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Comparison of storage stability and palatability in different UHT milks

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during 9 mon at ambient temperature

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Running title: Storage stability and sensory quality changes in imported UHT milks

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20

Abstract

21
22 This study evaluated the storage stability and palatability of imported ultra-high
23 temperature (UHT) milks during prolonged ambient storage (4–9 mon), compared with
24 domestic high temperature short time (HTST) milk stored under refrigeration for 1 wk. HTST
25 milk, produced within 7 d, was purchased from a local market and stored under refrigeration
26 as a control. UHT milks produced 3 mon prior from Australia (UHT-A), Germany (UHT-G),
27 and Poland (UHT-P) were stored at $25 \pm 2^\circ\text{C}$ in a temperature-controlled incubator. All milks
28 had a comparable amount of total solids, with fat (3.4–3.5 g/100 g), protein (3.0–3.3 g/100 g),
29 and carbohydrate (4.7–5.0 g/100 g) contents. UHT milks consistently exhibited higher
30 thiobarbituric acid reactive substances values than HTST milk throughout storage ($p < 0.05$),
31 although all values remained below the safety threshold for consumption. Protein degradation
32 was observed in all UHT milks during storage ($p < 0.05$), except for α_s -casein ($p > 0.05$). β -
33 casein gradually decreased in UHT-A and UHT-G from 4 to 9 mon ($p < 0.001$), while κ -casein
34 decreased in UHT-A and UHT-P over the same period ($p < 0.001$). Sensory evaluation by
35 trained panelists showed that HTST milk had a stronger milky flavor than all UHT milks,
36 regardless of the storage period ($p < 0.001$). In contrast, all UHT milks had greater cooked
37 and cheesy flavors than HTST milk ($p < 0.001$), likely due to exposure to higher temperatures.
38 Rancid aromatic flavor increased during storage in UHT-A and UHT-P milks ($p < 0.001$). In
39 addition, all UHT milks showed higher viscosity and astringency scores than HTST milk
40 throughout storage ($p < 0.001$). Overall, prolonged ambient storage of imported UHT milk
41 induced persistent physicochemical changes, including lipid oxidation and protein
42 degradation, ultimately leading to a gradual decline in palatability, a critical determinant of
43 consumer acceptability.

44 **Keywords:** Ultra-high temperature milk, Storage stability, Lipid oxidation, Protein
45 degradation, Sensory quality

46

47 INTRODUCTION

48 The dynamics of consumer purchasing behavior have shifted substantially in response to
49 socio-demographic and environmental changes. These changes are characterized by
50 increasing urbanization, a rising prevalence of smaller or single-person households, and the
51 global impact of the coronavirus disease 2019 pandemic, which has resulted in heightened
52 consumer priorities regarding food safety, quality, and convenience [1,2,3]. In addition, these
53 evolving consumer demands have also impacted on the dairy industry, with a considerable
54 increase in preference for shelf-stable dairy products, particularly ultra-high temperature
55 (UHT) milk [4,5]. The global UHT milk market, which was valued at \$77.5 billion in 2024, is
56 projected to expand at a compound annual growth rate (CAGR) of 8.34%, reaching \$159.4
57 billion by 2033 [5]. Asia Pacific is estimated to have the highest growth, with the South
58 Korean UHT milk market projected to reach \$2,722 million by 2030, expanding at a CAGR
59 of 8.9% from 2025 to 2030 [4]. However, in the Korean market, the price of domestically
60 produced milk is gradually rising because of increasing production costs, which are driven by
61 higher feed, labor, and energy expenses, as well as changes in climate conditions [6]. As a
62 result, price-conscious consumers are increasingly seeking more affordable alternatives, thus
63 leading to a growing reliance on imported UHT milk from countries, such as Poland,
64 Germany, and Australia, which are comparatively cheaper than domestic HTST and UHT
65 milk [6].

66 UHT milk undergoes processing at temperatures of 135–150°C for 1–10 s, in accordance
67 with domestic standards of heating to 135°C or higher for 2–5 s, and is then aseptically
68 packaged into sterile containers. However, high temperature short time (HTST) processing
69 involves heating raw milk to at least 72°C for 15 s, and the shelf life of HTST milk is
70 generally 2–3 wk under refrigerated conditions. This method is the most widely used method
71 for pasteurization and is designed to preserve the taste and nutritional values [7]. From a

72 microbial perspective, both HTST and UHT treatments effectively enhance food safety;
73 however, the processing conditions of UHT milk not only effectively eliminate potentially
74 pathogenic bacteria, such as *Salmonella* spp., *Listeria monocytogenes*, and pathogenic
75 *Escherichia coli*, but also inactivate thermoresistant spores and enzymes [8,9]. This allows
76 UHT milk to be stored at ambient temperatures for 9–12 mon without the need for cold chain
77 transportation and refrigeration [10]. Thus, UHT milk generally has a significantly longer
78 shelf life; however, the severe heat treatment applied during UHT processing and the
79 subsequent extended ambient storage can induce continuous chemical and physical changes,
80 including protein denaturation and lipid oxidation, which may affect the overall quality and
81 consumer preferences [10]. It is well recognized that severe heat effects cause greater
82 disruption of milk fat globules and proteins compared to pasteurization processing, leading to
83 noticeable differences in flavor and taste [10]. In contrast, the timing and extent of quality
84 deterioration during storage remain variable, with noticeable physicochemical changes have
85 been reported after 3–6 mon depending on temperature conditions [11]. This issue is relevant
86 in the Korean market, where imported UHT milk typically reaches consumers approximately
87 three mon after production due to import and customs clearance procedures, and consumers
88 often purchase products in bundles produced 3–9 mon priors from online markets.
89 Consequently, consumers store these products for extended periods before consumption,
90 increasing the likelihood of quality deterioration during long-term storage. However, there is
91 a notable lack of research regarding changes in the physicochemical and sensory quality traits
92 that occur during its storage period after production, despite the continuous increase in
93 consumption of imported UHT milk in Korea. Therefore, the objective of this study was to
94 investigate the storage stability and organoleptic characteristics of various imported UHT
95 milks stored under ambient condition for 4 to 9 mon.

96

97 **MATERIALS AND METHODS**

98 **Milk materials**

99 A total of nine domestic HTST milks (Seoul Milk, Seoul Dairy Cooperative; produced
100 from Holstein-Friesians; HTST treated at 75°C for 15 s) were purchased from a local market,
101 immediately refrigerated at 4°C in the dark. All HTST milks remain unopened until analysis
102 on 7th d post-production. UHT milks from three different countries that were 4 mon post-
103 production were sourced from a local market and categorized based on their country of origin:
104 UHT-A (Australia's Own, Noumi Limited, Australia; UHT treated at 135°C for 4 s), UHT-G
105 (Oldenburger Dairy, DMK Group, Germany; UHT treated at 130–140°C for 2–4 s), and UHT-
106 P (Mlekovita 3.5%, Mlekovita, Poland; UHT treated at 130–145°C for 3 s). All UHT milks
107 were produced from pasture-raised dairy cows. The storage conditions and comparison
108 criteria among the milks were not equivalent in this study; however, HTST milk was included
109 as a control to provide insight into the extent of quality changes in imported milk during
110 storage under realistic conditions.

