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Study on the Drying Kinetics of Tempeh from Different Raw Materials

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Abstract: Tempeh, offers high nutrition and digestibility but boasts a limited shelf life due to microbial activity. This study aimed to extend tempeh's shelf life by drying it into chips. Soybean, Indian dhal, and chickpea tempeh were sliced, dried at 80, 90, and 100°C, and analyzed for moisture content, drying curves, sorption characteristics, and drying kinetics. Higher temperatures and longer drying times reduced moisture content. The initial moisture content for all beans were calculated ranging of 150%-200%(*wb*) and moisture equilibrium were below 5%(*wb*). The GAB model showed equilibrium moisture content in tempeh chips which increased with relative humidity but decreased with temperature. Drying kinetics were modeled using Newton, Logarithmic, and Henderson and Pabis models and only Newton showed a clear decrease in soybean tempeh moisture ratio with increasing temperature.

Keywords: tempeh; shelf life; drying; sorption isotherms; drying kinetics

1. Introduction

Tempeh, a classic Indonesian dish, is produced from dehulled, soaked, solid soybeans fermented with the fungus *Rhizopus spp*[1]. The most common variety of tempeh produced and consumed in Indonesia is prepared from soybeans. However, a large amount of research has shown the use of non-soybean materials as tempeh production substrates[2]. It can also be made from other materials such as a variety of beans, corn, rice, lentils, and barley[3]. The tempeh should have a structure that is solid and not easily destroyed when sliced with a knife. The colour should be white because of the development of *Rhizopus spp.* Mycelium and the odour should be natural and free of ammonia aroma. Also, the flavour should be meaty, mushroom-like, and nutty[4]. In addition, tempeh has the same nutritional value as meat or poultry and contains all important amino acids, thus tempeh is an excellent source of protein[5]. As a result, tempeh can be classified as a nutritionally valuable, readily digestible, and flavourful product, and as such, it satisfies a growing number of consumers looking for great meat replacements[6].

Despite its well-established health benefits, tempeh faces limitations related to shelf life. This is primarily due to the ongoing activity of microbial enzymes and the influence of storage conditions. During fermentation, the beneficial mold *Rhizopus oligosporus* introduces enzymes that break down complex carbohydrates and proteins into simpler molecules, contributing to tempeh's characteristic flavor and texture. However, these very enzymes continue their activity after fermentation, leading to a gradual decline in quality. This manifests as textural changes, off-flavor development, and ultimately, spoilage[7]. Therefore, when fresh tempeh is stored, it soon turns dark, the texture softens, ammoniacal odours develop, and the beans become apparent as the fungus's mycelium grows[6]. Storage conditions further influence tempeh's shelf life. Warmer storage temperatures exacerbate both enzyme activity and microbial growth, accelerating spoilage. Additionally, the selection of appropriate packaging is crucial as aerobic spoilage microbes proliferate in environments with high oxygen availability. Inadequate packaging facilitates air exchange, which can lead to both moisture loss from the product and potential contamination by undesirable microorganisms[8].

Therefore, to ensure optimal quality throughout the supply chain, careful attention is required at every stage. This includes meticulous manufacturing practices, the implementation of secure packaging solutions, proper handling procedures, and efficient transportation methods[9]. Thus, for a fresh tempeh, improper storage puts products at risk of damage, making them unsellable and destined for the landfill as food waste. Food or organic waste decomposes quickly and can lead to several concerns, including contamination of the ground and water and the spread of illness by flies, to mention a few[10]. This avoidable outcome highlights the importance of proper storage practices[11]. This suggests that improvements in technology, innovations, and storage efficiency are needed to prolong the shelf life of tempeh[12].

Drying is one of the most common preservation techniques in the food industry, extends shelf life by reducing the water activity of the product. This reduction inhibits the growth of microorganisms, including bacteria, mold, and yeast, which are primarily responsible for food spoilage[13]. An electric dehydrator and oven are two typical technologies for drying food. An electric dehydrator delivers high-quality dried items due to its effective structure for drying foods evenly while retaining the quality of the food. If an electric dehydrator is not obtainable, drying in an oven will indeed generate a satisfactory dried product. The electric oven included a knob that could be used to adjust the temperature[14]. In contrast to a dehydrator, drying in an oven takes longer and requires more energy. This drying, in addition to extending the shelf life, enables the manufacturing of tempeh chips, a unique food product.

Drying, on the other hand, influenced the physical, chemical, and qualitative aspects of products[15]. Notably, the process parameters, temperature and drying time significantly impact the final product's quality. While high temperatures expedite drying, exceeding optimal levels can lead to detrimental effects. These include nutrient loss due to degradation of heat-sensitive vitamins and minerals[16], color alterations caused by Maillard reactions (browning) that impact appearance, and diminished flavor resulting from the evaporation of volatile aroma compounds[17]. Conversely, extended drying times at low temperatures, although favorable for quality preservation, can promote microbial growth, raising safety concerns[16], and increase energy consumption due to longer processing periods[18]. Drying time also plays a crucial role. Excessive drying leads to product toughness and shrinkage through the removal of excessive moisture[18]. Additionally, prolonged heat exposure during over-drying further degrades heat-sensitive nutrients. Insufficient drying, on the other hand, creates a favorable environment for microbial growth, leading to spoilage and safety risks[16]. Furthermore, high moisture content promotes mold development[18]. Therefore, optimizing drying parameters is critical to ensure a balance between drying efficiency, product quality, and safety.

Thus, mathematical models of the drying process are applied to establish new drying methods, optimise existing ones, and even govern the drying process[19]. The thin-layer drying of various foods, particularly vegetables and fruits, has been studied experimentally and by quantitative modelling by several researchers. Mango slices[20], tomato slices[21], sweet cherry[22], and potato slices[23] are indeed some examples. Nevertheless, there is limited information and research on the kinetics of drying tempeh slices in previous studies. Therefore, the goals of this study were: (i) to produce three different kinds of tempeh from three different beans, namely soybeans, Indian dhal, and chickpeas; (ii) to determine the moisture content and drying curve of the tempeh chips; (iii) to analyse the sorption properties of the tempeh chips using the GAB equation; and (iv) to evaluate drying kinetics model for the tempeh chips.

