



# Shelf life prediction of dried garlic powder under accelerated storage conditions

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**Abstract** The shelf life of dried garlic powder packaged in high-density polyethylene (HDPE), low-density polyethylene (LDPE), and aluminum laminated pouch (ALP) under accelerated storage temperature (5° to 40 °C) and humidity (70–90% RH) conditions, was predicted using GAB mathematical model. The water activity value reduced significantly from 0.83 to 0.31 as the moisture content reduced. The temperature had a negative effect on color change and the lightness value and whiteness index of garlic powder significantly decreased from 62.21 to 56.06 and 50.67 to 44.91 respectively, when temperature increased from 70° to 90° C. The storage life of garlic powder was 24, 78 and 210 days in LDPE, HDPE, and ALP, respectively under domestic storage conditions (40 °C, 90% RH). Therefore, under industrial storage conditions (5 °C, 70% RH), garlic could be preserved for 1.32, 4.30 and 7.28 years in LDPE, HDPE and ALP, respectively.

**Keywords** Hot air drying · HDPE · LDPE · ALP · GAB · Monolayer moisture content

## Abbreviations

HDPE High density polyethylene  
LDPE Low density polyethylene  
ALP Aluminum laminated pouch  
GAB Guggenheim–Anderson-de Boer  
RH Relative humidity  
l Length

b Breadth  
t Thickness  
mm Millimeter  
g Gram  
MR Moisture ratio  
 $M_t$  Moisture content on dry basis at any drying time  $t$   
 $M_{t+dt}$  Moisture content on dry basis at any drying time  $t + dt$   
 $M_o$  Initial moisture content of raw garlic  
 $M_e$  Equilibrium moisture content  
t Time  
 $R^2$  Coefficient of determination  
SSE Sum square error  
RMSE Root mean square error  
 $a_w$  Water activity  
d.b Dry basic  
 $M_{mo}$  Monolayer moisture content  
h Hue angle  
C Chroma  
 $\Delta E$  Total colour change  
BI Browning index  
WI Whiteness index  
 $W_g$  Dry weight of garlic powder  
 $l_g$  Length of package  
 $b_g$  Width of package  
 $k_g$  Permeability of packaging material  
 $R_{hg}$  Relative environment of storage environment  
 $P_w^*$  Water vapor saturation pressure  
 $T_p$  Storage temperature  
 $\theta_{gs}$  Periods of storage in days  
m Meter  
d Days  
 $M_{gi}$  Moisture content of the garlic powder  
 $M_{gc}$  Critical moisture content of garlic  
M Dry basis moisture content

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h Hour  
k Drying rate constant

## Introduction

Garlic (*Allium sativum* L.) has been used globally both as food and nutraceutical, dated back to 3000 B.C. Olden civilizations like Chinese, Indian, Egyptian, Babylonian, Roman, Greek, Phoenicians, and Viking use garlic for the treatment of wounds, skin diseases, headache, diarrhea, respiratory infections, ulcers, heart conditions, pulmonary complaints, tumors, symptoms of aging, abdominal growths and arthritis. Recent studies also show that bioactive compounds (allicin, selenium, superoxide dismutase and germanium) in garlic play major roles in its medicinal properties like antidiabetic, antimicrobial, antibiotic, antioxidant, anticancer, immune-boosting, antifibrinolytic and antiplatelet aggregatory activity (Santhosha et al. 2013; Kar and Sutar 2022). Garlic is a semi perishable product and microbial spoilage accounts for 30% loss of fresh garlic, which is induced by the lack of suitable storage and transportation facilities. Under a favourable environment, the sprouting of garlic occurs and it loses its nutritional properties (Kar et al. 2018). Therefore garlic bulbs are dried to make garlic powder. The storage of garlic powder at high temperature and humid condition results in fungal and mould growth and such storage conditions are unfavorable for garlic (Pitt and Hocking 2009). The quality of garlic during storage is dependent on moisture content and water activity (Ramesh et al. 2001; Topuz 2008). The chemical stability and shelf life of any food product can be determined from sorption isotherm, which depicts the relationship between moisture content and water activity and is useful in drying processes modeling, selection of packaging material and sorption enthalpy calculation (Labuza and Altunakar 2020; Fontana Jr and Carter 2020). Sorption isotherms have been proposed by many researchers in form of theoretical, semi-empirical and empirical models but Guggenheim–Anderson-de Boer (GAB) model is found to be more successful and is useful in the calculation of monolayer moisture content (Behera et al. 2017). Shelf life study is essential for food safety as well as consumers' high-quality experience (Tian et al. 2019). Along with water activity, packaging material (moisture and gas barrier properties) and packaging environment (vacuum packaging, modified atmosphere packaging) play a crucial role in the shelf life of food products (Singh et al. 2019). In India, garlic is subjected to various temperature and humidity conditions due to the unavailability of proper storage at farms and retail stores. Therefore it has a high chance of quality change during storage. Under each storage condition, finding the

