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Storage stability of aerobically packaged superchilled paneer

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Abstract

Despite its great nutritional value and varied culinary applications, paneer is perishable due to its high moisture content, which causes rapid physicochemical, microbiological, and sensory deterioration. This study assessed the storage durability of aerobically packaged paneer under chilling, superchilling, and freezing temperatures for several periods of time, aiming to determine the best preservation strategy. During storage, the moisture content of fresh paneer began to decrease from $69.32 \pm 0.13\%$. By day 15, moisture loss was highest under chilling ($64.47 \pm 0.92\%$), while higher retention was found under superchilling ($67.07 \pm 0.44\%$) and freezing ($67.90 \pm 0.48\%$). Acidity increased significantly in chilled samples ($0.46 \pm 0.004\%$ to $0.61 \pm 0.007\%$), but less so in superchilling ($0.53 \pm 0.007\%$) and freezing ($0.48 \pm 0.007\%$). The TBA value of lipid oxidation rose. Oxidative alterations were significantly reduced by chilling (0.12 ± 0.004 to 0.77 ± 0.008), but were effectively slowed by superchilling (0.39 ± 0.007) and freezing (0.22 ± 0.004). Proteolysis (tyrosine value) increased to 54.28 ± 0.79 mg/100 g during chilling, but decreased during superchilling (45.46 ± 0.39 mg/100 g) and freezing (45.06 ± 0.40 mg/100 g). Microbiological investigation showed that chilling increased total plate count from $2.28 \log_{10} \text{cfu/g}$ to $8.82 \log_{10} \text{cfu/g}$ by day 15, superchilling $6.51 \log_{10} \text{cfu/g}$, and freezing $4.20 \log_{10} \text{cfu/g}$. Psychrophilic counts followed a similar trend with no coliforms. Chilling caused a quick decline in sensory quality, resulting in a 2.24 ± 0.16 decline in overall acceptability. Superchilled paneer had better texture and sensory scores (11.18 - 22.76). Overall, Superchilling protected paneer quality, safety, and shelf life better than chilling storage.

Keywords: Paneer, preservation, superchilling, freezing, storage

Introduction

World milk production is dominated by India, which produces 25% of it. Milk output rose from 239.30 million tonnes in 2023-24 to 247.87 million tonnes in 2024-25, with per capita milk availability at 485 g/day, more than the world average dietary guideline. Uttar Pradesh (15.66%), Rajasthan (14.82%), Madhya Pradesh (9.12%), Gujarat (7.78%), and Maharashtra (6.71%) produce 54.09% of India's milk. The dairy sector supports millions of small and marginal farmers in India and boosts the economy. The organized dairy sector has grown rapidly due to investments in milk processing, cold-chain infrastructure, and quality certification. Large amounts of milk and milk products are still sold informally. The Indian dairy sector would exceed rupees 21 trillion by 2025 due to rising demand for value-added dairy products like paneer, curd, cheese, and fermented milk (IMARC Group, 2024) [15]. India's plentiful milk supplies allow dairy output to grow. Cheese, flavored milk, whey beverages, organic milk, and probiotic dairy products are likely to expand at rates surpassing 20% yearly, while liquid milk is expected to grow by 16% during the next five to six years. Paneer, ghee, khoa, and ice cream are predicted to rise 11-20% annually.

Paneer, a healthful, high-protein vegetarian dairy product, has grown in popularity. Due to health consciousness, urbanization, and the growth of organized retail and food service, the Indian paneer market was worth 648 billion in 2024 and is expected to reach 2 trillion by 2033 (IMARC Group, 2024) [15]. India consumes 5% of its milk as heat and acid-coagulated paneer, chhana, and sandesh. It is prepared by coagulating cow milk, buffalo milk, or their blend using food-grade acids such as citric acid or lactic acid (FSSAI, 2011) [13]. Standard paneer has maximum 70% moisture and minimum 50% milk fat on a dry matter basis. Vegetarian diets benefit from paneer's high-quality protein (18-20%), fat (25%), minerals, and vitamins (Sachdeva, 1998) [24].

Despite its great nutritional value and widespread consumption, paneer is perishable and has a refrigerated shelf life of 5-6 days. High moisture and nutrient content make paneer sensitive to microbial contamination and rapid biochemical deterioration, especially in poor hygienic circumstances (Thakral, 1986) ^[27]. Microbial development on the surface causes slime, discoloration, off-flavors, and product rejection (Sachdeva and Singh, 1990) ^[25]. Recently, consumer awareness of food safety and quality has highlighted the need for better preservation and packaging solutions. Rapid industrialization, global food trade, and demand for fresh and minimally processed foods have raised the need for better storage solutions (Alizadeh *et al.*, 2007) ^[1]. Packaging plays a vital role in extending the shelf life of dairy products by protecting them from microbial contamination, oxygen, moisture, and physical damage. Paneer is sometimes frozen to lengthen its shelf life, however big ice crystals can disrupt the microstructure, impacting texture, physicochemical properties, and sensory quality (Charoenrein and Owcharoen, 2016) ^[11]. Superchilling, which stores food slightly below freezing without ice crystal formation, is a new preservation method. This approach reduces microbial growth and structural damage compared to conventional freezing. Superchilling has been extensively investigated in fish, meat, fruits, and vegetables, while paneer and other fresh dairy products have received less attention. Therefore, this study examined the effects of superchilling on paneer's storage stability, physicochemical, microbiological, and sensory quality providing new insights into extending its shelf life and maintaining quality during storage.