2. Methodology

2.1 Material

The five types of beans used in this experiment, soybean, chickpea and Indian dhal beans were purchased at a Giant supermarket in Seksyen 7, Shah Alam, Malaysia. Approximately 100 grams were needed for each variety of bean. Then, a total of roughly 18 grams of *Rhizopus oligosporus* were used in the inoculation step, of which each type of bean needed only 6 grams. In order to determine the equilibrium moisture content, an experiment involving the sorption isotherm was conducted. This experiment included a number of different salt solutions, including LiCl (64.1%), $MgCl_2.6H_2O$ (86.7%), K_2CO_3 (69.0%), $CaCl_2$ (25%), KCl (71.4%), and KNO_3 (71.4%), equivalent to a relative humidity range of 11% to 93%.

2.2 Experimental devices

The experimental setup to produce the tempeh involved the use of a normal stove and a pot. In this pot, a 1:3 ratio of sample to fresh water was used, with 100 grams of each kind of bean being soaked in 300 ml of fresh water, then the beans were peeled and cooked for 20 to 30 minutes. A hot air oven (E 15158 E – Memmert UNB 500, Germany) was also used to dry the tempeh in order to carry out the initial moisture content experiment and form tempeh chips. Next, a balance machine (GF-3000- AND Columbus) is utilised to weigh the samples and petri dishes. In addition, a vacuum desiccator (Brand: DWK Life Sciences Kimble™,USA) was used to conduct the sorption isotherm experiment and to cool down the petri dish once it had been dried. Moreover, a stopwatch was used as a timer for the drying time of the samples' food.

2.3 Methods

2.3.1 Preparation of tempeh

100 grams of soybeans were soaked in fresh water for 6 to 24 hours to increase moisture to ease peeling process [4]. The soybeans were allowed to soak until they become tripled in size. Any damaged beans or insect bites were eliminated from the soybeans after they were drained. The soybeans were then split, by gently rubbing them with fingertips. Next, the beans were placed in the pot and boiled after being washed and having their hulls removed. In order to get rid of its' raw flavour and eradicate any pathogens or spoilage organisms that could be present and could possibly impair the fermentation process, the

soybeans were boiled for 20 to 30 minutes[4]. Once the soybeans were perfectly cooked, the cooking water was discarded. The cooked beans were then cooled to a lukewarm temperature at 35 °C. Next, the soybeans were inoculated with 6 grams of *Rhizopus oligosporus* for fermentation. In a plastic bag, the 150 grams of inoculated beans were spread out to a thickness of 2 to 3 cm. On both sides of the plastic bag, 1.5-cm-diameter holes were made to encourage air circulation. The samples were then fermented for 48 hours at a temperature of 25°C[24]. The same procedure for this experiment was repeated with other types of beans, which wereIndian dhal and chickpeas.

2.3.2 Determination of initial moisture content (Mi)

To determine the amount of moisture content of tempehin the dish, the clean petri dish was dried in the oven for 20 minutes at 105 °C. A desiccator was used to cool down the petri dish after drying. The petri dish was then set on the balance machine to determine its weight. To determine the initial weight of the sample, the thinly cut tempeh was placed on the petri dish. The petri dish containing the sample was dried in a hot air oven and at 80 °C. For every 10 minutes, the sample was weighed, and the data was collected until there was no weight changes. The dish was weighed once again at this point to evaluate the weight of the final product or the moisture loss from the tempeh chips[25]. This experiment was conducted in triplicate in order to acquire more accurate findings, and the experiment was repeatedly carried out at 90 °C and 100 °C. As a result, the initial moisture content of each sample at three different temperatures were determined.

2.3.3 Sensory analysis of the tempeh chips

The sensory evaluation of the three different kinds of tempeh chips produced was investigated by 20 UiTM Shah Alam undergraduate students. The sensory analysis focuses on five sensory elements like appearance, smell, taste, flavor, texture, and overall rating of the three various types of chips.

2.3.4 Determination of sorption isotherm and equilibrium moisture content

The saturated salt solution (SSS) gravimetric static technique was used to estimate the sorption isotherms of food products. In this approach, a sample with a known weight is placed in a closed container, such as a desiccator, toenabled the sample to reach equilibrium with the salt solution's at the specified relative humidity[26].

To determine the sorption isotherm of tempeh chips, six different saturated salt solutions with relative humidity levels ranging from 11% to 93% were prepared and placed in petri dishes[26]. The salt solutions with known water activity that were utilized in this experiment are shown below in Table 1.

Table 1. Water activity and the quantities of salt and distilled water used in the preparation of saturated salt solution[26,27]

Salts	Water activity	Salt (kg)	Water (kg)
LiCl (64.1 %)	0.11	0.075	0.042
$MgCl_2 . 6H_2O$ (86.7%)	0.33	0.150	0.023
K_2CO_3 (69.0%)	0.44	0.200	0.090
$CaCl_2$ (25%)	0.68	0.200	0.060
KCl (71.4%)	0.85	0.200	0.080
KNO_3 (71.4%)	0.93	0.200	0.080

Three empty petri dishes were then prepared and weighed to record their weight. Thethree types of tempeh were then placed in each petri dish, and dried at 80 °C until they attained a constant mass to form the tempeh chip. The initial weight was recorded by weighing each sample individually. These steps were repeated with slices of tempeh dried at 90 °C and 100 °C. The petri dish that was filled with saturated salt solution was placed into a vacuum desiccator at room temperature, along with a total of nine petri dishes of sample[28].

These samples were weighed during the first seven days to ascertain that they had been no resulting weight increase or decrease. If there has not been any further weight gain or moisture loss, equilibrium is assumed to have been reached at this phase[25]. The equilibrium moisture content of the samples was then examined for each relative humidity level. The average equilibrium moisture was then calculated andthe same experiments were conducted again with another type of saturated salt solutions.

