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Behaviour of physicochemical properties of foam mat dried acerola powder during drying process and storage

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Abstract:

Acerola is a rich source of vitamin C. However, the fruit is highly perishable after harvest. One widely adopted technique for extending the shelf life of fresh fruit and producing new products is dehydration. This study aimed to investigate the effects of drying temperatures (55, 65, and 75°C) and storage conditions (e.g., relative humidity and temperature) on the characteristics (moisture content, polyphenols, vitamin C) of acerola powder. The results indicated that a drying temperature of 75°C produced powder with the highest solubility (75.89%), vitamin C content (2571.56 mg/100 g dry matter (DM)), and total phenolic content (2245.36 mg GAE/100 g DM). The sorption isotherm curve of the acerola powder was described by the equation $y=3.4687e^{0.0244x}$. Moreover, under all storage conditions (e.g., 4-6°C and room temperature), the powder's water activity did not exceed 0.6. The degradation of vitamin C and polyphenols during storage followed the Arrhenius equation and first-order kinetics. These attributes exhibited z-values of 208.33 and 48.54°C, respectively, with activation energies of 8.03 and 34.71 kJ/mol. Low storage temperatures effectively reduced the loss of vitamin C and polyphenols. The findings suggest that acerola powder can serve as a valuable supplement to enhance food products with bioactive compounds.

Keywords: **acerola powder, bioactive compound, drying temperature, foam-mat drying, storage.**

Classification numbers: **3.4, 3.5**

1. Introduction

Malpighia glabra L., commonly referred to as acerola or sơ ri (Vietnamese name), belongs to the *Malpighiaceae* family. Several studies have identified acerola fruit as an excellent source of bioactive compounds such as vitamin C and polyphenols, making it a promising dietary ingredient for health benefits [1]. However, acerola has a short shelf life due to continued respiration after harvest and ethylene production, which accelerates ripening and perishability if not consumed promptly [2].

Producing value-added products from raw materials offers a sustainable solution to this issue. Dehydration is a widely employed method to extend the shelf life of fresh fruit and create new products. During dehydration, water is gradually removed from the material until it reaches a safe level, typically with water activity below 0.6. This water reduction reduces transportation costs, inhibits microbial and chemical reactions, and enables dried products to be stored at room temperature. Fruit powder, a common dried food product, is ideal for industrial applications as a key ingredient in beverages, confectionery, dairy products, bakery items, and food supplements [3].

Foam-mat drying is one of the most commonly used techniques for producing fruit powder. This method involves whipping liquid or semi-liquid material into foam, spreading it into a thin mat, and drying it using freeze drying, hot air drying, or microwaves. Advantages of this method include simplicity, cost-effectiveness, rapid drying rates, and the resultant powder's excellent rehydration properties [4]. Many studies have been conducted globally to develop foam-mat-dried powders from fruits such as blueberries [5], tamarinds [6], and mangoes [7]. However, there has been limited investigation into the dehydration conditions of acerola and the degradation kinetics of its bioactive compounds in foamed fruit powders.

According to existing reports, the quality of fruit powders is strongly influenced by drying and storage conditions. Therefore, the objective of this study was to examine the effects of drying temperatures on the physicochemical properties of acerola powder. Additionally, this study aimed to determine optimal storage conditions for maintaining the quality of acerola powder.

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2. Materials and methods

2.1. Materials

Sour acerola fruits (*Malpighia glabra* L.) were procured from a farm in Go Cong town, Tien Giang province, Vietnam, and transported to the laboratory within one day. The selected fruits were bright red, undamaged, and free from mould. The fruit characteristics included a moisture content of 91%, a total soluble solid content averaging 7.9%, and an acidity content averaging 0.76%. After sorting, the fresh fruits were washed, drained, and packed in zip-lock bags before being frozen at -18°C for subsequent studies.

Maltodextrin (DE 15) was supplied by Qinhuangdao Lihua Starch Co., Ltd. (China), and hydroxypropyl methylcellulose (HPMC) was obtained from Luzhou North Chemical Industries Co., Ltd. (China).

The chemicals used in this study included iodine, gallic acid (99%), and Folin-Ciocalteu reagent (99.5%) from Merck (Germany); sodium carbonate (Na_2CO_3, 98%), soluble starch, and potassium iodide (KI) from Guangdong (China); and other reagents such as hydrochloric acid (HCl, 38%), magnesium nitrate ($Mg(NO_3)_2$), sodium chloride (NaCl), sodium hydroxide (NaOH), potassium acetate (CH_3COOK), potassium chloride (KCl) from Xi Long (China), and methanol (CH_3OH) from Chemsol (Vietnam).

