Milk and dairy products are excellent sources of mineral elements, including Ca, P, Mg, Na, K and Zn. The purpose of this study was to determine the effect of non-thermal (homogenization) and thermal (heat treatment) treatments on the distribution of mineral elements in 4 milk fractions: fat, casein, whey protein, and aqueous phase. The study results revealed that the distribution of mineral elements (such as Mg and Fe) in fat fractions is extremely low, while significant mineral elements such as Ca, Zn, Fe, and Cu are mostly dispersed in casein fractions. For non-treated goat milk, Mo is the only element identified in the whey protein fraction, while K and Na are mostly found in the aqueous phase. Mineral element concentrations in fat (K, Zn, etc.) and casein fraction (Fe, Mo, etc.) increased dramatically after homogenization. Homogenization greatly decreased the concentration of mineral elements in the whey protein fraction (Ca, Na, etc.) and aqueous phase (Fe, Cu, etc.). After heat treatment, the element content in the fat fraction and casein fraction increased greatly when compared with raw milk, such as Cu and Mg in the fat fraction, Na and Cu in the whey protein fraction, the concentration of components such as Mg and Na in casein fraction increased considerably. On the other hand, after homogenization, Zn in the aqueous phase decreased substantially, whereas Fe increased significantly. Therefore, both homogenization and heat treatment have an effect on the mineral element distribution in goat milk fractions.

Keywords: goat milk, homogenization, heat treatment, element distribution

Goat milk and dairy products have received increasing attention in recent years for their nutritional and health properties due to their abundant nutritional supplements like fat and protein (Sun et al., 2023). Accordingly, goat milk has the second-largest sales volume in the world and its annual production can reach 15.5 million tons, especially in developing countries (Nayik et al., 2021). Aside from that, goat milk is high in minerals such as Ca, Mg, Fe, and Zn. Elements in milk not only give nutritious supplements but also preserve milk stability by improving the stability of casein micelles. The balance of osmotic pressure caused by mineral element ions could keep milk’s ion balance and element speciation from altering the texture of dairy products (Sandra et al., 2012, Oh and Deeth, 2017). Mineral element levels in milk from various animals have been thoroughly researched, generally, mineral elements of Ca, Mg, Na, and K, were found in high concentrations, while Se, Fe, Cu, and Zn were found in low concentrations (Clark and García, 2017). Furthermore, multiple comparison studies have established stable mineral elemental profiles (Chen et al., 2020).

Because of its impact on the value and quality of milk and dairy products, the distribution of mineral elements in milk has received increased attention. It was linked to element bioavailability, influencing absorption, and can change the mouthfeel of the dairy product (Kibangou et al., 2005, Oh and Deeth, 2017). Fuente et al. investigated the mineral element distribution in goat milk and discovered considerable changes in element distribution between colloidal and soluble phases (De la Fuente et al., 1997). Singh et al. discovered that Mg, Na, and K were primarily dispersed in the soluble fraction of goat milk, whereas Ca, P, Zn, Fe, Cu, and Mn were primarily distributed in the colloidal fraction (Singh et al., 2019). Debski et al. concluded that casein contains more Se than fat in raw goat milk (Debski et al., 1987). However, relatively little research
on the distribution of mineral elements in raw goat milk has been undertaken, because mineral element distinction in goat milk might be modified by processing processes. Because raw milk must be further treated before it can be sold, simply analyzing the distribution of components in raw goat milk is insufficient. The mineral element distribution in goat milk varies based on the processing method utilized. Homogenization and heat treatment, both commonly used methods in the production and processing of milk and dairy products, can reduce the size of milk fat globules, increase the stability of milk fat, extend the shelf life of milk, and reduce the content of spoilage microorganisms (Meunier-Goddik and Sandra, 2016, Ye et al., 2017). Previous research has found that these 2 processing processes influence the distribution of mineral components in goat milk. Fuente et al. investigated the effects of high pressure and heat treatment on Ca, P, and Mg distribution in goat milk. Their findings revealed that high pressure and heat treatment had a substantial impact on the concentrations of Ca, Mg, and P in the soluble phase (DE LA FUENTE et al., 1999). Raynal and Remeuf investigated the influence of heat treatment on the soluble Ca content of goat milk. They noted that different heat treatment conditions resulted in varying degrees of soluble Ca concentration decrease (Raynal and Remeuf, 1998). Changes in the distribution of mineral elements generated by homogenization and heat treatment, as fundamental processing techniques, may impact their bioavailability and quality. Furthermore, the present study on the distribution of mineral components in goat milk involves fewer types of elements and is not split into identifiable fractions, indicating the need for more extensive research.

