**Original Research Article**

**Moisture Sorption Isotherm (MSI) of Greek yogurt**

**ABSTRACT**

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| --- |
| **Aims:** In this study, Greek yogurt was investigated at 15°C, 25°C and 35°C using the gravimetric method.**Study design:** This research was experimental and performed in a laboratory.Place and Duration of study: The study was conducted at the Department of Dairy Engineering, College of Dairy Science, KU, Amreli, India from February 2023 to January 2025.**Methodology:** Four models (GAB, BET, Halsey and Caurie) were tested for predicting the sorption data, the best fit as indicated by % RMSE, %RE and R2 values. The Caurie equation was used to compute sorbed water properties.**Results:** The Moisture sorption isotherm (MSI) of Greek yogurt exhibited a sigmoid shape and was classified as Type II. The equilibrium moisture content increased gradually at the lower water activities followed by a steep rise at higher water activities. The BET monolayer decreased from 6.8 g of water /100g of solid at 15°C to 6.5 g of water /100g of solids at 35°C. The GAB monolayer decreased from 10.5 g of water /100g of solid at 15°C to 9.6 g of water /100g of solids at 25°C and further reduced to 9.1 g of water/100g of solids at 35°C. Caurie equation was used to determine the properties of sorbed water in Greek yogurt. The bound water in Greek yogurt decreased from 13.92 % at 15°C to 11.03% at 35°C.**Conclusion:** Among the Halsey, Caurie, BET and GAB models were tested, the GAB model was found to best fit the EMC range of 0.07-0.977 for Greek yogurt. |

*Keywords:* *Greek yogurt, BET, GAB, Halsey, Isotherm, Sorbed water*

1. **INTRODUCTION**

The relationship between equilibrium moisture content (EMC) and corresponding relative humidity (RH) at constant temperature was called moisture sorption isotherm (MSI). For a given material the EMC increases with relative humidity but decreases with an increase in temperature. Moisture sorption isotherms (MSI) of foods provide critical information that was used in predicting shelf-life. MSI was used to investigate structural features such as specific surface area, pore volume, pore size distribution and crystalline of food products (Rizvi, 1995). Static gravimetric method, the product in an atmosphere with which it then comes into equilibrium (weight loss or gain stops) without mechanical agitation of the air or product. Modeling of adsorption equilibrium data by moisture isotherm models was a widely used method of investigating sorption mechanisms (Wang and Guo, 2020). The phenomenon where the EMC during the adsorption and the desorption process is different is called ‘‘hysteresis.’’ Many research studies on the sorption isotherms of certain foods, temperature dependence of isotherms, determination of heat of sorption, and mathematical models to represent sorption isotherms have been reported in the literature (Ho et al., 2008). Moisture sorption isotherm of plain, concentrated, freeze-dried, and freeze-dried concentrated yogurts at 20, 35, and 50°C were used to calculate integral properties (Azuara and Beristain, 2006).

Moisture sorption characteristics of foods were often represented by moisture sorption isotherms (MSIs), which graphically express the relationship between water activity (or equilibrium relative humidity) values and corresponding moisture contents at certain temperatures (Aviara, 2020). Information on MSI of Shrikhand was reported in literature by Khojare (2018). Caurie models were two-parameter equations for defining sorption isotherms, which may be used to assess the characteristics of sorbed water. Guggenheim-Anderson-de Boer’ (GAB) equation was the three- parameter theoretical model in giving the best fit for food isotherms (Abdolshahi et al., 2020).

Greek yogurt is yogurt that has been strained to remove its whey, resulting in a thicker consistency than that of unstrained yogurt, while preserving yogurt's distinctive sour taste (Lange *et al.,* 2020). Because the sorption behavior of Greek yogurt is affected by the particle size and raw material properties, determination of the MSI of Greek yogurt was required. MSI concept was studied in dairy and food science, particularly in understanding how Greek yogurt's texture, shelf life, and other properties are affected by temperature. Hence our efforts were to study of moisture sorption isotherm of Greek yogurt at three different temperatures (15, 25, 35°C). To analyze with the help of different empirical models, quantify moisture sorption parameters and determination of sorbed water properties in Greek yogurt.