shelf life of garlic powder by experiment is difficult. Thus, shelf life prediction can be a better solution to find out the shelf life of the product under any storage conditions. However, no literature study is available on shelf life study of dried garlic powder. Since different storage conditions accelerate different physical, chemical and microbiological changes in the product. The shelf life analysis helps to know what changes are likely to occur before testing. Properly conducted shelf life studies ensure that the product quality will be maintained throughout the product life-cycle and greatly reduce the chances of customer complaints related to quality. Hence, the present study was undertaken for shelf life prediction of garlic powder using sorption modeling at different storage conditions so that on an industrial scale, garlic powder storage and transportation will be benefited.

## Material and methods

### Raw material

Garlic bulbs (*Allium sativum*) of uniform size, colour, and without injury and infections were bought from a local market of Rourkela, Odisha (India) and were stored at room temperature ( $22 \pm 2$  °C) till further use. The initial moisture content of the product was determined (Sharma and Prasad 2006) and found to be 1.86–1.95 g water g<sup>-1</sup> dry matter. Garlic clove had 3 axis ( $l = 26.20 \pm 1.76$  mm,  $b = 11.60 \pm 1.63$  mm,  $t = 10.80 \pm 1.34$  mm). The weight of each garlic clove varied from  $0.93 \pm 0.2$  to  $0.43 \pm 0.4$  g, depending on their size.

### Hot air oven drying of garlic cloves

Garlic cloves were dried in a universal hot air oven at 60°, 70°, 80° and 90 °C at constant air velocities. The ambient air temperature and relative humidity varied from 10° to 25 °C and 40 to 65% relative humidity during drying experiments. 5 g of samples placed in one layer was used in each drying condition. The sample was taken out every 20 min during drying to calculate the weight loss data using a digital balance (SEC, India, with the precision of  $\pm 0.01$  g). The hot air oven temperature was set through an already existing temperature controller fitted to the oven and the set temperature was controlled throughout the experiments.

### Drying characterization

The moisture content data of garlic cloves at different temperatures during hot air oven heating were converted to moisture ratio using Eq. 1 (Akpınar et al. 2003) which is mentioned below:

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

From the moisture loss data, the drying rate was calculated by using Eq. 2 (Doymaz 2006)

$$Dryingrate = \frac{dM}{dt} = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

where MR refers to the moisture ratio, the moisture content on dry basic (g water g<sup>-1</sup> dry matter) of garlic at any drying time t and t + dt minutes are represented as M<sub>t</sub> and M<sub>t + dt</sub> respectively. M<sub>o</sub> refers to initial moisture content of raw garlic (g water g<sup>-1</sup> dry matter) and equilibrium moisture content (g water g<sup>-1</sup> dry matter) is represented as M<sub>e</sub> and is assumed to be 0.

### Modeling drying characteristics

The hot air oven drying data of garlic are fitted to the page model by using curve fitting tool MATLAB software (Ver-2021b, Math works, USA). The R<sup>2</sup> (coefficient of determination), SSE (sum square error) and RMSE (root mean square error) were determined to know the curve fitting quality (Doymaz 2005).

$$MR = e^{-kr^n} \tag{3}$$

### Effective moisture diffusivity estimation

Various moisture transport mechanisms like evaporation, condensation, surface diffusion, capillary flow, Knudsen diffusion are involved in the drying. All these processes contribute towards the moisture migration from inside to the surface of products during drying. The mass transfer process can be better explained by Fick’s second law of unsteady state diffusion. The garlic clove can be considered as a thin slab and the Fick’s second law for infinite series was applied to determine the diffusivity by using the following equation.

Where MR is moisture ratio, b = thickness of garlic cloves in m, t = time in second, and D<sub>e</sub> is effective moisture diffusivity.

$$\frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n + 1)^2} \exp\left(- (2n + 1)^2 \frac{\pi^2 D_e t}{4b^2}\right) \tag{4}$$

The above series terms become negligible for n = 2 or 3 as compared to n = 1 (1.37 × 10<sup>-5</sup>) thus the equation can be simplified to first term of series

$$MR = \frac{8}{\pi^2} \exp\left(- \frac{\pi^2 D_e t}{4b^2}\right) \tag{5}$$

$$\ln(MR) = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_e t}{4b^2} \tag{6}$$