2.4 Data analysis

2.4.1 Initial moisture content and drying curve

The following equation can be applied to calculate the initial moisture content for all sample:

$$Mi = \frac{W_i - W_D}{W_D} \quad (1)$$

Where W_i represents the product's initial weight and W_D denotes its final weight. The drying curve may be constructed from the moisture content data gathered every 10 minutes by plotting the drying times against moisture content or weight loss. The drying curves of tempeh chips at three different temperatures were illustrated.

2.4.2 Equilibrium moisture content (EMC) and the GAB isotherm

The following equation was used to estimate the experimental data on equilibrium moisture content from sorption isotherm experiment:

$$Me = \frac{We}{Wi} \times (Mi + 1) - 1 \qquad (2)$$

Where, W_i indicates the initial weight of the product, W_e represents its final weight, Mi its initial moisture content, and Me its equilibrium moisture content.

An experimental moisture isotherm graph displaying the average equilibrium moisture content (Me) against relative humidity was plotted using data obtained for each salt solution and its relative humidity. The values of α, β, and ϒ, were determined by utilizing the second polynomial, a graph of Aw/Me against Aw[25]. These values were then inserted in Equations (3), (4), (5), and (6) to define the three constants in the GAB model, k, C, and Wm[40].

$$T = \frac{\beta^2}{(-\alpha\gamma)} + 4 \qquad (3)$$

$$C = \frac{T + \sqrt{T^2 - 4T}}{2} \qquad (4)$$

$$\beta = \frac{1}{Wm}\left(1 - \frac{2}{C}\right) \qquad (5)$$

$$\gamma = \frac{1}{WmCk} \qquad (6)$$

The GAB (Guggenheim–Anderson–de Boer) equation (7), which was also used to predict the equilibrium moisture content, was applied to model the water sorption of tempeh chips[40].

$$\frac{Wm}{Me} = \frac{(1 - kaw) \times (1 - kaw + Ckaw)}{Ckaw} \qquad (7)$$

Where Me represents the equilibrium moisture content of the product (on a dry basis), Aw indicates water activity (RH%/100), Wm denotes the water content in the monolayer, C represents the Guggenheim constant, and k represents the factor-correcting characteristics of the multilayer molecules in relation to the bulk liquid. From the findings, the predicted moisture sorption isotherm graph of the GAB equilibrium moisture content against relative humidity was plotted. The graph was then compared with the experimental data.

Following that, the equilibrium moisture content data from experimental and predicted data from the GAB model were compared by using the Root Mean Square Error (RMSE) equation as indicated in Eq. (8):

$$RMSE(\%) = \sqrt{\frac{\sum(Mexp - Mcalc)^2}{N}} \times 100 \qquad (8)$$

Where, $Mexp$ is the moisture content that was measured experimentally, $Mcalc$ is the calculated moisture content, and N denotes the number of experimental units.

2.4.3 Moisture ratio (MR) and drying kinetic model analysis

The predicted data of moisture ratio (MR) of the tempeh chips was determined using the equation below:

$$MR = \frac{Xt - Xe}{Xo - Xe} \qquad (9)$$

Where MR is the dimensionless moisture ratio, Xt is the moisture content at any particular time, Xe represents the equilibrium moisture content, that can be obtained from the drying curve, and Xo is the initial moisture content.

Three mathematical modelling techniques as shown in Table 2 were used to determine the moisture ratio as a function of drying time. The findings of the three model equation models were analysed to determine drying kinetics of tempeh chips.

The drying kinetic model in this study was analyzed and visualized using Microsoft Excel to performcalculations. Rrelevant equations for the chosen drying kinetic model were implemented within the Excel spreadsheets to determine model parameters. Additionally, Excel's data analysis and charting functionalities were used to extract and plot the drying data used for defining drying kinetics.

Table 2. The selected thin layer drying equation models[29]

Models name	Model equation
Newton	$MR = \exp(-kt)$
Logarithmic	$MR = a\exp(-kt + c)$
Henderson and Pabis	$MR = a\exp(-kt)$

3. Results and discussion

3.1 Sample preparation of tempeh

Tempeh production from three different raw materials including soybeans, chickpeas beans, and Indian Dhal beans requires several processing steps. To beginproduction, three types of beans were washed and soaked in clean water for 8 hours. The following figure shows results after soaking process, where the size of the beans becomes bigger.

Table 1. The soaking process of beans

Types of beans	Before soaking process	After 8 hours soaked in water
Soybeans		
Chickpea beans		
Indian Dhal beans		

Table 2. Result of tempeh produced

Types of beans	Before fermentation	After 48h
Soybeans		
Chickpea s beans		
Indian Dhal beans		

Next, the beans were dehulled, cooked, dried, mixed with *Rhizopus oligosporus*, and incubated. Figure 1 illustrate the mentioned processes.

(a) (b) (c) (d) (e)

Fig. 1: The processes for production of tempeh which are dehulling (a), cooking (b), drying (c), mixing with *Rhizopus oligosporus* (d), and incubation (e).

As a result, after 48h of incubation process, the three types of tempeh were successfully produced as shown in the Table 4. Based on the samples, tempeh should be firm yet slightly yielding to the touch. It should have a pleasant, nutty aroma and flavor. The specific texture of tempeh at this stage can be influenced by factors like bean type, hulling process, and starter culture. Unhulled soybeans create a coarser texture, and different cultures may affect growth patterns, potentially impacting firmness. However, since all three types of beans undergo hulling and utilizing *Rhizopus oligosporus* as the starter culture, the primary factor influencing the texture of the tempeh is the type of bean used.

Therefore, for soybean tempeh, it is the classic tempeh, known for its firmness and slightly chewyness texture. Meanwhile, chickpeas are smaller than soybeans, potentially resulting in a finer, denser texture compared to soybean tempeh. Due to its smaller size and naturally softer texture compared to soybeans and chickpeas, Indian dhal tempeh (after 48 hours of fermentation) were less firm, slightly more yielding, and potentially more prone to crumbling.