Materials and Methods

Fresh buffalo milk was obtained from the cattle and buffalo farm of Nagpur Veterinary College and standardized to 6% fat and 9% solids-not-fat to ensure optimal paneer quality. Paneer was made according to the established protocol of Bhattacharya *et al.* (1971) ^[9], which entailed boiling milk to 82 °C for 5 minutes, cooling to 70 °C, inducing coagulation with 1% citric acid, draining the whey, pressing at 2 kg/cm² for 15 minutes, chilling for 2-3 hours, and finally cutting. The newly made paneer was packaged aerobically in food-grade low-density polyethylene (LDPE) pouches and stored under temperature conditions (chilling, superchilling, and freezing). The proximate composition of fresh paneer, encompassing moisture, fat, protein, and ash, was assessed in accordance with the standard techniques established by AOAC International (2016) ^[4]. Moisture was quantified through oven drying, protein via the Kjeldahl method with an automated Kjeltac system, fat by the Gerber method, and ash through muffle furnace cremation. The physicochemical parameters, including titratable acidity, pH, thiobarbituric acid (TBA) value, and tyrosine value, were assessed during storage to evaluate biochemical and oxidative alterations. The microbiological quality, encompassing total plate count, psychrophilic count, and coliform count, was assessed utilizing conventional methodologies outlined by the American Public Health Association (1984) ^[2]. Serial dilutions were aseptically prepared, inoculated onto selective media, and findings were reported as log₁₀ cfu/g. A sensory evaluation was

conducted utilizing a 9-point hedonic scale in accordance with Bureau of Indian Standards norms by a qualified panel. The textural qualities of paneer held at various temperature conditions (chilling, superchilling, and freezing) were assessed using a texture analyzer (TA-XT2i, Stable Micro Systems, UK). Uniform cubes of paneer (1×1×1 cm) were evaluated for hardness, cohesiveness, springiness, chewiness, and shear force by Texture Profile Analysis. The experimental data were subjected to statistical analysis utilizing standard analysis of variance techniques as outlined by Gomez and Gomez (1984).

Results and Discussion

The storage stability of aerobically packaged paneer under chilling, superchilling and freezing conditions revealed significant variations in proximate composition and physicochemical parameters during the storage period (Sachdeva and Singh, 1988; Rao *et al.*, 1997) ^[24, 23]. The change in the proximate composition and physicochemical qualities of paneer stored under different temperature during the storage period has been presented in Table 1. A gradual decline in moisture content was observed in all treatments; however, the loss was more pronounced under chilling, mainly due to increased drip loss, surface dehydration and moisture migration, whereas superchilling and freezing effectively retained moisture by reducing metabolic activity and water mobility (Watharkar *et al.*, 2015) ^[28]. Protein and fat contents showed a slight increasing trend during storage, particularly under chilling and superchilling conditions, which was attributed to concentration effects resulting from moisture reduction rather than actual synthesis or accumulation (Pal and Kapoor, 2000) ^[20]. Frozen samples exhibited comparatively lower changes in these parameters, indicating better compositional stability (Rai *et al.*, 2008) ^[22]. Ash content remained almost constant throughout the storage period in all treatments, reflecting the stability of mineral constituents irrespective of temperature (Sachdeva & Singh, 1988) ^[24]. Among physicochemical attributes, acidity increased significantly during storage, with the highest increase under chilling due to enhanced microbial activity and fermentation of residual lactose, while superchilling retarded acid development and freezing showed minimal changes (Singh *et al.*, 1988; Kumar *et al.*, 2008) ^[24, 18]. Correspondingly, pH decreased gradually in all treatments, with the greatest decline in chilled samples and better stability under superchilling and freezing (Masud *et al.*, 2007; Bukhari *et al.*, 2012) ^[19, 10]. Lipid oxidation, measured by TBA value, increased progressively during storage, with chilling showing the highest oxidation rate, whereas superchilling significantly slowed oxidative changes and freezing exhibited the lowest TBA values (Rao *et al.*, 1997; Arora *et al.*, 2003) ^[23, 5]. Overall, superchilling emerged as the most effective storage method, maintaining moisture, limiting excessive concentration of nutrients, controlling acidity and pH changes, and reducing lipid oxidation, thereby enhancing the overall quality and storage stability of paneer compared to conventional chilling while avoiding the structural and textural drawbacks often associated with freezing, as supported by Dairy Science and Technology and Fundamentals of Cheese Science.

Table 1: Changes in the proximate composition and changes in physico-chemical qualities of paneer stored under different temperature (chilling, superchilling and freezing) has been presented as below

