energy required to initiate a process (chemical or physical). In the context of rehydration, activation energy represents the energy barrier that must be overcome for water molecules to diffuse into the material. Temperature plays a significant role in rehydration and generally, as the temperature increases, the rate of water absorption and the diffusivity of water molecules also increase. This relationship is often described by the Arrhenius equation.

Table 1. Theoretical model

| Rehydration Temperature (OC) | $D_{eff}$ $(m^2s^{-1})$ | Activation energy kJ/mol |
|---|---|---|
| 30 | 4.4569 E-10 | 0.1387 |
| 50 | 4.9381 E-10 | |
| 70 | 6.3562 E-10 | |

From Table 1, it is observed that at 30, 50 and 70°C rehydration temperature, $D_{eff}$ is 4.4569 E-10, 4.9381 E-10 and 6.3562 E-10 m/s, respectively. These values showed an increase in effective moisture diffusivity with rising temperature, indicating that water molecules diffuse more readily into the material at higher temperatures. In addition, the activation energy given is 0.1387 kJ/mol and can be used to explain the temperature dependence of the diffusivity. The low activation energy suggests that the process requires relatively little energy to proceed, indicating that the material can rehydrate easily over a range of temperatures. This is attributed to possible alteration of the microstructure of the mushroom as a result of blanching and drying. Similar reports have been made by authors such as Garcı´a-Pascual (2006) and Vega-Gálvez *et al.*, (2009) in their dried food and leave rehydration studies. Therefore, the results showed that higher temperatures facilitated faster rehydration, as indicated by the increased effective diffusivity. The low activation energy suggests that the material does not require significant energy input to rehydrate, making it suitable for processes where energy efficiency is crucial.

### 4.3 Empirical Modelling

Empirical models are used to fit experimental data to mathematical equations, allowing for the prediction of characteristics under various conditions. In this study, the Peleg and Weibull models were employed to describe the rehydration kinetics of dried mushroom material at different temperatures. The result is summarized in Table 2.

Table 2. Empirical modelling parameter

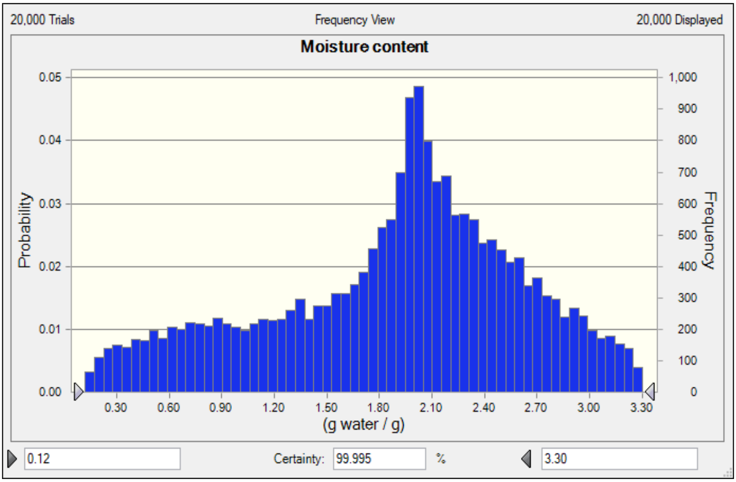
| Peleg model Rehydration Temperature (OC) | SSE | $R^2$ | Adj. $R^2$ | RMSE | k1 | k2 |
|---|---|---|---|---|---|---|
| 30 | 0.0488 | 0.9976 | 0.9975 | 0.0471 | 9.785 | 0.2496 |
| 50 | 0.1491 | 0.9935 | 0.9932 | 0.0842 | 171.2 | 0.2766 |
| 70 | 0.8058 | 0.9445 | 0.9416 | 0.2059 | 51.89 | 0.2776 |

| Weilbull model Rehydration Temperature (OC) | SSE | $R^2$ | Adj. $R^2$ | RMSE | $M_e$ | α | β |
|---|---|---|---|---|---|---|---|
| 30 | 0.0108 | 0.9995 | 0.9991 | 0.0226 | 3.465 | 0.8645 | 46.03 |
| 50 | 0.0851 | 0.9963 | 0.9959 | 0.06525 | 3.484 | 0.6728 | 1006 |
| 70 | 0.0313 | 0.9978 | 0.9976 | 0.0417 | 3.962 | 0.4305 | 541.2 |