111 According to the information provided by the manufacturers, all milks had a similar
112 amount of total solids, with a fat content ranging from 3.4–3.5 g/100 g, a protein content
113 ranging from 3.0–3.3 g/100 g, and a carbohydrate content ranging from 4.7–5.0 g/100 g.
114 Eighteen milk samples from each group were stored in a precisely temperature-controlled
115 incubator at $25 \pm 2^\circ\text{C}$. Six samples per each group were then randomly selected for analysis at
116 4, 6, or 9 mon post-production (total 3 groups; 6 samples \times 3 periods \times 3 replicates = 54
117 samples). No additional preparation steps, such as centrifugation, were performed before
118 analysis. During each period, three samples per each group were collected in 50-mL conical
119 tubes and stored at -80°C for subsequent evaluation of thiobarbituric acid reactive substances
120 (TBARs) and protein compositions. The remaining three samples per each group were used
121 for sensory quality evaluation.

122

123 **Lipid oxidation**

124 Lipid oxidation during storage was assessed using the TBARs assay as previously
125 described by Buege and Aust [12]. In brief, 2 mL of the milk sample was mixed with 0.2%
126 butylated hydroxytoluene and 10% trichloroacetic acid and then centrifuged at 1,700 g for 15
127 min. The supernatant (2 mL) was collected and centrifuged again at 12,000 rpm for 10 min.
128 Thereafter, 1 mL of the resulting supernatant was then combined with the 2-thiobarbituric
129 acid reagent. This mixture was heated at 85°C for 45 min in a water bath and then cooled in
130 cold water. Absorbance was measured at 532 nm, and results were expressed as mg
131 malondialdehyde (MDA) per kg of sample.

132

133 **Protein composition analysis**

134 The protein profiles were analyzed using sodium dodecyl sulfate polyacrylamide gel
135 electrophoresis (SDS-PAGE). For each storage period, 40 µL of UHT milk samples were
136 mixed with 960 µL of sample buffer and diluted in a Tris-HCl sample buffer (0.1% SDS in
137 0.5 M Tris-HCl buffer at pH 6.8). To reduce the disulfide bonds, 20 µL of 2-mercaptoethanol
138 was added to each sample, and the sample mixtures were heated at 95°C for 5 min. All
139 samples from each milk group were loaded onto a single gel (12% resolving; 4% stacking),
140 and the SDS-PAGE was conducted using a Mini-PROTEAN system (Bio-Rad Laboratory
141 Inc., Richmond, CA, USA) at 120 V, according to previously described methods [13,14].
142 After electrophoresis, the gels were stained with Coomassie Brilliant Blue R-205 (Sigma-
143 Aldrich, Deisenhofen, Germany) and destained with 5% acetic acid. The protein band
144 intensity was analyzed using one-dimensional image analysis software (Eastman Kodak Co.,
145 Rochester, NY, USA), and the intensity of each band in HTST milk stored for 1 wk after
146 manufacturing was used as the standard for normalization. All experiments were repeated six

147 times.

148

149 **Sensory quality evaluation**

150 For sensory quality evaluation, a total of 36 milk samples (27 UHT and 9 HTST milk
151 samples) were used during nine sessions (4 samples per session). Before each session, the
152 milk samples were moved to the refrigerator until they reached 4°C, and the organoleptic
153 characteristics were evaluated using a 9-point hedonic scale (low–high; 1–9). These
154 characteristics included six flavor attributes (milky flavor, cooked milk flavor, cheesy flavor,
155 sweet flavor, rancid aromatic flavor, and grassy flavor), four taste attributes (sweetness,
156 saltiness, sourness, and fattiness), and four texture attributes (mouth coating, amount of
157 perceptible residue, viscosity, and astringency). The assessments were performed by trained
158 panelists (six women and five men; 25–46 years old), following a previously described
159 method [15]. All training and sensory evaluations were performed at Kyungpook National
160 University (KNU), and human ethics approval was granted by the Bioethics Committee of
161 KNU (protocol number: 2019-0027, renewed annually). The panelists were provided with
162 water and salt-free crackers to cleanse their palates between samples, except for the flavor
163 evaluation.

164

165 **Statistical analysis**

166 Data were analyzed using the general linear model procedure in SAS software (SAS
167 Institute, Cary, NC). Storage stability and protein composition assessments were conducted
168 using a linear mixed model with the milk types and storage periods as fixed effects and the
169 replicates as random effects. For sensory evaluation, a linear mixed model was applied, with
170 the UHT milk types and storage period as fixed effects and the panelists and replications as
171 random effects. Significant differences in the least-square means of the measured parameters

172 across the groups were determined using the probability difference option at a significant
173 level of $p < 0.05$ and were presented with standard errors.

174

175 **RESULTS**

176 **Comparison of lipid oxidation among HTST and imported UHT milks**

177 Fig. 1 compares the TBARs levels of different UHT milk samples during the various
178 storage periods with those of domestic HTST milk stored for 1 wk. HTST milk exhibited the
179 lowest TBARs value compared to UHT milks across all storage periods ($p < 0.001$). All UHT
180 milks sourced from different countries tended to show a significant increase in TBARs values
181 from 4 to 9 mon of ambient storage after manufacturing ($p < 0.001$). Notably, the TBARs
182 levels at 6 mon were significantly higher than those at 4 mon in each UHT group ($p < 0.001$).
183 However, a decrease in TBARs values was observed between the 6 and 9 mon of storage in
184 the UHT-A (0.29 vs. 0.21 mg MDA/kg, $p < 0.001$) and UHT-P groups (0.19 vs. 0.16 mg
185 MDA/kg, $p < 0.001$), while no difference was detected in the UHT-G group (0.18 vs. 0.16 mg
186 MDA/kg, $p > 0.05$). There was no difference among the UHT groups at 4 mon of storage ($p >$
187 0.05); however, after 9 mon of storage, UHT-A milk showed a higher value compared to the
188 other UHT milks ($p < 0.05$).

189

190 **Comparison of protein degradation among HTST and imported UHT milks**

191 Fig. 2 shows the protein degradation in the UHT milk samples throughout the 9-mon
192 storage period and in the HTST milk stored for 1 wk. No significant difference in the α_s -
193 casein level was observed in the HTST and UHT milk samples during the storage period ($p >$
194 0.05). In contrast, other milk proteins, including β -casein, κ -casein, and β -lactoglobulin,
195 exhibited significant differences between the groups ($p < 0.05$). In terms of β -casein content,
196 the UHT-G milk group at 4 mon of storage showed the highest level compared to the other

197 groups at 4 mon ($p < 0.001$). There was no difference in the β -casein level between HTST
198 milk at 1 wk and UHT-A milk at 4 mon (1.00 vs. 1.00, $p > 0.05$); however, the UHT-A group
199 at 9 mon exhibited a lower protein level (0.41, $p < 0.001$) compared to the UHT-A group at 4
200 mon. No difference was observed in the κ -casein content between HTST milk and UHT-A
201 milk at 4 mon (1.00 vs. 1.00, $p > 0.05$), although all imported UHT milks at 9 mon showed
202 lower levels than HTST milk at 1 wk ($p < 0.001$). Similar to that of β -casein, UHT-G milk
203 stored for 4 mon exhibited a higher β -lactoglobulin level compared to HTST milk at 1 wk and
204 other UHT milks at all measured storage periods ($p < 0.001$). Moreover, UHT-G milk at 9
205 mon exhibited a higher level of β -lactoglobulin compared to UHT-A and UHT-P milks at 9
206 mon (1.01 vs. 0.40 and 0.80, $p < 0.001$).

