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Characteristics of Isothermic Sorption Curves and Determination of the Best Equation Model for Egg Flour

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***Abstract*— Egg flour storage is influenced by temperature, relative humidity, and water activity. Equilibrium of moisture content is closely related to sorption isotherm to determine optimal storage conditions. This research evaluated the characteristics of isothermic sorption curves and determined the appropriate equation model to describe isothermic sorption curves on various types of egg flour. The egg flour used is egg white flour, egg yolk flour, and whole egg flour (white and yolk), which is ohmic pasteurized for 5 minutes at 60^0C, then oven and vacuum dried. After that, the samples were stored in a desiccator with different humidity levels (10-80%) at a temperature of 30^0C. The desiccator is inserted into the incubator to maintain the temperature. This research used four equation models: Oswin, Chung-Pfost, Caurie, and Helsey. The results showed that the isothermic sorption curve of egg flour had a sigmoid absorption type, which reflected a Type II isothermic pattern. Based on the coefficient of determination (R^2) and RMSE, the Oswin equation model is the most appropriate for describing the isothermic sorption pattern for all egg flour tested. This model can be used to predict optimal storage conditions for egg flour.**

***Keywords*— Isotermic sorption curves, equilibrium of moisture content, egg flour**

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I. INTRODUCTION

Egg flour provides many advantages, such as practical use, extended shelf life, and smaller volume of ingredients to save space, reduce storage and transportation costs, and maintain important nutritional values [1]. Egg flour is a product derived from eggs essential in the food industry as a binder, emulsifier, and nutritional enhancer in various food products [2]. Egg flour can be made by drying it. Drying is a preservation method that removes the water content of food. The egg drying process consists of several methods, including the oven and vacuum methods [3], [4]

Several factors can influence the final quality of the dried product. This includes handling methods, sanitation practices, conditions during processing (temperature, pressure, pH, time, and moisture content), pasteurization procedures, type of drying, and conditions in which dried egg products are stored [5], [6]. These changes usually occur over time and are influenced by storage temperature, relative humidity, and water activity (aw) [7].

The water absorption or desorption rate from a food product depends on the water vapor pressure present in the food sample and its surroundings. Biological materials at constant moisture content and temperature exhibit typical vapor pressures and tend to approach equilibrium with the surrounding gases' temperature and atmospheric vapor pressure. To reach this equilibrium, the material will either absorb water vapor from the environment or lose water vapor to the environment, depending on whether the surrounding vapor pressure is higher or lower than the vapor pressure of the material. The process of absorbing water vapor from the environment is called adsorption, and the process of releasing water vapor to the environment is called desorption. The moisture content at which the water vapor pressure in the food is equal to the surrounding vapor pressure is referred to as the equilibrium moisture content (EMC) [8], [9]. Isothermic sorption is usually presented as a curve that describes the relationship between the moisture content in a food ingredient and the water activity at a specific temperature. Isothermic sorption curves can explain food ingredients' hydration properties, especially their ability to absorb water from the surrounding air and release some of the water they contain [10].

In the field of food technology, understanding and knowledge of isothermic sorption is very important for designing and optimizing drying equipment, packaging design, quality prediction, storage life, and calculating moisture changes that may occur during storage [11]. Equilibrium moisture content is closely related to the phenomenon of water absorption isotherm, which is obtained by involving temperature and relative humidity factors. According to [12], the equilibrium water content can also be used to describe isothermic sorption properties.

Several equation models are quite good and commonly used in research to obtain information on the isothermic sorption curve, such as the Oswin, Chung-Pfost, Caurie, and Helsey models, which are quite good and commonly used in research. The characteristics of the isothermic sorption curve for egg flour are exciting and relevant to research in food product development. Knowledge of the relationship between moisture content and water activity is crucial for understanding egg flour's physical and chemical properties, determining optimal storage conditions, and avoiding damage or degradation of the product during storage. Therefore, this research evaluates the characteristics of isothermic sorption curves and determines the appropriate equation model to describe the isothermic sorption curves of various egg flours stored at 30ºC with different humidity levels. This model can predict the optimal storage conditions for egg flour.