1. **MATERIAL AND METHODS**

**2.1 Location and Period of Study**

The present work was conducted at the Department of Dairy Engineering, College of Dairy Science, Kamdhenu University, Amreli, Gujarat, India from February 2023 to January 2025.

**2.2** **Chemical and Equipment**

The moisture sorption isotherms (MSI) of Greek yogurt were determined with the standard static-gravimetric method (Spiess and Wolf, 1983). Seven types of salts, namely, sodium hydro-oxide, potassium acetate, Magnesium chloride, Magnesium nitrate, Sodium chloride, Potassium chloride and Potassium sulfate will be taken for water activity (aw) range of 0.07 to 0.977. Wide mouth glass bottle (200 ml) with vapor-tight lid, weighing beaker (25 ml) and sample beaker (10 ml).

**2.3** **Methodology**

Greek yogurt was collected from the local market. 2.0 gram (g) samples were taken into the tare weight of each container, which was then transferred to the sorption container, containing saturated salt slurries. Compositional analysis of Greek yogurt was done as per the AOAC methods by IS: SP: 18 (Part XI). The Salt solutions with their corresponding ERH at three different temperatures, i.e., 15, 25 and 35°C were given in Table 1 (Greenspan, 1977). Three replications of the same experiment were carried out. The desiccators containing Greek yogurt samples were kept in incubators maintained thermostatically at 15, 25 and 35°C respectively.

**Table 1: Water activity (aw) values of the saturated salt solutions at three temperatures used in the experiments.**

|  |  |  |  |
| --- | --- | --- | --- |
| **S. No.** | **Salt Name** | **Chemical formula** | **Water activity (aw)** |
| **15°C** | **25°C** | **35°C** |
| 1 | Sodium hydro-oxide | NaOH | 0.075 | 0.072 | 0.070 |
| 2 | Potassium acetate | CH3COOK | 0.241 | 0.222 | 0.212 |
| 3 | Magnesium chloride | MgCl2 | 0.332 | 0.327 | 0.320 |
| 4 | Magnesium nitrate | Mg(NO3 )2 | 0.558 | 0.528 | 0.498 |
| 5 | Sodium chloride | NaCl | 0.755 | 0.751 | 0.747 |
| 6 | Potassium chloride | KCl | 0.858 | 0.842 | 0.827 |
| 7 | Potassium sulfate | K2SO4 | 0.977 | 0.972 | 0.967 |

The salts will be dissolved in distilled water to form a saturated solution. The level of saturated salt solution (slush) was kept at the bottom of each jar to a depth of about 0.5 cm. 2.0 gram (g) samples were taken into sample beakers, which were then transferred to the sorption container, containing saturated salt slurries. Samples will be weight at an interval of 72 h, till time when equilibrium is reached (two consecutive reading weights did not exceed 1 mg). The moisture content of each sample will be measured by oven method IS 2785(1979). At each water activity and temperature maintained, the equilibrium was carried out for about two weeks.

**2.3.1 Study of Mathematical models**

In the present study four mathematical models (Halsey, Caurie, BET and GAB) were used to fit the experimental data on moisture sorption Isotherm. The experimental EMC data were processed using the non-linear regression procedure (Hssaini *et al*., 2020). The sorption equations are shown in Table 2.