208 **Comparison of sensory flavor attributes among HTST and imported UHT milks**

209 To analyze the changes of sensory flavor attributes during ambient storage of the
210 imported UHT milks, a sensory evaluation was conducted by trained panelists, and significant
211 differences were observed in all flavor attributes among the milk groups ($p < 0.001$; Fig. 3).
212 The HTST milk group exhibited the highest milky flavor score compared to all UHT milk
213 groups, regardless of their storage duration ($p < 0.001$). The milk flavor score of each UHT
214 milk group at 9 mon of storage was lower than that of each milk group at 4-mon storage ($p <$
215 0.001), and no difference was observed among the UHT-A, UHT-G, and UHT-P groups at 9
216 mon of storage (4.60, 5.00, and 5.20, $p > 0.05$). As expected, the UHT milk samples,
217 regardless of storage period, exhibited higher scores of cooked flavor and cheesy flavor
218 compared to HTST milk at 1 wk ($p < 0.001$). The cooked flavor value of imported UHT milks
219 showed a tendency to decrease as the storage period extended from 4 to 9 mon. UHT-G milk
220 at 9 mon had a lower cheesy flavor value compared to that at 4 mon (5.25 vs. 7.62, $p < 0.001$),
221 and no difference was observed in UHT-A milk across the different storage periods ($p > 0.05$).

222 In terms of sweet flavor score, UHT milks at 4 mon had a higher value compared to HTST
223 milk ($p < 0.001$), although there was no significant difference between HTST milk at 1 wk
224 and UHT milks at 9 mon ($p > 0.05$). The rancid aromatic flavor of HTST milk did not differ
225 significantly from that of UHT-A and UHT-P milks (1.15 vs. 1.14 and 1.36, $p > 0.05$);
226 however, UHT-G milk after 9 mon of storage had a lower value compared to UHT-A and
227 UHT-P milks after the same storage period (1.40 vs. 2.40 and 2.60, $p < 0.001$). After 4 mon of
228 storage, a similar intensity of grassy flavor was observed between UHT-G and UHT-P milks
229 (1.21 and 1.14, $p > 0.05$). Although no significant change in grassy flavor was observed in the
230 UHT-A group during storage ($p > 0.05$), the UHT-G and UHT-P groups showed an increased
231 intensity over the storage period ($p < 0.001$).

232

233 **Comparison of sensory taste and texture attributes among HTST and imported** 234 **UHT milks**

235 The organoleptic taste and texture characteristics of HTST milk stored for 1 wk and the
236 imported UHT milks during the storage periods are presented in Fig. 4. In terms of taste
237 attributes, HTST milk exhibited a lower sweetness score compared to all UHT milks ($p <$
238 0.001), except for UHT-G milk after 9 mon of storage, where the difference was not
239 statistically significant ($p > 0.05$). A significant decline in sweetness score was observed in the
240 UHT-A (7.26 vs. 6.50, $p < 0.001$) and UHT-G (6.57 vs. 5.85, $p < 0.001$) groups between 4 and
241 6 mon of storage, with no further changes detected between 6 and 9 mon ($p > 0.05$). On the
242 other hand, there were no differences in saltiness, sourness, and fattiness among the milk
243 groups, regardless of the storage period ($p > 0.05$).

244 Regarding the texture characteristics, milk from the pasteurization processing showed a
245 lower score in the amount of perceptible residue compared to milks from the UHT processing
246 across all storage periods ($p < 0.001$). The UHT-P group exhibited a lower score at 4 mon

247 compared to 6 and 9 mon (5.50 vs. 6.36 and 6.86, $p < 0.001$). In contrast, the storage period
248 did not induce a change in the amount of perceptible residue in the UHT-A and UHT-G
249 groups ($p > 0.05$). HTST milk exhibited the lowest viscosity score compared to all imported
250 UHT milks, independent of the storage period ($p < 0.001$). Although the UHT-G group
251 exhibited similar viscosity scores irrespective of storage duration ($p > 0.05$), the UHT-A (6.00
252 vs. 7.00, $p < 0.001$) and UHT-P (5.57 vs. 6.14, $p < 0.001$) groups had increased scores as the
253 storage duration increased from 4 to 6 mon. A similar tendency was observed for the sensory
254 astringency, with HTST milk scoring significantly lower than the UHT groups, regardless of
255 storage period ($p < 0.001$). Samples from the UHT-A group showed a higher astringency
256 score at 9-mon storage than those at 4-mon storage (7.40 vs. 6.43, $p < 0.001$), whereas the
257 UHT-G and UHT-P groups did not change throughout the storage period ($p > 0.05$).

258

259 **DISCUSSION**

260 Thermal processing is a fundamental step in the dairy industry and is primarily
261 performed to ensure the microbiological safety of dairy products by eliminating pathogenic
262 microorganisms [16]. Milk classification based on thermal processing methods is primarily
263 distinguished as either pasteurization or sterilization, with HTST pasteurization and UHT
264 sterilization being the most widely employed efficient processes [16]. Despite the
265 effectiveness of heat treatments and the inherent structural integrity of milk, which includes
266 natural defenses against oxidation, certain thermoresistant microbial species and enzymes
267 may survive and remain active, leading to modification in the physicochemical properties of
268 milk during storage before consumption by the consumer [17–19]. These continuous changes
269 during storage result in the gradual quality deterioration and include: i) chemical oxidation,
270 either via enzyme-catalyzed reactions or the initiation of free radical formation; ii)
271 denaturation of whey proteins; iii) aggregation of κ -casein depleted casein micelles, often

272 mediated by interactions with denatured whey proteins; iv) the Maillard reaction that induces
273 lactose isomerization; and v) the formation of brown pigments and off-flavors through the
274 accumulation of increasing Maillard reaction products [10,20–22]. Thus, to ensure milk
275 quality, HTST-treated milk is typically assigned a code date ranging from 14 to 18 d under
276 refrigeration conditions, based on microbiological safety and hygiene standards [17]. The
277 extent of quality deterioration depends on the microbial counts after treatment and storage
278 temperature [17]. However, while UHT milk offers an extended shelf life, it undergoes
279 ongoing physicochemical changes during storage at ambient temperature, which can result in
280 a decline in consumer preferences [23].