2.2. Experimental design

2.2.1. Effect of drying temperature

Maltodextrin and derived cellulose were selected as food additives for powder production due to their solubility, cost-effectiveness, and allergen-free properties [4]. Drying temperatures between 50 and 80°C are frequently employed for fruits due to their efficiency in the drying process [4].

After thawing, acerola fruits were crushed using a kitchen juicer (Philips HR 1861, China). The puree (100 g) was mixed with 8% maltodextrin and 0.75% hydroxypropyl methylcellulose. The mixture was whipped for five minutes at maximum speed using a hand mixer (MX-SS1BRA, Panasonic, China). The foamed acerola puree samples were evenly spread over a mould (dimensions: 20 cm×15 cm) to a thickness of 3 mm. The foam was dried in a hot air dryer (Inox 304 VN 10K hot-air dryer, Vien Dong, Vietnam) at 55, 65, and 75°C until it achieved a moisture content below 5%.

The dried samples were processed into powder using a kitchen blender (HR2115, Philips, China). The resulting powder was packaged in laminated aluminum, sealed, and stored at -18°C for further analysis. The powder samples were evaluated for moisture content, solubility, total soluble solids, total acidity, vitamin C content, and total phenolic content. Each experiment was conducted in triplicate.

2.2.2. Determination of water sorption isotherm of acerola powder

Saturated solutions of sodium hydroxide (NaOH), potassium acetate (CH_3COOK), magnesium nitrate ($Mg(NO_3)_2$), sodium chloride (NaCl), and potassium chloride (KCl) were prepared to establish environments with relative humidity (RH) values of 10, 23, 57, 76, and 84%, respectively. A beaker containing 100 ml of the saturated solution was placed in desiccators and left for 24 hours to equilibrate.

Acerola powder samples (2 g) were spread on petri dishes and placed in the desiccators. The samples were stored in dark conditions at room temperature (29±2°C) until equilibrium was reached. The samples were analysed for water activity, moisture content, vitamin C content, and total phenolic content following the methodology outlined by T.C. Kha, et al. (2021) [8].

2.2.3. Effect of storage temperature on the physicochemical characteristics of acerola powder

Acerola powder (10 g) was packaged in laminated aluminium bags, sealed, and stored at various temperatures: 4-6°C (using a refrigerant, MGM105522F/MRL, Mantova, Italy), 29-31°C (room temperature), and 40°C (using an incubator, Memmert UF110, Germany).

The initial values of the samples taken at the start of the storage period served as the standard reference. During the 30-day storage period, samples were taken every five days and evaluated for water activity, moisture content, vitamin C content, and total phenolic content.

2.3. Analytical methods

2.3.1. Moisture content

Moisture content (MC) was determined by drying samples in an oven (Memmert UM200, Atmosafe, Germany) at 105°C until the weight remained constant. The dried samples were placed in a desiccator for 20 minutes, and their final weight was recorded. Moisture content was calculated using the following formula:

$$MC = \frac{m_1 - m_2}{m_1} \times 100\ (\%)$$

where MC is the moisture content (%); m_1 is the sample weight before drying (g); m_2 is the sample weight after drying (g).

2.3.2. Water activity (a_w)

The water activity of the powder was determined using an Aqualab Series 3 instrument (Decagon Devices, USA). Acerola powder was added to the sample cup, filling it halfway before measurements were taken.

2.3.3. Total soluble solids

Total soluble solids (TSS) in the powder were measured on the Brix scale using a hand refractometer (HRN 32, Krüss, Germany). One gram of acerola powder was reconstituted in 10 ml of distilled water. A few drops of the solution were placed on the refractometer's glass prism, covered with the plate, and the reading was recorded at the demarcation line.

2.3.4. Total acidity

The acidity of the powder was determined via titration with 0.1 N sodium hydroxide (NaOH), using 1% (w/v) phenolphthalein as the indicator.

2.3.5. Water solubility index

The water solubility index of acerola powder was measured following the procedure described by H. Do, et al. (2018) [9], with minor modifications.

Samples (1 g) were dissolved in 10 ml of distilled water and vortexed for one minute after soaking in water at 37°C for 30 minutes. The solution was centrifuged at 5000 rpm for 10 minutes using a centrifuge (Universal 320R, Hettich, Germany). The supernatant was dried in an oven at 105°C until it reached a constant weight. The WSI was calculated as follows:

$$\text{WSI} = \frac{\text{Dried supernatant weight}}{\text{Initial sample weight}} \ (\%)$$

2.3.6. Vitamin C content

Vitamin C content was measured via titration with 0.01 N iodine solution, using a 0.5% starch indicator, following the method of K. Pathy (2018) [10].