Parameters	Storage Days					
	0	3	6	9	12	15
Moisture (%)						
Chilling	69.32±0.13 ^{aA}	68.12±0.32 ^{abA}	67.02±0.52 ^{bA}	66.15±0.64 ^{bcA}	64.77±0.89 ^{cB}	64.47±0.92 ^{cB}
Superchilling	69.32±0.13 ^{aA}	68.56±0.29 ^{abA}	68.23±0.33 ^{abcA}	67.68±0.39 ^{bcA}	67.19±0.51 ^{cA}	67.07±0.44 ^{cA}
Freezing	69.32±0.13 ^{aA}	68.86±0.17 ^{aA}	68.41±0.40 ^{abA}	67.94±0.47 ^{bA}	67.97±0.42 ^A	67.90±0.48 ^A
Protein (%)						
Chilling	18.28±0.19 ^{cA}	18.49±0.19 ^{bcA}	18.75±0.19 ^{bcA}	19.01±0.18 ^{abA}	19.07±0.29 ^{abA}	19.52±0.18 ^{aA}
Superchilling	18.28±0.19 ^{cA}	18.39±0.19 ^{bcA}	18.59±0.19 ^{abcA}	18.79±0.19 ^{abcA}	18.95±0.21 ^{abA}	19.15±0.19 ^{aAB}
Freezing	18.28±0.19 ^A	18.28±0.19 ^A	18.36±0.19 ^A	18.46±0.19 ^A	18.56±0.19 ^A	18.66±0.19 ^B
Fat (%)						
Chilling	25.85±0.93 ^{aA}	26.01±0.90 ^{aA}	26.26±0.83 ^{aA}	26.57±0.80 ^{aA}	26.78±0.70 ^{aA}	27.03±0.66 ^{aA}
Superchilling	25.85±0.93 ^{aA}	25.91±0.91 ^{aA}	26.32±0.94 ^{aA}	26.64±0.94 ^{aA}	26.86±0.89 ^{aA}	26.94±0.82 ^{aA}
Freezing	25.85±0.93 ^{aA}	25.70±0.87 ^{aA}	25.64±0.82 ^{aA}	25.62±0.74 ^{aA}	25.43±0.61 ^{aA}	25.60±0.64 ^{aA}
Ash (%)						
Chilling	1.72±0.02 ^{aA}	1.69±0.01 ^{aA}	1.69±0.01 ^{aA}	1.71±0.02 ^{aA}	1.71±0.02 ^{aA}	1.69±0.01 ^{aA}
Superchilling	1.70±0.01 ^{aA}	1.70±0.01 ^{aA}	1.69±0.01 ^{aA}	1.69±0.02 ^{aA}	1.71±0.02 ^{aA}	1.69±0.01 ^{aA}
Freezing	1.70±0.01 ^{aA}	1.71±0.02 ^{aA}	1.70±0.01 ^{aA}	1.70±0.01 ^{aA}	1.69±0.02 ^{aA}	1.69±0.01 ^{aA}
Acidity (%)						
Chilling	0.46±0.007 ^{aA}	0.49±0.010 ^{bA}	0.52±0.010 ^{cA}	0.55±0.008 ^{dA}	0.58±0.009 ^{cA}	0.61±0.007 ^{fA}
Superchilling	0.46±0.007 ^{aA}	0.47±0.007 ^{aB}	0.47±0.007 ^{aB}	0.49±0.007 ^{bB}	0.51±0.004 ^{cB}	0.53±0.007 ^{dB}
Freezing	0.46±0.007 ^{aA}	0.46±0.007 ^{ac}	0.46±0.006 ^{ac}	0.47±0.007 ^{ac}	0.47±0.006 ^{ac}	0.48±0.007 ^{bc}
pH						
Chilling	5.62±0.15 ^{aA}	5.56±0.15 ^{aA}	5.50±0.15 ^{aA}	5.43±0.15 ^{aA}	5.37±0.16 ^{aA}	5.11±0.22 ^{aA}
Superchilling	5.62±0.15 ^{aA}	5.59±0.15 ^{aA}	5.57±0.15 ^{aA}	5.52±0.15 ^{aA}	5.49±0.15 ^{aA}	5.45±0.15 ^{aA}
Freezing	5.62±0.15 ^{aA}	5.61±0.16 ^{aA}	5.60±0.15 ^{aA}	5.59±0.15 ^{aA}	5.52±0.21 ^{aA}	5.55±0.15 ^{aA}
TBA						
Chilling	0.12±0.004 ^{aA}	0.20±0.005 ^{bA}	0.34±0.011 ^{cA}	0.45±0.007 ^{dA}	0.63±0.014 ^{eA}	0.77±0.008 ^{fA}
Superchilling	0.12±0.004 ^{aA}	0.16±0.009 ^{bB}	0.21±0.006 ^{cB}	0.27±0.009 ^{dB}	0.33±0.005 ^{cB}	0.39±0.007 ^{fB}
Freezing	0.12±0.004 ^{aA}	0.13±0.004 ^{ac}	0.15±0.004 ^{bc}	0.18±0.003 ^{cc}	0.20±0.005 ^{dc}	0.22±0.004 ^{cc}
Tyrosine (mg/100 g)						
Chilling	12.60±0.24 ^{aA}	23.23±0.84 ^{bA}	35.57±1.26 ^{cA}	43.54±1.12 ^{dA}	49.67±0.41 ^{eA}	54.28±0.79 ^{fA}
Superchilling	12.60±0.24 ^{aA}	20.53±0.57 ^{bB}	28.08±2.26 ^{cB}	34.91±1.39 ^{dB}	41.45±1.11 ^{cB}	45.46±0.39 ^{fB}
Freezing	12.60±0.24 ^{aA}	20.30±0.43 ^{bB}	25.94±0.53 ^{cc}	34.42±1.05 ^{dB}	40.78±0.85 ^{cB}	45.06±0.40 ^{fB}
	68.86±0.17 ^{aA}					

Mean ± S.E. with different superscripts in capital letters in a column and small letters in a row differ significantly ($p < 0.05$).

Microbial Quality

The microbial quality during the storage period, as indicated by changes in total plate count (TPC), psychophilic count and coliform status. The changes in the microbial quality of aerobically packaged paneer stored under different temperature during the storage period has been presented in Table 2. Fresh paneer showed very low microbial counts, reflecting good hygienic quality at manufacture, which agreed with the findings of Sachdeva and Singh (1988) [24] and Rao *et al.*, (1997) [23]. During storage, TPC increased significantly in all treatments, with the highest increase under chilling due to favourable growth conditions for psychrotrophic microorganisms, whereas superchilling effectively retarded microbial proliferation by reducing metabolic activity and unfrozen water availability. Frozen samples consistently recorded the lowest TPC, indicating effective microbial suppression. Similar trends were

reported by Watharkar *et al.*, (2015) [28], Goyal and Gandhi (2016) [14] and Badhe *et al.*, (2020) [6]. Psychophilic count also increased significantly during storage, with the highest growth in chilled samples, while superchilling reduced growth and freezing provided maximum inhibition, supporting the observations of Kumar *et al.*, (2008) [18] and Sharma *et al.*, (2013) [26]. No coliform growth was detected in any treatment, indicating excellent sanitary quality and effective hygienic practices, in agreement with Singh *et al.*, (1988) [24]. Overall, storage temperature played a decisive role in microbial control, with freezing being most effective, followed by superchilling, while chilling allowed rapid microbial growth. However, considering both safety and quality, superchilling emerged as the most suitable method for extending the shelf life of paneer by controlling microbial proliferation without the adverse quality changes associated with freezing.

Table 2: Changes in microbiological parameters of paneer stored under different temperature (chilling, superchilling and freezing) (n = 5) has been presented as below

Parameters	Storage Days					
	0	3	6	9	12	15
Total Plate Count (TPC) (cfu/g ₁₀)						
Chilling	2.28±0.047 ^{fA}	4.49±0.304 ^{eA}	5.21±0.173 ^{dA}	6.65±0.233 ^{cA}	7.62±0.162 ^{bA}	8.82±0.073 ^{aA}
Superchilling	1.95±0.007 ^{fB}	2.25±0.026 ^{eB}	3.86±0.021 ^{dB}	4.41±0.056 ^{cB}	5.31±0.148 ^{bB}	6.51±0.011 ^{aB}
Freezing	1.89±0.009 ^{fB}	2.11±0.011 ^{eB}	2.64±0.030 ^{dC}	2.92±0.061 ^{cC}	3.30±0.053 ^{bC}	4.20±0.007 ^{aC}
Psychrophilic count (cfu/g ₁₀)						
Chilling	0.60±0.245 ^e	1.27±0.013 ^{dA}	1.64±0.018 ^{cA}	2.18±0.009 ^{bA}	2.31±0.011 ^{bA}	2.66±0.010 ^{aA}
Superchilling	0.40±0.245 ^d	1.10±0.009 ^{cB}	1.28±0.007 ^{bC}	1.48±0.007 ^{bB}	1.95±0.008 ^{aB}	2.10±0.007 ^{aB}
Freezing	0.20±0.200 ^c	1.07±0.014 ^{bB}	1.15±0.014 ^{bC}	1.31±0.017 ^{abC}	1.41±0.009 ^{aC}	1.49±0.010 ^{aC}

Mean ± S.E. with different superscripts in capital letters in a column and small letters in a row differ significantly ($p < 0.05$).