281 Among the physicochemical modifications that occur in milk during storage, lipid
282 oxidation is an important factor that determines quality deterioration [24]. The primary targets
283 of lipid oxidation are unsaturated fatty acids, which react with oxygen to form free radicals
284 that produce hydroperoxides and are considered the main oxidation products [24].
285 Subsequently, these hydroperoxides subsequently decompose into secondary products, such as
286 aldehydes, ketones, and hydrocarbons [25]. Thus, the extent of lipid oxidation is commonly
287 assessed by measuring the peroxide values as an indicator of primary oxidation and aldehydes,
288 such as hexanal and MDA, for secondary oxidation to determine oxidative stability [26].
289 Additionally, milk proteins, including amino acids, peptides, caseins, and whey proteins, are
290 susceptible to rapid free radical-mediated oxidation, and aldehydes that are produced during
291 lipid oxidation can induce cross-linking in milk casein proteins, which leads to structural
292 modification of the proteins [25]. Consequently, considering these changes in lipid and
293 protein oxidation, a key indicator of oxidative stability in milk is the TBARs value, which
294 reflects the extent of lipid peroxidation through the quantification of MDA [26]. Panfil-
295 Kuncewicz et al. [27] reported that the TBARs values of UHT milk gradually increased from
296 0 to 6 mon of storage regardless of storage temperature. In addition, the storage temperature

297 significantly affected the TBARs values of milk, and milk stored at 23°C exhibited higher
298 values compared to UHT milk stored at 4°C after 3 and 6 mon [27], which aligns with the
299 other observations of oxidative progression during storage [28–30]. In the present study, the
300 TBARs values of the imported UHT milk groups remained below the critical threshold levels
301 for oxidation (1.0 mg MDA/kg) throughout the 9-mon storage period under ambient condition,
302 thus indicating that oxidative stability was maintained under these conditions. The TBARs
303 values in all UHT milks, which were higher than those in HTST milk, significantly increased
304 from 4 to 6 mon or from 4 to 9 mon of storage ($p < 0.001$). However, there was a somewhat
305 limited effect on the TBARs value between 6 and 9 mon of storage ($p > 0.05$). These results
306 were similar to a previous study [30], which reported that TBARs levels in UHT milks
307 showed a statistical increase from 3 to 12 mon, although significant differences were not
308 observed between 6 to 9 mon or 9 to 12 mon within each storage temperature group. This may
309 be explained by the reaction of MDA with the amino groups in milk proteins, especially
310 lysine residues, that form Schiff bases, which reduce measurable TBARs despite the ongoing
311 oxidation processes [31]. Therefore, while UHT milk can be stored under ambient conditions
312 for 9 mon and maintain storage stability for consumption, continuous lipid oxidation changes
313 have been observed.

314 Milk protein is highly sensitive to heat and undergoes more significant alterations during
315 UHT processing compared to other processing methods due to the intense heat treatment
316 involved [24]. Furthermore, while this intense heat treatment effectively inactivates most
317 harmful proteolytic enzymes that are responsible for milk deterioration, some indigenous
318 enzymes remain partially active during extended storage [32,33]. In addition, heat-stable
319 exogenous enzymes produced by some psychrotrophic bacteria can remain active during
320 storage [32,33]. Furthermore, casein breakdown caused by enzymes, such as plasmin and
321 bacterial proteases, leads to the gelation and sedimentation of UHT milk during storage [34].

322 These changes are major factors that limit its shelf life and cause sensory quality deterioration
323 [34]. The remaining enzymes after UHT processing primarily act on β -casein and, to a lesser
324 extent, α_s -casein, although they do not hydrolyze κ -casein and whey proteins [34]. Exogenous
325 enzymes can sequentially break down κ -casein, β -casein, and α_s -casein [35]. On the other
326 hand, non-enzymatic protein hydrolysis during storage involves considerable protein
327 modifications, such as denaturation and aggregation, along with chemical alterations in the
328 amino acids [36]. Additionally, intense heat treatment can induce protein linkages, such as the
329 formation of β -lactoglobulin– κ -casein complexes, which result in a three-dimensional protein
330 gel matrix [23]. In this study, there was no significant degradation in the α_s -casein content
331 between HTST milk stored refrigerated for 1 wk and imported UHT milks at any storage
332 period ($p > 0.05$), as this protein was less susceptible to enzymatic hydrolysis compared to the
333 other caseins [34]. However, the level of β -casein, which is most susceptible to enzymatic
334 reactions by plasmin, gradually decreased as the storage period increased in UHT milks from
335 4 to 9 mon ($p < 0.001$), except for UHT-P milk ($p > 0.05$). The degradation of κ -casein, which
336 is associated with the activity of exogenous proteases, was observed in the UHT-A and UHT-P
337 groups from 4 to 9 mon of storage ($p < 0.001$). As the storage period increased, the intensity
338 of β -lactoglobulin, a whey protein, gradually degraded in all UHT milks ($p < 0.001$). Thus,
339 imported UHT milks stored under ambient conditions during 9 mon of storage exhibited
340 continuous degradation of various milk proteins, which may be related to organoleptic
341 characteristic changes.

342 The organoleptic quality attributes of milk, such as flavor, taste, and texture, are crucial
343 factors that influence consumer purchasing and repurchasing decisions and develops through
344 a series of complex reactions [19]. Among these attributes, milk flavor is a key factor for
345 consumer acceptability and is shaped by a balance of various compounds that are formed
346 through physicochemical reactions during the heating process and further altered throughout

347 storage [24]. HTST milk, which undergoes mild heat treatment, retains a fresher and more
348 authentic milk flavor compared to sterilized milk due to the treatment conditions [7], as milk
349 flavor appears immediately after processing and is often accompanied by a sulfurous flavor
350 from volatile sulfur compounds, which typically dissipates within 7 to 10 d [20]. A similar
351 trend was observed in this study, where HTST milk at 7 d showed a stronger milky flavor
352 compared to UHT milks stored for 4 mon ($p < 0.001$). In all UHT milks, this flavor gradually
353 diminished as the storage period increased from 4 to 9 mon ($p < 0.001$). Sterilized milk is
354 known to develop more pronounced cooked and cheesy flavors than HTST milk due to the
355 formation of sulfur volatiles and Maillard-derived compounds generated at higher
356 temperatures [23]. Thus, sensory panelists can be distinguished in sensory traits between
357 HTST and UHT milks even though their storage conditions, such as storage temperature and
358 period, were the same [37]. Lee et al. [37] reported that UHT milk showed higher cooked and
359 sulfur flavors compared to HTST milk at 3 and 14 d post-production due to severe heat
360 treatment. In this study, all UHT milks, regardless of storage period, exhibited higher scores
361 of cooked and cheesy flavor scores compared to HTST milk stored for 7 d ($p < 0.001$).
362 However, these flavors tended to decrease as the storage period increased from 4 to 9 mon (p
363 < 0.001). It is explained that aroma-active volatiles from Maillard reaction are highly unstable
364 and tend to dissipate over time due to volatilization, oxidation, or participation in secondary
365 reactions [21,34]. In addition, during prolonged storage period, UHT milk can slowly yet
366 persistently develop a rancid flavor, primarily because of lipid oxidation. This process
367 involves the breakdown of unsaturated fatty acids and oxidative conversion of free fatty acids
368 to ketones aldehydes, and esters, resulting in the formation of off-flavor compounds [38].
369 Thus, similar to the TBARs result, the intensity of rancid aromatic flavor was not strong in all
370 the milks evaluated in this study, but it tended to increase from 4 to 9 ($p < 0.001$), except for
371 UHT-G milk ($p > 0.05$). Moreover, all imported UHT milks stored for 6 and 9 mon had a

372 higher grassy flavor intensity compared to domestic HTST milk ($p < 0.001$), likely due to
373 pasture-based feeding and lipid oxidation [39].

