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Article

Storage life and kinetic velocity of preserved onion paste at room and refrigerated temperatures

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Abstract: Onion paste is a convenient value-added product, but its high moisture content makes it susceptible to physicochemical deterioration and microbial spoilage during storage. This study evaluated the effects of preservative formulation, packaging material, and storage temperature on the physicochemical stability and acidity degradation kinetics of onion paste over eight months. Onion paste was prepared using three formulations: SB (10% salt, 1% citric acid, and 1000 ppm sodium benzoate), KMS (10% salt, 1% citric acid, and 1000 ppm potassium metabisulphite), and CA (1% citric acid), together with a commercially available market sample (MS). Treated samples were packed in plastic and glass containers and stored at room temperature (25 ± 5 °C) and refrigerated temperature (7 ± 2 °C), whereas the market sample was evaluated in its original plastic packaging. Changes in pH, titratable acidity (TA), total soluble solids (TSS), moisture content, and ash content were monitored at two-month intervals. Preservative treatment, packaging material, storage temperature, and storage duration significantly affected ($P<0.001$) most quality attributes. The pH increased progressively, whereas TA generally declined during storage. The KMS formulation showed comparatively high acidity retention and maintained TSS of 29.36–31.60 °Brix, moisture content of 71.88–73.55%, and ash content of 8.35–8.98%. SB-treated paste maintained TSS of 28.06–29.56 °Brix, moisture content of 71.34–71.97%, and ash content of 8.30–8.50%. In contrast, CA-treated paste showed lower TSS (21.16–24.70 °Brix), higher moisture content (74.08–80.30%), and substantially lower ash content (0.30–0.96%), while the market sample exhibited the lowest TSS (9.10–12.02 °Brix) and highest moisture content (84.10–90.03%). Acidity degradation was evaluated using a first-order kinetic model, although model fit varied considerably among treatment and storage combinations. The KMS-treated paste stored in glass under refrigerated conditions showed the strongest first-order fit (R^2 = 0.9153) and a predicted acidity half-life of 1.58 years. The combination of potassium metabisulphite, glass packaging, and refrigerated storage provided the most predictable acidity stability among the tested conditions. The findings provide a quantitative basis for optimizing onion-paste preservation and storage practices and demonstrate the potential of kinetic modelling for shelf-life assessment, quality control, and reduction of storage-related losses.

Keywords: preservation; preservative; acidity degradation; kinetics rate; KMS

1. Introduction

Onion (*Allium cepa* L.) is one of the most widely cultivated and consumed vegetable crops worldwide. It is valued for its distinctive flavor and for its sulfur-containing compounds and phenolic substances, which exhibit antioxidant and antimicrobial properties (Kumar *et al*., 2022). Due to its extensive use in culinary practices, the demand for onion and onion-based processed products has increased significantly in both household and industrial sectors (Majid *et al*., 2020). However, fresh onion is highly perishable and subject to substantial post-harvest losses caused by microbial spoilage, enzymatic degradation, and physiological changes during storage. These losses are especially severe in tropical and subtropical regions, where high ambient temperatures and inadequate storage infrastructure accelerate deterioration (Muhie, 2022). Processing onion into paste has therefore emerged as a practical strategy to reduce post-harvest losses while offering consumers and food processors a convenient, ready-to-cook, flavor-consistent ingredient that reduces preparation time. Yet, the mechanical processing involved in paste preparation disrupts cellular structures and releases intracellular enzymes and moisture, which increase the paste's susceptibility to physicochemical and microbiological changes during storage. Maintaining the stability and quality of onion paste over prolonged storage periods therefore remains a significant technical challenge (Arefin *et al*., 2019).

During storage, onion paste undergoes various physicochemical changes, including fluctuations in pH, titratable acidity (TA), total soluble solids (TSS), moisture content, and ash content. These changes arise primarily from enzymatic reactions, microbial growth, and chemical degradation processes. A rise in pH, for instance, may indicate the breakdown of organic acids or active microbial metabolism, both of which can compromise product safety and stability. Similarly, changes in TA reflect the degradation of organic acids that normally help preserve the product. Shifts in TSS may result from the hydrolysis of complex carbohydrates into simpler sugars or from moisture loss that concentrates soluble components (Priyanka *et al*., 2025). Preservatives such as citric acid lower pH, creating conditions unfavorable for microbial growth, while sodium benzoate (SB) and potassium metabisulfite inhibit bacteria, yeasts, and molds. The combined use of these preservatives has been reported to be more effective than individual application (Arefin *et al*., 2019). Packaging also plays a role: glass containers are generally considered superior due to their impermeability and chemical inertness. In contrast, plastic containers, though economical and lightweight, may allow limited gas and moisture permeability, which can accelerate deterioration (Farrell *et al*., 2024).

Storage temperature is another critical factor. Refrigerated storage reduces microbial growth and slows enzymatic and chemical reactions, thereby preserving quality for longer, whereas ambient temperature storage accelerates deterioration (Sharma and Lee, 2016). However, what remains poorly quantified is the precise, predictive rate of deterioration at room temperature (RT) relative to refrigeration, rather than simple before-and-after comparisons. Addressing this requires kinetic modeling. First and zero-order models are commonly used to derive degradation rate constants and half-life values from changes in quality parameters over time (Majid *et al*., 2019), but such kinetic characterization has not been systematically applied to onion paste specifically. The deterioration rate of onion paste under refrigeration and at RT, expressed through kinetic parameters such as rate constant and half-life, remains poorly quantified. This kinetic data would enable food processors and retailers to reliably predict shelf life and set evidence-based storage guidelines, ultimately leading to lower onion waste.

This study investigated the effect of storage temperature on the shelf life and physicochemical quality degradation rate of onion paste. It further examined whether changes in pH, TA, and TSS could support shelf-life prediction. We hypothesized that onion paste stored at RT would exhibit a significantly faster rate of physicochemical quality deterioration than paste stored under refrigerated conditions. Furthermore, the deterioration of selected quality attributes would follow a quantifiable kinetic pattern, describable by an appropriate reaction order model (e.g., zero or first-order kinetics), enabling the estimation of degradation rate constant and half-life. Although previous research has focused on the preservation and storage stability of whole onions and dehydrated onion powder, quantitative kinetic characterization of physicochemical quality deterioration specifically in onion paste under controlled temperature conditions appears limited. Therefore, this study addresses an important research gap by applying reaction-kinetic modeling to quantify temperature-specific quality degradation in onion paste. Moving beyond conventional descriptive assessments of storage stability, this study aims to establish a predictive framework based on degradation rate constants and related kinetic parameters to estimate shelf life under different temperature conditions. The findings are expected to provide food processors and retailers with a scientific basis for predicting onion paste shelf life, establishing evidence-based storage guidelines, improving quality assurance, reducing premature spoilage, and minimizing avoidable food waste during the production, storage, and distribution of onion paste.

2. Materials and methods

2.1. Ethical approval

Ethical approval was not required for this study.

2.2. Study area and periods

The experiments were conducted at two research facilities of the Bangladesh Agricultural Research Institute (BARI): the Postharvest Technology Division (PHTD), Gazipur, and the Spice Research Centre (SRC), Bogura (Figure 1). Fresh onion bulbs (*Allium cepa* L., cv. BARI Piaj 5) were collected from a local market at Mahasthangarh Bazar, Shibganj, Bogura, Bangladesh. The study was conducted from January to December 2025.

Figure 1. Study locations showing the onion collection site at Mahasthangarh Bazar, Shibganj, Bogura, Bangladesh (black box) and the Postharvest Technology Division (PHTD), Bangladesh Agricultural Research Institute (BARI), Gazipur (red box).