II. MATERIAL AND METHODS

A. Material

The materials used are chicken eggs, saturated salt solutions ($NaOH$, $MgCl_2$, K_2CO_3, $NaNO_2$, $NaCl$, and KCL). The instruments used are ohmic heating, incubator, desiccator, digital scales, aluminum foil container and 80 mesh sieve.

B. Methods

The procedure in this research consisted of three parts: preparing egg flour samples, creating an isothermic sorption curve, and determining the best model.

Preparation of egg powder samples

Chicken eggs with cracked/broken shells in the cage (the day after harvest) are separated based on their components, namely egg white, yolk, and whole (yellow and white), using an egg separator. Each egg component is collected in a container and homogenized using a mixer (Philips hand mixer) at a minimum speed for 1 minute. The liquid eggs are pasteurized by ohmic heating at 60°C for 5 minutes. After pasteurization, it is continued with different drying methods, namely using an oven at 45^0C for 10 hours and vacuum drying at 45^0C for 14 hours. After drying, sieving was carried out using an 80 mesh sieve.

Determination of Isothermic Sorption Curve Patterns

To adjust the RH of the desiccator, a saturated salt solution is used to determine the isothermic sorption curve with the following steps:

a. Determination of Equilibrium Water Content

Saturated salt solutions are used to determine isothermic sorption curves to change the RH or specific water activity (a_w). Five types of saturated salt solutions were prepared to obtain an equilibrium water activity or RH range of 10%-80%, namely $NaOH$, $MgCl_2$, K_2CO_3, $NaNO_2$, $NaCl$, and KCL.

TABLE 1
RELATIVE HUMIDITY AND WATER ACTIVITY VALUES SATURATED SALT SOLUTION

Salt solutions	Relative humidity (%RH)	Water activity (a_W)
Sodium hydroxide ($NaOH$)	10	0.10
Magnesium chloride ($MgCl_2$)	37	0.37
Potassium carbonate (K_2CO_3)	39	0.39
Sodium nitrite ($NaNO_2$)	66	0.66
Sodium chloride ($NaCl$)	75	0.75
Potassium chloride (KCl)	80	0.80

Research samples of three grams were prepared in aluminum foil containers and then put into each desiccator containing saturated salt at a temperature of 30^0C. The desiccator is put into the incubator. The samples were weighed and declared constant (sample weight showed a difference of less than 2%) for two consecutive weighings

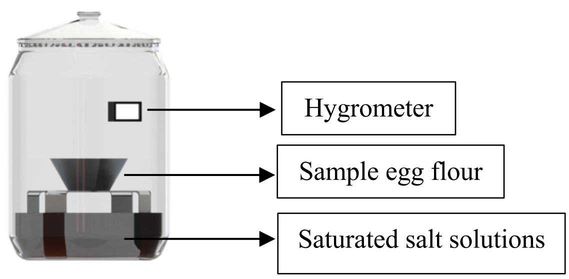


Fig. 1. A desiccator containing a saturated salt solution

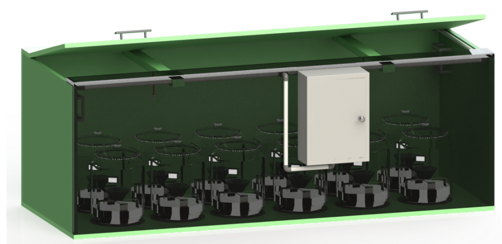


Fig. 2. Storage of egg powder samples in an incubator

Each sample that has reached a constant weight is then measured for its moisture content using the oven method at a temperature of 105^0C for 24 hours, expressed on a dry basis. This moisture content is the equilibrium moisture content at a specific RH. The equilibrium moisture content value will be plotted with the water activity value (a_w) to obtain an isothermic sorption curve. The research was carried out with three repetitions.