In this investigation, raw goat milk was homogenized and heat-treated separately and then separated into 4 fractions: fat, casein, whey protein, and aqueous phases. Inductively coupled plasma optical emission spectrometry (ICP-OES) was used to detect the concentrations of 12 elements in each fraction. Analysis of the distribution of elements in goat milk aids in determining acceptable processing methods and parameters, as well as providing support for future research on element absorption and goat milk technical qualities.

MATERIALS AND METHODS

Sample collection

The goat farm Qingdao Aote located in Shandong province, China, provided the milk samples and 10-L samples of raw goat milk were taken from milk tanks, placed in sterile plastic bottles, and kept at 4°C. The samples were then brought to the laboratory within 24h and kept frozen at −20°C until analyzed.

Sample preparation

Three raw goat milk samples of 200 mL were homogenized at 10 and 20 MPa (APV 2000, Copenhagen, Denmark). Three raw goat milk samples of 20 mL were heated at 65°C for 30 min and at 90°C for 10 min, respectively. Heat-treated and homogenized goat milk samples of 15 mL goat milk were centrifuged (4,000 × g, 30 min, 4°C) to obtain the upper fat fraction (Heal Force Neofuge 18R centrifuge, Heal Force Shanghai, China). The skim milk was then ultracentrifuged (60,000 × g, 2 h, 4°C) to obtain the casein fraction (Hitachi Koki Co. Ltd., Tokyo, Japan). Four times the volume of cold acetone (−20°C, GR, Sinopharm Chemical Reagent Co., Ltd.) was added to the remaining liquid. To obtain the whey protein fraction, the centrifugation of 9400 × g, 4°C for 10 min was applied to the remaining liquid, the lower precipitation was collected as whey protein fraction, and the upper liquid was collected as the aqueous phase. The different fractions obtained were freeze-dried and the dry matter was weighed (Alpha 2–4 LSC plus Laboratory freeze-dryer, Martin Christ, Osterode, Germany).

Lyophilized whole milk, fat, casein, whey protein, and aqueous phase samples of 2g (accurate to 0.001 g) were weighed, and then nitric acid of 10 mL (GR, Sinopharm Chemical Reagent Co., Ltd.) and perchloric acid of 2 mL (GR, Sinopharm Chemical Reagent Co., Ltd.) was added in sequence. Temperature-controlled heating plate was used to digest the solution at 120°C. When the solution is stable and transparent, raise the temperature to 150°C and heat for 2–3 h. Finally, the temperature of the plate was raised to 180°C to see if the digesting solution was brown. A tiny amount of nitric acid was added to continue digestion if the solution was brown, and to cease digestion when the solution was translucent or slightly yellow. While the digest solution was cooling, it was diluted with 50 mL of deionized water and thoroughly shaken. A blank digestion solution was made at the same time.

Preparation of standard solutions

Standard solutions of K, Ca, Na, and Mg, all with initial concentrations of 1000 μg/mL, were serially diluted with ultrapure water (Millipore Corp., Billerica, MA). The dilution gradient of K standard solution is 20mg/L, 50mg/L, 100mg/L, 200mg/L, and 400mg/L. The dilution gradient of Ca standard solution is 25mg/L, 50mg/L, 100mg/L, 250mg/L, and 500mg/L. The dilution gradient of Na and Mg standard solu-
tions is 5 mg/L, 10 mg/L, 20 mg/L, 50 mg/L, and 100 mg/L, respectively. Standard curves were established to quantify the elements, and the concentration of each element was expressed in μg/g.