Sensory Quality

The sensory quality of aerobically packaged paneer stored under chilling, superchilling and freezing conditions showed a progressive decline during storage; however, the rate of deterioration differed significantly among treatments. The changes in the sensory quality of aerobically packaged paneer stored under different temperature during the storage period has been presented in Table 3. Fresh paneer exhibited high and uniform scores for appearance, colour, odour, overall acceptability and absence of sliminess, indicating good hygienic quality and standardization of preparation. During storage, paneer kept under chilling conditions showed a rapid and significant reduction in sensory scores due to surface dehydration, moisture loss, microbial growth, biochemical changes and development of dullness, discolouration, off-odours and slime formation. In contrast, superchilling and freezing effectively retarded sensory deterioration and maintained significantly higher scores throughout the storage period. Superchilled paneer consistently showed superior retention of appearance,

creamy white colour, desirable odour and overall acceptability, while also delaying visible slime formation, followed closely by frozen samples. The better sensory stability under superchilling and freezing could be attributed to reduced microbial activity, lower biochemical reactions and improved moisture retention. These findings are in agreement with earlier reports of Sachdeva and Singh (1988) [24], Rao *et al.*, (1997) [23], Masud *et al.*, (2007) [19], Kumar *et al.*, (2008) [18], Watharkar *et al.*, (2015) [28] and Goyal and Gandhi (2016) [14], who also reported gradual sensory deterioration of paneer during storage and better quality retention under advanced low-temperature preservation methods. Overall, the results clearly demonstrated that sensory quality decreased significantly under chilling, whereas superchilling emerged as the most effective storage method for maintaining superior sensory attributes and extending shelf life, while freezing also improved stability but may lead to quality drawbacks during long-term storage.

Table 3: Changes in the sensory quality of aerobically packaged paneer stored under different temperature (chilling, superchilling and freezing) has been presented as below

Parameters	Storage Days					
	0	3	6	9	12	15
Appearance						
Chilling	5.00±0.03 ^{aA}	4.52±0.02 ^{bB}	4.32±0.03 ^c	3.68±0.03 ^{dB}	2.48±0.05 ^{eB}	2.26±0.07 ^{fB}
Superchilling	5.00±0.01 ^{aA}	5.00±0.00 ^{aA}	4.42±0.03 ^b	4.28±0.05 ^{bcA}	4.14±0.09 ^{cdA}	4.00±0.13 ^{dA}
Freezing	5.00±0.03 ^{aA}	4.50±0.04 ^{bB}	4.38±0.05 ^{bc}	4.22±0.05 ^{cdA}	4.08±0.08 ^{deA}	3.92±0.12 ^{eA}
Colour						
Chilling	5.00±0.03 ^{aA}	4.66±0.02 ^{bB}	3.52±0.03 ^{cB}	3.44±0.02 ^{cB}	3.02±0.13 ^{dB}	2.38±0.05 ^{eB}
Superchilling	5.00±0.01 ^{aA}	5.00±0.00 ^{aA}	4.86±0.02 ^{bA}	4.78±0.02 ^{cA}	4.62±0.03 ^{dA}	4.50±0.03 ^{eA}
Freezing	5.00±0.03 ^{aA}	5.00±0.00 ^{aA}	4.86±0.02 ^{ac}	4.70±0.03 ^{dA}	4.50±0.07 ^{eA}	4.40±0.07 ^{eA}
Odour						
Chilling	5.00±0.03 ^{aA}	4.44±0.12 ^{bB}	3.90±0.24 ^{cB}	3.26±0.15 ^{dB}	2.76±0.23 ^{eB}	2.20±0.11 ^{fB}
Superchilling	5.00±0.01 ^{aA}	4.82±0.03 ^{aA}	4.72±0.03 ^{abA}	4.38±0.22 ^{bA}	4.00±0.20 ^{cA}	3.38±0.05 ^{dA}
Freezing	5.00±0.03 ^{aA}	4.74±0.05 ^{aA}	4.64±0.05 ^{aA}	4.08±0.26 ^{bA}	3.78±0.20 ^{bA}	3.30±0.07 ^{cA}
Overall Acceptability						
Chilling	5.00±0.01 ^{aA}	4.42±0.03 ^{bB}	3.68±0.05 ^{cB}	3.58±0.05 ^{cB}	2.60±0.07 ^{dB}	2.24±0.16 ^{eB}
Superchilling	5.00±0.03 ^{aA}	5.00±0.00 ^{aA}	4.78±0.03 ^{bA}	4.60±0.04 ^{cA}	3.68±0.05 ^{dA}	3.52±0.04 ^{eA}
Freezing	5.00±0.03 ^{aA}	5.00±0.00 ^{aA}	4.70±0.03 ^{bA}	4.58±0.03 ^{cA}	4.62±0.03 ^{dA}	3.40±0.07 ^{eA}
Visible Sliminess						
Chilling	5.00±0.03 ^{aA}	4.50±0.04 ^b	4.22±0.11 ^{bB}	3.46±0.15 ^{cB}	2.66±0.05 ^{dB}	2.32±0.17 ^{eB}
Superchilling	5.00±0.01 ^{aA}	4.68±0.05 ^b	4.54±0.06 ^{bcA}	4.36±0.10 ^{cA}	4.14±0.08 ^{dA}	3.86±0.08 ^{eA}
Freezing	5.00±0.03 ^{aA}	4.60±0.06 ^b	4.46±0.05 ^{bcA}	4.36±0.05 ^{cA}	4.00±0.09 ^{dA}	3.72±0.08 ^{eA}

Mean ± S.E. with different superscripts in capital letters in a column and small letters in a row differ significantly ($p < 0.05$).

Textural Quality

The changes in texture scores of paneer stored under different conditions has been presented in Table 4. along with depicted in figure 1 to 6. Significant differences ($p < 0.05$) were observed among treatments at all storage

intervals, confirming a pronounced effect of storage method on texture. Paneer stored under chilling conditions exhibited comparatively lower texture scores with gradual increase during storage, reflecting progressive hardening and loss of desirable softness due to moisture loss, tightening of the

protein matrix and microbial and biochemical changes during refrigerated storage.