b. Determination of Isothermic Sorption Model

Several isothermic sorption equation models chosen for use on foodstuffs are the Oswin, Chung-Pfost, Caurie, and Halsey models. The equations for each model are:

Oswin :

$$Me = A\left[\frac{a_w}{1-a_w}\right]^B \quad \text{eq.(1)}$$

Chung and Pfost :

$$Me = A\, ln\left(\frac{B}{\ln a_w}\right) \quad \text{eq.(2)}$$

Caurie:

$$Me = \exp(A + B.a_w \quad \text{eq.(3)}$$

Helsey:

$$Me = \left(-\frac{A}{\ln a_w}\right)^{1/B} \quad \text{eq.(4)}$$

Where:

Me = equilibrium moisture content (%)
A,B = constant value
A_w = water activity

Test model constancy

The model accuracy test was carried out to determine which model could describe the overall isothermic sorption curve from the experiment. First, the values of the constants A and B for each equation are sought to test the accuracy of this model. The constants A and B values can be found using Microsoft Excel Solver. The solver calculates model constants by entering research data. The a_w values can be obtained from research that has been carried out. The constant values in the isothermic model being tested will be searched automatically by MS. Excel Solver produces the coefficient of determination (R^2) and Root Mean Squared Error (RMSE) values. The best model will create an RMSE value close to zero [13] and an R^2 value close to 1, indicating that the predicted and observed data have a reasonable correlation.

$$RMSE = \sqrt{\frac{\sum_{1=1}^{n}(Me - Me_{cal})^2}{n}} \quad \text{eq.(5)}$$

Where:

Me = experimental data
Me_{cal} = predicted data
n = amount of data

III. RESULT AND DISCUSSION

A. Equilibrium moisture content and isothermic sorption curves

To calculate the equilibrium moisture content in this study, the sample was placed in a desiccator containing a saturated salt solution with a constant relative humidity level. In addition, the temperature of the research environment was kept constant in the incubator for three weeks. The first weighing is carried out after storage for one week, and subsequent weighings are carried out periodically every week to ensure the material is in a constant condition.

TABLE 2
EQUILIBRIUM WATER CONTENT VALUES OF EGG FLOUR AT SEVERAL A_w VALUES

Sample	a_w	Initial moisture content (%w.b)	Wet basis moisture content (%)	Dry base moisture content (%)
Egg white flour (oven)	0.10	7.87	3.16	3.27
	0.37		8.52	9.33
	0.39		10.68	11.96
	0.66		12.47	14.25
	0.75		14.32	16.74
	0.80		16.61	19.93
Egg yolk flour (oven)	0.10	4.63	3.27	3.38
	0.37		6.42	6.87
	0.39		8.22	8.96
	0.66		10.76	12.06
	0.75		12.44	14.21
	0.80		14.70	17.24
Whole egg flour (oven)	0.10	4.79	3.54	3.68
	0.37		6.96	7.48
	0.39		8.59	9.40
	0.66		11.06	12.45
	0.75		12.79	14.66
	0.8		14.78	17.34
Egg white flour (vacuum)	0.10	7.80	5.01	4.11
	0.37		8.09	6.61
	0.39		10.93	9.33
	0.66		12.35	11.41
	0.75		14.29	15.24
	0.80		16.26	17.48
Egg yolk flour (vacuum)	0.10	4.57	3.66	3.81
	0.37		6.10	6.51
	0.39		8.56	9.37
	0.66		10.11	11.24
	0.75		13.00	14.95
	0.80		14.35	16.75
Whole egg flour (vacuum)	0.10	4.74	3.94	4.11
	0.37		6.20	6.61
	0.39		8.54	9.33
	0.66		10.24	11.41
	0.75		13.22	15.24
	0.80		14.88	17.48

Equilibrium moisture content is critical to determine whether the water content of a material increases or decreases under certain conditions. **Table 2** shows the equilibrium moisture content of egg flour at a water activity of 0.10-0.80. Under isothermic conditions, egg flour will undergo an adsorption and desorption process from the initial moisture content until the environmental conditions reach equilibrium. [10] say that during storage, water molecules will move from the environment into the product or from the product to the environment until a balanced humidity condition is achieved. Water vapor transfer is caused by relative humidity differences between environments and the product's water activity. [14] said that when a powder product is exposed to a certain relative humidity, it will experience an increase or decrease in water to adjust its humidity balance to environmental conditions.