The Peleg model offers simplicity and ease of use, with parameters directly related to the rate and capacity of rehydration. The Weibull model provides a more flexible fitting with parameters that can describe various shapes of rehydration curves. However, in accordance to the goodness of fit test represented in Table 2, the two models (that is, Peleg and Weibull) provided good fits for the rehydration data, with the Weibull model generally showing slightly better statistical fits (higher R-square and lower SSE and RMSE values). Weibull model also showed that equilibrium moisture content ($M_e$) increased with increase in temperature and signifies that more moisture are absorbed at increased temperature. The choice between the models can depend on the specific application and the ease of parameter interpretation. In achieving optimum control and management of the process under consideration, Weibull model should be utilized. Similar results were also made by Demiray and Tulek, (2017) in a study on the effect of temperature on water diffusion during rehydration of sun-dried red pepper (*Capsicum annuum L.*).

### 4.4 Sensitivity Analysis

The result of the certainty test that complements the observations in Figure. 1 (a) and (b) are depicted in Figure 2.



0.12 Certainty: 99.995 % 3.30

Figure 2. Certainty graph of the rehydration process

The histogram in Figure 2 is a graphical representation of the distribution of moisture content dataset. The histogram showed a divide of the data into bins (intervals) and displays the frequency (or probability) of data points within each bin. The y-axis can represent either the frequency (count of occurrences) or probability (normalized frequency), while the x-axis represents the moisture content.

The x-axis represents the moisture content in grams of water per gram of material (g water/g d.m). The range of moisture content spans from 0.12 (initial moisture content) to 3.30 g water/g (equilibrium moisture content). The peak of the histogram represents the most frequent moisture content value (2.10 g water/g) which can be used as a reference for quality control and process optimization. In terms of shape, the histogram has a unimodal distribution with a single peak. The distribution appears to be approximately symmetric, with a gradual decrease in frequency on both sides of the peak. Furthermore, the data represents 20,000 trials, providing a robust sample size for statistical analysis. At the bottom of the histogram, there are indicators for certainty and range. The certainty value is 99.995%, suggesting a high level of confidence in the data represented within the specified range. The range values (0.12 and 3.30) represent the minimum and maximum moisture content values within the dataset. A close result was made by Adeyi et al., (2021) in a study on effective moisture diffusivity of *Sierrathrissa leonensis* cracker: optimization, sensitivity and uncertainty analyses.

The sensitivity quantification is represented in Figure 3. Sensitivity analysis is a technique used to determine how different variables affect a particular outcome. In this case, the analysis examines how time and temperature impact the moisture content of the material.