374 Among the four taste characteristics analyzed in this study, three traits (saltiness,
375 sourness, and fattiness) did not show significant differences ($p > 0.05$). However, HTST milk
376 tended to exhibit weaker values of sweet flavor and taste compared to UHT samples, as the
377 Maillard reaction under severe heat treatment generates lactulose and other reducing sugars,
378 thus further intensifying the sweet taste and sweet flavor perception compared to mild heat
379 treatment [40]. In UHT milks, sweetness statistically decreased over storage time ($p < 0.01$),
380 except for UHT-P milk, due to the breakdown of milk sugars and changes in flavor
381 compounds as the product ages [41]. For the texture attributes, there was no difference in
382 mouth coating among the milk groups ($p > 0.05$), as the fat content in all milks was similar.
383 On the other hand, all UHT milks, regardless of storage period, had a higher amount of
384 perceptible residue after consumption compared to HTST milk ($p < 0.001$). This may be
385 because UHT processing causes an increased extent of whey protein denaturation and thermal
386 decomposition, and denatured whey proteins can then form complexes with various
387 components, including other whey proteins, caseins, and fat globules [23]. Furthermore,
388 proteolysis by indigenous and exogenous enzymes in UHT milk during long-term storage
389 leads to the accumulation of hydrophobic peptides and protein aggregates, which are closely
390 linked to the development of bitter flavor, astringency, and viscosity, and these attributes are
391 related to the presence of residual milk in the oral cavity after consumption [21]. Li et al. [21]
392 reported that HTST milk exhibited lower astringency and viscosity scores than those of
393 sterilized milk stored for over 8 wk, despite there being no significant differences in the
394 mechanical viscosity. These findings are consistent with the present study, where prolonged
395 storage of UHT milk was linked to increased astringency and viscosity ($p < 0.001$). Therefore,
396 continuous changes in the organoleptic characteristics of UHT milk during extended storage

397 at ambient temperature were attributed to lipid oxidation and protein degradation, which were
398 potentially mediated by both endogenous and exogenous enzymes.

399

400 **CONCLUSION**

401 In response to the recent global inflation and economic downturns, consumers are
402 prioritizing price as a key criterion when purchasing food, and repurchase decisions are
403 largely influenced by the sensory experience of the product [42]. In Korea, the import and
404 consumption of UHT milk have increased because of its affordable price, long shelf life, and
405 suitability for storage and distribution under ambient conditions without the requiring
406 refrigeration. In the current study, imported UHT milks that have been stored for over 6 mon
407 at ambient temperature exhibited continuous physicochemical changes of the various milk
408 components. Due to these changes, the eating quality of all UHT milks tended to gradually
409 decline from 4 to 9 mon, which allowed panelists to clearly distinguish their flavor and
410 texture characteristics from those of HTST milk stored under refrigerated conditions for 1 wk.

411

412

References

- 414 1. Cho DK, Lee B, Oh H, Lee JS, Kim YS, Choi YM. Effect of searing process on quality
415 characteristics and storage stability of sous-vide cooked pork patties. *Foods*. 2020;9:1011.
416 <https://doi.org/10.3390/foods9081011>.
- 417 2. Damari Y, Kissinger M. Changing food preferences and choices – A framework for
418 analyzing households food purchases over time. *Int J Gastron Food Sci*. 2024;36:100920.
419 <https://doi.org/10.1016/j.ijgfs.2024.100920>.
- 420 3. Kapaj A, Deci E. World milk production and socio-economic factors effecting its
421 consumption. In Watson RR, Collier RJ, Preedy VR, editors. *Dairy in human health and*
422 *disease across the lifespan*. Amsterdam: Elsevier; 2017. p. 107-115.
423 <https://doi.org/10.1016/B978-0-12-809868-4.00007-8>.
- 424 4. Grand View Research. South Korea ultra high temperature milk market size & outlook.
425 2024 [cited 2025 April 18]. [https://www.grandviewresearch.com/horizon/outlook/ultra-](https://www.grandviewresearch.com/horizon/outlook/ultra-high-temperature-milk-market/south-korea)
426 [high-temperature-milk-market/south-korea](https://www.grandviewresearch.com/horizon/outlook/ultra-high-temperature-milk-market/south-korea).
- 427 5. Straits Research. UHT milk market size, growth, share & report forecast by 2033. 2024
428 [cited 2025 April 18]. <https://straitsresearch.com/report/uht-milk-market>.
- 429 6. United States Department of Agriculture. Dairy and Products Annual. 2024 [cited 2025
430 April 15].
431 [https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName](https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Dairy%20and%20Products%20Annual_Seoul%20ATO_Korea%20-%20Republic%20of_KS2024-0025.pdf)
432 [=Dairy%20and%20Products%20Annual_Seoul%20ATO_Korea%20-](https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Dairy%20and%20Products%20Annual_Seoul%20ATO_Korea%20-%20Republic%20of_KS2024-0025.pdf)
433 [%20Republic%20of_KS2024-0025.pdf](https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Dairy%20and%20Products%20Annual_Seoul%20ATO_Korea%20-%20Republic%20of_KS2024-0025.pdf).
- 434 7. Lorenzen PC, Clawin-Rädecker I, Einhoff K, Hammer P, Hartmann R, Hoffmann W,
435 Martin D, Molkentin J, Walte HG, Devrese M. A survey of the quality of extended shelf
436 life (ESL) milk in relation to HTST and UHT milk. *Int J Dairy Tech*. 2011;64:166–178.
437 <https://doi.org/10.1111/j.1471-0307.2010.00656.x>.

- 438 8. Burton H. Review of the progress of dairy science: The bacteriological, chemical,
439 biochemical and physical changes that occur in milk at temperatures of 100–150°C. *J*
440 *Dairy Res.* 198;51:341–363. <https://doi.org/10.1017/S002202990002361X>.
- 441 9. Kessler HG. *Food and bio process engineering: dairy technology*. Verlag A. Kessler, 2002.
- 442 10. Akkerman M, Johansen LB, Rauh V, Sørensen J, Larsen LB, Poulsen NA. Relationship
443 between casein micelle size, protein composition and stability of UHT milk. *Int Dairy J.*
444 2021;112:104856. <https://doi.org/10.1016/j.idairyj.2020.104856>.
- 445 11. Malmgren B, Ardö Y, Langton M, Altskär A, Bremer MGEG, Dejmeck P, Paulsson M.
446 Changes in proteins, physical stability and structure in directly heated UHT milk during
447 storage at different temperatures. *Int Dairy J.* 2017;71:60–75.
448 <https://doi.org/10.1016/j.idairyj.2017.03.002>.
- 449 12. Buege JA, Aust SD. Microsomal lipid peroxidation. *Methods Enzymol.* 1978;52:302–310.
450 [https://doi.org/10.1016/S0076-6879\(78\)52032-6](https://doi.org/10.1016/S0076-6879(78)52032-6).
- 451 13. Anema SG. The use of “lab-on-a-chip” microfluidic SDS electrophoresis technology for
452 the separation and quantification of milk proteins. *Int Dairy J.* 2009;19:198–204.
453 <https://doi.org/10.1016/j.idairyj.2008.11.001>.
- 454 14. Anema SG, Klostermeyer H. Heat-induced, pH-dependent dissociation of casein micelles
455 on heating reconstituted skim milk at temperatures below 100°C. *J Agric Food Chem.*
456 1997;45:1108–1115. <https://doi.org/10.1021/jf960507m>.
- 457 15. Ochi H, Sumi M, Nakata I, Saito H, Uozumi M, Iwatsuki K. Sensometric calibration of
458 sensory characteristics of commercially available milk products with instrumental data. *J*
459 *Dairy Sci.* 2010;93:1794–1806. <https://doi.org/10.3168/jds.2009-2575>.
- 460 16. Ritota M, Di Costanzo MG, Mattera M, Manzi P. New trends for the evaluation of heat
461 treatments of milk. *J Anal Methods Chem.* 2017;2017:1864832.
462 <https://doi.org/10.1155/2017/1864832>.