Standard solutions of Zn, Fe, Cu, Mn, Co, Mo, Ni, and Cr, all with initial concentrations of 100 μg/mL, were serially diluted with 2.5% nitric acid (Millipore Corp., Billerica, MA). The dilution gradient of Zn and Fe standard solutions is 100 μg/L, 200 μg/L, 500 μg/L, 1000 μg/L, and 2000 μg/L, respectively. The dilution gradient of standard solutions of Cu, Mn, Co, Mo, Ni, and Cr is 0 μg/L, 50 μg/L, 100 μg/L, 200 μg/L, and 500 μg/L, respectively. Standard curves were established to quantify the elements, and the concentration of each element was expressed in ng/g.

ICP-OES analysis

An inductively coupled plasma optical emission spectrometer was used to determine the content of mineral elements (iCAP 7200 ICP-OES, Thermo Fisher Scientific, Waltham, MA, USA). The instrument parameters were set as follows: RF generator power: 1300 W, plasma flow rate: 12.0 L/min, peristaltic pump speed: 45 r/min, fog chamber: high-efficiency cyclonic fog chamber, cleaning time: 30 s, integration time: 0.5 min, frequency: 40.6 MHz, nebulizer flow rate: 0.55 L/min, pump feed volume: 1.5 mL, nebulizer pressure: 0.2 MPa, Auxiliary gas flow rate: 0.5 L/min, Repetition times: 3. Wait for the instrument to stabilize for about 30 min before the sample measurement. A computerized data acquisition system was used to process the data and generate standard curves to complete the quantification of mineral elements. The sampling system was rinsed with 3% dilute nitric acid and deionized aqueous for 5–10 min after the analysis.

Methodological validation

The method sensitivity and accuracy were validated using standard mineral elements spiked recovery test, method detection limit, and limit of quantification. Table 1 shows the ICP-OES method’s recovery rate, detection limit, and quantification limit. The recoveries of the 12 elements detected by standard addition in this test range between 91.15% and 107.47%, indicating that the approach is accurate and trustworthy.

Statistical analysis

Software SPSS (version 22.0, SPSS Inc., Chicago, IL) was used to perform the Shapiro-Wilk test for the data of element content in different fraction (P > 0.05). To analyze the significant difference in element content between different treatments and fractions, 2-way ANOVA analysis was performed using SPSS and verified by the Tukey test (P < 0.05). All figures were made by GraphPad Prism (Version 8.0.1, La Jolla, CA).

RESULTS

Distribution of mineral element concentrations analyzed in goat milk

Our study looked at the concentrations of 12 metal elements in goat milk, and all metal elements except Co were found (Table 2). After homogenization and heat treatment, the element concentrations in goat milk remained unchanged. As depicted in Table 3, the fat, casein, whey protein, and aqueous phase content of goat milk did not vary considerably. None of the elements we examined were most abundant in the fat fraction, but the data show that some Fe and Mo are distributed in it. Ca, Zn, Fe, and Cu are the most abundant elements in casein fractions. Mo is the only element discovered that is mostly prevalent in the whey protein fraction, but we also found that parts of Fe, Cu, and Ni are bound to whey protein. Elements like K and Na are mostly found in the aqueous phase.