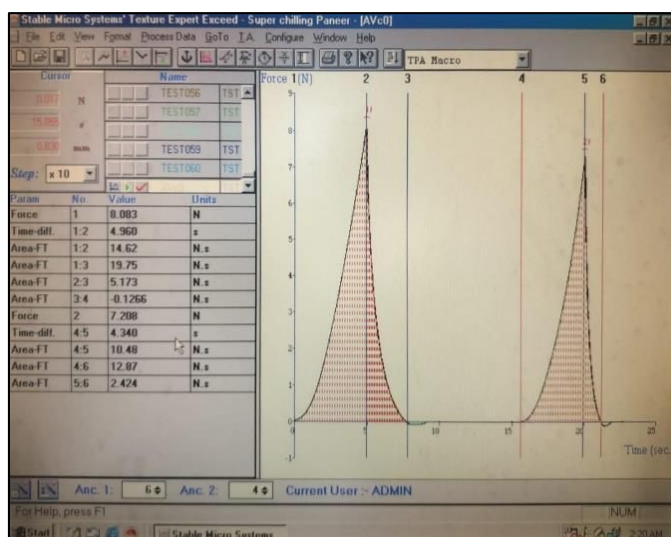
Table 4: Changes in the texture of paneer during storage under chilling, superchilling and freezing temperature during storage period (n = 5)

Days	Chilling	Super chilling	Freezing
0	3.36 ± 0.46^c	11.18 ± 0.29^e	6.35 ± 0.28^c
3	4.24 ± 0.24^c	12.75 ± 0.30^d	6.75 ± 0.32^c
6	5.41 ± 0.37^b	16.18 ± 0.37^c	7.17 ± 0.23^{bc}
9	6.23 ± 0.34^b	17.40 ± 0.28^b	8.14 ± 0.22^b
12	7.82 ± 0.31^a	18.30 ± 0.31^b	9.62 ± 0.53^a
15	8.11 ± 0.24^a	22.76 ± 0.31^a	10.43 ± 0.67^a

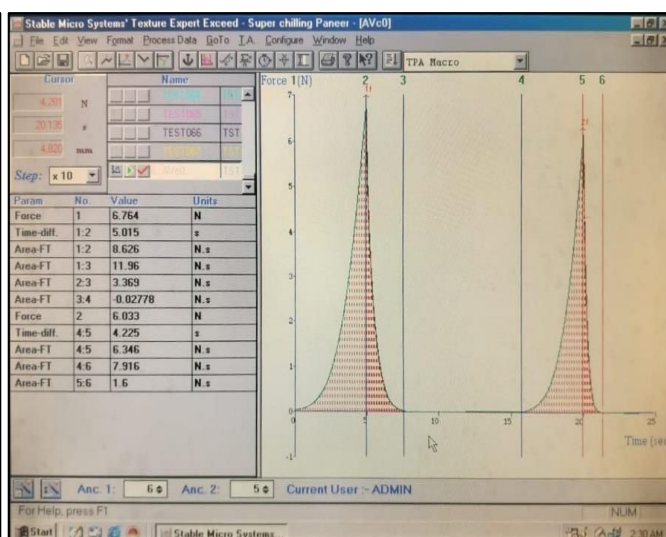
Mean $\pm$ S.E. with different superscripts in capital letters in a row and small letters in a column differ significantly ($p < 0.05$).

In contrast, superchilled paneer consistently recorded the highest texture scores, indicating better retention of desirable firmness and cohesiveness, which could be attributed to improved moisture retention, reduced protein denaturation and controlled biochemical reactions at subzero

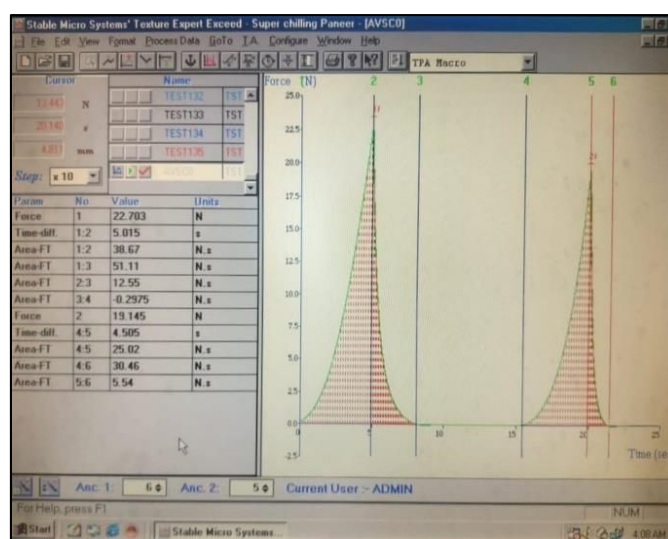
temperature. Frozen paneer also showed increased hardness, mainly due to structural damage and protein aggregation caused by ice crystal formation during freezing. The results further confirmed highly significant treatment effects at all storage intervals, emphasizing the decisive role of storage temperature in determining texture. These findings are in agreement with earlier reports of Sachdeva and Singh (1988) [24], Patel *et al.*, (1991) [21], Rao *et al.* (1997) [23], Aneja *et al.* (2002) [3], Masud *et al.* (2007) [19], Kumar *et al.* (2008) [18], Kadam *et al.* (2012) [16] and Watharkar *et al.*, (2015) [28], who also reported gradual textural deterioration of paneer during storage, particularly under refrigeration. Recent instrumental studies by Kaura *et al.*, (2023) [17], Badshah *et al.*, (2023) [7], Bhardwaj *et al.*, (2024) [8] further supported that better moisture retention and controlled storage improved texture stability. Overall, superchilling emerged as the most effective method for preserving desirable texture of paneer by maintaining optimal firmness and cohesiveness while minimizing structural damage compared to chilling and freezing.