### Measurement of water activity (a<sub>w</sub>) and modeling of sorption phenomena

The garlic procured from the market was subjected to hot air drying at 70 °C at 40% RH to bring the garlic moisture content down to 4.59, 6.18, 8.91, 10.06 and 17.52% d.b., respectively. The dried garlic cloves were powdered and kept in a water activity meter (Rotronic-HC2-Aw, Rotronic Measurement Solutions, and Switzerland) to measure the water activity. Brunauer, Emmett and Teller (BET) and Guggenheim, Anderson and De Boer (GAB), both the isotherm models have an extensive application to water sorption in food products. Both BET and GAB isotherms follow the same statistical model and are closely related but the BET model holds its application to a limited range of water activity (0.3–0.4) whereas the GAB model can apply to adsorption and desorption of foods over a wide range of water activities (Prothon and Ahrné 2004). The versatility of the GAB model is due to the introduction of a second well-differentiated sorption stage for water molecules as it considers water molecules inside the second and higher layers are the same as each other but different from that in the liquid state. This assumption introduces an additional degree of freedom (an additional constant, k) by which the GAB model gains its greater versatility (Timmermann et al. 2001). Therefore the GAB model was selected over the BET model. The monolayer moisture content of garlic powder was determined from the a<sub>w</sub> and equilibrium moisture content data by using the Guggenheim–Anderson–de Boer (GAB) model (Eq. 7).

$$M = \frac{M_{mo} C_g K_w a_w}{(1 - K_w a_w) \times (1 - K_w a_w + C_g K_w a_w)} \tag{7}$$

$$\frac{a_w}{M} = \frac{K_w}{M_{mo}} \left(\frac{1}{C_g} - 1\right) a_w^2 + \frac{1}{M_{mo}} \left(1 - \frac{2}{C_g}\right) a_w + \frac{1}{M_{mo} C_g K_w} \tag{8}$$

Substituting l<sub>1</sub>, l<sub>2</sub> and l<sub>3</sub> in place of  $\frac{K_w}{M_{mo}} \left(\frac{1}{C_g} - 1\right)$ ,  $\frac{1}{M_{mo}} \left(1 - \frac{2}{C_g}\right)$  and  $\frac{1}{M_{mo} C_g K_w}$  respectively in Eq. 8

$$\frac{a_w}{M} = l_1 a_w^2 + l_2 a_w + l_3 \tag{9}$$

By solving Eq. 9 we can get the K<sub>w</sub>, M<sub>mo</sub> and C<sub>g</sub> value

$$K_w = \frac{-l_2 + \sqrt{l_2^2 - 4l_1l_3}}{2l_3} \tag{10}$$

$$M_{mo} = \frac{1}{l_2 + 2l_3K_w} \tag{11}$$

$$C_g = \frac{1}{l_3M_{mo}K_m} \tag{12}$$

**Change in surface colour**

The color values ( $L^*$ ,  $a^*$  and  $b^*$ ) of dried garlic powder were determined by Hunterlab, Colorflex EZ, USA colorimeter. Hue angle, chroma, total colour change ( $\Delta E$ ), browning index (BI) and whiteness index (WI) were determined from the  $L^*$ ,  $a^*$ ,  $b^*$  values using Eqs. 13, 14, 15, 16 and 18, respectively. Lower  $\Delta E$  value represents better colour retention while BI is associated with enzymatic and non-enzymatic browning and WI is the indicator of whiteness and is related to consumers’ preferences towards white colour (Pathare et al. 2013).

$$\text{Hueangle}(h^\circ) = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{13}$$

$$\text{Chroma}(C) = \sqrt{(a^{*2} + b^{*2})} \tag{14}$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{15}$$

$$BI = \frac{[100(x - 0.31)]}{0.17} \tag{16}$$

$$\text{Where, } x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)} \tag{17}$$

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \tag{18}$$

where  $L_0^*$ ,  $a_0^*$  and  $b_0^*$  represents  $L^*$ ,  $a^*$  and  $b^*$  of raw garlic.

**Shelf life prediction of garlic powder under different storage conditions**

The shelf life of garlic powder was predicted at domestic and industrial storage conditions in high density polyethylene (HDPE), low density polyethylene (LDPE) and aluminum laminated packages (ALP). Generally, 40 °C temperature and 90% RH has been considered as the most unfavorable condition for storage in domestic conditions. Whereas industrial storage conditions vary in a wider range of temperatures and RH combinations (5°, 10°, 15°, and 20 °C with 70% RH) (Surkan et al. 2009; Perez-Galvez et al. 2009). For shelf life prediction of garlic, the initial moisture content can be assumed as the monolayer moisture, as garlic powder is most stable at monolayer moisture content.