Distribution of elements in goat milk following homogenization

The distribution of mineral element concentrations in different fractions of goat milk following homogenization is shown in Figure 1. After homogenization, the distribution of mineral element concentration altered dramatically. Mineral element concentrations of K, Na, Zn, Cr, Cu, Mn, and Mo in the fat fraction and Na, K, Fe, Cr, Mn, Ni, and Mo in the casein fraction increased considerably after homogenization. Mineral element concentrations of Ca, Na, Zn, Fe, Cr, Mn, Ni, and Mo in the whey protein and Ca, K, Na, Fe, Cr, Cu, and

<table>
<thead>
<tr>
<th>Mineral elements</th>
<th>Spike recovery (%)</th>
<th>LOD (mg/L)</th>
<th>LOQ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>98.53 ± 3.61</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>Ca</td>
<td>92.27 ± 2.06</td>
<td>0.18</td>
<td>0.60</td>
</tr>
<tr>
<td>Na</td>
<td>107.47 ± 5.53</td>
<td>0.37</td>
<td>1.23</td>
</tr>
<tr>
<td>K</td>
<td>95.89 ± 3.06</td>
<td>0.63</td>
<td>2.10</td>
</tr>
<tr>
<td>Cr</td>
<td>92.16 ± 2.21</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Cu</td>
<td>92.15 ± 1.32</td>
<td>0.005</td>
<td>0.017</td>
</tr>
<tr>
<td>Fe</td>
<td>95.43 ± 1.12</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Mn</td>
<td>101.99 ± 5.56</td>
<td>0.005</td>
<td>0.017</td>
</tr>
<tr>
<td>Ni</td>
<td>93.89 ± 4.05</td>
<td>0.002</td>
<td>0.007</td>
</tr>
<tr>
<td>Zn</td>
<td>100.2 ± 2.87</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>Mo</td>
<td>91.15 ± 6.00</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Co</td>
<td>95.00 ± 2.19</td>
<td>0.0007</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Mo in the aqueous phase decreased significantly following homogenization treatment. However, Mn content in the aqueous phase was not found after homogenization, which could be due to the Mn concentration becoming too low to detect. Figure 1 depicts the effect of high-pressure and low-pressure homogenization on the distribution of mineral element concentration in different fractions of goat milk. The results showed that 10 MPa homogenization did not affect mineral element concentrations, whereas, 20 MPa homogenization significantly increased Zn and Mo concentrations in the fat fraction and Fe concentration in the casein fraction. In contrast, Fe concentration in the aqueous phase did not change considerably after 10 MPa homogenization and reduced significantly after 20 MPa homogenization. Furthermore, Zn concentration in whey protein fraction and K concentration in fat fraction decreased or increased with increasing homogenization intensity.

**Distribution of elements in goat milk following heat treatment**

Figure 2 displays the metal element distribution in different fractions of goat milk after heat treatment. Heat treatment significantly affected the distribution of metal elements in the 4 fractions. When compared with raw milk, the mineral element concentration (Cu and Mg) in the fat fraction, Mg and Na in the casein fraction, Na in the whey protein fraction, and Ca in the aqueous phase changed significantly regardless of heating temperature. Other mineral element concentrations, on the other hand, did not alter much after heat treatment. Metal element concentrations (for example, Fe in fat, Mg and Ca in whey protein) decreased significantly following heat treatment at 90°C, whereas there were no significant changes after heat treatment at 65°C. In contrast, the Mo content in casein and aqueous phases increased significantly following heat treatment at 90°C, but not much after heat treatment at 65°C. Despite this, no substantial changes in other mineral element concentrations were seen after heat treatment.

**DISCUSSION**

**Distribution of elements in raw milk**

The mineral element concentrations and content of each component in goat milk found in this investigation were comparable to previous research (Claeys et al., 2014, Manoni et al., 2021). Fe, Ca, Cu, Cr, Mg, Mn, and Zn were found to be primarily distributed in the casein fraction, which is consistent with findings from mid-lactation Madrid goat milk and Indian Alpine and Beetle goat milk (De la Fuente et al., 1997, Singh et al., 2019). Na and K in goat milk are primarily distributed in the aqueous phase, as previously described (Gaucheron, 2005), which is similar to donkey milk (Fantuz et al., 2022). The whey protein fraction of goat milk has the highest Mo content, which differs from the study on donkey milk (Fantuz et al., 2022).