Chilling

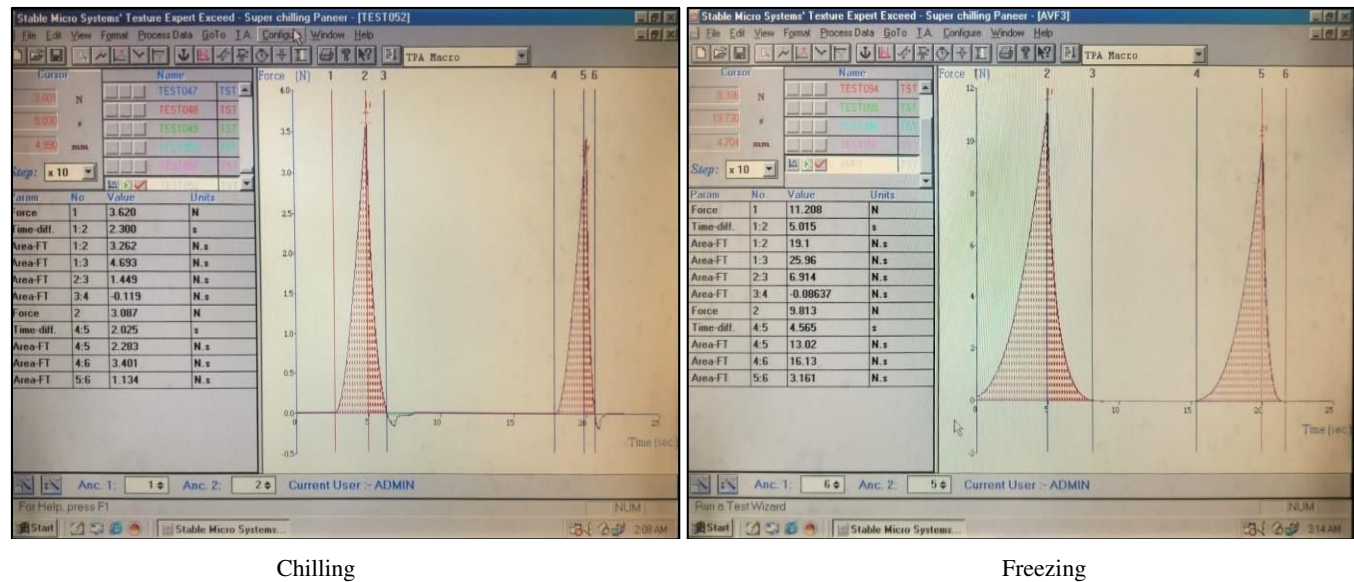


Freezing



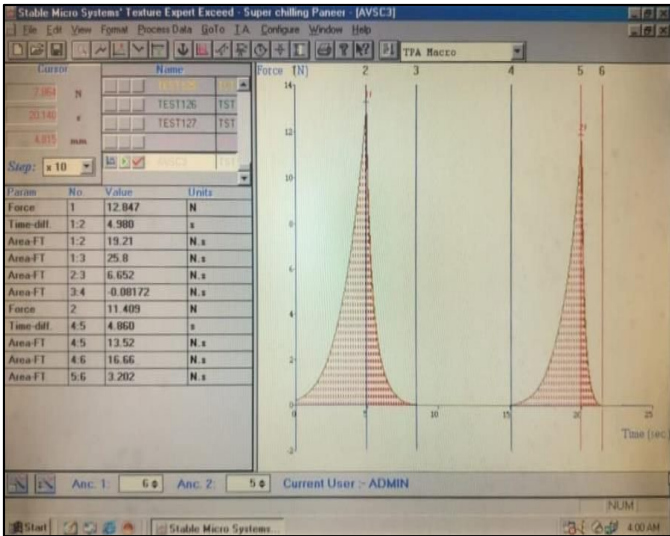
Super Chilling

Fig 1: Changes in Texture of paneer on day zero.



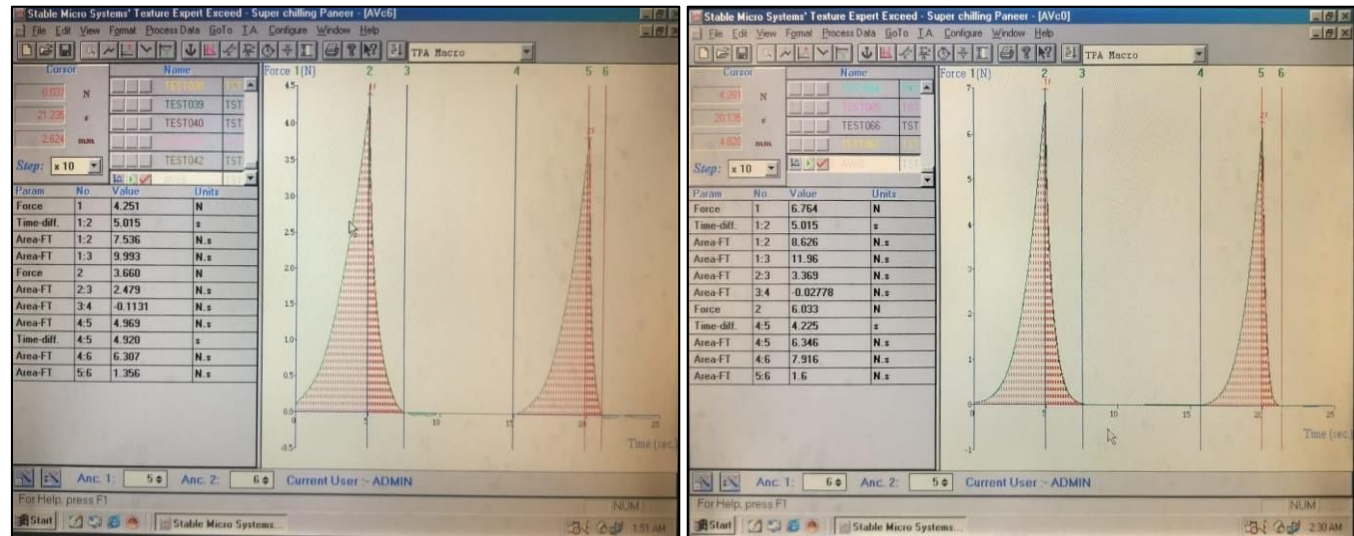
Chilling

Freezing



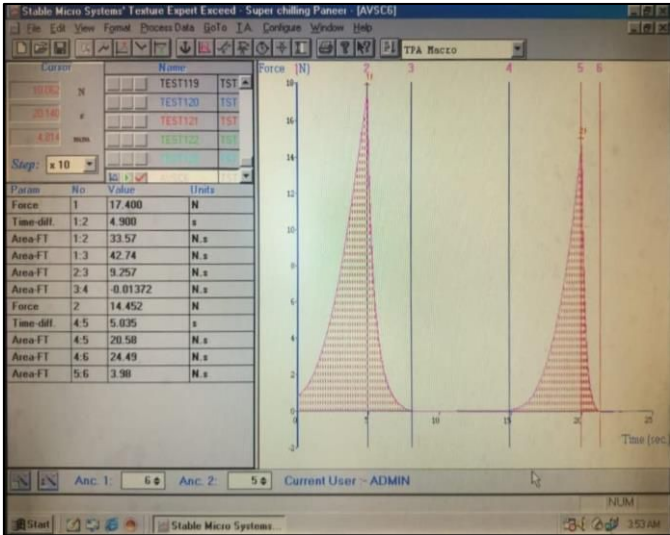
Super Chilling

Fig 2: Changes in the Texture of paneer on 3rd day of storage.