3.2 Determination initial moisture content and drying curve

For initial moisture content, the data for three types of beans were obtained at three different temperatures with the same initial weight of samples, which were dried until they reached a constant weight. For each temperature, the experiment was repeated three times. Thus, the calculated average moisture content along with standard deviation and error were tabulated in Table 4. Then, a graph of an average moisture content against temperature of the three types of tempeh was plotted and presented in Fig. 2.

Based on the results, all three types of tempeh indicated that high temperature would decrease the moisture content of the samples. This is due to higher temperature, which provide more heat energy in the heat transfer process. Thus, more moisturewas reduced compared other lower temperatures. In addition, by comparing all types of tempeh, soybean tempeh showed lowest moisture content, followed by Indian dhal tempeh and chickpea tempeh. This might be influence by several factor, for instance, soybeans are generally larger than chickpeas and Indian dhal. This translates to a smaller overall surface area per unit weight. During fermentation, *Rhizopus oligosporus* grows on the surface of the beans, potentially leading to less overall moisture utilization in larger soybeans compared to smaller beans with a higher surface area to volume ratio[30]. Additionally, soybeans also have a higher protein content (36-40%) compared to chickpeas (16-20%) and Indian dhal (22-25%)[31,32,33]. Rhizopus oligosporus primarily utilizes carbohydrates for growth. While it can break down some proteins into simpler sugars, the higher protein content in soybeans might limit the readily available carbohydrates, potentially leading to less overall moisture utilization during fermentation compared to the other legumes.

Apart from that, while a target moisture content of 60% to 65% is ideal for high-quality tempeh[34], producing tempeh chips requires a different approach. For shelf-stable tempeh chips, a higher moisture content is generally desired compared to fresh tempeh. This is because the drying process used to create tempeh chips removes moisture, impacting their texture. Besides that, optimal temperature range for tempeh fermentation is generally considered to be 28°C to 35°C (82°F to 95°F)[24]. This temperature range promotes optimal growth of *Rhizopus oligosporus* while minimizing the risk of growth from undesirable microorganisms.

Table 3. Result of average moisture content, standard deviation and error

Type of beans	Avg moisture content (%)	Standard deviation	Standard error
Soybeans	139.40	1.4509	0.8377
	136.53	1.4164	0.8178
	132.36	1.3668	0.7891
Chickpeas	197.74	1.2990	0.7500
	194.05	1.2607	0.7278
	191.88	1.2421	0.7171
Indian Dhall	193.33	2.5028	1.4450
	187.62	1.2062	0.6964
	182.15	2.0154	1.1636

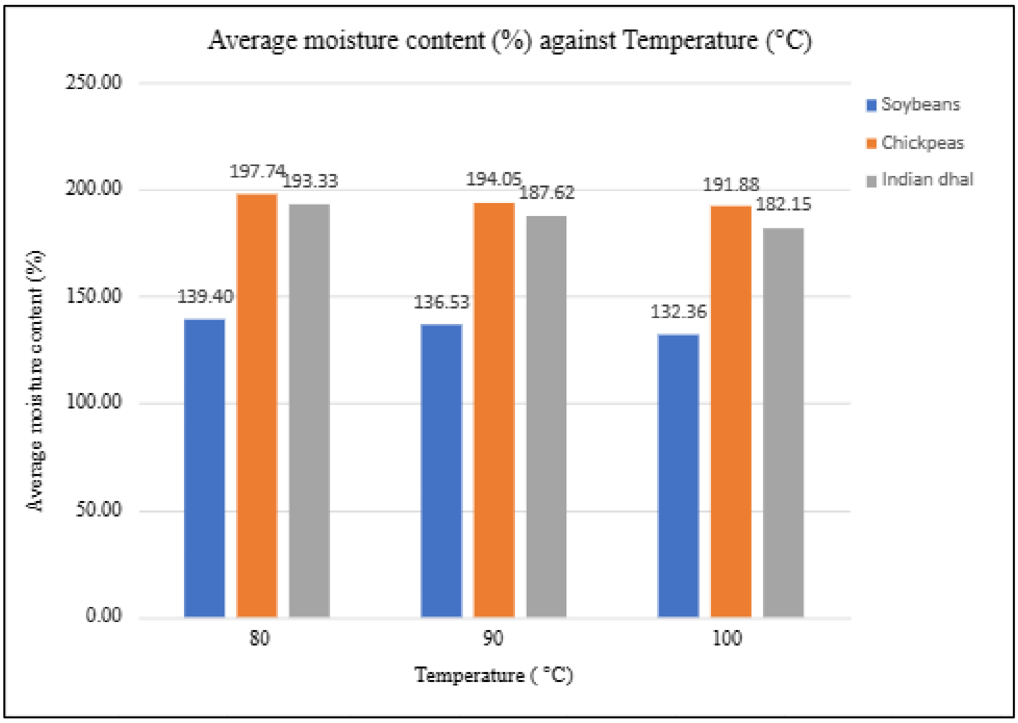

Fig. 2: Average moisture ccontent against temperature

Furthermore, the drying curve of moisture content (%) versus drying time (min) of all varieties of tempeh at three different temperatures were constructed using the data to highlight the drying process of tempeh. Based on Figures. 3, 4 and 5, the curve showed that as drying time increases, the sample's moisture content decreases. This is due to the fact that when over time, the sample's moisturediffuses and evaporates in the dryers. Hence, samples continue to dry.