**Table 2. The content of mineral elements in goat milk undergo different processing**

<table>
<thead>
<tr>
<th>Mineral elements</th>
<th>Raw Milk</th>
<th>10 MPa</th>
<th>20 MPa</th>
<th>65°C (30 min)</th>
<th>90°C (10 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg (μg/g)</td>
<td>161.34 ± 8.55</td>
<td>157.01 ± 22.76</td>
<td>159.92 ± 7.11</td>
<td>157.39 ± 5.27</td>
<td>150.57 ± 8.10</td>
</tr>
<tr>
<td>Ca (μg/g)</td>
<td>1173.42 ± 80.73</td>
<td>1139.07 ± 163.34</td>
<td>1180.53 ± 25.97</td>
<td>1125.70 ± 66.35</td>
<td>1127.38 ± 78.72</td>
</tr>
<tr>
<td>Na (μg/g)</td>
<td>422.44 ± 15.42</td>
<td>423.05 ± 16.01</td>
<td>426.78 ± 18.12</td>
<td>421.24 ± 11.82</td>
<td>421.54 ± 19.70</td>
</tr>
<tr>
<td>K (μg/g)</td>
<td>1279.58 ± 24.45</td>
<td>1237.20 ± 31.59</td>
<td>1250.18 ± 44.32</td>
<td>1266.81 ± 34.68</td>
<td>1254.01 ± 50.88</td>
</tr>
<tr>
<td>Cr (ng/g)</td>
<td>8.77 ± 0.37</td>
<td>8.63 ± 0.56</td>
<td>8.80 ± 0.11</td>
<td>8.90 ± 0.79</td>
<td>8.93 ± 0.46</td>
</tr>
<tr>
<td>Cu (ng/g)</td>
<td>612.91 ± 39.56</td>
<td>613.87 ± 23.71</td>
<td>616.81 ± 23.80</td>
<td>610.17 ± 36.07</td>
<td>610.68 ± 12.39</td>
</tr>
<tr>
<td>Fe (ng/g)</td>
<td>1028.18 ± 66.85</td>
<td>1024.31 ± 33.65</td>
<td>1025.11 ± 66.10</td>
<td>1032.03 ± 36.24</td>
<td>1027.66 ± 47.24</td>
</tr>
<tr>
<td>Mn (μg/g)</td>
<td>61.48 ± 4.01</td>
<td>65.68 ± 3.95</td>
<td>66.23 ± 5.40</td>
<td>63.06 ± 1.82</td>
<td>64.54 ± 5.01</td>
</tr>
<tr>
<td>Ni (μg/g)</td>
<td>36.36 ± 2.08</td>
<td>36.18 ± 6.50</td>
<td>35.26 ± 1.61</td>
<td>34.27 ± 1.30</td>
<td>35.88 ± 0.92</td>
</tr>
<tr>
<td>Zn (ng/g)</td>
<td>3761.79 ± 172.08</td>
<td>3761.87 ± 64.26</td>
<td>3789.75 ± 128.34</td>
<td>3763.01 ± 121.42</td>
<td>3783.54 ± 45.70</td>
</tr>
<tr>
<td>Mo (ng/g)</td>
<td>21.71 ± 4.00</td>
<td>21.17 ± 3.01</td>
<td>22.56 ± 5.73</td>
<td>21.48 ± 2.64</td>
<td>22.14 ± 2.75</td>
</tr>
<tr>
<td>Co (ng/g)</td>
<td>ND*</td>
<td>ND*</td>
<td>ND*</td>
<td>ND*</td>
<td>ND*</td>
</tr>
</tbody>
</table>

* “ND” in the table “not detected.”