A 10 ml aliquot of the diluted sample solution and 1 ml of starch indicator were mixed, and the sample was titrated with 0.01 N iodine solution. The titration continued until a blue colour appeared and persisted for 60 seconds. The titration was repeated three times, and the volume of the iodine solution used was recorded. The vitamin C content was calculated using the formula:

$$\text{Vitamin C} = \frac{V \times V_1 \times 0.88 \times 100}{V_2 * m} \ (\text{mg/100 g DM})$$

where V is the volume of I_2 solution used for titration (ml), V_1 is the volume of the diluted sample solution (100 ml), V_2 is the volume of the sample used for titration (10 ml), m is the mass of the sample (g, dry matter), and 0.88 is milligrams of vitamin C equivalent to 1 ml of 0.01 N I_2 solution.

2.3.7. Total phenolic content

The extraction process for total phenolic content (TPC) followed the method of G. Xu, et al. (2008) [11]. One gram of sample was mixed with 9 ml of 80% methanol in a 50 ml centrifuge tube and allowed to extract for 30 minutes at room temperature under shaded conditions. The extract was filtered using filter paper and diluted to the appropriate concentration before analysis.

The TPC was determined using the method of Y.Y. Lim, et al. (2007) [12], with modifications.

A mixture of 0.3 ml of the extract and 1.5 ml of 10% (v/v) Folin-Ciocalteu reagent was shaken well in a test tube and left to stand for 5 minutes under shaded conditions. Subsequently, 1.2 ml of 7.5% (w/v) sodium carbonate (Na_2CO_3) solution was added, and the mixture was shaken well. After 30 minutes at room temperature, the absorbance was measured at 765 nm.

The total phenolic content was expressed as milligrams of gallic acid equivalent (GAE) per 100 g dry matter (DM), based on a standard curve constructed using gallic acid concentrations of 10, 20, 30, 40, 50, 60, and 70 µg/ml. The TPC was calculated using the formula:

$$\text{TPC} = \frac{(y-b) \times V \times df \times 100}{a \times m \times (100\% - MC\%) \times 1000} \ (\text{mg GAE/100 g DM})$$

where y is the optical density (OD) of the sample, a and b are the coefficients of the gallic acid standard curve equation (10-70 µg/ml), V is the extract volume, df is the dilution factor, m is the mass of the sample, and 100/1000 is the conversion factor from µg/g to mg/100 g.

2.3.8. Determination of sorption moisture content

The Brunauer-Emmett-Teller (BET) and Guggenheim-Anderson-de Boer (GAB) equations were employed to compute the monolayer moisture content (M_0, dry basis) [13].

$$\text{BET Equation: } M_0 = \frac{M_C C a_w}{(1-a_w)[1+(C-1)a_w]}$$

$$\text{GAB Equation: } M_0 = \frac{M_C C_0 K_G a_w}{(1-K_G a_w)(1-K_G a_w+C_G K_G a_w)}$$

where MC is the moisture content of the powders expressed in g per 100 g solids, M_0 is the monomolecular layer of water adsorbed per 100 g dry solids (g), a_w is the water activity at the given moisture content, C is the BET constant, and C_0, K_G, and C_G are the GAB equation parameters.

2.3.9. Calculation of kinetic parameters

The reaction rate constants and degradation parameters of foamed acerola powder were estimated using the Arrhenius kinetic computational model. The reductions in vitamin C and total phenolic content during storage were calculated using first-order kinetic reaction equations [13].

First-order kinetics: $lnC = lnC_0 - kt$

where C is the concentration at time t, C_0 is the concentration at time zero, k is the degradation rate constant (day^{-1}) obtained from the slope of ln C/C_0 versus t, and t is the storage time (days).

The half-life was calculated at a specific temperature by the equation:

$t_{1/2} = ln(2)/k$

The activation energy (E_a, kJ/mol) was determined using the Arrhenius equation as follows:

$k = Ae^{-E_a/RT}$

where A is a constant dependent on temperature (also known as the Arrhenius or the frequency factor), R is the universal gas constant (1.987 kJ/mol), and T is the absolute temperature (K).

The necessary treatment time to reduce vitamin C and polyphenols by 90% was calculated using:

$D = \ln(10)/k$

$D = D_0\ 10^{-T/z}$

where D is the treatment time (min), D_0 is the value of D at T=0 (min), T is storage temperature (°C), and z is the necessary temperature to reduce by log10 D (°C).