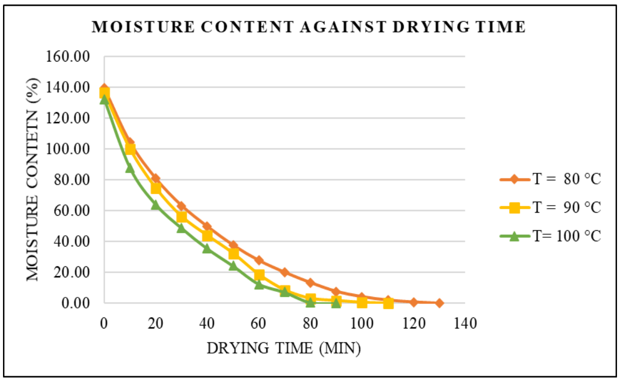

Fig. 3: Drying curve of soybean tempeh

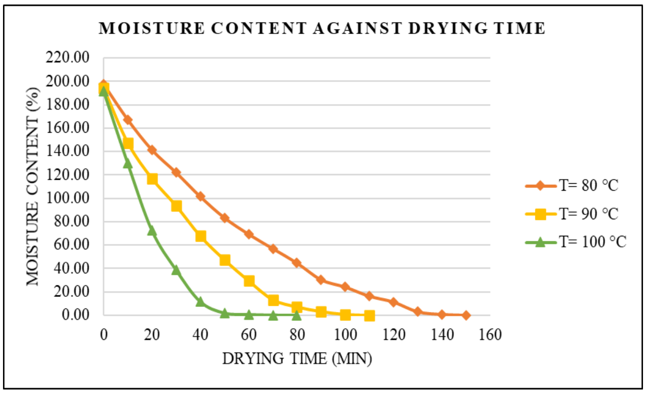

Fig. 4: Drying curve of chickpea tempeh

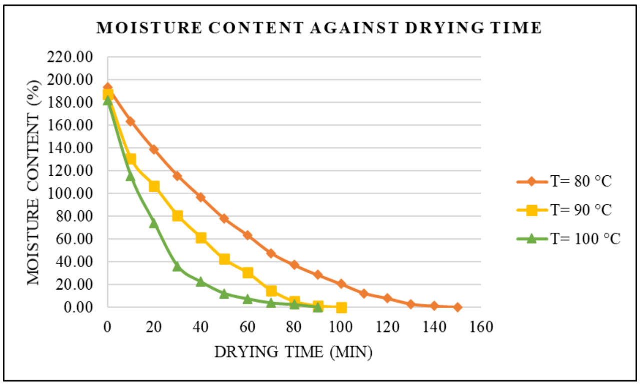

Fig. 5: Drying curve of Indian dhal tempeh

3.3 Sensory analysis of the tempeh chips

Figure 6 illustrated the result of the sensory evaluation of the three types of tempeh chips which includes soybean tempeh chips, chickpea tempeh chips and Indian dhal tempeh chips. Thus, each student received a set of three different kinds of tempeh chips along with a questionnaire that had six questions. The samples must be rated by the students on a scale of 1 to 3, with 3 being the highest score. As a result, for the appearance of tempeh chips, most students preferred soybean tempeh chips, as they might look more appealing compared to others. From the result, Indian dhal tempeh chips scored the highest rating for smell since it contained the strongest aroma. In terms of taste and flavor, the students favored chickpea tempeh chips over all others. Since the tempeh was baked in an oven, the texture of these tempeh chips is crunchy. Hence, Figure 6 below showed little difference in the rating of the texture of the all three chips. Finally, soybean tempeh chips earned the highest overall rating, making them the most well-liked type of chips among students.

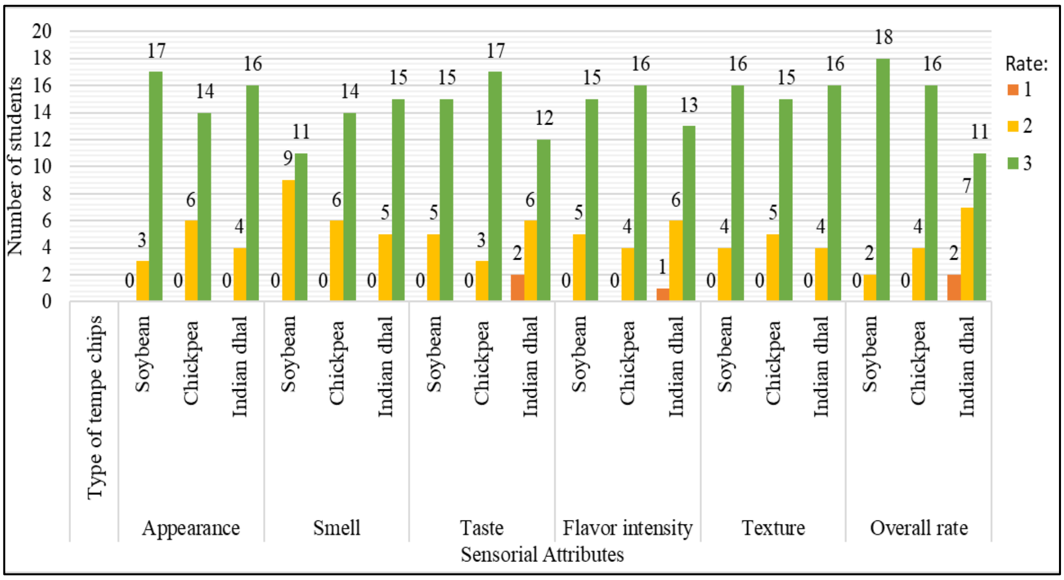

Fig. 6: The result of sensory analysis

3.4 Equilibrium moisture content (EMC) and the GAB isotherm

The data for equilibrium moisture content (EMC) was obtained through a sorption isotherm experiment, where dry tempeh chips were placed in a desiccator with various salt solutions until a constant weight was reached (typically within 7 days). The type of salt solution used significantly affects the EMC of the material. This is because different salt solutions create varying relative humidity (RH) environments, which influenced the water activity (Aw) of the material and its interaction with moisture[35]. As RH increases, so does Aw. Aw represents the availability of free water in a material for interaction with its surroundings. For example, a material placed in a saturated lithium chloride (LiCl) solution (which has a lower RH than a saturated potassium chloride (KCl) solution) will have a lower EMC due to the lower Aw environment.