The  $a_w$  more than 0.55 is considered as the upper limit for unaccepted change (Shirkole and Sutar 2018). Therefore critical moisture content of garlic powder was taken as 8.90% d.b. at 0.63  $a_w$ . Equation 19 expresses the change in moisture content of garlic ( $dM/d\theta_g$ ) during storage ( $\theta_g$ ) at temperature ( $T_p$ ).

$$W_g \frac{dM}{d\theta_g} = 2k_g b_g I_g (R_{hg} P_w^* - a_w P_w^*) \tag{19}$$

where  $W_g$  is garlic powder dry weight,  $R_{hg}$  refers to the storage environment’s relative humidity in fraction,  $k_g$  is the permeability of packaging material ( $\text{kg water m}^{-2} \text{d}^{-1} \text{Pa}^{-1}$ ),  $I_g$ ,  $b_g$  and  $2b_g I_g$  are length (m), width (m) and the package surface area ( $\text{m}^2$ ) respectively.  $M$  is dry basis moisture content in %,  $a_w$  refers to the water activity in fraction and  $\theta_{gs}$  refers to the periods of storage in days (d),  $T_p$  is the storage temperature (°C) and  $P_w^*$  refers to the water vapor saturation pressure ( $P_a$ ) at  $T_p$  (°C). The shelf life of garlic powder has been predicted by using Eq. 20.

$$\theta_{gs} = \int_{\theta}^{\theta_{gs}} d\theta_g = \frac{W_g}{2k_g b_g I_g P_w^*} \int_{M_{gi}}^{M_{gc}} \frac{dM}{R_{hg} - a_w} \tag{20}$$

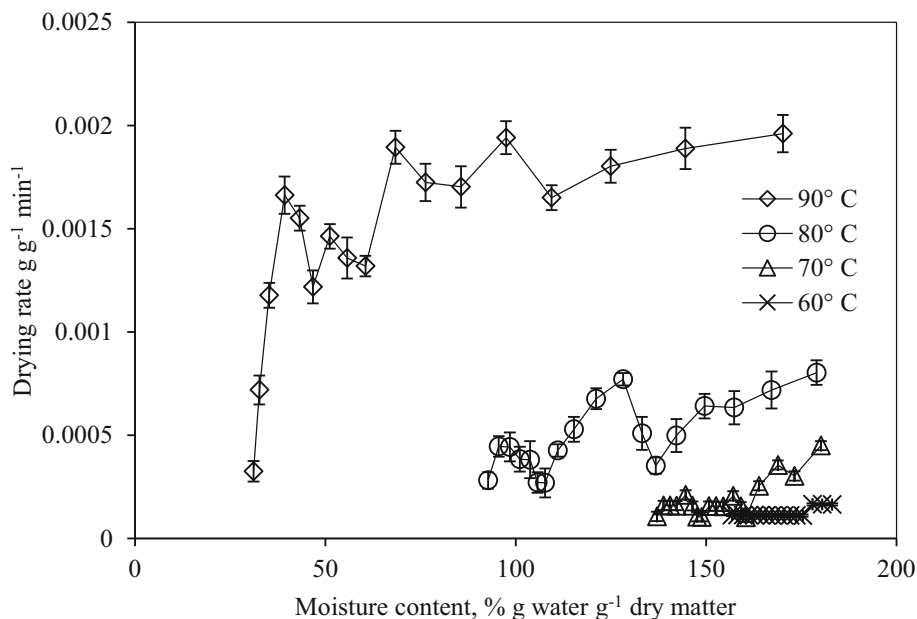
where  $\theta_{gs}$  is the garlic powder shelf life in days,  $M_{gi}$  and  $M_{gc}$  refers to the moisture content of the garlic powder and critical moisture content of garlic (% d.b.), respectively. The  $M_{gi}$  should be near to the monolayer moisture ( $M_{mo}$ ) of the product.

**Results and discussions**

**Effect of temperature on drying characteristics and its modeling**

The drying rate shows the variation in moisture content of the product with time under varying conditions. Figure 1 showed that initial drying rates were high and falls as moisture content decreased. The temperature profile of garlic during the hot air oven drying was found to be in 3 distinctive stages, stage I (warm-up period), stage II (rapid heating period), stage III (final isothermal stage). The temperature profile increased drastically in the rapid heating stage resulting from the large amount of thermal energy provided by the hot air oven under the high temperature difference between the hot air and the thin layer of garlic. Therefore initially drying rates were high due to high-temperature gradients along with the availability of more free moisture inside the product which led to a higher rate of moisture removal. Further, the specific heat capacity decreases with the decreasing moisture content, which could have led to initial rapid heating. After particular