The prediction for the shelf life of vitamin C and polyphenols in acerola powder is given by the following equation [14]:

$$Ex = e^{-[\frac{S}{T}+I-\ln\left(-\ln\left(\frac{p\%}{100}\right)\right)]}$$

where Ex is the shelf life of the product, S and I are the slope and intercept obtained from the Arrhenius plot, T is the storage temperature (K), and $p\%$ is the percentage retention of vitamin C or polyphenols.

2.3.10. Scanning electron microscopy (SEM) analysis

The acerola powder samples were examined using scanning electron microscopy (SEM) (S4800, Hitachi, England). The samples were coated with platinum by thermal evaporation, achieving a coating thickness of 50 nm. The SEM was operated at an accelerating voltage of 10 kV, with magnifications of 500× and 1000×.

2.4. Statistical analysis

Each experiment was conducted in triplicate (n=3), and the results were expressed as the mean ± standard deviation. Data were processed and graphed using Excel 2016 software. Statistical analysis was performed using SPSS version 20. Analysis of variance (ANOVA) and the least significant difference (LSD) method were used to compare differences between experimental formulations at a significance level of p value of 0.05.

3. Results and discussion

3.1. Effect of drying temperature

3.1.1. Drying kinetics

Figure 1 shows the behaviour of the moisture content in foamed acerola samples during the drying process. The final moisture content of the powder was 3.63, 3.74, and 3.62% after drying for 300, 240, and 180 minutes at temperatures of 55, 65, and 75°C, respectively. The inverse relationship between drying temperature and drying time aligns with observations in other studies, including those on tamarind powder [6], noni powder [8], and peach powder [15].

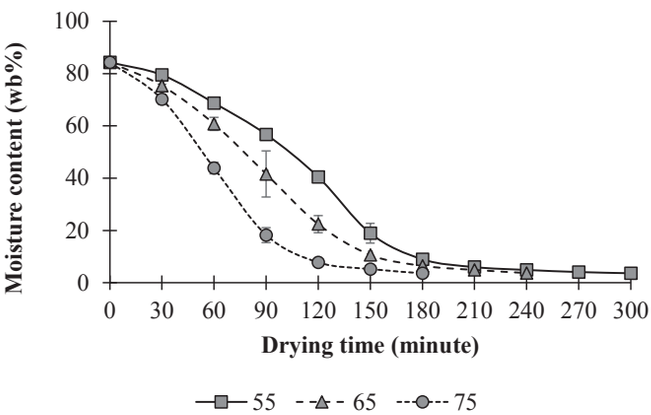

Fig. 1. The change in moisture content of foamed acerola samples during drying at various temperatures.

During drying, moisture diffuses from the interior to the surface of the material due to differences in temperature and water concentration gradients at the air-product interface [16]. The increased molecular mobility at higher temperatures enhances the evaporation rate, resulting in shorter drying times [8]. Hence, higher temperatures are favourable for removing water from the material efficiently.

Additionally, Fig. 1 demonstrates that the moisture content of all samples decreased rapidly during the first 120 minutes of drying before gradually declining in the later stages. This trend is attributed to the nature of water in food materials, which exists as free and bound water. Free water comprises water molecules that are not attached to other molecules and are easier to remove, whereas bound water is associated with organic or inorganic molecules [8, 15]. The rapid removal of free water during the initial drying phase explains the steep decline in moisture content at the beginning of the process.

3.1.2. Physicochemical properties

The solubility of the acerola powder varied significantly among samples, as indicated by statistical analysis (Table 1). Solubility improved consistently from 55 to 75°C. This result can be attributed to the stabilisation of the foam's porous structure during faster drying, which reduces the likelihood of structural collapse [6]. However, the solubility of the foam-mat-dried acerola powder (65-72%) was lower than that of acerola powder produced by spray drying (approximately 99%) [17]. This difference is likely due to the use of maltodextrin and hydroxypropyl methylcellulose (HPMC) in this study, compared to maltodextrin and gum Arabic in previous research. Additionally, studies have shown no significant difference in solubility between blueberry powder produced by freeze drying and spray drying, with solubilities exceeding 95% [5]. Freeze drying may enhance the solubility of fruit powders compared to hot air drying.

Table 1. The impact of drying temperatures on the physicochemical properties of acerola powder.

Temperature (°C)	Solubility (%)	Total acidity (%)	Total soluble solids (%)	Vitamin C (mg/100 g DM)	TPC (mg GAE/100 DM)
55	65.29^{b}±5.95	3.16^{a}±0.06	8.93^{a}±0.06	1930.08^{c}±64.15	1690.13^{b}±85.52
65	72.67^{ab}±0.43	3.20^{a}±0.00	8.93^{a}±0.06	2279.59^{b}±46.40	2212.02^{a}±148.96
75	75.89^{a}±6.45	3.13^{a}±0.06	8.97^{a}±0.06	2485.71^{a}±33.55	2245.36^{a}±193.63

Values in the same column followed by different superscripts (a-c) were significantly different ($p<0.05$).