2.3. Raw materials collection and treatment design

Fresh onion bulbs (*Allium cepa* L. cv. BARI Piaj 5) were selected based on visual freshness, uniform size, and absence of mechanical damage or microbial spoilage. Plastic containers and glass jars served as packaging materials for storing the onion paste. Anhydrous citric acid, sodium benzoate (E211), and potassium metabisulfite (E224) were obtained from Merck, Germany. All other analytical-grade materials and reagents were procured from a local scientific supply store in Tikatuly, Dhaka, Bangladesh. The BARI Piaj 5 onion bulbs were peeled, washed, and cut before being immediately processed into a homogeneous paste using a laboratory-sized blender (Jaipan CM/L-7360065, Japan) (Majid *et al.*, 2020). The resulting onion paste samples were then treated with various preservative combinations, as detailed in Table 1.

Table 1. Treatments applied to onion (*Allium cepa* L. cv. BARI Piaj 5) paste using salt, citric acid, potassium metabisulfite, and sodium benzoate.

Treatment	Composition
SB	Onion paste treated with 10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate.
KMS	Onion paste treated with 10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite.
CA	Onion paste treated with only 1% (w/w) citric acid.
MS	Market sample (commercially prepared onion paste purchased from the local market).

2.4. Storage studies

The paste samples from both market and treated samples were stored for eight months under two different conditions: RT (25 ± 5 °C) and refrigeration (7 ± 2 °C). The treated onion paste samples were stored in clean, sterilized plastic containers and glass jars. Market paste samples, however, were only available in plastic containers; therefore, glass container samples from the market were excluded from analysis. All paste samples were analyzed every two months for changes in quality characteristics, including pH, TA, TSS (°B), moisture (%), and ash (%).

2.5. Determination of functional properties of onion paste

2.5.1. pH and titratable acidity (TA)

The pH of onion paste samples was measured using a calibrated digital pH meter, following AOAC (2011) official method 981.12. TA was determined using the classical acid-base titration method described by Seifu *et al.* (2018). In this method, a known weight of the sample was homogenized with distilled water and then titrated against a standardized 0.1 N NaOH solution. Phenolphthalein served as an indicator, with the endpoint marked by the appearance of a persistent pink color. The results were expressed as a percentage of citric acid equivalent.

2.5.2. Total soluble solids (TSS)

TSS were determined using a PAL-3 digital hand refractometer (Brix range: 0.0–93.0%; ATAGO Co., Ltd., Tokyo, Japan). The onion paste was filtered through muslin cloth to obtain a clear extract, and a drop of the filtrate was placed on the refractometer prism. Results were recorded as °Brix.

2.5.3. Moisture content and ash content

Moisture and ash percentages of the onion paste were determined according to the descriptions of Khatri *et al.* (2017). Approximately 5 g of onion paste was weighed into a pre-weighed moisture dish and dried in a hot air oven at 105 °C until a constant weight was obtained. After drying, the sample was cooled in a desiccator and reweighed. Moisture content was calculated using the following equation:

$$Moisture\ (\%) = \frac{W_1 - W_2}{W1} \times 100$$

where W_1 and W_2 represent initial and final drying sample weight in grams (g). For ash percentage, approximately 5 g of the dried sample was placed in a pre-weighed crucible and incinerated in a muffle furnace at 550 °C for 4-6 hours until a light grey ash was obtained. The ash percentage was calculated using the following formula,

$$Ash\ (\%) = \frac{Weight\ of\ ash}{Weight\ of\ sample} \times 100$$

2.6. Kinetics of acidity percentage change during storage

The degradation of % acidity was predicted to follow the standard equation for preserved onion paste in plastic and glass containers at room and refrigerated temperatures. The first-order kinetic model was calculated as described by Majid *et al.* (2019):

$$lnC = lnC_0 - kt$$

where C denotes the percentage of acidity at a definite time interval t, and C_0 denotes the percentage of acidity at the zero time interval. The degradation rate constant, k (day–1), is obtained from the slope of a plot of the natural log of C/C_0 versus time. The storage time (days) is represented by t.

The degradation of the acidity percentage from zero to a definite time interval (50%) was calculated as half-life using the following equation:

$$t_{\frac{1}{2}} = \frac{ln2}{k}$$

2.7. Statistical analysis

The experimental data were analyzed using analysis of variance (ANOVA) following a Randomized Complete Block Design (RCBD). The following statistical model was used,

$$Y_{ijklm} = \mu + T_i + C_j + Temp_k + M_l + R_m + e_{ijklm}$$

where Yijklm represents the observed value of the response variable, μ is the overall mean, T_i is the effect of the i th treatment, C_j is the effect of the j th storage container type, Tempk is the effect of the k th storage temperature, Ml is the effect of the l th storage month, Rm is the effect of the m th replication, and eijklm is the random experimental error.

Analysis of variance was conducted using R statistical software (version 4.4.1). When significant differences among treatments were detected, mean separation was performed using Tukey's Honestly Significant Difference (HSD) test at the 1% and 5% levels of significance. Microsoft Excel 2016 was used for data processing, analysis, and graphic visualization. Spatial distribution maps were generated using ArcGIS 10.8 to support further spatial analysis.

3. Results

3.1. Effect of storage conditions on onion paste quality traits

Analysis of variance revealed that treatment and storage container (e.g., plastic, glass pot) were the dominant sources of variation for most quality traits. Treatment had particularly large effects on moisture content (mean square, ms = 14547.60, $P<0.001$) and TSS (ms = 7081.80, $P<0.001$), while storage container most strongly influenced moisture content (ms = 28313.10, $P<0.001$) and pH (ms = 151.64, $P<0.001$). The treatment × container interaction (Tr × C) was similarly substantial for these same traits (ms = 28230.00 for MC and 137.69 for pH, both $P<0.001$), indicating that packaging material and treatment type jointly drove most of the observed variability. Temperature and month individually contributed comparatively smaller but still significant effects across all traits (e.g., temperature ms = 30.30 for MC, 3.26 for ash, 0.39 for pH, 0.18 for acidity, and 16.20 for TSS, all $P<0.001$). Among the interactions, Tr × Temp was non-significant only for pH (ms = 0.03, ns) but significant for all other traits. Tr × M was non-significant for MC (ms = 1.00, ns) and acidity (ms = 0.01, ns) but significant for ash, pH, and TSS. Temp × M was largely non-significant across traits, except for ash content (ms = 0.63, $P<0.001$) and TSS (ms = 1.40, $P<0.05$). This suggests that the temperature effect remained stable across the eight-month storage period for most parameters, with ash content being the notable exception. Ash and TSS emerged as the traits most broadly responsive to every source of variation and interaction tested, whereas moisture content and acidity showed effects concentrated mainly in treatment, container, and their interaction (Table 2).

Table 2. Analysis of variance (mean squares) for onion paste storage quality traits.

Source of variation	df	MC	Ash	pH	Acidity	TSS
Treatment	3	14547.60***	1318.16***	33.70***	10.30***	7081.80***
Storage container	1	28313.10***	3.59***	151.64***	1.71***	636.80***
Temperature	1	30.30***	3.26***	0.39***	0.18***	16.20***
Month	4	12.20***	3.33***	0.36***	0.12***	42.90***
Tr × C	3	28230.00***	2.76***	137.69***	1.74***	349.80***
Tr × Temp	3	122.60***	1.88***	0.03 ns	0.45***	32.90***
Tr × M	12	1.00 ns	1.04***	0.05**	0.01 ns	4.00***
Temp × M	4	2.80 ns	0.63***	0.03 ns	0.01 ns	1.40*

Note: df=degree of freedom, MC= moisture content, TSS=total soluble solids, Tr=treatment, C= storage container, Temp=temperature, M=month; ***, ** and ns mean significant effect at the $P\leq0.001$, 0.05 and not significant effect, respectively.