From the result, by using Eqn. (2), the value of Me calculated for three types of tempeh chips is shown in the Table 6. According to the data, the equilibrium moisture content of the tempeh chips is directly proportional to the salt solution's relative humidity. This is evident by the data for soybean tempeh chips at 80°C. At 11% relative humidity (lower RH), the EMC is 1.4158. However, when the relative humidity increases to 33% (higher RH), the EMC value also increases to 1.4694. This demonstrates that tempeh chips absorb more water when the surrounding environment has a higher relative humidity due to the presence of more water vapor[36].

Apart from that, the equilibrium moisture content is also impacted by temperature. In this study, temperatures of 80°C, 90°C, and 100°C were chosen for the EMC experiment. These temperatures represent a range commonly used for drying food products and provide a spectrum for observing the effect of temperature on EMC. Additionally, these temperatures might be relevant to potential drying methods considered for the production of tempeh chips. The temperature is the most significant component in maintaining product quality since it directly influences the physiological and biological processes in the products. While relative humidity is important in managing moisture loss from products to maintain their physical and biological look[37]. The EMC at each temperature may be compared, and it can be shown that as the temperature increases, the EMC decreases at constant relative humidity. This is because sorptive behavior is temperature dependent. The molecules in a tempeh chip have higher energy at high temperatures. The water molecules may be attracted to and attach to the sorption sites of tempeh chips when they come into contact. However, if the temperature is too high, the water molecules will have too much energy and will be easier to release into the surroundings and break away from the sorption sites. Thus, at higher temperatures, there are less attractive interactions between the sorption sites and the water molecules[38,39].

Table 6. The equilibrium moisture content (EMC), Me

Salt Solutions	RH (%)	Soybean tempeh chips			Chickpea tempeh chips			Indian dhal tempeh chips		
		T = 80 °C	T = 90 °C	T = 100 °C	T = 80 °C	T = 90 °C	T = 100 °C	T = 80 °C	T = 90 °C	T = 100 °C
LiCl	11	1.4158	1.3819	1.3418	2.0244	1.9727	1.9709	1.9533	1.8879	1.8445
$MgCl_2 . 6H_2O$	33	1.4694	1.4396	1.4074	2.0943	2.0772	2.0617	2.0529	1.9716	1.9445
K_2CO_3	44	1.5405	1.5213	1.3842	2.2702	2.1817	2.1547	2.1655	2.0825	2.0047
$CaCl_2$	68	1.6261	1.5902	1.5427	2.2747	2.2732	2.2714	2.2954	2.2102	2.1010
KCl	85	2.0774	1.9985	1.9337	2.8588	2.8547	2.8488	2.8757	2.7669	2.6309
KNO_3	93	2.2805	2.2167	2.1374	3.1385	3.1378	3.1255	3.1593	3.0326	2.9782

Following that, a graph of Aw/Me against Aw was plotted to obtain the 2nd polynomial equation, which can be used to determine the values of α, β, and ϒ. Figures. 7, 8, and 9 illustrate the graph for soybean, chickpea, and Indian dhal tempeh chips, respectively.

The values of α, β, and ϒ were then inserted in Eqns. (3), (4), (5), and (6) to define the values of k, C, and Wm as tabulated in Tables 7, 8, and 9.

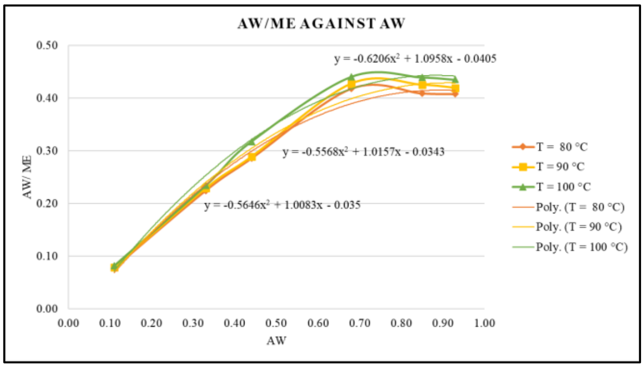

Fig. 7: Graph Aw/Me against Aw for soybean tempeh chips

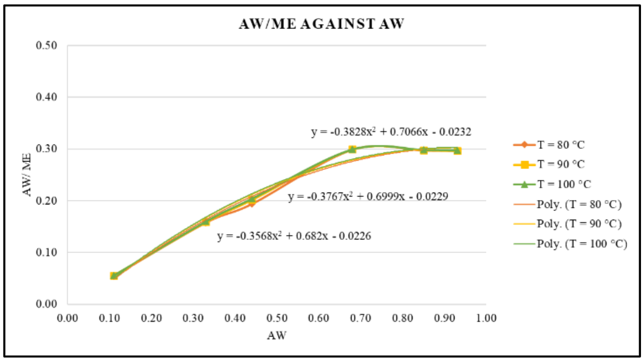

Fig. 8: Graph Aw/Me against Aw for chickpea tempeh chips

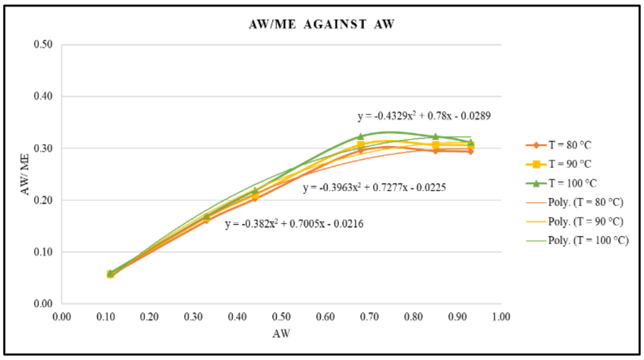

Fig. 9: Graph Aw/Me against Aw for Indian dhal tempeh chips

Table 4. Data of constant values for GAB model equation

Parameters	Soybean tempeh chips		
	T = 80 °C	T = 90 °C	T = 100 °C
α	-0.5646	-0.5568	-0.6206
β	1.0083	1.0157	1.0958
ϒ	-0.0350	-0.0343	-0.0405
T	-47.4483	-50.0179	-43.7745
C	0.9798	0.9808	0.9781
Wm	-1.0327	-1.0232	-0.9534
k	28.2373	29.0535	26.4781