**Table 3. Different milk composition content expressed in goat milk at different processing methods**

<table>
<thead>
<tr>
<th>Fraction of Milk</th>
<th>Raw Milk</th>
<th>10MPa</th>
<th>20MPa</th>
<th>65°C (30 min)</th>
<th>90°C (10 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat (mg/g)</td>
<td>3.85 ± 0.17</td>
<td>4.05 ± 0.37</td>
<td>4.02 ± 0.47</td>
<td>4.18 ± 0.20</td>
<td>4.02 ± 0.33</td>
</tr>
<tr>
<td>Casein (mg/g)</td>
<td>2.41 ± 0.13</td>
<td>2.55 ± 0.076</td>
<td>2.48 ± 0.09</td>
<td>2.44 ± 0.15</td>
<td>2.61 ± 0.08</td>
</tr>
<tr>
<td>Whey Protein (mg/g)</td>
<td>0.85 ± 0.17</td>
<td>0.94 ± 0.08</td>
<td>0.93 ± 0.09</td>
<td>0.91 ± 0.08</td>
<td>0.91 ± 0.05</td>
</tr>
<tr>
<td>Aqueous phase (mg/g)</td>
<td>6.93 ± 0.09</td>
<td>6.5 ± 0.57</td>
<td>6.63 ± 1.0</td>
<td>6.52 ± 0.78</td>
<td>6.54 ± 0.76</td>
</tr>
</tbody>
</table>
Figure 1. Distribution of mineral element concentrations in different fractions of goat milk after homogenization. “a-c” means the significant difference between different processed milk ($P < 0.05$). “w-z” means the significant difference between different fractions of goat milk ($P < 0.05$).
Numerous studies have demonstrated that homogenization treatments can modify the distribution of mineral elements in milk. Zamora et al. investigated the effects of ultra-high-pressure homogenization and pasteurization on the mineral element composition of bovine milk whey. They found that pasteurization reduced the amount of Ca and Mg in whey fractions significantly. In addition, homogenization also dramatically changes the distribution of Ca and Mg content (Zamora et al., 2007), which is similar to our data. The Ca content was decreased in the aqueous phase and whey protein fractions after homogenization but did not change in fat or casein fractions. Homogenization reduces the size of milk fat globules while increasing milk fat stability (Ye et al., 2008). This mechanism results in the adsorption of casein and whey proteins to the surface of fat globules, which may result in a decrease in Ca concentrations in whey protein fractions and, as a result, increased Ca concentration in fat fractions. In addition, previous research also demonstrated that homogenization alters the structure of whey protein, which could be a reason for decreased Ca content in whey fractions (Qi et al., 2015). Furthermore, as Ca content in whey protein plays a significant role in stabilizing the whey protein against heat-induced precipitation and leads to a decrease in the heat stability of goat milk after homogenization.

The Mg content in the whey protein fraction was found to decrease, but remained constant in other fractions following homogenization. Several previous studies reported that the Mg concentration in whey protein decreased significantly in cow milk following high-pressure homogenization (200–330 MPa), which is consistent with our findings (DE LA FUENTE et al., 1999). On the contrary, Zamora, Ferragut, et al., 2007 reported that Mg content in whey increased significantly after homogenization at 100–130 MPa, which is inconsistent with our findings (Zamora et al., 2007), possibly due to treatment methods and species differences. On the other hand, very few studies on how Mg content changes in residual components after homogenization have been found in the literature. According to the research of (Ye et al., 2008), the interaction of whey protein and milk fat globule membrane post-homogenization may be responsible for the decrease in Mg content in whey protein. Although this study observed no significant changes in Mg levels in fat fractions, several research studies have shown that Mg binds to and

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**Effects of homogenization on the distribution of elements in goat milk**

Figure 1 (Continued). Distribution of mineral element concentrations in different fractions of goat milk after homogenization. "a-c" means the significant difference between different processed milk ($P < 0.05$). "w-z" means the significant difference between different fractions of goat milk ($P < 0.05$).
Figure 2. Distribution of mineral element concentrations in different fractions of goat milk after heat treatment. *" means the significant difference between different processed milk ($P < 0.05$). **" means the significant difference between different fractions of goat milk ($P < 0.05$).
activates alkaline phosphatase in fat fractions and that homogenization affects alkaline phosphatase activity (Puttige and Nooralabettu, 2012).