3.2. Physicochemical changes of onion paste during storage in plastic and glass containers

3.2.1. pH changes in onion paste under different storage conditions

Initial pH varied significantly among treatments in both packaging types ($P<0.05$). In plastic containers, SB (4.32 ± 0.04) and KMS (4.34 ± 0.02) did not differ from each other. CA was significantly higher (4.77 ± 0.05), and MS (5.78±0.10) was the highest overall (Table 3). In glass containers, the treatment ranking differed slightly: CA was highest (4.49 ± 0.03), SB was intermediate (4.30 ± 0.20), and KMS had the lowest value (4.19 ± 0.04) (Table 4). The pH increased gradually in all treatments and both packaging types over storage, with the rise consistently greater under RT than RFT. By month 8, SB and KMS remained comparatively stable in both plastic (4.40 ± 0.14 to 4.66 ± 0.05 and 4.45 ± 0.03 to 4.47 ± 0.09, RFT to RT) and glass (4.35 ± 0.02 to 4.43 ± 0.15 and 4.30 ± 0.02 to 4.35 ± 0.03, RFT to RT). Glass yielded marginally lower final values for these two treatments. CA-treated samples showed a larger increase in both packaging types (plastic: 4.84 ± 0.04 to 4.90 ± 0.06; glass: 4.80 ± 0.02 in RFT to 4.85 ± 0.09 in RT). MS, present only in the plastic comparison, exhibited by far the largest deviation, exceeding pH 6.77 ± 0.05 under RT.

3.2.2. Titratable acidity changes in onion paste during storage

Initial TA was consistently higher in glass than in plastic across all three shared treatments: SB (1.41 ± 0.03% glass vs. 1.19 ± 0.01% plastic), KMS (1.44 ± 0.01% vs. 1.25 ± 0.00%), and CA (1.36% vs. 1.15 ± 0.02%). MS (plastic only) was the lowest overall (0.80 ± 0.10%). TA declined over storage in all treatments and both packaging types. By month 8, packaging effects diverged by treatment. KMS retained TA better in plastic under RFT (1.11 ± 0.03%) than in glass (1.19 ± 0.01%), whereas CA performed similarly in plastic (1.10% RFT) and glass (1.28 ± 0.02% RFT). SB retained the highest TA in plastic at month 8 under both RFT (1.23 ± 0.03%) and RT (1.20 ± 0.04%), outperforming its glass counterpart (1.01 ± 0.21% under both conditions). MS remained the lowest throughout the end of storage (0.51 ± 0.05% in RFT – 0.78 ± 0.04% in RT) (Table 3 and 4).

3.2.3. Changes in total soluble solids of onion paste during storage

Initial TSS was statistically similar between SB and KMS within each packaging type (plastic: 28.06 ± 1.72 and 29.36 ± 0.76 °Brix; glass: 27.00 ± 0.80 and 26.60 ± 1.00 °Brix) but significantly lower in CA (plastic: 21.16 ± 0.48 °Brix; glass: 21.33±1.09 °Brix). MS (plastic only) had the lowest TSS overall (9.10 ± 0.30 °Brix). TSS increased modestly across all treatments and both packaging types during storage, with a slightly larger increase observed in plastic packaging compared to glass for SB and KMS. By month 8, KMS in plastic packaging reached the highest TSS under RFT (31.60 ± 1.36 °Brix), while the glass values for SB and KMS converged closely (28.06 ± 0.24 – 28.80 ± 1.12 °Brix). CA consistently remained significantly lower than SB and KMS in both packaging types throughout the storage period (Table 3 and 4).

3.2.4. Changes in moisture content of onion paste during storage

Moisture content exhibited an inverse relationship with TSS. Initial moisture was lowest in SB for both packaging types (71.97 ± 1.85% in plastic and 71.97 ± 0.13% in glass) and highest in CA among the shared treatments (77.98 ± 2.11% in plastic, 77.85 ± 0.95% in glass). MS (plastic only) had the highest initial moisture overall (90.03 ± 1.04%). Moisture in SB and KMS gradually decreased over storage in both packaging types. By month 8, glass packaging showed marginally better moisture retention (SB: 71.34 ± 0.80–71.98 ± 1.32% in glass vs. 71.23 ± 0.62–71.88 ± 0.26% in plastic). CA displayed the most pronounced packaging-dependent divergence. In glass, moisture remained high under RT storage (80.30 ± 0.76% at month 8) but decreased more significantly under refrigerated temperature (RFT) storage (74.08 ± 0.89%). This temperature effect was less pronounced in plastic packaging, where CA's RFT and RT values remained closer (75.10 ± 0.20% and 80.25 ± 1.93%, respectively). MS experienced the largest overall moisture loss among all samples, declining to between 87.85 ± 1.36% and 84.10 ± 1.52% (Table 3 and 4).

3.2.5. Changes in ash content during storage

Ash content was substantially higher in SB and KMS than in CA and MS across both packaging types, reflecting the 10% salt added to SB and KMS formulations. Initial ash content was statistically similar within each pair (plastic: SB 8.31 ± 0.45% vs. KMS 7.12 ± 1.10%; glass: SB 8.30 ± 0.10% vs. KMS 8.35 ± 0.21%), while CA was markedly lower in both (0.34 ± 0.02% in plastic, 0.30 ± 0.13% in glass). Ash content increased modestly over storage in SB and KMS across both packaging types, reaching 9.40 ± 0.50% to 8.08 ± 1.14% by month 8, depending on treatment, packaging, and temperature. CA showed the largest proportional increase in both packaging types, nearly tripling in plastic (from 0.34 ± 0.02% to 0.96 ± 0.09% under RFT) and rising more modestly in glass (from 0.30 ± 0.13% to 0.45 ± 0.01–0.46 ± 0.04%). However, CA's ash content remained an order of magnitude lower than SB and KMS throughout the study (Table 3 and 4).

3.3. Percentage of acidity kinetics during storage

Quality deterioration in processed foods is commonly described using zero-order or first-order reaction kinetics, which explain the rate of change in physiochemical parameters during storage. Figure 2-5 illustrates the patterns of acidity degradation in onion paste, considering container type (plastic vs. glass) and storage temperature (RT vs. refrigeration) across four treatments over 8 months. In plastic containers at RT, the SB-treated sample exhibited the greatest acidity stability, followed by KMS and citric acid treatments. In contrast, the market sample showed severe early degradation ($\ln(C/C_0) \approx -1.1$), with partial recovery by month 8 (Figure 2). At RT, the kinetic degradation rate constant (k) ranged from 0.0002 to 0.0005 days^{-1} across treatments, with corresponding half-lives ranging from 3.80 to 9.50 years. The KMS and CA-treated samples had half-lives of 3.80 years and showed the best model fit (R^2 = 0.8697 and 0.8629, respectively). The SB sample, however, exhibited the longest half-life (9.50 years) but a poor model fit (R^2 = 0.1975). The market sample had a half-life of 6.33 years but a very low R^2 value (0.0064), indicating a poor fit of the kinetic model to its acidity degradation (Table 5).

Table 3. Functional properties of onion (BARI Piaj 5) paste in plastic container.