Table 5. Data of constant values for GAB model equation

Parameters	Chickpea tempeh chips		
	T = 80 °C	T = 90 °C	T = 100 °C
α	-0.3568	-0.3767	-0.3828
β	0.6820	0.6999	0.7066
ϒ	-0.0226	-0.0229	-0.0232
T	-53.6814	-52.7859	-52.2195
C	0.9820	0.9817	0.9816
Wm	-1.5199	-1.4819	-1.4684
k	29.6444	30.0153	29.9052

Table 6. Data of constant values for GAB model equation

Parameters	Indian dhal tempeh chips		
	T = 80 °C	T = 90 °C	T = 100 °C
α	-0.3820	-0.3963	-0.4329
β	0.7005	0.7277	0.7800
ϒ	-0.0216	-0.0225	-0.0289
T	-55.4702	-55.3879	-44.6299
C	0.9826	0.9826	0.9785
Wm	-1.4781	-1.4229	-1.3383
k	31.8757	31.7881	26.4227

The predicted data of equilibrium moisture content by the GAB model were calculated by applying Eqn. (7) after obtaining the constant values for GAB model. These calculated data were tabulated in Table 10. The GAB equilibrium moisture content of Indian dhal tempeh chips for each salt solution showed the highest, followed by chickpea and soybean tempeh chips.

The equilibrium moisture content of experimental and predicted data (GAB model) can be compared, and it can be shown that the data are only slightly different. As can be seen in Figures. 10, 11, and 12, the experimental and predicted data were plotted against relative humidity. Since all the graphs illustrated only a slight difference in value, they demonstrate the successful use of the GAB model equation to correlate the relationship between equilibrium moisture content and the water activity of food products.

Table 10. The equilibrium moisture content, Me by GAB model

Salt solutions	RH (%)	Soybean tempeh chips			Chickpea tempeh chips			Indian dhal tempeh chips		
		80 °C	90 °C	100 °C	80 °C	90 °C	100 °C	80 °C	90 °C	100 °C
LiCl	11	1.5923	1.5561	1.5166	2.2868	2.2208	2.2047	2.1640	2.0852	2.1292
$MgCl_2.6H_2O$	33	1.3968	1.3736	1.3016	2.0171	1.9755	1.9609	1.9647	1.8913	1.8196
K_2CO_3	44	1.4699	1.4435	1.3686	2.1113	2.0742	2.0600	2.0690	1.9913	1.9090
$CaCl_2$	68	1.7455	1.7046	1.6280	2.4622	2.4386	2.4261	2.4451	2.3522	2.2567
KCl	85	2.0525	1.9918	1.9207	2.8398	2.8348	2.8255	2.8540	2.7444	2.6453
KNO_3	93	2.2442	2.1692	2.1048	3.0687	3.0774	3.0708	3.1055	2.9855	2.8874

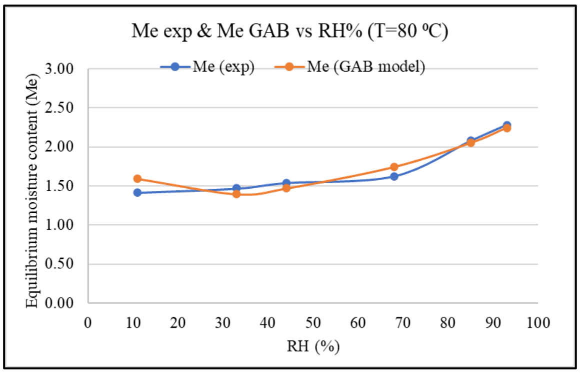

Fig. 10: Predicted and experimental moisture isotherm vs relative humidity for soybean tempeh chips

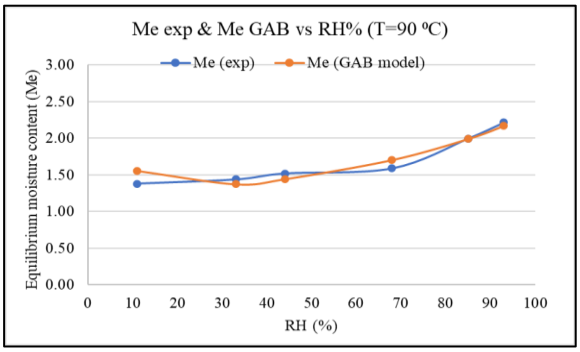

Fig. 11: Predicted and experimental moisture isotherm vs relative humidity for chickpea tempeh chips

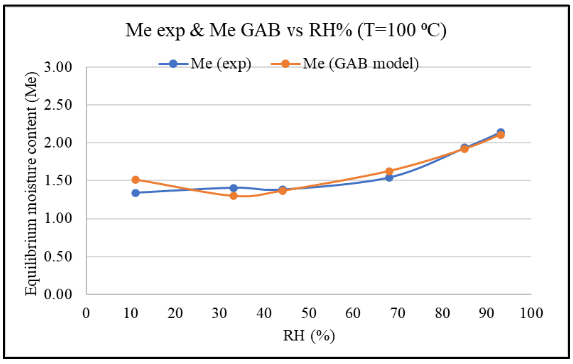

Fig. 12: Predicted and experimental moisture isotherm vs relative humidity for Indian dhal tempeh chips

The findings of Table 11 displayed the root mean square error (% RSME) of the GAB model. The data gathered showed that the range of %RSME values was from 9.18% to 15.30%. The RSME value of the GAB model for soybean tempeh chips was the lowest compared to others. For water sorption isotherm , low RSME values often increases the GAB model's utility[40].

Thus, this GAB model might be used to determine the sorption isotherm, providing a relationship between water activity and water content over a diverse range of food products with various forms of isotherms, under greatly changing conditions of temperature, moisture, and water activity[25].