**Fig. 1** Effect of temperature on drying rate

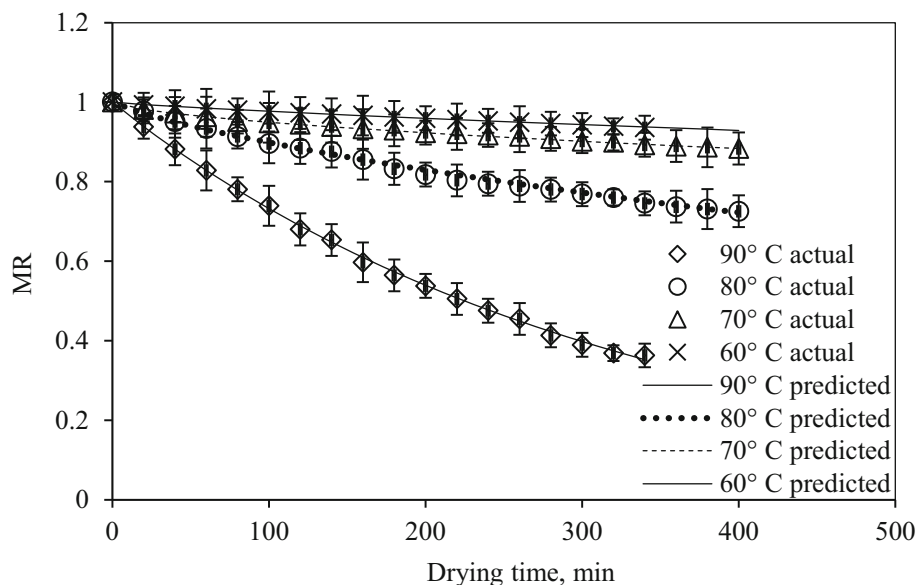


moisture content, the decrease in drying rate signifies the drying occurred at a falling rate period. It might be due to the isothermal stage appearing after a particular period of drying, where temperature gradient would have fallen with low availability of free moisture. Meanwhile, the drying rate increased drastically when the hot air oven temperature increased from 60 to 90 °C (Fig. 1). The increase in drying rate with the temperature was due to higher thermal energy provided at high temperatures, which is the key requirement for moisture evaporation. The moisture diffusivity at 90 °C varied from  $8.01 \times 10^{-10}$  to  $1.04 \times 10^{-9}$  m<sup>2</sup>/s and at 80 °C diffusivity value varied from  $2.21 \times 10^{-11}$  to  $9.67 \times 10^{-11}$ . The increase in temperature increased the

vapour pressure within the garlic thus helping in faster diffusion of moisture and higher drying rate at higher temperatures. Moisture ratio refers to the ratio of moisture amount remaining in garlic to the initial moisture content. Figure 2 shows the effect of temperature on moisture ratio. The drying time is taken to reduce the moisture content from 1.86 to 1.95 g water g<sup>-1</sup> dry matter to 0.06 g water g<sup>-1</sup> dry matter (approximately) was 8.5 and 28 h at 90 °C and 60 °C hot air oven temperature respectively.

Table 1 shows the page model constants. The drying data had a good fit to the page model as R<sup>2</sup> and RMSE values are in the range of 0.9991–0.9988 and 0.0064–0.0001 respectively. The drying rate constant

**Fig. 2** Effect of temperature on moisture ratio (predicted by Page model and actual)



**Table 1** Effect of temperature on page model constant, R<sup>2</sup>, SSE and RMSE value

Temperature °C	Page model constant				
	k	n	R <sup>2</sup>	SSE	RMSE
90	0.0033	0.9874	0.9991	0.0006	0.0064
80	0.0027	0.7997	0.9962	0.0001	0.0054
70	0.0028	0.6271	0.9967	0.0001	0.0019
60	0.0005	0.8340	0.9988	0.0001	0.0001

(k) reduced as the temperature decreased. In all the drying conditions, n value was less than 1 which showed sub diffusion phenomena during the drying process (Simpson et al. 2017).

**Effect of moisture content on a<sub>w</sub> and GAB constants estimation**

The water activity (a<sub>w</sub>) of the product is responsible for microbial activity and product stability during storage (Staack et al. 2008). Table 2 shows the a<sub>w</sub> within the experimental moisture content range (4.59–17.52% dry basic). The a<sub>w</sub> of garlic powder decreased from 0.83 to 0.31, with a decrease in moisture content. At constant temperature, the sorption isotherm shows a decrease in water activity with a decrease in moisture content. At low and intermediate moisture content the rise in water activity was linear due to multilayer sorption whereas, at higher moisture content, the water activity was more due to more availability of water because of capillary condensation (Goula et al. 2008). The correlation was developed between water activity and moisture content of garlic and is given in Eq. 21.

$$a_w = 0.243 + 0.036M(R^2 = 0.84) \tag{21}$$

Where a<sub>w</sub> refers to the garlic powder water activity infraction and M is the moisture content in % d.b. The plot of a<sub>w</sub>/M vs. a<sub>w</sub> is shown in Fig. 3. A second-order polynomial equation was fitted and the GAB model constants K<sub>w</sub>, M<sub>mo</sub>, and C<sub>g</sub> were determined using Eqs. 10, 11 and 12, respectively. The K<sub>w</sub>, M<sub>mo</sub>, and C<sub>g</sub> were found to be 0.975, 0.033 and 42.429.