Table 2 shows that if the water activity is low, then the moisture content in the material is also low, and vice versa; if the water activity is high, then the moisture content in the material is also high. The increase in moisture content occurs at a water activity of 0.37 to 0.80. This is in accordance with the research results of [10], where storage at RH ranging from 32% to 84% saw an increase in equilibrium water content, which was higher than the initial water content. The decrease in water content is due to the desorption process or release of water vapor from the product into the environment because the water activity in the product is higher than the environmental humidity. Meanwhile, the increase in moisture content is caused by the adsorption process or absorption of water vapor from the environment into the food because the environmental RH is higher than the product a_w.

The isothermic sorption curve pattern is created by relating the equilibrium moisture content to water activity. According to [15], the relationship between water activity (aw) and moisture content of food at constant temperature and pressure is described in sorption isotherms. Sorption isotherms describe how water interacts with food at specific environmental conditions. The oven-drying and vacuum-drying egg flour curves can be seen in **Figure 1** and **Figure 2**. The graph shows egg flour's isothermic sorption curve pattern at several water activity values. The higher the water activity value, the higher the equilibrium moisture content of the material. A high water activity value indicates a high relative humidity level around the material. This is in accordance with the opinion of [16] as the relative humidity increases, the water concentration in the air will also increase so that hygroscopic materials such as flour can absorb more water molecules in the air.

The curves produced in **Figure 3** and **Figure 4** are sigmoid in shape, where the curve is concave upwards (resembling an S shape), which reflects a type II pattern. Type II sorption isotherm curves have a sigmoid or S-shape. They reflect the presence of three main zones: monolayer, multilayer, and capillary condensation zones, which are usually found in carbohydrate- and protein-containing foods [17]. This type of curve is used to illustrate how food absorbs moisture at various relative humidity levels. The sigmoid shape of the curve indicates that the amount of water absorbed increases slowly at low relative humidity. However, at medium to high relative humidity, the amount of water absorbed increases rapidly before reaching a saturation point where water absorption slows down again [18]. The interactions between water molecules and components in the food, such as carbohydrates, proteins, and fats, strongly influence the moisture content of food. These interactions determine how water is bound in the food matrix and affect the physical and functional properties of the foodstuff. These interactions also play a role in determining food's water activity (aw), which is a critical factor in food's microbiological and chemical stability.

Water activity is affected by how water molecules interact with food components, affecting food products' shelf life and quality [19], [20]. This is in accordance with the research results of [2], where the isothermic sorption curve for egg flour is generally type II. Proteins follow type II behavior because proteins have plastic properties where the availability of all polar groups increases with increasing moisture content. This is supported by [21] who said that the isotherms most often found in food products are types II and IV. Type II often exhibits multilayer behavior and is usually associated with food products, which have strong interactions between water molecules and food components such as carbohydrates and proteins. Meanwhile, type IV exhibits multilayer behavior with the characteristic hysteresis in particular foodstuffs, such as gelatin products or products with more complex pore structures.

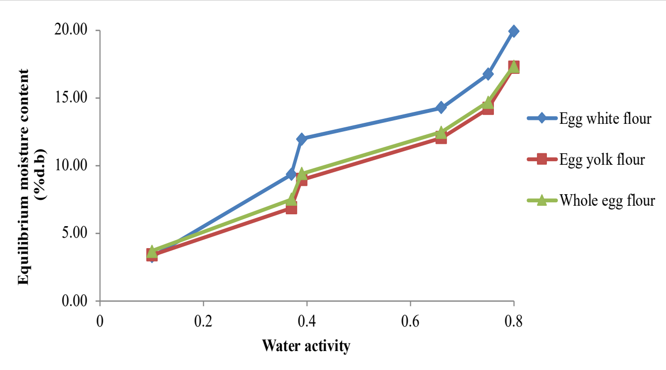


Fig. 3. Relationship between egg flour type and water activity and equilibrium moisture content in the oven drying method.