- 463 17. Cappozzo JC, Koutchma T, Barnes G. Chemical characterization of milk after treatment
464 with thermal (HTST and UHT) and nonthermal (turbulent flow ultraviolet) processing
465 technologies. *J Dairy Sci.* 2015;98:5068–5079. <https://doi.org/10.3168/jds.2014-9190>.
- 466 18. Duncan JB, Webster JB. Oxidation and protection of milk and dairy products. In: Decker
467 E, McClements DJ, Elias R, eds. *Oxidation in foods and beverages and antioxidant*
468 *applications*. Cambridge: Woodhead Publishing Limited; 2010. p. 121 –155.
- 469 19. Khan MU, Yu P, Wu Y, Chen Z, Kong L, Farid A, Cui J, Yang J. Comprehensive review
470 of enzymes (protease, lipase) in milk: Impact on storage quality, detection methods, and
471 control strategies. *Compr Rev Food Sci Food Saf.* 2025;24:e70164.
472 <https://doi.org/10.1111/1541-4337.70164>.
- 473 20. Lewis MJ. Improvements in the pasteurisation and sterilisation of milk. In: Smit G, ed.
474 *Improving quality*. Boca Raton: CRC Press; 2003. p. 81–103.
- 475 21. Li H., Xi B, Yang, X, Wang H, He X, Li W, Gao Y. Evaluation of change in quality
476 indices and volatile flavor components in raw milk during refrigerated storage. *LWT.*
477 2018;165:113674. <https://doi.org/10.1016/j.lwt.2022.113674>.
- 478 22. Souza AB, Stephani R, Tavares GM. Stability of milk proteins subjected to UHT
479 treatments: challenges and future perspectives. *Crit Rev Food Sci Nutr.* 2024;64:12352–
480 12362. <https://doi.org/10.1080/10408398.2023.2250865>.
- 481 23. Chavan RS, Chavan SR, Khedkar CD, Jana AH. UHT milk processing and effect of
482 plasmin activity on shelf life: a review. *Compr Rev Food Sci Food Saf.* 2011;10:215–268.
483 <https://doi.org/10.1111/j.1541-4337.2011.00157.x>.
- 484 24. Deeth HC. Stability and spoilage of lipids in milk and dairy products. In: McSweeney
485 PLH, Fox PF, O’Mahony JA, eds. *Advanced dairy chemistry*. Berlin: Springer; 2020. p.
486 345–373. https://doi.org/10.1007/978-3-030-48686-0_11.
- 487 25. Duncan S, Webster J. Oxidation and protection of milk and dairy products. In: Decker EA,

- 488 Elias RJ, McClements DJ, eds. Oxidation in foods and beverages and antioxidant
489 applications. Cambridge: Woodhead Publishing Limited; 2010. p. 121–155.
- 490 26. Dias FFG, Augusto-Obara TR, Hennebelle M, Chantieng S, Ozturk G, Taha AY, de Souza
491 Vieira TMF, de Moura Bell JMLN. Effects of industrial heat treatments on bovine milk
492 oxylipins and conventional markers of lipid oxidation. *Prostag Leukotr Ess*.
493 2020;152:102040. <https://doi.org/10.1016/j.plefa.2019.102040>.
- 494 27. Panfil-Kuncewicz H, Kuncewicz A, Juskiewicz M. The influence of the sterilization
495 method on the changes in UHT milk fat fraction. *Milchwissenschaft*. 2005;60:33–36.
- 496 28. Ajmal M, Nadeem M, Imran M, Junaid M. Lipid compositional changes and oxidation
497 status of ultra-high temperature treated milk. *Lipids Health Dis*. 2018;17:227.
498 <https://doi.org/10.1186/s12944-018-0869-3>.
- 499 29. Johnson DS, Duncan SE, Bianchi LM, Chang HH, Eigel WN, O’Keefe SF. Packaging
500 modifications for protecting flavor of extended-shelf-life milk from light. *J Dairy Sci*.
501 2015;98:2205–2214. <https://doi.org/10.3168/jds.2014-8857>.
- 502 30. Lu J, Langton M, Sampels S, Pickova J. Lipolysis and oxidation in ultra-high temperature
503 milk depend on sampling month, storage duration, and temperature. *J Food Sci*.
504 2019;84:1045–1053. <https://doi.org/10.1111/1750-3841.14514>.
- 505 31. Nawar WW. Lipids. In Fennema OR, ed. *Food chemistry*. New York: Marcel Dekker;
506 1996. P. 225–319.
- 507 32. Fox PF. Enzymology of milk and dairy products: Overview. In: Kelly AL, Larsen LB, eds.
508 *Agents of change: Enzymes on milk and dairy products*. Berlin: Springer Nature; 2021. p.
509 1–10.
- 510 33. Sun Y, Wang R, Li Q, Ma Y. Influence of storage time on protein composition and
511 simulated digestion of UHT milk and centrifugation presterilized UHT milk in vitro. *J*
512 *Dairy Sci*. 2023;106:3109–3122. <https://doi.org/10.3168/jds.2022-22602>.

- 513 34. Deeth HC, Lewis MJ. Chapter 6: Changes during heat treatment of milk. In: Deeth HC,
514 Lewis M, eds. High temperature processing of milk and milk products. New Jersey: John
515 Wiley and Sons Ltd; 2017. p. 190–192.
- 516 35. Zhang C, Bijl E, Hettinga K. Destabilization of UHT milk by protease AprX from
517 *Pseudomonas fluorescens* and plasmin. Food Chem. 2018;263:127–134.
518 <https://doi.org/10.1016/j.foodchem.2018.04.128>.
- 519 36. Krishna TC, Najda A, Bains A, Tosif MM, Papliński R, Kaplan M, Chawla P. Influence
520 of ultra-high treatment on properties of milk proteins. Polymers. 2021;13:3164.
521 <https://doi.org/10.3390/polym13183164>.
- 522 37. Lee AP, Barbano DM, Drake MA. The influence of ultra-pasteurization by indirect
523 heating versus direct steam injection on skim and 2% fat milks. J Dairy Sci.
524 2017;100:1688–1701. <https://doi.org/10.3168/jds.2016-11899>
- 525 38. Singh RRB, Ruhil AP, Jain DK, Patel AA, Patil GR. Prediction of sensory quality of UHT
526 milk – A comparison of kinetic and neural network approaches. J Food Eng.
527 2009;92:146-151. <https://doi.org/10.1016/j.jfoodeng.2008.10.032>.
- 528 39. Kicawley KN, Faulkner H, Clarke HJ, O’Sullivan MG, Kerry JP. Factors influencing the
529 flavour of bovine milk and cheese from grass based versus non-grass based milk
530 production system. Foods. 2018;7:37. <https://doi.org/10.3390/foods7030037>.
- 531 40. Jo Y, Benoist DM, Barbano DM, Drake MA. Flavor and flavor chemistry differences
532 among milks processed by high-temperature, short-time pasteurization or ultra-
533 pasteurization. J Dairy Sci. 2018;101:3812–3828. <https://doi.org/10.3168/jds.2017-14071>.
- 534 41. Karlsson MA, Langton M, Innings F, Malmgren B, Höjer A, Wikström M, Lundh Å.
535 Changes in stability and shelf-life of ultra-high temperature treated milk during long term
536 storage at different temperatures. Heliyon. 2019;5:e02431.
537 <https://doi.org/10.1016/j.heliyon.2019.e02431>.