$$\frac{a_w}{M} = -28.169a_w^2 + 28.193a_w + 0.7152(R^2 = 0.98) \tag{22}$$

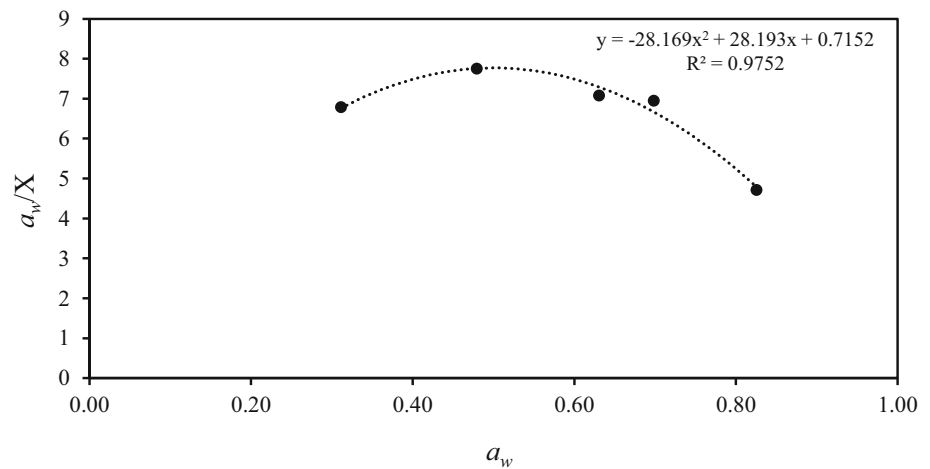
The GAB constants C<sub>g</sub> and K<sub>w</sub> are related to the heat of sorption of the first layer and total heat of sorption of multilayer respectively. K<sub>w</sub> represents the interaction in the multilayer between garlic and water vapour. The K<sub>w</sub> value for garlic was 0.975 at 70 °C. Shirkole et al. (2021) found

**Table 2** The physicochemical characteristics of garlic at different moisture content

MC % db	Physical characteristics, 70° C, 40% RH									
	a <sub>w</sub>	L*	a*	b*	C	h°	BI	WI	ΔE	
4.59	0.31 ± 0.002 <sup>a</sup>	61.32 ± 0.64 <sup>a</sup>	6.02 ± 0.56 <sup>a</sup>	19.55 ± 0.02 <sup>a</sup>	20.57 ± 0.02 <sup>a</sup>	72.37 ± 0.79 <sup>a</sup>	45.76 ± 0.37 <sup>a</sup>	56.51 ± 0.98 <sup>a</sup>	11.24 ± 0.65 <sup>d</sup>	
6.18	0.48 ± 0.004 <sup>b</sup>	62.33 ± 0.12 <sup>a</sup>	8.24 ± 0.01 <sup>c</sup>	30.55 ± 0.11 <sup>d</sup>	31.64 ± 0.10 <sup>d</sup>	74.89 ± 0.05 <sup>b</sup>	75.09 ± 0.21 <sup>d</sup>	50.79 ± 0.05 <sup>a</sup>	10.71 ± 0.05 <sup>c</sup>	
8.91	0.63 ± 0.004 <sup>c</sup>	62.83 ± 0.09 <sup>a</sup>	8.86 ± 0.32 <sup>b</sup>	30.86 ± 0.66 <sup>c</sup>	32.10 ± 0.72 <sup>c</sup>	73.97 ± 0.22 <sup>a</sup>	75.96 ± 2.21 <sup>c</sup>	50.87 ± 0.43 <sup>a</sup>	10.97 ± 0.48 <sup>b</sup>	
10.06	0.70 ± 0.003 <sup>d</sup>	63.01 ± 0.39 <sup>a</sup>	6.83 ± 0.12 <sup>a</sup>	27.30 ± 0.13 <sup>b</sup>	28.14 ± 0.14 <sup>b</sup>	75.95 ± 0.20 <sup>c</sup>	63.39 ± 0.79 <sup>b</sup>	53.52 ± 0.35 <sup>a</sup>	8.35 ± 0.36 <sup>a</sup>	
17.52	0.83 ± 0.005 <sup>e</sup>	65.57 ± 0.21 <sup>b</sup>	4.31 ± 0.29 <sup>a</sup>	17.73 ± 0.42 <sup>a</sup>	18.25 ± 0.38 <sup>a</sup>	77.05 ± 0.33 <sup>d</sup>	35.7 ± 0.88 <sup>a</sup>	61.03 ± 0.36 <sup>b</sup>	9.60 ± 0.34 <sup>a</sup>	
Temperature °C	Garlic powder at 6% d.b. moisture content									
	L*	a*	b*	C	h°	BI	WI	ΔE		
70	62.21 ± 0.09 <sup>b</sup>	8.26 ± 0.01 <sup>a</sup>	30.61 ± 0.11 <sup>b</sup>	31.70 ± 0.08 <sup>c</sup>	74.89 ± 0.05 <sup>a</sup>	83.68 ± 0.21 <sup>b</sup>	50.67 ± 0.05 <sup>c</sup>	10.80 ± 0.05 <sup>a</sup>		
80	56.93 ± 0.26 <sup>a</sup>	8.06 ± 0.13 <sup>a</sup>	26.95 ± 0.24 <sup>a</sup>	28.13 ± 0.27 <sup>a</sup>	79.17 ± 2.03 <sup>b</sup>	72.84 ± 1.36 <sup>a</sup>	48.55 ± 0.36 <sup>b</sup>	13.96 ± 0.31 <sup>b</sup>		
90	56.06 ± 0.13 <sup>a</sup>	11.6 ± 0.06 <sup>b</sup>	31.12 ± 0.08 <sup>c</sup>	33.22 ± 0.08 <sup>b</sup>	80.07 ± 2.42 <sup>c</sup>	93.10 ± 0.08 <sup>c</sup>	44.91 ± 0.05 <sup>a</sup>	17.42 ± 0.10 <sup>c</sup>		