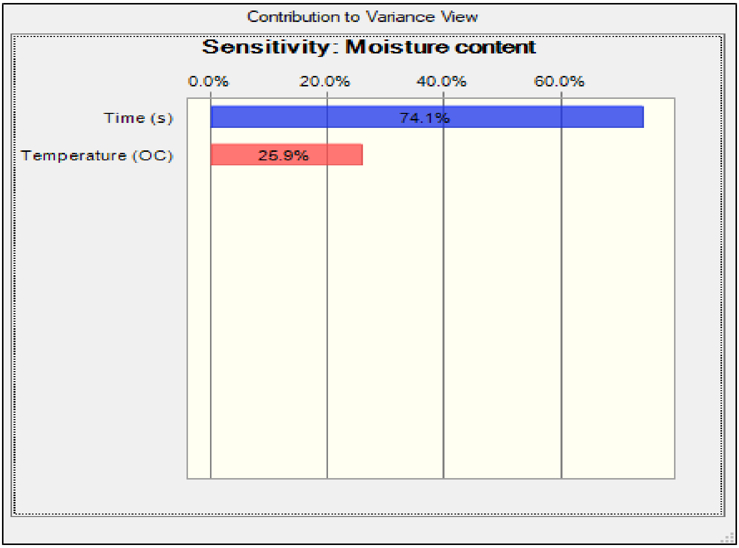


Figure 3. Sensitivity analysis of the rehydration process

The figure is a bar chart representing the contribution to variance view for moisture content, showing the sensitivity of moisture content to the process factors time (sec) and temperature ($^{O}$C). The sensitivity analysis assists in identifying which factor(s) have the most significant impact on the variability of the moisture content in the dried mushroom.

The figure represents the percentage contribution to the variance in moisture content. It ranges from 0% to 60% in increments, highlighting the relative importance of each factor.

Two horizontal bars indicate the contribution of each factor to the variance in moisture content and the length of each bar corresponds to the percentage contribution of that factor. The bar for time (s) shows a contribution of 74.1% to the variance in moisture content. This indicates that time is the most significant factor affecting the moisture content, accounting for nearly three-quarters of the variability. Furthermore, the bar for temperature (°C) shows a contribution of 25.9% to the variance in moisture content. While still important, temperature has a lesser impact compared to time, contributing just over a quarter of the total variance. The sensitivity analysis provides several discernments to the process under study. For instance, since time is the most influential factor, controlling the duration of the rehydration process can significantly impact the final moisture content. Precise timing can help achieve desired moisture levels more consistently. Knowing which factors are most critical allows for better allocation of resources and efforts. In this case, more attention should be given to monitoring and controlling time during the process. In addition, sensitivity analysis helps in setting up quality control measures. In this case, since time significantly affects moisture content, ensuring consistent timing across batches can lead to more uniform product quality.

The analysis may prompt further research into why time has such a significant impact. Understanding the underlying mechanisms can lead to more refined models and improved process control strategies. This result ably justifies the previous observations of Figure. 1 (b). A close result was also reported by Adeyi et al., (2023) in a study on heat-assisted extraction of phenolic-rich bioactive antioxidants from *Enantia chlorantha* stem bark: multi-objective optimization, integrated process techno-economics and profitability risk assessment.

## 5. CONCLUSION

This study analyzed the rehydration kinetics of convectively dried mushrooms using both theoretical and empirical modeling approaches, along with sensitivity analysis. It was confirmed that rehydration temperature and time significantly affect water mass transfer into dried mushrooms. Water diffusivity increased with temperature, ranging from 4.4569 E-10 to 6.3562 E-10 $m^2s$-1, indicating faster absorption at higher temperatures. The low activation energy (0.1388 J/mol) suggested that moisture migration is energetically favorable, with the microstructure of dried mushrooms easily penetrable. Theoretical models like Fick's second law and the Arrhenius equation offered a reliable framework for understanding the temperature dependence of moisture diffusivity. Empirical models, such as Peleg and Weibull, accurately described the rehydration process, with the Weibull model outperforming based on key metrics ($R^2$, RMSE, SSE). Sensitivity analysis using Monte Carlo Simulation revealed that time (74.1%) was a more influential factor than temperature (25.9%), indicating the importance of optimizing time in the rehydration process.

The integration of modelling with sensitivity analysis provides a comprehensive understanding of rehydration kinetics in dried mushrooms. The results highlight that while higher rehydration temperatures can accelerate the process, they need careful control to avoid compromising product quality. This study's approach not only identifies critical factors that influence rehydration but also offers a foundation for optimizing drying and rehydration protocols, thereby enhancing the quality of rehydrated foods. Future research should explore the effects of various drying techniques and pre-treatments on rehydration kinetics to further improve dried food quality and process efficiency in food preservation.

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