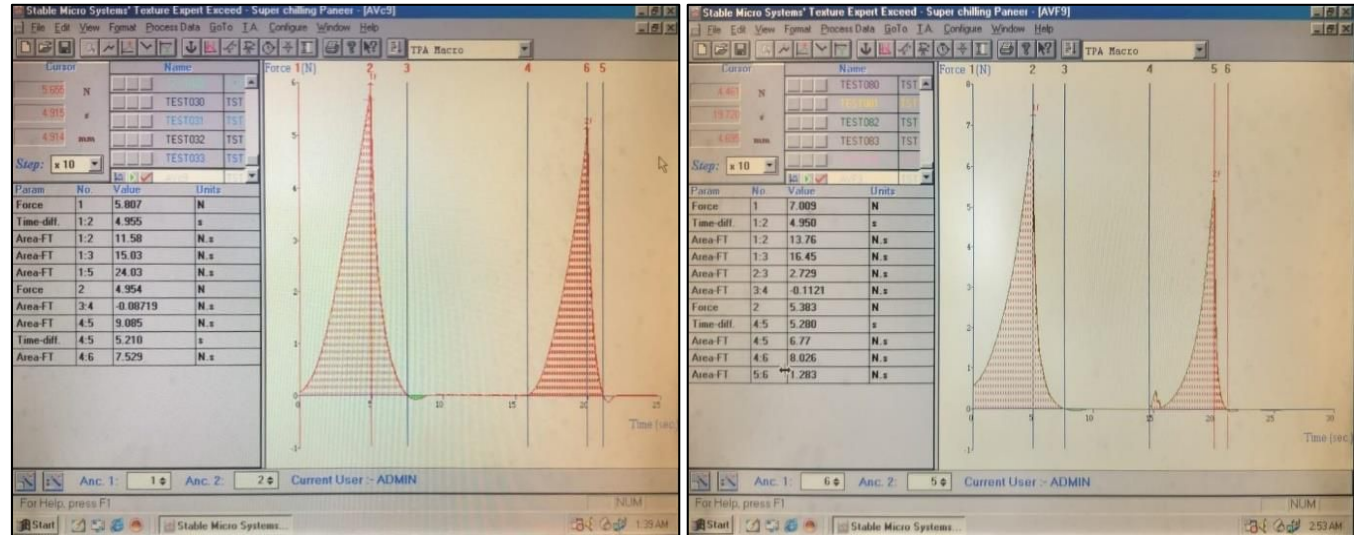
Chilling

Freezing



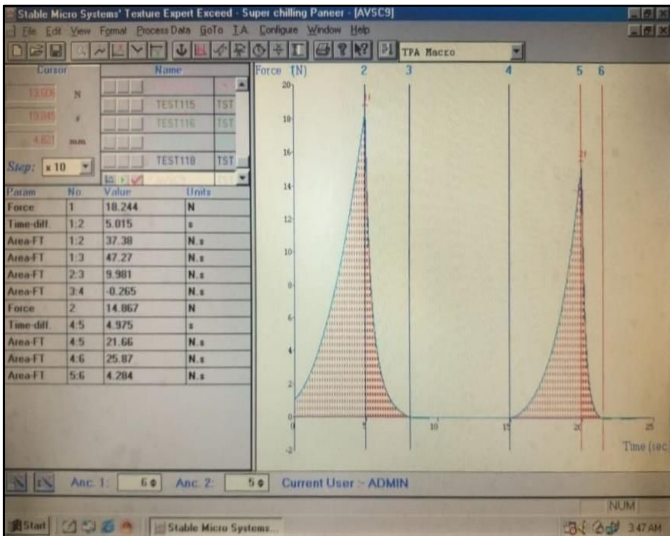
Super Chilling

Fig 3: Changes in the Texture of paneer on 6th day of storage.



Chilling

Freezing



Super Chilling

Fig 4: Changes in the Texture of paneer on 9th day of storage.