Parameters	Treatment	Initial	Duration of storage (months)							
			2		4		6		8	
			RFT	RT	RFT	RT	RFT	RT	RFT	RT
pH	SB	4.32 ± 0.04^{c}	4.33 ± 0.01^{b}	4.30 ± 0.09^{c}	4.32 ± 0.04^{c}	4.39 ± 0.07^{c}	4.40 ± 0.18^{c}	4.66 ± 0.08b^{c}	4.40 ± 0.14^{c}	4.66 ± 0.05^{c}
	KMS	4.34 ± 0.02^{c}	4.38 ± 0.98^{b}	4.35 ± 0.07^{c}	4.40 ± 0.02^{c}	4.40 ± 0.08^{c}	4.45 ± 0.03^{c}	4.47 ± 0.07^{c}	4.45 ± 0.03^{c}	4.47 ± 0.09^{d}
	CA	4.77 ± 0.05^{b}	4.79 ± 0.03^{ab}	4.86 ± 0.02^{b}	4.81 ± 0.07^{b}	4.89 ± 0.03^{b}	4.84 ± 0.04^{b}	4.90 ± 0.31^{b}	4.84 ± 0.04^{b}	4.90 ± 0.06^{b}
	MS	5.78 ± 0.10^{a}	5.85 ± 0.02^{a}	5.89 ± 0.03^{a}	5.90 ± 0.25^{a}	6.02 ± 0.08^{a}	6.25 ± 0.05^{a}	6.77 ± 0.05^{a}	6.25 ± 0.01^{a}	6.77 ± 0.05^{a}
Acidity (%)	SB	1.19 ± 0.01^{a}	1.16 ± 0.02^{a}	1.25 ± 0.03^{a}	1.10 ± 0.11^{b}	1.21 ± 0.11^{a}	1.23 ± 0.01^{a}	1.20 ± 0.06^{a}	1.23 ± 0.03^{a}	1.20 ± 0.04^{a}
	KMS	1.25 ± 0.00^{a}	1.24 ± 0.02^{a}	1.15 ± 0.11^{a}	1.20 ± 0.02^{a}	1.10 ± 0.11^{a}	1.11 ± 0.03^{b}	1.09 ± 0.03^{a}	1.11 ± 0.03^{b}	1.09 ± 0.13^{a}
	CA	1.15 ± 0.02^{a}	1.10 ± 0.20^{a}	1.11 ± 0.09^{a}	1.10 ± 0.10^{b}	1.10 ± 0.14^{a}	1.01 ± 0.01^{c}	1.10 ± 0.16^{a}	1.01 ± 0.04^{b}	1.10 ± 0.18^{a}
	MS	0.8 ± 0.10^{b}	0.27 ± 0.02^{b}	0.85 ± 0.03^{b}	0.40 ± 0.10^{c}	0.82 ± 0.04^{b}	0.51 ± 0.03^{d}	0.80 ± 0.02^{b}	0.51 ± 0.05^{c}	0.78 ± 0.04^{b}
TSS (^{o}Brix)	SB	28.06 ± 1.72^{a}	28.87 ± 0.89^{b}	25.53 ± 1.05^{a}	28.93 ± 0.22^{b}	27.60 ± 0.54^{a}	29.4 ± 0.45^{b}	29.56 ± 0.72^{a}	29.40 ± 0.62^{b}	29.56 ± 0.38^{a}
	KMS	29.36 ± 0.76^{a}	30.57 ± 0.01^{a}	26.70 ± 0.42^{a}	31.4 ± 0.84^{a}	27.40 ± 1.52^{a}	31.60 ± 0.66^{a}	28.60 ± 1.22^{a}	31.60 ± 1.36^{a}	28.60 ± 0.86^{a}
	CA	21.16 ± 0.48^{b}	22.10 ± 0.32^{c}	22.65 ± 0.59^{b}	23.26 ± 0.38^{c}	23.60 ± 0.64^{b}	24.70 ± 0.78^{c}	23.80 ± 0.34^{b}	24.70 ± 0.12^{c}	23.80 ± 0.44^{b}
	MS	9.10 ± 0.30^{c}	9.15 ± 0.03^{d}	11.45 ± 0.79^{c}	9.18 ± 0.02^{d}	11.83 ± 1.59^{c}	9.18 ± 0.06^{d}	12.02 ± 0.16^{c}	9.18 ± 0.04^{d}	12.02 ± 0.76^{c}
Moisture (%)	SB	71.97 ± 1.85^{c}	71.05 ± 0.61^{c}	71.62 ± 0.74^{c}	70.48 ± 0.72^{c}	71.60 ± 0.60^{c}	70.22 ± 1.12^{c}	71.44 ± 0.84^{c}	70.12 ± 0.52^{c}	71.24 ± 0.62^{c}
	KMS	73.55 ± 1.34^{bc}	72.43 ± 0.69b^{c}	72.19 ± 1.25^{c}	72.5 ± 1.19^{c}	72.10 ± 0.92^{c}	72.27 ± 0.39^{c}	72.00 ± 0.12^{c}	72.20 ± 1.98^{bc}	71.88 ± 0.26^{c}
	CA	77.98 ± 2.11^{b}	76.90 ± 1.0^{b}	80.60 ± 1.46^{b}	75.83 ± 1.51^{b}	80.42 ± 1.01^{b}	75.29 ± 1.05^{b}	80.35 ± 0.87^{b}	75.10 ± 0.20^{b}	80.25 ± 1.93^{b}
	MS	90.03 ± 1.04^{a}	88.87 ± 3.52^{a}	85.20 ± 0.76^{a}	88.44 ± 0.61^{a}	84.22 ± 0.90^{a}	88.91 ± 0.96^{a}	84.12 ± 0.7^{a}	87.85 ± 1.36^{a}	84.10 ± 1.52^{a}
Ash (%)	SB	8.31 ± 0.45^{a}	6.80 ± 0.30^{b}	7.45 ± 0.19^{b}	9.11 ± 0.55^{a}	8.87 ± 0.05^{a}	9.16 ± 0.29^{b}	8.34 ± 0.58^{a}	9.26 ± 0.38^{a}	8.34 ± 0.34^{b}
	KMS	7.12 ± 1.10^{a}	8.45 ± 0.24^{a}	8.67 ± 0.19^{a}	9.81 ± 0.96^{a}	8.65 ± 0.13^{b}	9.760 ± 0.06^{a}	8.89 ± 0.23^{a}	9.96 ± 0.71^{a}	8.89 ± 0.07^{a}
	CA	0.34 ± 0.02^{b}	0.39 ± 0.03^{c}	0.40 ± 0.02^{d}	0.64 ± 0.06^{b}	0.42 ± 0.02^{d}	0.84 ± 0.06^{c}	0.45 ± 0.07^{b}	0.96 ± 0.09^{b}	0.47 ± 0.05^{d}
	MS	0.45 ± 0.08^{b}	0.46 ± 0.08^{c}	0.90 ± 0.04^{c}	0.51 ± 0.03^{b}	0.92 ± 0.04^{c}	0.72 ± 0.03^{c}	0.93 ± 0.01^{b}	0.74 ± 0.02^{b}	0.95 ± 0.03^{c}

Note: means ± standard deviation values on the same column within each variable following by different superscript letters ($^{a\text{-}d}$) differed significantly (P<0.05) as determined by Tukey HSD test. SB = 10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate. KMS = 10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite. CA = 1% (w/w) citric acid and MS = market sample. RFT=refrigerated temperature (7±2 °C), RT=room temperature (25±5 °C), TSS= total soluble solids as °Brix.

Table 4. Functional properties of onion (BARI Piaj 5) paste in glass container.