Values are mean ± Standard deviation (n = 3) followed with different letter in the same column, differs significantly at a 5% level of significance

**Fig.3** Plot of change of  $a_w/M$  with respect to  $a_w$



out the increase in  $K_w$  value from 0.89 to 0.99 due to a rise in temperature of paprika from 30° to 60 °C. The higher  $K_w$  value in garlic shows the higher interactions of water molecules during desorption in the multilayer. The monolayer moisture content of 0.033 is near to the previously reported monolayer moisture content of garlic as 0.02–0.025 by (Mohammad et al. 1986). They reported caking of garlic powder above 9% moisture content (5 1.4% RH) and found it to be the critical point of garlic powder. The literature study shows for the prediction of shelf life the initial moisture content should be near to monolayer moisture content.

#### Effect of temperature and moisture content on surface colour change

The change in colour value at different moisture content during drying of garlic at 70° is presented in Table 2.  $L^*$  value decreased from 65.57 to 61.32 when the moisture content was reduced from 17.52 to 4.59% d.b. The  $L^*$ ,  $a^*$ , and  $b^*$  values of freshly crushed raw garlic slices were found to be  $69.06 \pm 3.65$ ,  $1.22 \pm 0.01$ , and  $26.10 \pm 0.004$ , respectively. Table 2 shows, the  $L^*$  value dropped significantly ( $p < 0.05$ ) whereas  $a^*$  and  $b^*$  increased significantly ( $p < 0.05$ ) due to decrease in moisture content. As  $L^*$  was the indicator of lightness, the fall in  $L^*$  value due to decrease in moisture content led to the darkening of the product during dehydration. Below 6% moisture content, the redness ( $a^*$ ) and yellowness ( $b^*$ ) values fall after rising to a maximum value of 8.86 and 30.86 at 8.91% d.b. respectively. This shows the destruction of red and yellow pigment due to long time exposure at high temperature (70 °C). Table 2 showed the decrease in  $L^*$  value from  $62.21 \pm 0.09$  to  $56.06 \pm 0.13$  with an increase in the temperature from 70 to 90 °C. This implied more darkening of garlic powder due to increase in temperature and/or time. It is similar to the study reported by

Sharma and Prasad (2001). Chroma determines the intensity of colour perceived by humans. The chroma value and hue angle increased with an increase in temperature from 70 to 90 °C which shows higher temperature saturated the colour of the product during drying.

#### Effect of temperature and moisture content on the browning index, whiteness index and total colour change

Browning index indicates the purity of brown colour in the food product and measures the browning of food product containing sugar due to Maillard reactions between sugar and amino acids. The low BI value indicates lesser browning and higher BI value shows higher browning. BI value increased significantly ( $p < 0.05$ ) from 35.79 to 45.76, as the moisture content decreased during the experiment and shown in Table 2. The dried garlic powder obtained at 90 °C showed the highest browning index value of  $93.10 \pm 0.08$ . Higher oven temperature accelerated the Maillard reaction and oxidation of ascorbic acid thus resulting in the browning of the product. The BI was also related to redness value and showed similar trends for both BI and  $a^*$  value. It can be observed from Table 2 that higher hot air oven temperature resulted in severe colour damage to the dried garlic. Whiteness index (WI) refers to the degree of whiteness on a scale from 0 to 100 and is mainly associated with the colour preferences of consumers towards white. Mathematically it combines lightness and yellow–blueness into a single term. The whiteness value was high at 17.52% d.b. moisture content and reduced significantly ( $p < 0.05$ ) as the moisture content decreased. Table 2 shows the negative effect of temperature on the whiteness of the product. The results of WI value showed that the visual quality of garlic was deteriorated due to high temperature exposure during drying. The total colour change ( $\Delta E$ ) was calculated to characterize the

total colour change during processing compared to the initial colour values of raw garlic. It can be shown from Table 2 that ΔE value was more at low moisture content and higher temperature operations which shows the overall colour degradation of the product.