Table 11. The data of RSME of GAB model

Temperature (°C)	RSME (%)		
	Soybean tempeh	Chickpea tempeh	Indian dhal tempeh
80	9.80	15.30	12.06
90	9.67	13.84	11.30
100	9.18	12.99	15.19

3.5 Moisture ratio (MR) and drying kinetic model analysis

The predicted moisture ratio (MR) was computed by using Eqn. (9). The drying curve, which was previously displayed in Figs. 3, 4, and 5, was used to calculate the nomenclature needed in the equation, such as equilibrium moisture content, Xe, and the moisture content at any particular time, Xt. The computation of MR then utilized the value of Xt obtained at 50 minutes, while for the Xe value, it was taken at a point where the curve is getting constant. The obtained data of MR is therefore presented in Table 12, and it demonstrates that when the temperature rises, the moisture ratio of any variety of tempeh decreases. This is because it is impacted by the moisture content's value differential at a certain moment in time[37].

Table 72. The predicted data of moisture ratio (MR)

Temperature (°C)	Moisture Ratio (MR)		
	Soybean tempeh chips	Chickpea tempeh chips	Indian dhal tempeh chips
80	0.3528	0.5115	0.4969
90	0.3186	0.3466	0.3229
100	0.2649	0.0604	0.1113

The empirical models (Newton, Logarithmic, and Henderson and Pabis) have been applied to establish the experimental moisture ratio as a function of drying time. The kinetic parameter, k (min^{-1}), as well as the empirical parameters, a and c, are constant parameters in these model equations[41]. the use of the following equations, the values of these parameters might be determined for any given temperature[42]:

$$a = 0.001T + 0.945 \tag{10}$$

$$k = 1.49E\text{-}06T^2 - 0.0001T + 0.005 \tag{11}$$

$$c = 8E\text{-}05T^2 - 0.01T + 0.256 \tag{12}$$

In Table 13, the estimated parameters for each drying condition were displayed. It was discovered that ' k ' and ' a ' increased in value with rising temperature. This may be clarified through how drying temperature affects diffusivity and heat transmission. As temperature rises, water moves more quickly through the product's internal diffusion mechanism into the surrounding air[43]. Additionally, the increase drying rate constant (k) suggested that when temperature rises, the drying curve steepens, indicating an increase in the drying rate[42].

Table 8. Comparison of different drying models with drying coefficients at different drying temperatures

Models	Temperature (°C)	Model constants
Newton	80	k = 0.0065
	90	k = 0.0081
	100	k = 0.0099
Logarithmic	80	a = 1.0250, k = 0.0065, c = -0.0320
	90	a = 1.0350, k = 0.0081, c = 0.0040
	100	a = 1.0450, k = 0.0099, c = 0.0560
Henderson and Pabis	80	a = 1.0250, k = 0.0065
	90	a =1.0350, k = 0.0081
	100	a = 1.0450, k = 0.0099

Table 14: The moisture ratio by thin layer drying models

Models	Temperature (°C)	Moisture Ratio (MR)		
		Soybean tempeh	Chickpea tempeh	Indian dhal tempeh
Newton	80	0.9849	0.9827	0.9827
	90	0.9840	0.9840	0.9853
	100	0.9836	0.9853	0.9836
Logarithmic	80	0.9775	0.9753	0.9753
	90	1.0224	1.0224	1.0238
	100	1.0839	1.0856	1.0839
Henderson and Pabis	80	1.0095	1.0073	1.0073
	90	1.0184	1.0184	1.0198
	100	1.0279	1.0296	1.0279

4. Conclusion

According to the study, the drying temperatures and time had a significant impact on the quantity of moisture removed from the tempeh slices. The samples' moisture content decreased due to high temperatures and longer drying times. Furthermore, it is demonstrated that at constant temperature, the equilibrium moisture content (EMC) of tempeh chips increases when relative humidity increases. Meanwhile, with constant relative humidity, the rise in temperature led to a reduction in EMC. For instance, EMC values of soybean tempeh chips at 11% relative humidity were 1.4158, 1.3819, and 1.3418 at 80, 90, and 100 °C, respectively. Then, at 33% relative humidity, EMC values were increased to 1.4694, 1.4396, and 1.4074. Furthermore, the study of the GAB isotherm model succeeded in capturing the predicted data, as the model can accurately predict the EMC of the tempeh chips under different conditions. In addition, the predicted data for the moisture ratio (MR) analysis depicts that the MR of any type of tempeh chips decreases as the temperature increases. For instance, the MRs of soybean tempeh chips were 0.3528, 0.3186, and 0.2649 for temperatures of 80, 90, and 100 °C, respectively. Finally, to understand the drying process of tempeh chips, three different mathematical models were employed to analyze the experimental data. These models helped describe how the moisture content of the chips changed over time during drying. Additionally, sensory evaluation revealed that soybean tempeh chips were the most favorable option compared to chips made from chickpea and Indian dhal tempeh.

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Nomenclature

W_i	The product's initial weight (g)
W_D	The product's final weight (g)
W_e	Final weight of the product (g)
M_i	Initial moisture content (%)
M_e	Equilibrium moisture content
A_w	Water activity
α	Linear expansion coefficient
β	Thermal expansion coefficient
Υ	Volume expansion coefficient
W_m	The water content in the monolayer
C	The Guggenheim constant
k	The factor-correcting characteristics of the multilayer molecules in relation to the bulk liquid
M_{exp}	The moisture content that was measured experimentally
M_{calc}	The calculated moisture content
N	Number of experimental units
k	Kinetic parameter (min^{-1})
α	Constant parameters in thin layer model
c	Constant parameters in thin layer model
X_t	Moisture content at any particular time
X_e	The equilibrium moisture content
EMC	Equilibrium Moisture Content
GAB	Guggenheim-Anderson-De Boer
SSS	Saturated Salt Solution
RMSE	Root Mean Square Error
MR	Moisture Ratio
RH	Relative Humidity

LiCl	Lithium Chloride
$MgCl_2$. $6H_2O$	Magnesium chloride hexahydrate
K_2CO_3	Potassium carbonate
$CaCl_2$	Calcium chloride
KCl	Potassium Chloride
KNO_3	Potassium nitrate

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