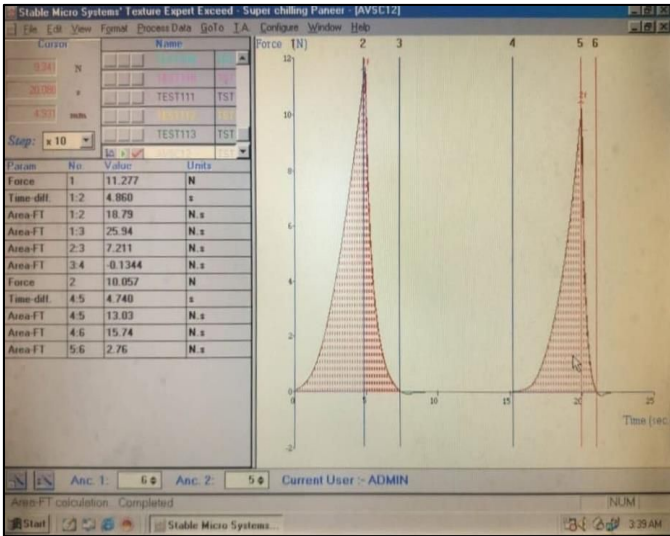
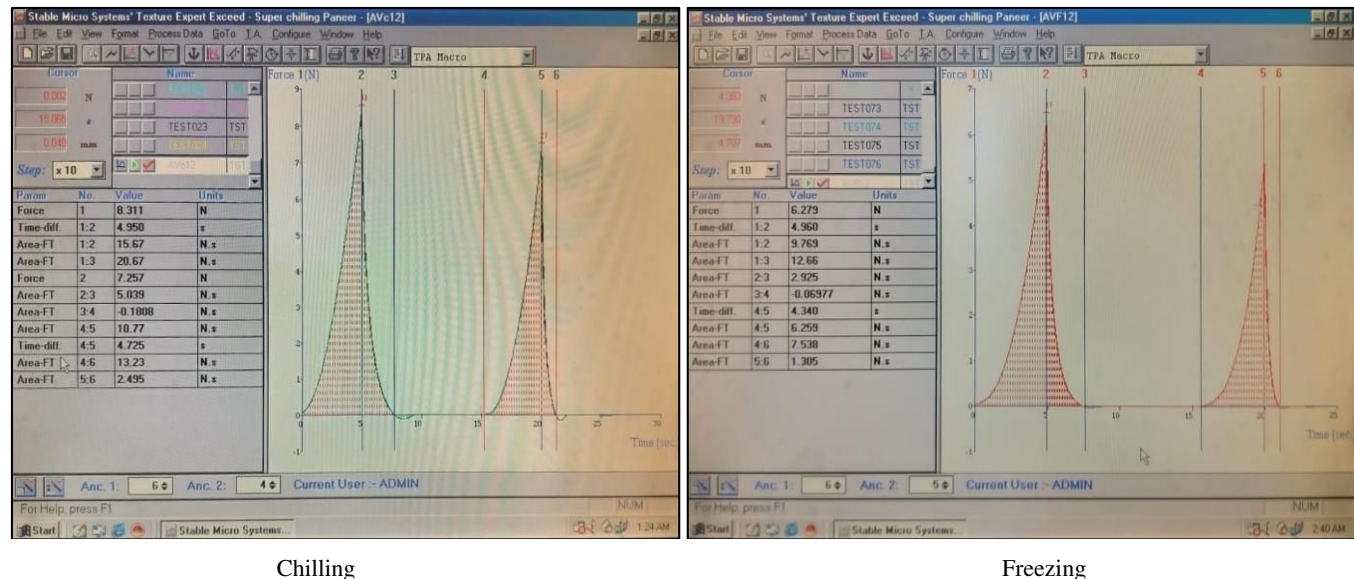
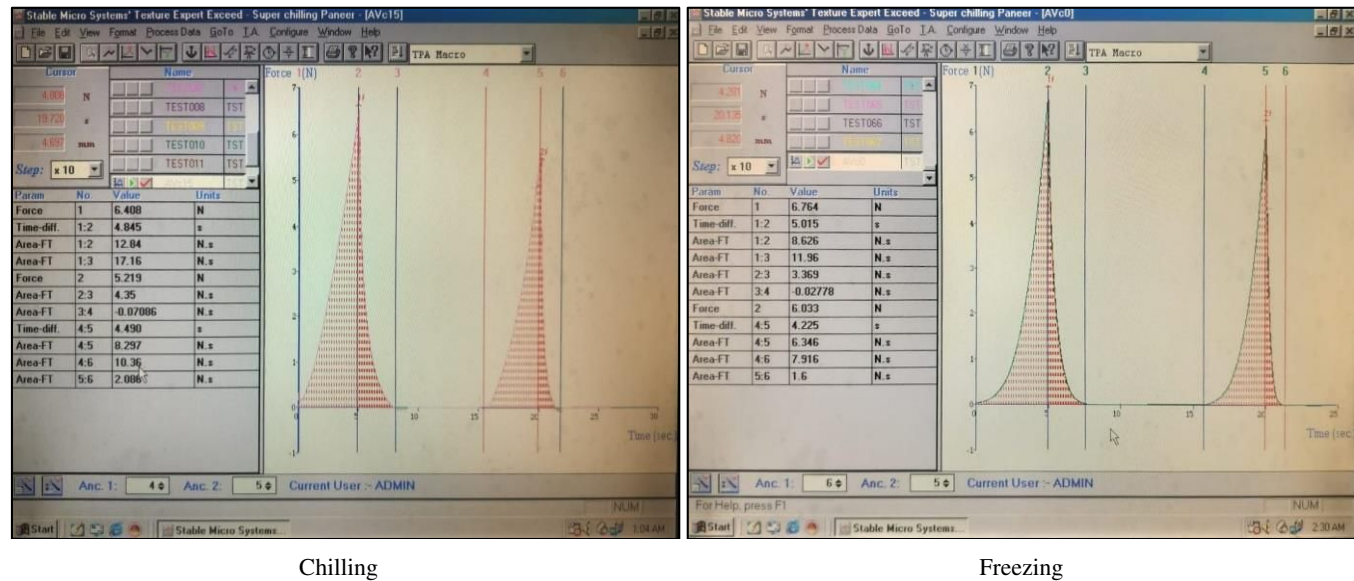
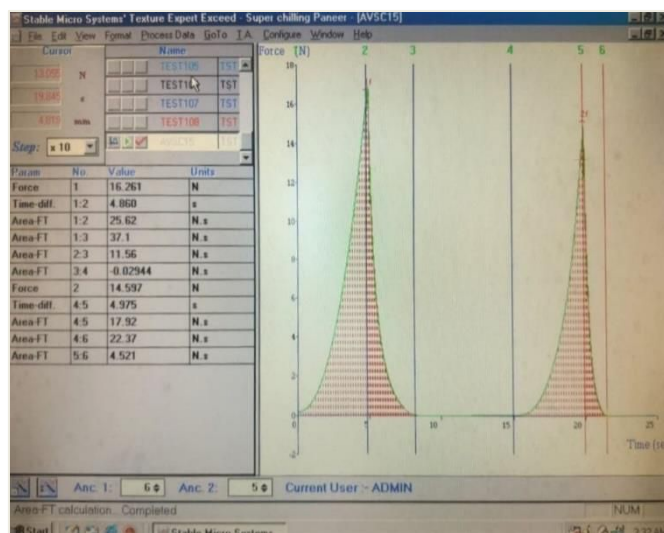


Fig 5: Changes in the Texture of paneer on 12th day of storage.





Super Chilling

Fig 6: Changes in the Texture of paneer on 15th day of storage.

Conclusion

The present investigation clearly demonstrated that storage temperature and duration significantly influenced the physicochemical, microbiological, textural and sensory quality of aerobically packaged paneer during the entire storage period. Thus, it was concluded that superchilling provided the best balance between shelf-life extension and maintenance of physicochemical, microbial, sensory and textural quality, and could be considered the most suitable and effective method for preserving aerobically packaged paneer with extended storage period than chilling method.

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