As shown in Table 1, the vitamin C content ranged from 1989.78 to 2571.56 mg/100 g dry matter (DM) as the drying temperature increased from 55 to 75°C. A similar trend was observed in dried blueberries, where higher drying temperatures (80-90°C) with shorter drying times resulted in less vitamin C degradation compared to lower temperatures (50-70°C) with longer drying times [18].

Polyphenol content was also affected by drying conditions. The total phenolic content (TPC) of the samples was 1690.13, 2212.02, and 2245.36 mg GAE/100 g DM at 55, 65, and 75°C, respectively. Previous studies have shown that higher drying temperatures over shorter periods retain more TPC than lower temperatures over longer periods. For example, apples dried at 80°C exhibited less phenolic degradation than those dried at 60°C [19], and polyphenol concentration in carrots was better preserved at temperatures between 60 and 75°C [20]. This indicates that higher temperatures can reduce the exposure time of samples to heat, thereby preserving bioactive compounds.

The vitamin C and polyphenol contents observed in this study differ from those reported in studies using spray drying or freeze drying for acerola powder. Prior research reported phenolic content ranging from 1016.83 to 1052.91 mg GAE/100 g [17], and vitamin C content between 220.76 and 462.86 mg/100 g [17], 1593.2 mg/100 g [21], and 7210 mg/100 g [22]. Variations in these results may stem from differences in acerola cultivars, ripeness, and drying technologies.

Notably, the vitamin C content in 2.3 g of acerola powder produced in this study meets the Recommended Dietary Allowance (RDA) for adults of 45 mg/day, as established by the Institute of Medicine in the United States [17].

3.1.3. Visual appearance and morphology

Most powder samples exhibited a reddish-orange tone; however, the powder dried at 55°C had a darker colour than those dried at higher temperatures (Fig. 2). The colour of acerola fruit is attributed to anthocyanins and carotenoids, which are sensitive to heat and oxidation [1]. Shorter drying times limit exposure to oxygen and heat, thereby reducing oxidation and non-enzymatic browning reactions. This helps preserve the pigments and maintain the desired colour during food processing [7].

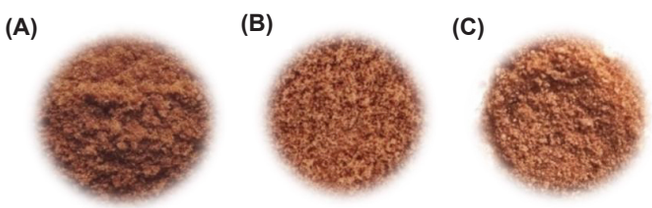

Fig. 2. The effect of temperature on the visual appearance of the acerola powder: (A) 55°C, (B) 65°C, and (C) 75°C.

The scanning electron microscopy images (Fig. 3) reveal that the morphology of the dried powders did not differ significantly across the various drying temperatures. In general, the powders displayed a flat shape with streaks near the edges, free from agglomeration, with irregular shapes and smooth surfaces. This morphology contrasts with that of acerola powder produced by spray drying, which typically results in microparticles with smooth surfaces, spherical shapes, and irregular sizes [17, 21]. However, the observed morphology is consistent with previous reports on blueberry powder [5], mango peel powder [7], and peach powder [15].

In conclusion, the powder dried at 75°C was selected for further experiments due to its shorter drying time and favourable characteristics.

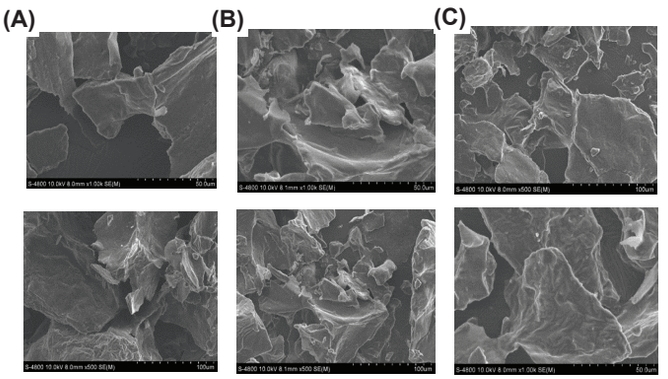

Fig. 3. Scanning electron microscopy micrographs of the powders dried at (A) 55, (B) 56, and (C) 75 under various magnifications.