**Table 2: Equations describing the sorption equilibrium isotherm of Greek yogurt.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **SN.** | **Sorption model** | **Equations** | **Constants/Parameter** | **References** |
| 1. | Halsey | **M= Ch** $[\frac{-1}{ln\left(aw\right)}]^{b\_{h}}$Hasley plot of -1/lnaw vs. Mover aw range was used to obtain Hasley constants. | bh:Hasley parameter, Ch: Hasley constant | Halsey,1948 |
| 2. | Caurie |  $\frac{1}{M}$**=** $\frac{1}{Cc.Mc}$$[\frac{1-a\_{w}}{a\_{w}}]^{\frac{2Mc}{Cc}}$ln($\frac{1}{M}$)= -ln (Cc.Mc)+ $\frac{2Mc}{Cc}$ ln$ (\frac{1-a\_{w}}{a\_{w}}$ ) Caurie’s plot of ln[(1 – aw)/ aw] vs. ln(1/M) over the aw was used to obtain Caurie’s slope. | Mc : Caurie monolayer moisture content (db), Cc : Density of sorbed water | Caurie, 1981 |
| 3. | BET | M=$\frac{C\_{b}.M\_{b }}{(1-a\_{w})[1+\left(C\_{b}-1\right)a\_{w}]}$$\frac{a\_{w}}{M.(1-a\_{w})}$**=**$\frac{1}{C\_{b}.M\_{b }}+\frac{C\_{b}-1}{C\_{b}.M\_{b }}.a\_{w}$A plot of $\frac{a\_{w}}{M.(1-a\_{w})} $against $a\_{w} $used to obtain BET constants | Mb: the BET monolayer moisture content ( db), Cb: a surface heat constant | Brunaur et al., 1938 |
| 4. | GAB | **M=**$Mg\frac{Cg. k.aw}{(1-k.aw)(1-k.aw+Cg.k.aw)}$$\frac{a\_{w}}{M}$= A.aw2 +B.aw +CSolved by plotting aw/Magainst aw and fitting a polynomial of the second order to the plots. This yielded the following functionsA= $\frac{k}{Mg}$($\frac{1}{Cg}-1$), B= $\frac{Cg-2}{Mg Cg}$ and C= $\frac{1}{Mg.Cg.k}$ | Cg : GAB constant , Mg: GAB monolayer moisture content ( db), k: multilayer factor. | Van den Berg and Bruin, 1981 |

*M: moisture content (db), aw: Water activity*

**2.3.2 The study of water-binding mechanism and determination of sorbed water properties**

Caurie equation was used to estimate the properties of sorbed water for Greek yogurt at 15, 25 and 35°C. The number of adsorbed monolayer was obtained by the formulae (Caurie 1981):

$\frac{2C\_{c}}{M\_{c}}$ **= S =** $\frac{2}{Nm}$

Percent bound water is calculated using the Caurie monolayer water content (Mc) and the number of adsorbed monolayer’s (Nm).

**2.4 Statistical Analysis**

In order to ascertain the precision of fit of the sorption data in the model the coefficient of determination (R2), % relative error (% RE)and percent root mean square error (% RMSE). A model was considered acceptable if the RE values and RMSE values were below 10% and R2 values were higher than 0.95.

  **% RE =** $\frac{100}{N}$$\sum\_{i=1}^{N}(\frac{Mexp- Mcal}{Mcal } $**)**

 **% RMSE = 100**$√\sum\_{i=1}^{N}\frac{(Mexp- Mcal)^{2}}{N} $

Where:

Mexp : Experimental moisture content (db)

Mcal: Predicted moisture content (db)

N: Number of experimental data.

1. **RESULTS AND DISCUSSION**

**3.1 Proximate Composition of Greek Yogurt**

The proximate composition (mean± standard deviation) of Greek yogurt obtained for moisture, total fat, protein, carbohydrate and ash contents were 84.97± 0.09, 2.0±0.05, 7.17±0.24, 5.17±0.24 and 0.97 ±0.05 (% wb). The initial moisture content of the Greek yogurt was 565.30 ±0.09% (dry basis).

**3.2 Equilibrium Moisture Content (EMC) of Greek Yogurt**

 Equilibrium moisture content (EMC) of Greek yogurt at 15°C, 25°C and 35°C with corresponding water activity (aw) were shown in Table 3.