538 42. Sloan AE. The top 10 functional food trends of 2023. 2023 [cited 2025 April 15].

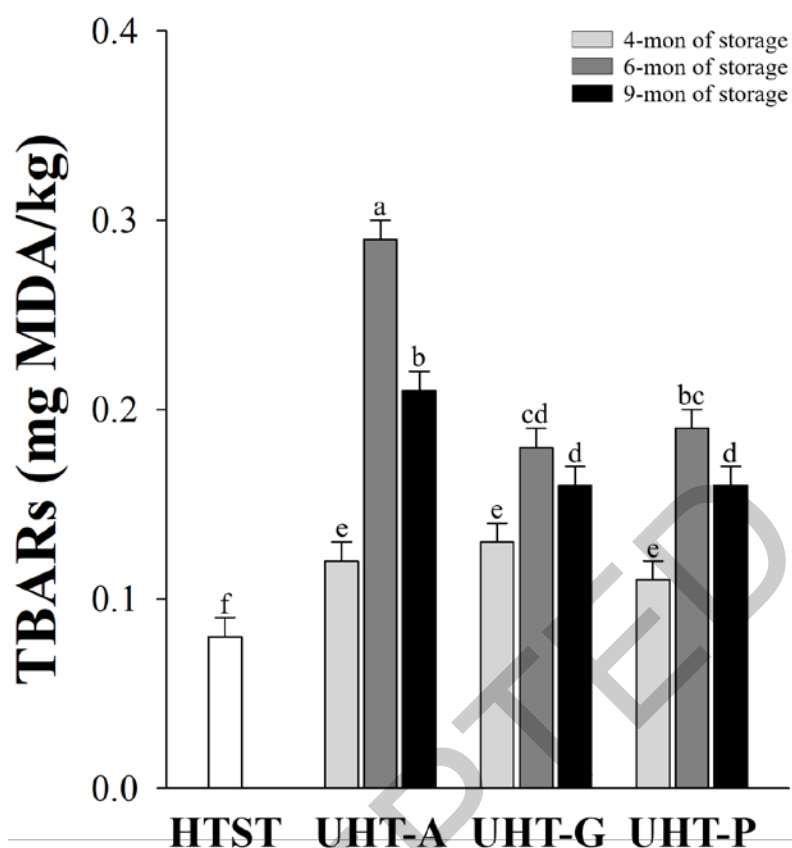
539 <https://www.ift.org/news-and-publications/food-technology->

540 [magazine/issues/2023/april/features/the-top-10-food-trends-of-2023.](https://www.ift.org/news-and-publications/food-technology-magazine/issues/2023/april/features/the-top-10-food-trends-of-2023)

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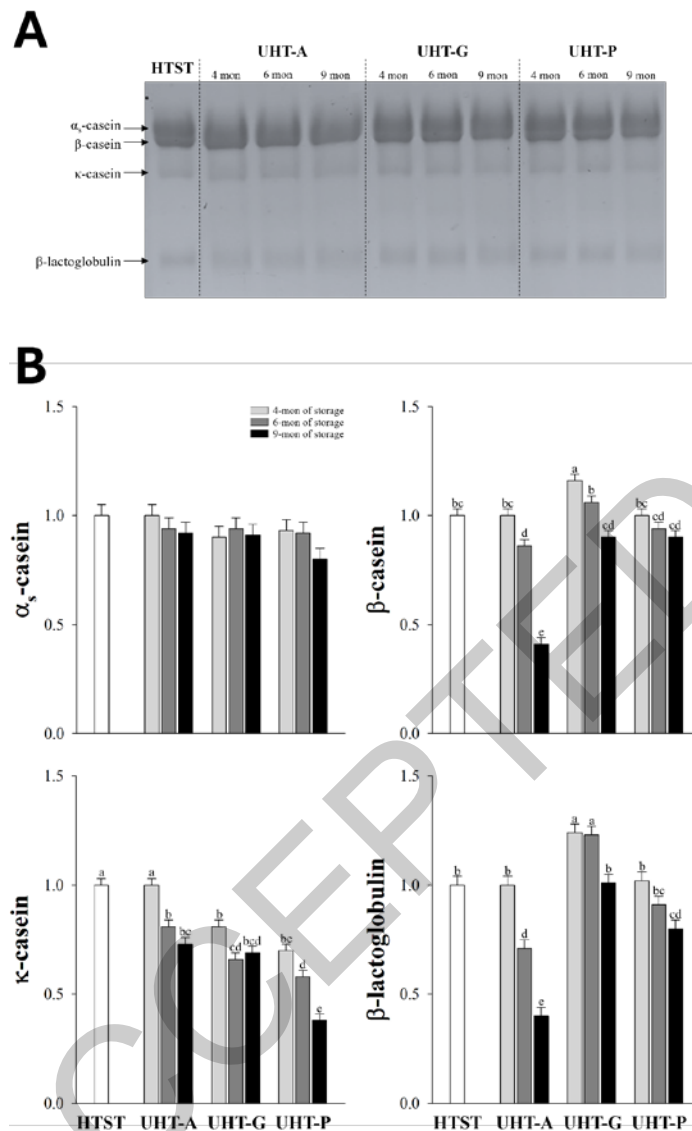
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544
 545 **Fig. 1.** Comparison of lipid oxidation in the imported ultra-high temperature (UHT) milks
 546 stored for 4 to 9 mon under ambient conditions versus domestic high temperature short time
 547 (HTST) milk stored at 4°C for 1 wk. Bars indicate standard errors of least square means.
 548 Different letters denote significant differences ($p < 0.05$). Abbreviations: TBARs, 2-
 549 thiobarbituric acid reaction substances; MDA, malondialdehyde; HTST, high temperature
 550 short time; UHT-A, imported UHT milk from Australia; UHT-G, imported UHT milk from
 551 Germany; UHT-P, imported UHT milk from Poland.