Parameters	Treatment	Initial	Duration of storage (months)							
			2		4		6		8	
			RFT	RT	RFT	RT	RFT	RT	RFT	RT
pH	SB	4.30 ± 0.20^{ab}	4.31 ± 0.03^{b}	4.42 ± 0.04^{b}	4.33 ± 0.03^{b}	4.43 ± 0.03^{b}	4.35 ± 0.02^{b}	4.43 ± 0.19^{b}	4.35 ± 0.02^{b}	4.43 ± 0.15^{b}
	KMS	4.19 ± 0.04^{b}	4.23 ± 0.02^{c}	4.30 ± 0.10^{b}	4.25 ± 0.02^{c}	4.34 ± 0.08^{b}	4.30 ± 0.02^{b}	4.35 ± 0.07^{b}	4.30 ± 0.02^{c}	4.35 ± 0.03^{b}
	CA	4.49 ± 0.03^{a}	4.72 ± 0.04^{a}	4.78 ± 0.04^{a}	4.79 ± 0.03^{a}	4.79 ± 0.07^{a}	4.80 ± 0.16^{a}	4.85 ± 0.03^{a}	4.80 ± 0.02^{a}	4.85 ± 0.09^{a}
Acidity (%)	SB	1.41 ± 0.03^{ab}	1.26 ± 0.02^{b}	1.24 ± 0.02^{a}	1.26 ± 0.02^{a}	1.10 ± 0.30^{a}	1.23 ± 0.03^{ab}	1.01 ± 0.21^{ab}	1.23 ± 0.02^{b}	1.01 ± 0.21^{a}
	KMS	1.44 ± 0.01^{a}	1.29 ± 0.01^{ab}	1.23 ± 0.03^{a}	1.27 ± 0.03^{a}	1.15 ± 0.05^{a}	1.19 ± 0.01^{b}	1.08 ± 0.04^{a}	1.19 ± 0.01^{b}	1.02 ± 0.12^{a}
	CA	1.36 ± 0.04^{b}	1.31 ± 0.02^{a}	1.12 ± 0.06^{b}	1.30 ± 0.02^{a}	1.10 ± 0.10^{a}	1.28 ± 0.03^{a}	1.07 ± 0.05^{a}	1.28 ± 0.02^{a}	1.07 ± 0.03^{a}
TSS (^{o}Brix)	SB	27.00 ± 0.80^{a}	27.33 ± 0.08^{a}	27.30 ± 1.12^{a}	27.63 ± 0.09^{a}	28.60 ± 0.32^{a}	28.80 ± 0.42^{a}	28.80 ± 0.46^{a}	28.80 ± 0.40^{a}	28.80 ± 1.12^{a}
	KMS	26.60 ± 1.00^{a}	26.70 ± 0.82^{a}	26.40 ± 1.00^{a}	27.75 ± 0.91^{a}	27.43 ± 0.95^{a}	29.30 ± 0.04^{a}	28.06 ± 1.76^{a}	29.30 ± 0.50^{a}	28.06 ± 0.24^{a}
	CA	21.33 ± 1.09^{b}	21.35 ± 0.77^{b}	21.30 ± 1.12^{b}	22.90 ± 1.02^{b}	22.33 ± 0.71^{b}	23.78 ± 0.40^{b}	23.40 ± 1.14^{b}	23.78 ± 1.14^{b}	23.40 ± 0.92^{b}
Moisture (%)	SB	71.97 ± 0.13^{b}	71.82 ± 1.37^{b}	71.8 ± 1.16^{b}	70.15 ± 1.26^{b}	71.75 ± 1.21^{b}	70.02 ± 2.07^{b}	71.50 ± 0.82^{b}	70.00 ± 1.08^{b}	71.34 ± 0.80^{b}
	KMS	73.40 ± 1.05^{b}	72.29 ± 0.93^{b}	72.28 ± 1.04^{b}	73.31 ± 1.12^{a}	72.15 ± 0.01^{b}	72.18 ± 0.73^{ab}	72.02 ± 0.60^{b}	73.36 ±1.15^{a}	71.98 ± 1.32^{b}
	CA	77.85 ± 0.95^{a}	76.96 ± 1.63^{a}	80.64 ± 1.48^{a}	74.44 ± 1.40^{a}	80.46 ± 1.80^{a}	74.16 ± 0.59^{a}	80.40 ± 1.54^{a}	74.08 ± 0.89^{a}	80.30 ± 0.76^{a}
Ash (%)	SB	8.30 ± 0.10^{a}	9.11 ± 0.22^{a}	7.81 ± 0.13^{b}	9.20 ± 0.25^{a}	8.14 ± 0.02^{b}	9.30 ± 0.40^{a}	8.50 ± 0.68^{a}	9.40 ± 0.50^{a}	8.50 ± 0.32^{a}
	KMS	8.35 ± 0.21^{a}	8.78 ± 0.63^{a}	8.92 ± 0.20^{a}	7.67 ± 0.22^{b}	8.69 ± 0.17^{a}	8.92 ± 0.94^{a}	8.08 ± 0.10^{a}	8.98 ± 0.02^{a}	8.08 ± 1.14^{a}
	CA	0.30± 0.13^{b}	0.38 ± 0.03^{b}	0.39 ± 0.01^{c}	0.39 ± 0.09^{c}	0.42 ± 0.02^{c}	0.43 ± 0.02^{b}	0.44 ± 0.02^{b}	0.45 ± 0.01^{b}	0.46 ± 0.04^{b}

Note: Means ± standard deviation values on the same column within each variable following by different superscript letters ($^{a\text{-}d}$) differed significantly (P<0.05) as determined by Tukey HSD test. SB = 10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoat e. KMS = 10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite. CA = 1% (w/w) citric acid. Market sample of glass containers did not find. RFT=refrigerated temperature (7±2 °C), RT=room temperature (25±5 °C), TSS= total soluble solids as °Brix.

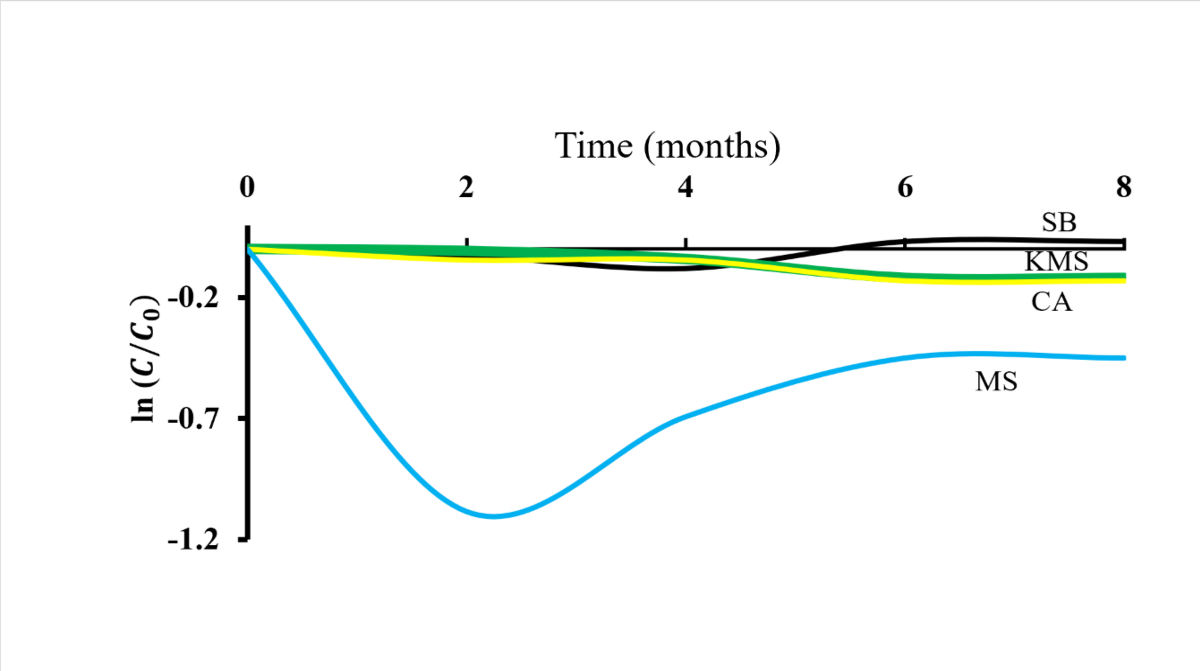

Figure 2. Onion paste stored in plastic container at room temperature. The natural logarithmic acidity ratio, was plotted against storage time (0–8 months) for four treatments: SB [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate], KMS [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite], CA [1% (w/w) citric acid], and MS (market sample). SB, KMS, and CA remained closely clustered near the baseline throughout storage, with SB showing the greatest stability by month 8. Market sample underwent rapid, severe acidity loss, followed by partial recovery and stabilization at approximately −0.45 from month 6 to 8.