**Table 3: EMC of Greek yogurt with corresponding water activity at different temperatures**

|  |  |  |  |
| --- | --- | --- | --- |
| **Sr. No.** | **Salt Name** | **Water activity (aw)** | **Greek yogurt****Moisture content (% db)** |
| **15°C** | **25°C** | **35°C** | **15°C** | **25°C** | **35°C** |
| **1.** | Sodium hydro-oxide | 0.075 | 0.072 | 0.070 | 2.4 | 2.1 | 2.0 |
| **2.** | Potassium acetate | 0.241 | 0.222 | 0.212 | 3.8 | 3.5 | 3.0 |
| **3.** | Magnesium chloride | 0.332 | 0.327 | 0.320 | 4.9 | 4.5 | 3.9 |
| **4.** | Magnesium nitrate | 0.558 | 0.528 | 0.498 | 13.0 | 12.1 | 11.3 |
| **5.** | Sodium chloride | 0.755 | 0.751 | 0.747 | 26.8 | 25.1 | 24.0 |
| **6.** | Potassium chloride | 0.858 | 0.842 | 0.827 | 52.4 | 46.8 | 40.2 |
| **7.** | Potassium sulfate | 0.977 | 0.972 | 0.967 | 512.0 | 486.0 | 465.0 |

The MSI of Greek yogurt at 15°C, 25°C and 35°C was shown in Figure 1. The plots of moisture sorption isotherms of Greek yogurt exhibited the sigmoid shape and corresponded to type II behavior according to the BET classification, typical of the many sorption isotherms of food (Ho et al., 2008). Two bends were noted in each curve, which dividesthe Greek yogurt isotherm into three regions for all three temperatures. Each region indicates the specific state of moisture in foods. At very low moisture contents, the sorption isotherm curve was relatively flat, indicating that the Greek yogurt was not very sensitive to small changes in water activity. The initial moisture content of Greek yogurt was 565.30 ±0.09% (db); and this corresponds to water activities of 0.98. This implies that the product would lose moisture when stored at a relative humidity lower than 98 %.

The EMC increases gradually with an increase in water activities and temperatures. An increase in temperature at constant moisture content causes shifting of Greek yogurt isotherm curves on lower side which would lead to an increase in water activity, making Greek yogurt more susceptible to microbial spoilage. The equilibrium moisture content increases with decreasing temperature at constant aw. This phenomenon can be explained by the fact that the proteins and carbohydrates are known to have more water-binding capacity at low temperatures compared to high temperatures. This indicates that the powder became less hygroscopic at higher temperatures. Similar results have been reported in the literature for the sorption curve of yogurt powder (Azuara and Beristain, 2006)

**Figure 1: Typical moisture sorption isotherms of Greek yogurt samples at different temperatures**

**3.3 To Analyze Models and Generate Information to Quantify Greek Yogurt Moisture Sorption Parameters**

The BET, GAB, Halsey and Caurie models were tested to predict the moisture sorption data and to establish the sorption behavior of Greek yogurt (Figure 2-5). The BET, GAB, Halsey and Caurie models appeared to be suitable to describe the sorption relationship in Greek yogurt. From Table 5, it can be noted that the GAB, Halsey and Caurie equations gave a relatively good fit at 15°C, 25°C and 35°C with aw ranges (0.07- 0.977). BET model equations were a good fit at 15°C, 25°C and 35°C with aw ranges (0.07- 0.558) of Greek yogurt. The BET monolayer decreased from 6.8 g of water /100g of solid at 15°C to 6.5 g of water /100g of solids at 35°C.

 The GAB model was the best fit for the sorption data of Greek yogurt for the entire range of water activity. In GAB model, the value of K provides a measure of interactions between the molecules in the multilayer with the adsorbent, and it tends to fall between the energy value of the molecules in the monolayer and that of free water (Lavoyer et al., 2013). In GAB model, the k value for Greek yogurt decreased from 0.964 to 0.839 as the temperature increased from 15°C to 35°C. The results are in agreement with Kumar and Mishra (2006) for mango-soy-fortified yogurt powder. If K value is equal to 1, the multilayer have properties of liquid water and the sorption behavior could be modeled by the BET equation (Gabas et al., 2007). GAB constant (Cg) value was decreased with increasing temperatures, 0.25 (at 15°C) and 0.196 (at 35°C). The GAB monolayer content (Mg) decreased from 10.5 g of water /100g of solid at 15°C to 9.6 g of water /100g of solids at 25°C and further reduced to 9.1 g of water/100g of solids at 35°C. GAB monolayer moisture content (Mg) obtained by the GAB model was higher than that of BET model.