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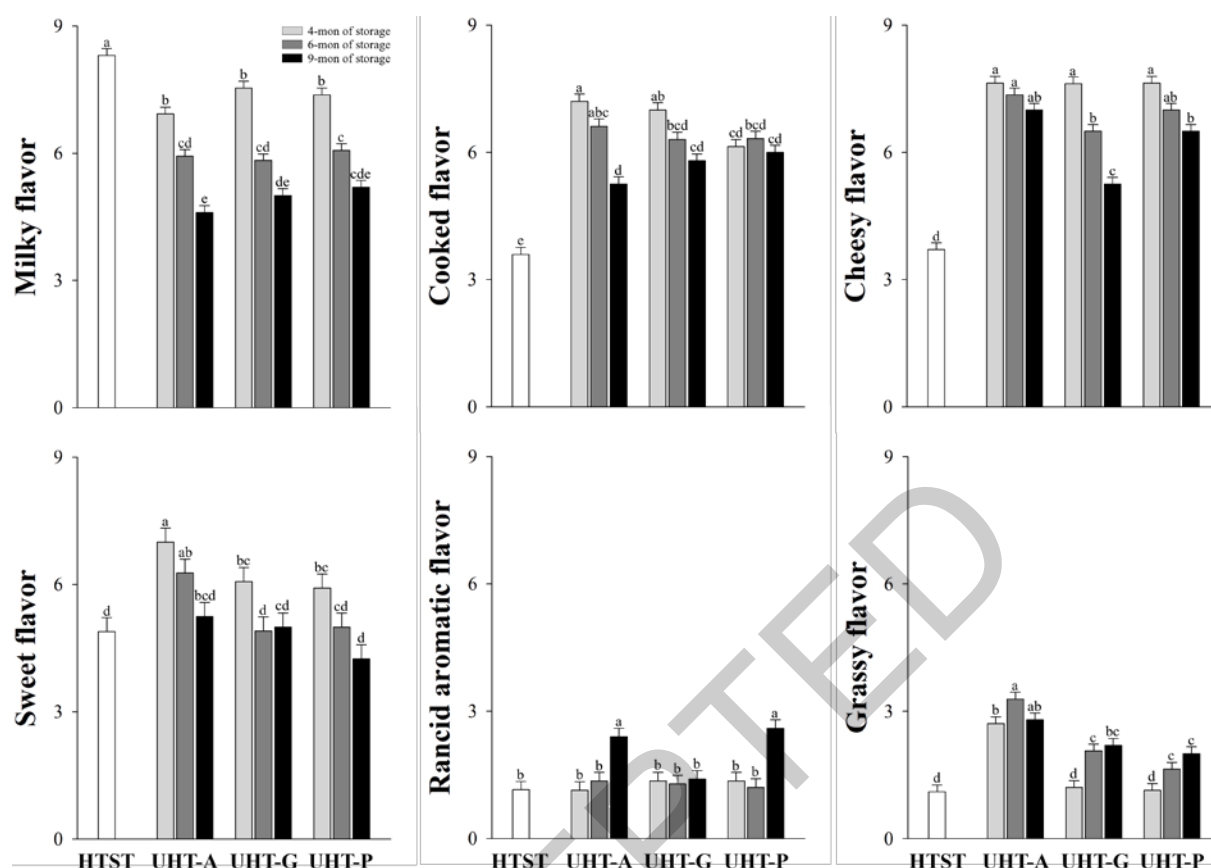
556 **Fig. 2.** SDS-PAGE images (A) and relative protein intensities (B) of the imported ultra-high
 557 temperature (UHT) milks stored for 4 to 9 mon under ambient conditions versus domestic
 558 high temperature short time (HTST) milk stored at 4°C for 1 wk. Bars indicate standard errors
 559 of least square means. Different letters denote significant differences ($p < 0.05$).

560 Abbreviations: HTST, high temperature short time; UHT-A, imported UHT milk from
 561 Australia; UHT-G, imported UHT milk from Germany; UHT-P, imported UHT milk from
 562 Poland.

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564

565 **Fig. 3.**



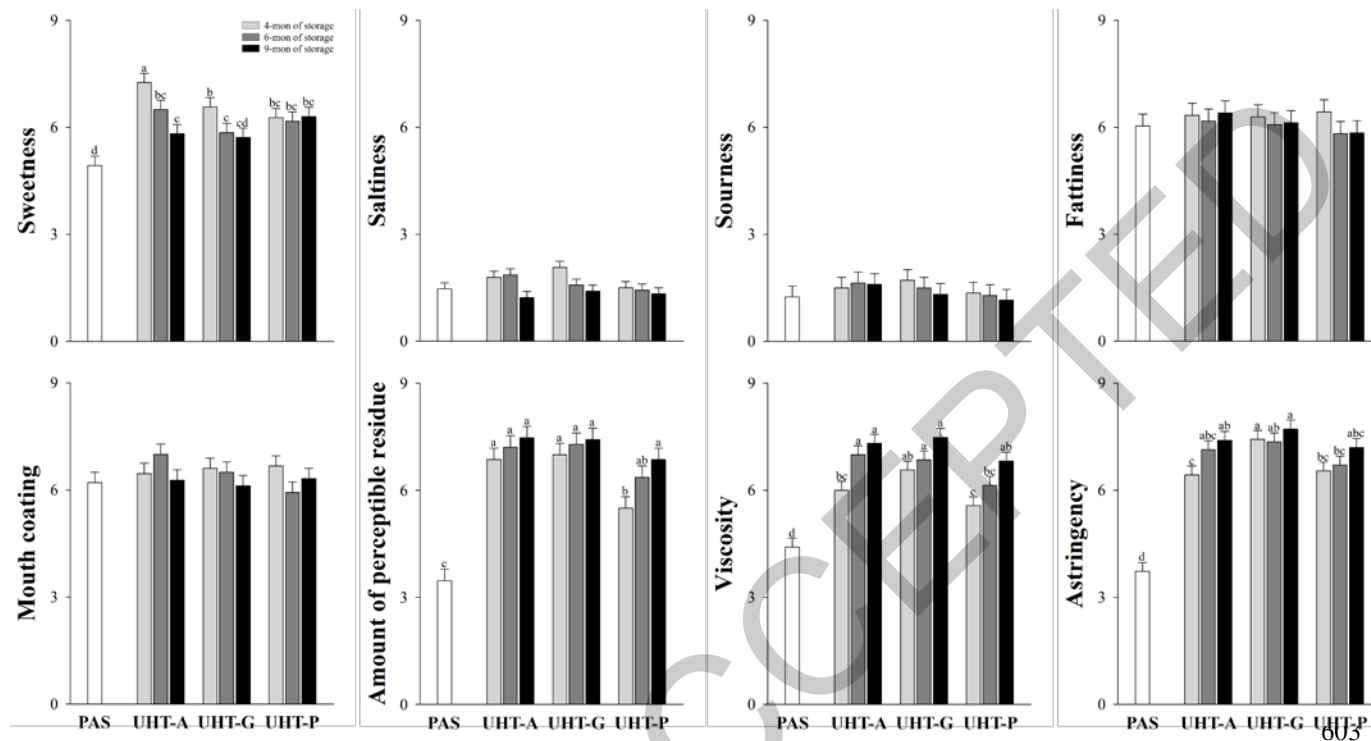
566
 567 **Fig. 3.** Comparison of sensory flavor attributes in the imported ultra-high temperature (UHT)
 568 milks stored for 4 to 9 mon under ambient conditions versus domestic high temperature short
 569 time (HTST) milk stored at 4°C for 1 wk. Sensory flavor evaluation was conducted by trained
 570 panelists and was assessed using a 9-point scale (low to high; 1 to 9). Bars indicate standard
 571 errors of least square means. Different letters denote significant differences ($p < 0.05$).
 572 Abbreviations: HTST, high temperature short time; UHT-A, imported UHT milk from
 573 Australia; UHT-G, imported UHT milk from Germany; UHT-P, imported UHT milk from
 574 Poland.

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606 **Fig. 4.** Comparison of sensory taste and texture attributes in the imported ultra-high temperature (UHT) milks stored for 4 to 9 mon under
 607 ambient conditions versus domestic high temperature short time (HTST) milk stored at 4°C for 1 wk. Sensory taste and texture evaluations
 608 conducted by trained panelists were assessed on a 9-point scale (low to high; 1 to 9). Bars indicate standard errors of least square means.
 609 Different letters denote significant differences ($p < 0.05$). Abbreviations: HTST, high temperature short time; UHT-A, imported UHT milk from
 610 Australia; UHT-G, imported UHT milk from Germany; UHT-P, imported UHT milk from Poland.