3.2. Effect of relative humidity during storage

3.2.1. Moisture sorption isotherms

The effect of relative humidity on acerola powder was examined at room temperature (29-31°C) under five relative humidity (RH) conditions. As equilibrium relative humidity (ERH) increased from 10 to 84%, the equilibrium moisture content (EMC) rose from 4.67 to 27.17%, while water activity increased from 0.31 to 0.61 (Fig. 4). A sharp increase in water uptake was observed when ERH increased from 57 to 76%. This behaviour is attributed to the gradual transformation of sugar from a crystalline to an amorphous state, which increases water absorption sites on both the surface and within the crystalline structure [22].

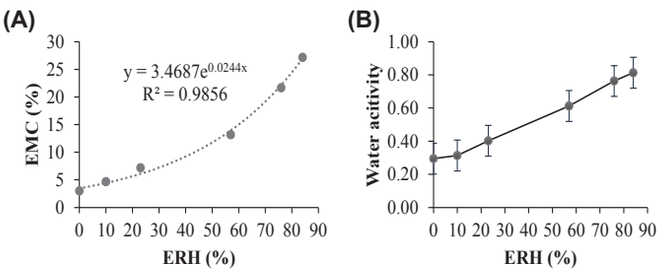

Fig. 4. Effect of humidity on (A) moisture content and (B) water activity of the acerola powder samples at room temperature. EMC: Equilibrium moisture content; ERH: Equilibrium relative humidity.

The rapid moisture absorption can also be explained by the hygroscopic nature of maltodextrin and the initial moisture gradient between the acerola powder (3.33%) and the environment. Similar moisture sorption behaviour has been reported for mango peel powder [23] and gac powder [12].

The moisture sorption isotherm of the acerola powder was modelled using the Brunauer-Emmett-Teller (BET) and Guggenheim-Anderson-de Boer (GAB) equations. The monolayer moisture content (M_0) was identified as 5.11 and 3.38% (dry basis) using the BET equation (R^2=0.7) and the GAB equation (R^2=0.84), respectively. These findings suggested that the GAB equation was more reliable for forecasting M_0 because of the higher R^2 value. The C and K values of GAB model were 4.17 and 0.26, respectively, satisfying the conditions $0<K\leq1$ and $C>0$. The GAB equation yields a sigmoidal curve with a point of inflection (type II of Brunauer's curve) for $C\geq2$. The comparatively flat portion of the sorption isotherm is described in Part II using the standard *w-aw* plot depiction [24].

Previous studies reported M_0 values of 12.60% for mango peel powder [23], 0.0573% for spray-dried acerola powder [25], and 2.43% for gac powder [12]. Differences in carbohydrate composition, structure, and drying methods contribute to variations in M_0 across powders [23]. For maximum shelf life, the initial moisture content should be near or slightly above M_0 [8]. In this study, the initial moisture content of the acerola powder (3.33%) was close to M_0, suggesting potential for long-term storage.

3.2.2. Bioactive compounds

Figure 5 illustrates the gradual decline in vitamin C and TPC as relative humidity increases. Vitamin C content decreased from 2522.67 to 1114.67 mg/100 g DM, and TPC reduced from 2248.71 to 1136.65 mg GAE/100 g DM, when RH rose from 10 to 84% over 14 days of storage at room temperature. Statistical analysis confirmed significant differences ($p<0.05$) between the samples under different RH conditions. This effect can be explained by the fact that the samples were kept at RHs ranging from 10 to 23% and had water activities of 0.31 to 0.61. The low water activity prevents undesirable reactions such as oxidation, browning, and hydrological reactions [22]. When kept at a constant RH of 34 to 87%, the content of polyphenols and flavonoids in noni powder decreased [8].

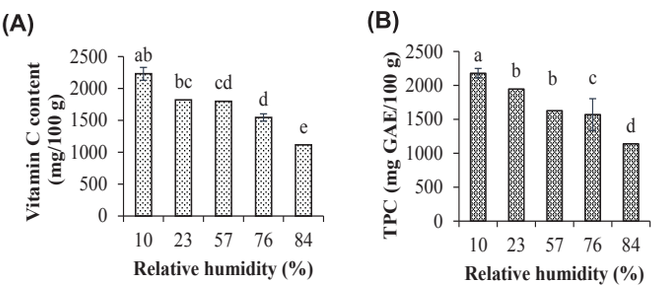

Fig. 5. Effect of relative humidity on (A) vitamin C content and (B) total phenolic content of acerola powder kept at room temperature for 14 days.