Table 5. Kinetic parameters for acidity percentage degradation of onion paste in plastic container at room and refrigerated temperature.

Treatment	Kinetic parameters					
	RT			RFT		
	k	$t_{1/2}$	R^2	k	$t_{1/2}$	R^2
SB	0.0002	9.50	0.1975	0.00004	47.48	0.0441
KMS	0.0005	3.80	0.8697	0.0005	3.80	0.7203
CA	0.0005	3.80	0.8629	0.0001	18.99	0.5889
MS	0.0003	6.33	0.0064	0.0002	9.50	0.3289

Note: k is the rate constant ($days^{-1}$), $t_{1/2}$ is the half-life (years), and R^2 is the correlation coefficient. SB =10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate; KMS =10%(w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite; CA =1% (w/w) citric acid; MS = market sample. RT= room temperature (25 ± 5 °C); RFT = refrigerated temperature (7±2 °C).

Under refrigerated plastic storage, SB and market samples initially showed an increase in acidity degradation, which then stabilized. CA treated samples exhibited a modest decline, while KMS treated samples displayed the most sustained acidity degradation across all treatments, falling to a value of -0.14 by months 6 to 8 (Figure 3). However, the overall degradation was generally slower than at RT. KMS retained the same rate constant (k = 0.0005 $days^{-1}$, t1/2 = 3.80 years) with a slightly reduced R^2 (0.7203) compared to RT. CA-treated samples showed a reduced rate constant (k = 0.0001 $days^{-1}$) and an extended half-life (t1/2 = 18.99 years), with a moderate R^2 (0.5889). SB exhibited the slowest degradation (k = 0.00004 $days^{-1}$, t1/2 = 47.48 years) but with a very poor model fit (R^2 = 0.0441). The market sample, conversely, had a rate constant of 0.0002 $days^{-1}$, a half-life of 9.50 days, and an R^2 of 0.3289 (Table 5).

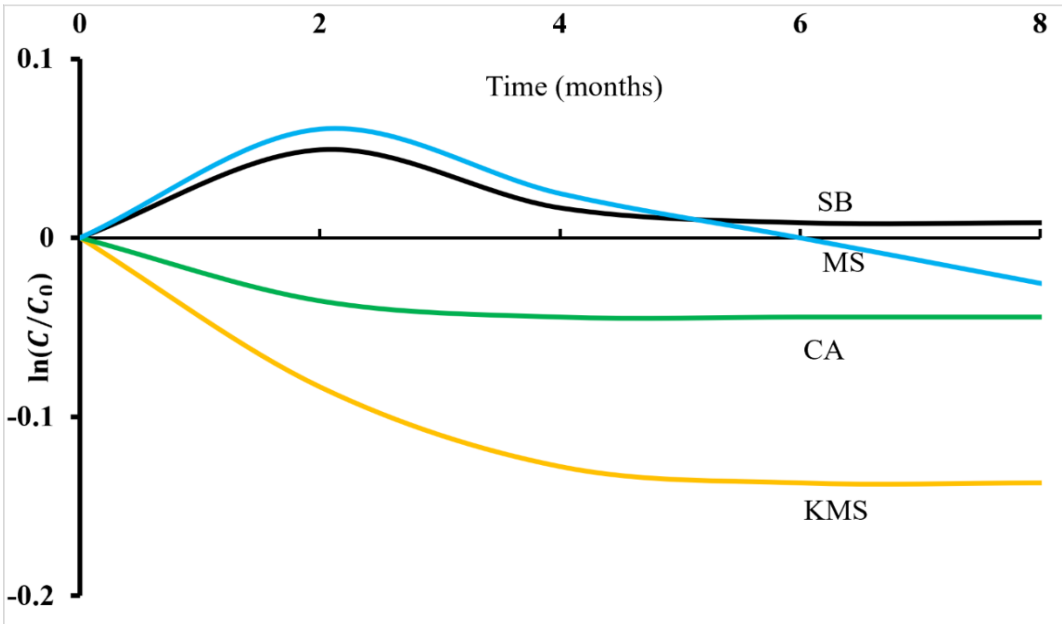

Figure 3. Onion paste stored in plastic container at RFT conditions. The natural logarithmic acidity ratio, was plotted against storage time (0–8 months) for four treatments: SB [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate], KMS [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite], CA [1% (w/w) citric acid], and MS (market sample). SB and MS sample both exhibited an initial increase before declining and stabilizing. KMS declined quickly and remained essentially constant thereafter, indicating strong early stabilization.

In glass containers at RT, only the 1% citric acid-treated sample retained the highest acidity stability, producing a -0.06 value by month 8. In contrast, the SB and KMS-treated samples degraded more markedly, with KMS exhibiting the greatest loss, yielding a -0.19 value (Figure 4).

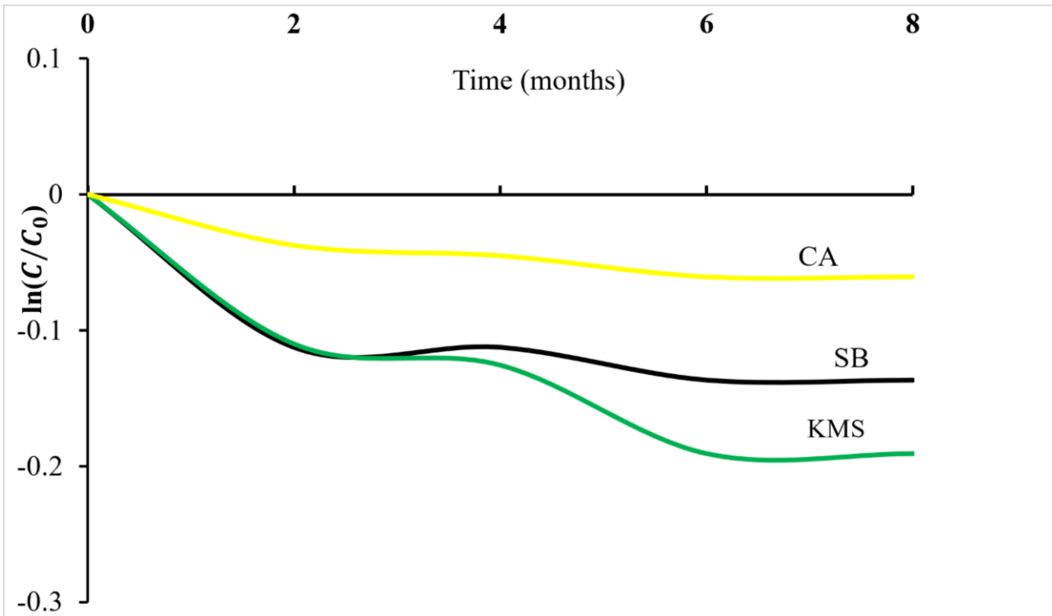

Figure 4. Onion paste preserved in glass container at room temperature. The natural logarithmic acidity ratio, was plotted against storage time (0–8 months) for four treatments: SB [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate], KMS [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite], CA [1% (w/w) citric acid], and MS (market sample). SB, KMS, and CA treated all sample showed continuous declines whereas CA exhibited the greatest stability, SB and KMS both dropped sharply.