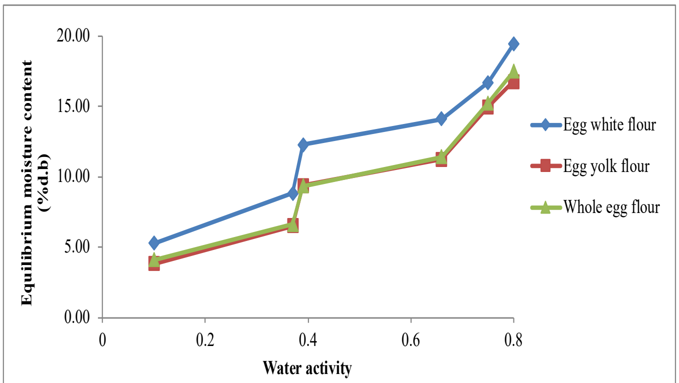


Fig. 4. Relationship between egg flour type and water activity and equilibrium moisture content in the vacuum drying method

B. Determination of the best model

This study evaluated four equation models: the Oswin model and the Chung-Pfost, Caurie, and Helsey models. This is supported by [14], who state that several semi-empirical equations with two or three parameters are suitable for describing water absorption isotherms. The most commonly used equations to describe food product absorption include the Oswin and Halsey models.

The results of the analysis of determining the isothermic sorption model are presented in **Table 3**. The constants A and B values in the mathematical model equation tested using Microsoft Excel Solver were obtained from experimental approaches from research data. Based on several models tested, the Oswin equation shows the most appropriate model to represent the behavior of equilibrium moisture content in all types of egg flour, both oven and vacuum drying, where R^2 ranges from 0.97-0.99 with RMSE values ranging from 0.61-1.09. [14], [22] stated that Oswin's equation is the best to describe starchy foods' isotherm. The model is used to predict the relationship between moisture content and water activity at various temperature and humidity conditions, which is particularly relevant in the storage and stability of starchy food products. This is supported research by [23] the Oswin equation is well suited to describe the sorption isotherm of rice flour. The Oswin equation gives a high coefficient of determination (R^2) value for rice flour of 0.95 and gelatinized rice flour of 0.99, which means that this model can accurately predict the relationship between moisture content and water activity for rice flour. Research results of [24] show that the Oswin equation is the most appropriate model to describe the behavior of Equilibrium Moisture Contents of konjac at a storage temperature of 30^0C

C. Implications for Storage

The study's significance lies in its contribution to the understanding and optimization of egg flour storage. Egg flour is a valuable ingredient in the food industry, and its quality and shelf life are highly dependent on storage conditions. The research findings provide valuable insights into how moisture content and water activity interact in different types of egg flour (egg white, egg yolk, and whole egg) under varying storage conditions.

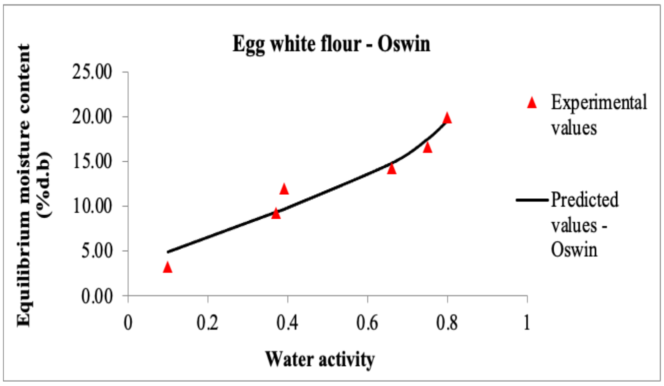
Specifically, the study identifies the Oswin equation model as the most suitable for predicting moisture sorption behavior in egg flour. This model allows for accurate prediction of the equilibrium moisture content at different relative humidity levels, which is crucial for determining optimal storage conditions. By understanding the relationship between moisture content and water activity, food manufacturers and processors can make informed decisions regarding packaging, storage temperature, and humidity control to prevent spoilage, maintain quality, and extend the shelf life of egg flour.