 The Caurie monolayer decreased from 5.8 g of water /100g of solid at 15°C to 4.9 g of water /100g of solids at 35°C. The Caurie monolayer values for Greek yogurt were significantly lower when compared to BET and GAB monolayer. Furthermore, the Halsey equation representing multilayer adsorption gave the best fit to the experimental data for Greek yogurt powder studied at different temperatures within a wide water activity.

**Figure 2: BET model to best fit experimental data for Greek yogurt at 15°C, 25°C and 35°C with aw ranges (0.07- 0.558).**

**Figure 3: GAB model to best fit experimental data for Greek yogurt at 15°C, 25°C and 35°C**

**Figure 4: Caurie model to best fit experimental data for Greek yogurt at 15°C, 25°C and 35°C**

**Figure 5: Halsey model to best fit experimental data for Greek yogurt at 15°C, 25°C and 35°C**

**3.4 Analysis Result of Different Models**

**Table 4: Variation of model equations and Coefficient of determination (R2) at three different temperatures.**

|  |  |  |  |
| --- | --- | --- | --- |
| **Model equations**  | **Temperature(°C)** | **Regression model**  | **Goodness of fit (R2)** |
| **BET** | 15°C | $\frac{a\_{w}}{M.(1-a\_{w})}$=$2.1832+13.088.a\_{w}$ | 0.988 |
| 25°C | $\frac{a\_{w}}{M.(1-a\_{w})}$=$2.685+12.228.a\_{w}$ | 0.997 |
| 35°C | $\frac{a\_{w}}{M.(1-a\_{w})}$=$3.2587+11.521.a\_{w}$ | 0.997 |
| **GAB** | 15°C | $\frac{a\_{w}}{M}$= -12.642.aw2 +10.132.aw +2.3476 | 0.991 |
| 25°C | $\frac{a\_{w}}{M}$= -12.499.aw2 +9.8757.aw +2.7102 | 0.995 |
| 35°C | $\frac{a\_{w}}{M}$= -12.077.aw2 +8.6202.aw +3.2327 | 0.995 |
| **Caurie** | 15°C | ln($\frac{1}{M}$)= 1.9359+ 0.8359.ln$ (\frac{1-a\_{w}}{a\_{w}}$ )  | 0.971 |
| 25°C | ln($\frac{1}{M}$)= 1.9566+ 0.8603.ln$ (\frac{1-a\_{w}}{a\_{w}}$ )  | 0.968 |
| 35°C | ln($\frac{1}{M}$)= 1.9940+ 0.8892. ln$ (\frac{1-a\_{w}}{a\_{w}}$ )  | 0.966 |
| **Halsey** | 15°C | M= 10.473 $[\frac{-1}{ln\left(aw\right)}]^{0.9101}$ | 0.994 |
| 25°C | M= 9.801 $[\frac{-1}{ln\left(aw\right)}]^{0.8682}$ | 0.992 |
| 35°C | M= 9.311 $[\frac{-1}{ln\left(aw\right)}]^{0.8252}$ | 0.990 |