**Shelf life prediction of garlic powder under different storage conditions**

Garlic cloves containing 6% moisture content d.b. has been selected for making garlic powder as the colour analysis showed excellent results at 6% d.b. moisture content. The shelf life of garlic powder was predicted using Eq. 20. For predicting the shelf life of garlic powder, the monolayer moisture content of garlic was determined by using the GAB model and it was found to be 3.3% d.b. Drying till monolayer moisture content can enhance the shelf life of any product but it is not advisable to go till monolayer moisture content as the colour of the garlic powder colour was darkened with a further decrease in moisture content from 6% d.b. Therefore garlic having 6% d.b. (near to  $M_{mo}$ ) moisture content was chosen as shelf life prediction as the water activity was low and colour value was good. The packaging materials like HDPE, LDPE and ALP were chosen for shelf life prediction. The surface area of the pouch has been taken as 0.02 m<sup>2</sup>. The water vapor permeability of ALP, LDPE and HDPE were  $6.14 \times 10^{-12}$ ,  $3.38 \times 10^{-11}$  and  $1.04 \times 10^{-11}$  kg water m<sup>-2</sup> s<sup>-1</sup> Pa<sup>-1</sup>, respectively (Patel and Sutar 2016; Jena and Das 2012). 70 g of garlic powder could be kept in a pouch from which 65.80 g was the dry solid mass. The shelf life of garlic will be minimum during domestic storage (40 °C and 90% RH) condition and the shelf life of garlic having 6.0% d.b. moisture content was found to be 2.61, 0.8 and 7.02 months when stored in HDPE, LDPE and ALP packages, respectively. In industries 5°, 10°, 15°, 20 °C temperature and 70% RH is usually adopted for storage. The shelf life of garlic at 5 °C temperature and 70% RH was found to be 1.32, 4.30 and 7.28 years in LDPE, HDPE

and ALP packages, respectively. The predicted shelf life under different storage conditions has been depicted in Table 3.

Under accelerated storage conditions, there was a significant difference ( $p < 0.05$ ) in the water activity of the garlic powder after the first month in all types of packages. The rise in water activity of the product was because of the moisture migration through the packaging material. The water activity of garlic powder stored in HDPE and LDPE at 40 °C temperature and 90% RH has been estimated at different intervals within the predicted shelf life period, and the water activity was found to be less than 0.5, which proved that the model predicted the shelf life precisely. Shelf life of garlic powder at all storage conditions could not be validated as the time requirement will be too high.

**Conclusions**

Moisture migration and GAB model were found suitable for shelf life prediction of dried garlic powder under various storage conditions. The garlic shelf life can be extended by storing the garlic at monolayer moisture content at low temperatures. The water activity decreased significantly by lowering the moisture content from 17.52 to 4.59 (% d.b.). Colour characteristics ( $L^*$ ,  $a^*$ ,  $b^*$ , chroma, hue angle and ΔE) deteriorated with an increase in temperature and decrease in moisture content. Garlic powder can be stored up to 1–5 years at 5 °C temperature and 70% RH in HDPE, LDPE and ALP. Garlic can be stored in ALP for a longer duration as the water vapor permeability of ALP was lower than HDPE and LDPE. This research study can be useful in shelf life prediction of dried garlic powder under different industrial and domestic storage conditions.

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**Availability of data and material** All data generated or analyzed during this study are included in the manuscript.

**Code availability** Not Applicable.

**Table 3** Predicted shelf life data of garlic cloves at different storage and packaging conditions

Storage conditions		Shelf life, months		
T (°C)	RH (%)	HDPE	LDPE	ALP
40	90	2.61	0.80	7.02
30	70	10.59	3.26	17.94
20	70	19.23	5.91	32.56
15	70	26.39	8.12	44.69
10	70	36.68	11.28	62.11
5	70	51.61	15.88	87.39



## Declarations

**Conflict of interest** We have acknowledged the funding agency as well as all authors involved in the research work has been incorporated in the authors section. We declare no conflict of interest.

**Consent to participate** The submission of manuscript to JFST publication has been approved by all authors.

**Consent for publication** I, the undersigned, give my consent for the publication of the manuscript to be published in the above Journal and Article. I have discussed this consent form with P.P Sutar, who is an author of this paper.

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