Furthermore, the study's findings have broader implications for the food industry as a whole. The principles and methodologies used in this research can be applied to other food powders and ingredients, contributing to a better understanding of moisture sorption phenomena and enabling the development of more effective preservation and storage strategies. This knowledge is essential for ensuring food safety, reducing food waste, and improving the overall efficiency and sustainability of food production and distribution systems.

TABLE 3
PARAMETERS FOR DETERMINING THE BEST ISOTHERMIC SORPTION MODEL FOR EGG FLOUR

Sample	Model	A	B	R^2	RMSE
Egg white flour (oven)	Oswin	11.48	0.38	0.98	1.09
	Chung-Pfost	6.48	4.33	0.97	1.23
	Caurie	1.54	1.77	0.96	1.55
	Halsey	66.48	1.91	0.96	1.53
Egg yolk flour (oven)	Oswin	9.33	0.42	0.99	0.67
	Chung-Pfost	5.64	3.97	0.97	0.76
	Caurie	1.24	1.95	0.98	0.87
	Halsey	30.82	1.74	0.99	0.80
Whole egg flour (oven)	Oswin	9.80	0.40	0.99	0.61
	Chung-Pfost	5.57	4.35	0.99	0.66
	Caurie	1.47	1.66	0.98	0.91
	Halsey	42.84	1.84	0.98	0.80
Egg white flour (vacuum)	Oswin	9.53	0.42	0.97	1.06
	Chung-Pfost	5.68	5.88	0.97	1.08
	Caurie	1.68	1.56	0.97	1.24
	Halsey	28.66	2.15	0.97	1.18
Egg yolk flour (vacuum)	Oswin	9.36	0.41	0.98	0.89
	Chung-Pfost	5.43	4.25	0.97	1.01
	Caurie	1.27	1.90	0.97	1.01
	Halsey	15.69	1.50	0.98	1.20
Whole egg flour (vacuum)	Oswin	9.53	0.42	0.98	0.89
	Chung-Pfost	5.58	4.22	0.97	1.09
	Caurie	1.27	1.94	0.98	1.00
	Halsey	16.10	1.49	0.98	1.11

The best isothermic sorption curve can be seen in **Figure 5** and **Figure 6**. The agreement between the research data results and the predicted data looks very good for water activity (0.1-0.8).