The visual appearance of acerola powder was remarkably influenced by relative humidity, as seen in Fig. 6. At low RH (10-23%), with water activity ranging from 0.31 to 0.61, undesirable reactions such as oxidation, browning, and hydrolytic reactions were minimised [22]. However, at higher RH (>50%), visible stickiness and caking developed in the powders (Fig. 6). This phenomenon occurs due to moisture migration from the environment into the powder, leading to surface plasticisation of the particles [25]. Similar behaviour has been observed in mango peel powder [23] and spray-dried acerola powder [25].

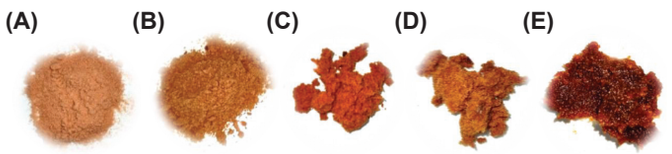

Fig. 6. The physical appearance of acerola powder after 14 days of storage at room temperature under different relative humidities: (A) 10%, (B) 23%, (C) 57%, (D) 76%, and (E) 84%.

3.3. Effect of temperature storage

3.3.1. Moisture content and water activity

As storage time increased, the moisture content of acerola powder gradually rose, while water activity fluctuated (Fig. 7). Acerola powder stored at low temperatures (4-6°C) and room temperature exhibited moisture content and water activity values ranging between 3-6% and 0.25-0.3, respectively. These values align with those reported for spray-dried acerola powder, which had moisture content and water activity of 3.9% and 0.25, respectively [21].

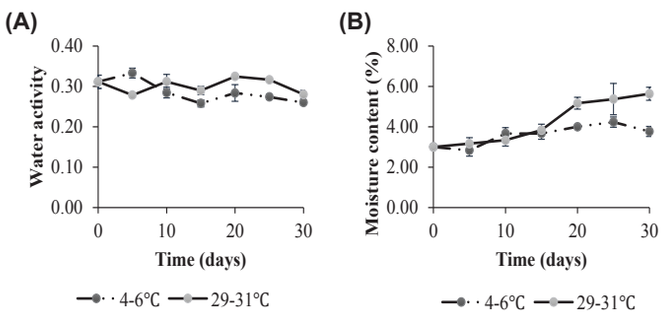

Fig. 7. The impact of temperature on (A) water activity and (B) moisture content of acerola powder throughout storage.

A similar pattern was observed in mango peel powder, where moisture content slightly decreased from 4.26 to 4.10% while water activity increased from 0.36 to 0.43 [23]. For *Campomanesia adamantium* powder, both moisture content and water activity increased continuously during storage [26]. This behaviour is attributed to the permeability of the packaging materials, which allowed environmental moisture to be absorbed by the powder, leading to increased moisture content over time [26].

Despite these changes, the foamed acerola powder in this study maintained low water activity (below 0.6), which helps inhibit the growth of spoilage microorganisms, unexpected enzymatic reactions, and non-enzymatic browning [21].

3.3.2. Degradation kinetics of vitamin C and polyphenols

First-order reactions are chemical processes where the reaction rate is directly proportional to the concentration of a reactant. The temperature dependence of such processes is described by the Arrhenius equation, which is widely applied in chemical kinetics [27].

The degradation kinetics of vitamin C and polyphenols in acerola powder were temperature-dependent and followed first-order and Arrhenius models. These models have also been used to study bioactive compound degradation in gac fruit powder [8], mango peel powder [23], and spray-dried acerola powder [26].

For vitamin C, the degradation rate constant (k) increased with temperature, with values of 0.0099, 0.0132, and 0.0141 day^{-1} at 4-6, 29-31, and 40°C, respectively. This indicates that vitamin C is less stable at temperatures above 30°C. Storage temperature significantly influenced the half-life ($t_{1/2}$) of vitamin C, which decreased as temperature increased. Specifically, $t_{1/2}$ was 73 days at 4-6°C and 55 days at 40°C (Table 2). Similarly, for spray-dried acerola powder, the k value rose from 0.044 to 0.074 hour^{-1} as the temperature increased from 30 to 40°C [21]. For mango peel powder, k increased from 0.0004 to 0.0054 day^{-1} as storage temperature rose from 10 to 35°C [21]. Additionally, k values for Campomanesia adamantium powder increased from 0.00163 to 0.00177 day^{-1} between 25 and 35°C [26].

Polyphenol degradation was also temperature-dependent, with faster deterioration at 40°C compared to 4-6°C. The k values were 0.0006 and 0.0026 day^{-1}, respectively, corresponding to $t_{1/2}$ values of 1155 days at 4-6°C, 277 days at room temperature, and 267 days at 40°C. For kiwi puree, k expanded from 1.59 to 6.54×10^{-3} hour^{-1} as storage temperature increased from 5 to 45°C [28].