**Table 5. Estimated Parameters of different isotherm equations fitted to sorption models for Greek yogurt at different temperatures.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model** | **Parameter** | **15°C** | **25°C** | **35°C** |
| **BET** | Mb | 0.068 | 0.067 | 0.065 |
| Cb | 6.995 | 5.554 | 4.535 |
| R2 | 0.988 | 0.997 | 0.997 |
| %RMSE | 0.30 | 0.12 | 0.10 |
| %RE | 3.99 | 2.16 | 1.88 |
| **GAB** | Cg | 0.250 | 0.218 | 0.196 |
| Mg | 0.105 | 0.096 | 0.091 |
| k | 0.964 | 0.954 | 0.839 |
| R2 | 0.991 | 0.995 | 0.995 |
| %RMSE | 1.26 | 1.26 | 0.71 |
| %RE | 3.51 | 3.34 | 2.79 |
| **Caurie** | Mc | 0.058 | 0.053 | 0.049 |
| Cc  | 0.735 | 0.724 | 0.697 |
| R2 | 0.971 | 0.968 | 0.966 |
| %RMSE | 6.41 | 4.35 | 3.25 |
| %RE | 6.84 | 4.64 | 4.00 |
| **Halsey** | Bh | 0.910 | 0.861 | 0.825 |
| ch | 10.473 | 9.802 | 9.311 |
| R2 | 0.994 | 0.992 | 0.990 |
| %RMSE | 4.43 | 4.25 | 4.74 |
| %RE | 6.47 | 6.84 | 8.78 |

The results of the nonlinear regression analysis of fitting the sorption equations to the experimental data are presented in Table 5. Variation of model equations and Coefficient of determination (R2) at three different temperatureswere shown in Table 4.The mean relative percentage deviation (%RE), %RMSE, and correlation of determination (R2) values were given in Table 5. The BET model gives the lowest % RE & % RMSE % value and high R2 value, indicating good fitness of curve in the water activity range 0.11–0.58.

It can be seen that the GAB equation (Table 5) gave the best fit to the experimental MSI data of Greek yogurt for a wide range of water activity (0.07–0.97). To confirm the GAB equation’s ability to predict the equilibrium moisture content data for Greek yogurt powder, RE (%) values at three temperatures were calculated and the results were found to be 3.51% at 15°C, 3.34% at 25°C, and 2.79 % at 35°C which was less than 5%.

**3.5 Properties of Sorbed Water**

Caurie model was used to estimate the properties of sorbed water for Greek yogurt at 15°C, 25°C and 35°C and values obtained were presented in Table 6. The properties of sorbed water are useful to understand the behavior of the moisture at different temperatures and also for shelf-life determination. The bound water in Greek yogurt decreased from 13.92 % at 15°C to 11.03% at 35°C. Similar trends were observed by Khojare (2018) in shrikhand at 20 and 30°C. However, the number of adsorbed monolayers decreased from 2.40 to 2.25 with an increase in temperature from 15°C at 35°C. .

**Table 6: Properties of sorbed water in Greek yogurt at different temperatures**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Temp(°C) | Mc(kg moisture / kg dry solid) | Caurie’s slope | No. of adsorbed monolayers (Nm) | Bound water (%) | R2 | %RE | %RMSE |
| 15 | 0.058 | 0.834 | 2.40 | 13.92 | 0.971 | 6.84 | 6.41 |
| 25 | 0.053 | 0.860 | 2.33 | 12.50 | 0.968 | 4.64 | 4.35 |
| 35 | 0.049 | 0.889 | 2.25 | 11.03 | 0.966 | 4.00 | 3.25 |

1. **CONCLUSION**

Moisture sorption Isotherm (MSI) curves for Greek yogurt exhibited a sigmoid shape and were described as type II. Two bends were noted in each curve, which divides the Greek yogurt isotherm into three regions for all three temperatures. The equilibrium moisture content (EMC) of Greek yogurt increased with an increase in water activity and decreased with increasing temperature. Among the four models viz., Halsey, Caurie, BET and GAB were tested over a water activity. The GAB model was found as the best fit for experimental sorption data in the Greek yogurt range of 0.07-0.977. The BET model was best fit over water activity range of 0.07-0.558. Caurie equation was used to determine the properties of sorbed water in Greek yogurt. Moisture sorption data generated will be useful for the selection of packaging material, drying conditions and process upgradation for Greek yogurt.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (Chat GPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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