Under refrigerated glass storage, acidity degradation was most pronounced overall, with SB and KMS declining steadily to approximately -0.33 and -0.35, respectively, by month 8. Meanwhile, CA degraded rapidly within the first 2 months before stabilizing at a comparatively higher level (-0.24) (Figure 5).

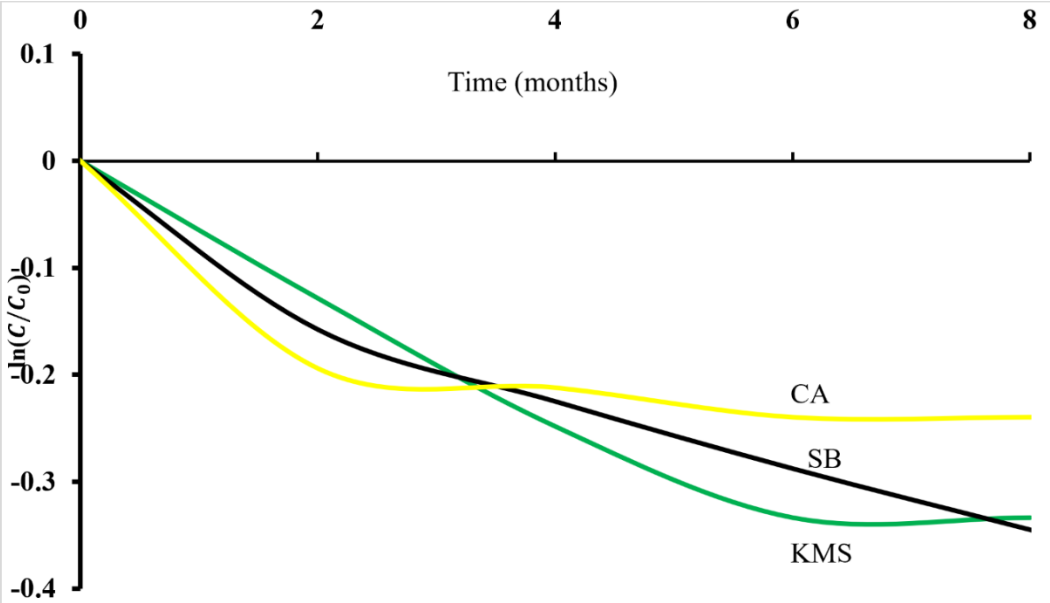

Figure 5. Onion paste stored in glass container at refrigerated conditions. The natural logarithmic acidity ratio, was plotted against storage time (0–8 months) for four treatments: SB [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate], KMS [10% (w/w) salt, 1% (w/w) citric acid, and 1000 ppm potassium metabisulfite], CA [1% (w/w) citric acid], and MS (market sample). CA treated sample declined rapidly within the first 2 months before stabilizing through month 8. SB and KMS declined more gradually at first 2 month but continued degrading steadily throughout storage.

Furthermore, the kinetic parameters describing acidity (%) degradation were determined for glass-packaged onion paste stored at RT and RFT across three treatments: SB, KMS, and CA. Degradation consistently followed first-order kinetics. Rate constants (k) were higher and half-lives shorter under RFT compared to RT across all treatments. The first-order kinetic model provided the strongest fit for KMS under refrigerated storage (R^2 = 0.9153), followed closely by SB under the same condition (R^2 = 0.8654). This indicates that the model most reliably describes acidity degradation in these treatments at low temperatures. In contrast, the CA treatment under RFT showed the weakest fit (R^2 = 0.6232), suggesting a greater deviation from first-order behavior for citric acid alone under refrigerated conditions (Table 6).

Table 6. Kinetic parameters for acidity percentage degradation of onion paste in glass container at room and refrigerated temperature.

Treatment	Kinetic parameters					
	RT			RFT		
	k	**$t_{1/2}$**	**R^2**	**k**	**$t_{1/2}$**	**R^2**
SB	0.0004	4.75	0.6292	0.0013	1.46	0.8654
KMS	0.0007	2.71	0.8232	0.0012	1.58	0.9153
CA	0.0002	9.50	0.7872	0.0008	2.37	0.6232

Note: k is the rate constant ($days^{-1}$), $t_{1/2}$ is the half-life (years), and R^2 is the correlation coefficient. SB =10%(w/w) salt, 1% (w/w) citric acid, and 1000 ppm sodium benzoate; KMS =10%(w/w) salt, 1%(w/w) citric acid, and 1000 ppm potassium metabisulfite; CA =1%(w/w) citric acid. RT= room temperature (25 ± 5 °C); RFT = refrigerated temperature 7 ± 2 °C.

4. Discussion

The study, conducted in 2025, investigated the physicochemical characteristics and degradation kinetics of preserved onion paste stored in plastic and glass containers under room and refrigeration conditions. Onion processing can significantly impact income generation in rural and semi-urban areas, potentially opening access