According to the findings in Table 2, the E_a value of the polyphenol was higher than that of vitamin C. However, its z value was lower than vitamin C. These parameters indicate that the polyphenols in foamed acerola powder were more

heat-sensitive than vitamin C. Furthermore, the E_a value of vitamin C obtained in the present study was lower than that of orange juice (105.27 kJ/mol), lemon juice (53.43 kJ/mol), grapefruit juice (76.86 kJ/mol), and tangerine juice (79.24 kJ/mol) [29]. Polyphenol has a higher E_a than kiwi puree (28.15 kJ/mol) [28].

Table 2. Degradation kinetics parameters *k*, $t_{1/2}$, *D*, *z*, E_a value for vitamin C and polyphenols in foamed acerola powder at various storage temperature.

Attribute	Storage temperature (°C)	k (day^{-1})	$t_{1/2}$ (day)	R^2	D (day)	z (°C)	E_a (kJ/mol)
Vitamin C	4-6	0.0099	70	0.83	232.58	208.33	8.03
	29-31	0.0132	53	0.76	174.44		
	40	0.0141	49	0.78	163.30		
Polyphenols	4-6	0.0006	1155	0.93	3837.64	48.54	34.71
	29-31	0.0025	277	0.85	921.03		
	40	0.0026	267	0.81	885.61		

3.3.3. Shelf life predictive of vitamin C and polyphenols

Figure 8 illustrates the predicted degradation of vitamin C and TPC in foamed acerola powder if the storage period is extended beyond 30 days. The results indicate that low temperatures significantly prolong the retention of vitamin C and TPC during storage. Consequently, storing foamed acerola powder at low temperatures is recommended to maintain its quality.

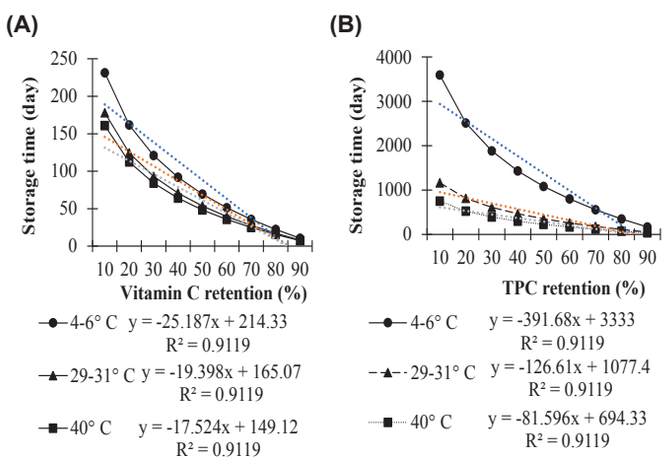

Fig. 8. Predictive percentage retention (%) of (A) vitamin C and (B) polyphenols in foamed acerola powder at various storage temperatures over time.

After 30 days of storage at 4-6°C, the vitamin C content remained at 71.32% of its initial value, whereas retention at room temperature and 40°C decreased to 62.79 and 60.47%, respectively. A similar trend was observed for TPC, with the highest retention level (97.96%) recorded at 4-6°C.

These findings align with previous studies demonstrating the strong dependence of bioactive compound retention on storage temperature. For example, spray-dried acerola powder exhibited reductions in vitamin C content of 77.8 and 91.3% after 30 days of storage at 30 and 40°C, respectively [21]. Juices made from orange, lemon, grapefruit, and tangerine retained 80.5, 70.2, 72.11, and 71.50% of their vitamin C content, respectively, after 8 weeks of storage at 28°C [29]. Guava powder retained only 45% of its vitamin C content after 49 days of storage at 25°C [24].

Similarly, the retention of TPC in kiwi puree was reported as 81.69 and 70.47% after 12 hours of storage at 25 and 45°C, respectively [28]. These comparisons emphasise the critical role of low storage temperatures in preserving bioactive compounds in acerola powder.

4. Conclusions

The optimal drying temperature for foamed acerola powder was determined to be 75°C. The GAB model was found to effectively describe the sorption isotherm curve. Relative humidity below 60% was favourable for powder preservation, maintaining water activity below 0.6. The first-order, Arrhenius, and Ball models accurately described the degradation kinetics of phenolic content and vitamin C during storage.

Low storage temperatures (4-6°C) were critical in minimising increases in water activity and moisture content while ensuring the stability of vitamin C and polyphenols in acerola powder.

Acerola powder is suitable for use in beverages, bakeries, ice cream, yoghurt, and functional foods as a supplemental source of vitamin C. Future research should investigate the stability of acerola powder under various packaging materials to further extend its shelf life.

CRediT author statement

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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