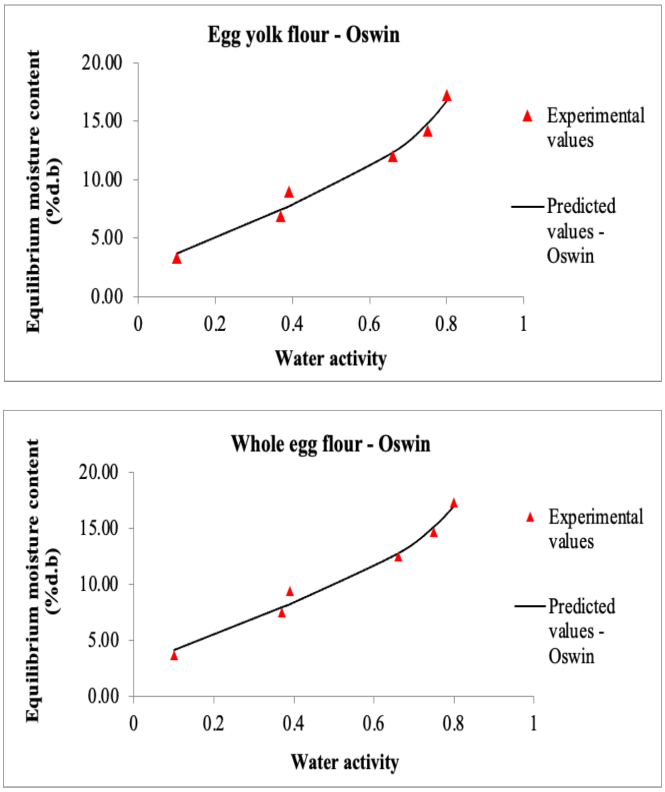
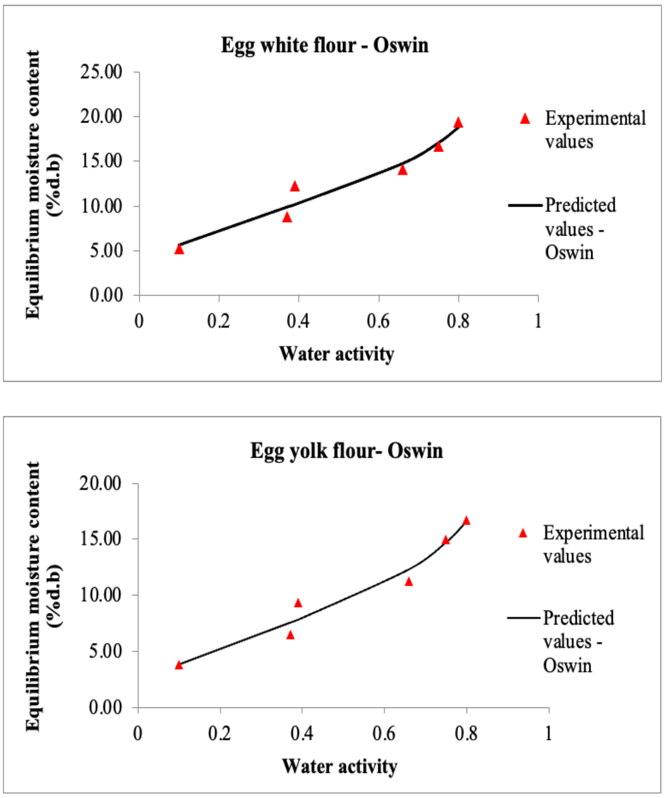


Fig. 5. Graph of the isothermic sorption curve of oven-drying egg flour based on the best model



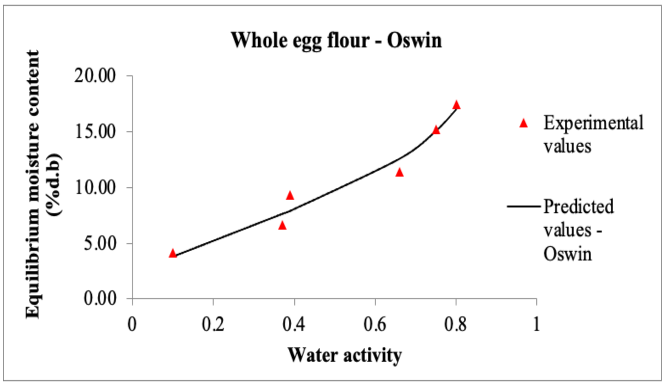


Fig. 6. Graph of the isothermic sorption curve of vacuum-drying egg flour based on the best model

IV. CONCLUSION

Isothermic sorption has an essential role in dry food storage due to its sensitivity to changes in humidity. The isothermic sorption curve of egg flour has a sigmoid absorption type, which reflects the Type II isothermic pattern. The Oswin model equation is the most appropriate model to describe the isothermic sorption water absorption pattern in all samples, namely egg white flour (oven and vacuum drying), egg yolk flour (oven and vacuum drying), and whole egg flour (oven and vacuum drying). Storage shows that the higher the RH value of the salt solution (10% - 80%), the higher the equilibrium moisture content value for all types of egg flour, both oven and vacuum dried.

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CONFLICT OF INTEREST

Authors declare no conflict of interest to disclose.

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