to international markets due to its distinctive flavors and extended shelf life. This research evaluated the quality of onion paste for commercial manufacturers and retailers over an eight-month storage period.
Onion paste quality was influenced by treatment, container, storage temperature, and duration. Moisture content, pH, and acidity were significantly affected by these parameters ($P \leq 0.001$). The paste's pH remained relatively stable throughout storage, unlike market samples, which consistently showed a pH above 4.50 under both room and refrigeration temperatures. Samples treated with SB and KMS maintained a pH below 4.50. However, the citric acid-treated sample exhibited a higher pH due to its inherent acidity. Refrigerated samples showed comparatively smaller pH increases than those stored at RT. Arefin *et al*. (2019) similarly reported the lowest pH value (4.06) in onion paste treated with a combination of 0.8% citric acid and potassium metabisulfite. The gradual increase in pH during storage can be attributed to metabolic activity, microbial growth, and the degradation of organic acids. This can create favorable conditions for microbial growth, ultimately contributing to quality deterioration and spoilage during prolonged storage (Arefin *et al*., 2019). Lower temperatures slow microbial proliferation and enzymatic reactions, thereby preserving the acidity of processed foods. Previous studies have also indicated that lower temperature storage reduces most metabolic reactions and microbial growth, resulting in minimal quality losses (Tarlak, 2023; Chang *et al*., 2025).
Titratable acidity gradually decreased throughout the storage period in both plastic and glass containers. The initial titratable acidity was higher in the KMS-treated sample, demonstrating more consistent stability under both room and refrigeration conditions in plastic containers by the end of storage. SB-treated samples maintained relatively higher acidity values compared to other treatments, while market samples exhibited the lowest acidity during storage. Notably, both SB and KMS samples achieved a pH below 4.50, which helps control the growth of pathogenic food microorganisms, excluding molds and yeasts (Seifu *et al*., 2018).
The TSS consistently recorded the highest values in KMS-treated onion paste samples, whereas market samples exhibited the lowest. The TSS of onion paste remained constant in SB and KMS treatments at both temperatures for two months of storage. In contrast, it was slightly lower in CA treatment and considerably lower in market samples. The increasing trends in TSS observed in several treatments during storage may be attributed to the hydrolysis of complex carbohydrates into simpler soluble sugars, as well as slight moisture loss leading to the concentration of soluble components. Similar increases in TSS during storage have been reported in processed fruit and vegetable products due to biochemical transformations and concentration effects. However, some studies have reported slight decreases in TSS during storage due to fermentation or microbial metabolism of sugars. Therefore, the variation in TSS during storage depends on the balance between sugar hydrolysis and microbial utilization (Chi *et al*., 2026). Refrigerated storage in glass containers helped maintain relatively stable TSS levels compared with RT storage, suggesting that low temperatures reduce metabolic activity and limit sugar degradation reactions. Similar findings have been reported for minimally processed fruits and vegetables stored under controlled temperature conditions (Gu *et al*., 2024).
The significant interactions among treatment, container, and temperature suggest that formulation components (e.g., preservatives, antioxidants) may interact with the physical barrier properties of packaging materials, thereby influencing moisture dynamics. Seifu *et al.* (2018) observed that fresh onion samples of Sweet Carolin exhibited a significantly higher moisture content (90.3%) compared with Bombay Red (83.3%) and Qellafo (81.7%). During storage, moisture diffuses between the components of fresh-filled pasta and the package headspace, as well as between the package and the external environment, until thermodynamic equilibrium is reached. Therefore, the packaging properties, water activity of the components, and storage conditions collectively determine the gain or loss of moisture during storage (Zardetto *et al*., 2025). For glass containers, refrigerated storage consistently resulted in lower rates of moisture degradation compared with RT storage. Additionally, glass containers provide slightly better stability than plastic containers due to their superior barrier properties against oxygen and moisture. Arefin *et al*. (2019) found that the change in moisture content was higher in onion paste samples stored at ambient temperature than under refrigerated conditions, likely due to greater moisture evaporation through packaging materials at higher temperatures, whereas refrigeration helps retain moisture and extend shelf life.
Initially, the ash content of onion paste stored in plastic containers, SB, and KMS-treated samples exhibited the highest percentage, whereas citric acid and market samples showed the lowest values. Among all treatments, the KMS-treated sample stabilized, but the SB-treated sample increased slightly, while the citric acid and market samples remained constant. On the other hand, paste preserved in glass containers revealed a similar trend for SB, KMS, and citric acid-treated samples. At the end of storage, SB and KMS samples were nearly at RT, but the SB-treated sample exhibited a slightly higher ash content under RFT than the KMS sample. Minor variations may occur due to changes in moisture content or concentration effects during storage (Pelden *et al*., 2025).

However, the first-order kinetic model applied to acidity degradation did not fit equally well across all treatments, packaging materials, and storage temperatures. This variation in goodness-of-fit is itself informative, as the kinetic constant rate and correlation coefficient can predict the shelf-life of onion paste. Among different quality indicators, acidity (%) is widely considered an important index for assessing quality loss in spice-based products such as onion paste, due to the reactive nature of organic acids and their susceptibility to enzymatic and non-enzymatic reactions during storage (Zhang *et al*., 2021).

Using $R^2 \geq 0.90$ as a threshold for an acceptable first-order fit and $R^2 < 0.70$ as a poor fit, seven of the twelve treatment × packaging × temperature combinations were well described by the model, three were marginally described, and four SB and the market sample (MS), both in plastic packaging) were poorly described (R^2= 0.006–0.33). Among the well-fitted treatments, the KMS treated sample packed in glass containers at refrigerated temperatures exhibited the highest correlation coefficient (R^2> 0.90), indicating strong agreement with the first-order kinetic model, with a half-life of 1.5 years. This consistency is attributed to sulfur dioxide, which is released from potassium metabisulfite in aqueous systems, thereby suppressing microbial growth and inhibiting the oxidative and enzymatic reactions that would otherwise drive irregular, matrix-dependent degradation (Drosou *et al*., 2024). CA was also marginally fitted at RT in both packaging types (R^2 = 0.86; plastic, 0.79 glass) but declined to a poor fit under refrigeration in both (R^2 = 0.59 plastic, 0.62 glass). This suggests that citric acid's stabilizing effect on acidity retention is more predictable at RT than under refrigeration. By contrast, SB and MS in plastic packaging did not degrade in a manner consistent with first-order kinetics. The poor fit for these two treatments in plastic likely reflects a more irregular or non-monotonic degradation pattern over the eight-month storage period, potentially arising from fluctuating microbial activity in the absence of a strong preservative effect (MS) or from a distinct degradation mechanism not well captured by a single constant-rate model (SB), rather than an unusually slow or fast true degradation rate. Notably, SB was fitted in glass packaging (R^2 = 0.63 at RT, 0.87 at RFT), indicating that its poor first-order fit is specific to the SB-plastic combination rather than an inherent property of SB as a preservative.

A first-order kinetic model was also the best fit for vitamin C degradation in onion powder, with correlation coefficients (R^2) ranging from 0.92 to 0.94 in different packaging materials during storage (Majid *et al*., 2018). Onion paste typically contains high moisture levels, which facilitate hydrolytic reactions and enhance oxygen diffusion within the product matrix. Moisture content promotes biochemical reactions and microbial activity that accelerate the degradation of organic acids. Hence, the faster rate of acidity degradation observed in room-temperature samples may therefore be attributed to increased oxygen transmission and enhanced metabolic activities.

The kinetic analysis clearly indicates that both storage temperature and packaging material significantly affect the stability of acidity in onion paste during storage. Refrigerated storage combined with glass packaging resulted in the lowest degradation rate and longest predicted half-life of acidity, indicating better preservation of product quality. These findings suggest that maintaining low storage temperatures and selecting appropriate packaging materials are essential strategies for extending the shelf life of onion paste and maintaining its physicochemical stability (Gupta *et al*., 2025). However, the absence of direct microbial enumeration data limits the extent to which the pH- and mechanism-based explanations above can be confirmed rather than inferred. Future work pairing the physicochemical trends reported here with microbial counts would more directly substantiate the preservative-mechanism argument.

5. Conclusions

This study revealed that storage temperature, packaging material, and preservative treatment significantly influenced the physicochemical quality and degradation kinetics of onion paste. Refrigerated storage substantially slowed deterioration compared to room temperature. The potassium metabisulphite-based treatment, particularly when packaged in glass containers and stored under refrigeration, most effectively preserved acidity, soluble solids, moisture, and ash content. Acidity degradation followed first-order reaction kinetics with a strong model fit, confirming that onion paste quality deterioration can be up to three years. These findings offer processors and retailers a scientific basis for evidence-based storage and packaging decisions to reduce spoilage and food waste. However, kinetic modeling in this study was limited to acidity, leaving the degradation behavior of other quality attributes less understood. Future research should extend kinetic characterization to these remaining attributes and validate the predictive framework under real commercial storage and distribution conditions.

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Data availability statement
All data of the study are available in the text and tables of this manuscript.

Generative AI statement
No generative AI tools were used in the preparation of this article.

Authors' contributions
Md. Masud Alam: investigation, designed the study, supervised the research work, and monitored all experimental activities, funding acquisition; Md. Golam Ferdous Chowdhury : investigation, formal data analysis and interpretation, and writing the original manuscript; Robiul Islam: conceptualization, methodology, formal analysis, developed the experimental protocols, prepared the figures and tables, and writing - original draft manuscript; Md. Mazharul Anwar: reviewed and edited; Md. Faizul Haque Shikder: overall reviewed the article and finalized the manuscript. All authors have read and approved the final manuscript.

Conflict of interest
None to declare.

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