The Fe content was found to increase in whey protein fraction and decrease in the aqueous phase after homogenization. However, no research on the distribution of Fe content in different fractions of goat milk and other milk was found in the literature. In the casein fraction, Fe is related to phosphoserine, and the change in its content after homogenization may be attributed to a change in casein structure, which also affects Fe availability (Kibangou et al., 2005). The decrease in Fe content in the whey protein fraction could be attributed to whey protein migration into the fat fraction as a result of homogenization (Ye et al., 2008). Iron content will affect xanthine oxidase activity, but we did not find changes in Fe in the fat fraction, which may indicate that only a very small amount of XO in MFGM has been transferred to the other fraction (Manoni et al., 2021). The variation in experimental results could be attributable to variances in homogenization strength.

The Cu content increased in the fat fractions while decreasing in the aqueous phase following homogenization. Previous research has discovered that milk is less likely to develop off-flavors due to lipid oxidation after homogenization (Huppertz, 2022), which could be due to changes in the Cu content in the fat fractions and aqueous phases, as Cu can catalyze lipid hydroperoxides to form lipid oxyl radicals (Havemose et al., 2006).

The Zn content increased in the fat fractions while decreasing in the whey protein fraction following homogenization. In the fat fraction, Zn is primarily coupled with alkaline phosphatase (Manoni et al., 2021). Previous research has shown that high-pressure homogenization can impair alkaline phosphatase activity (Pinho et al., 2011), which may be related to the alterations in Zn concentration we observed. Despite the fact that homogenization reduced the amount of milk fat globule membrane due to casein and whey protein adsorption, the Zn level in fat increased dramatically (Ye et al., 2017). This could be due to the fact that the quantity of Zn transferred from casein and whey protein is greater than the amount lost from the milk fat globule membrane.

The Mo content of fat fractions and casein increased whereas the Mo content of whey protein declined after homogenization. Mo functions as a cofactor, catalyzing the metabolic processes of hypoxanthine to xanthine and xanthine to urate. (Okamoto et al., 2013). Previous research reported that xanthine activity increases by 60% to 90% after homogenization, which may be due to an increase in Mo concentration (Shaikh et al., 2023).
Chen et al. showed that when fresh goat milk was homogenized, the expression of xanthine dehydrogenase decreased, which could be accompanied by changes in Mo concentration (Chen et al., 2019). However, nothing is known about Mo content in whey protein and casein fraction, and more research is required.

**Effects of heat treatment on the distribution of elements in goat milk**

Many studies have found that heat treatment can vary the mineral element distribution in different milk fractions and that changes in mineral element distribution may be caused by changes in protein structure (Broyard and Gaucheron, 2015, Ye et al., 2017). Fuente et al. found that the Ca content in the aqueous phase of goat and cow milk was significantly decreased following heat treatment at 75°C and 85°C for 30 min (De la Fuente et al., 1997). Variations in the Ca content of the aqueous phase resulted in changes in the ratio of ionized to colloidal Ca, lowering the thermal stability of goat milk (Magan et al., 2022). Our results demonstrated that thermal treatment alters the ionic balance between the colloidal and soluble phases, leading to changes in mineral element utilization.

Ca content in the whey protein fraction dropped after heat treatment, but Ca content in the aqueous phase increased after 65°C heat treatment and decreased after 90°C heat treatment in this study. Changes in Ca in the colloidal phase after heating have been extensively studied (Seiquer et al., 2010), but we did not observe changes in Ca in casein fractions. This could be due to the high Ca concentration of casein, after heat treatment, the Ca transferred to casein has less of an effect on its Ca content. Furthermore, heat treatment denatures whey protein and causes it to interact with κ-casein, resulting in whey protein association with casein micelles and reduced Ca in whey (Anema and Li, 2003). Maillard products formed by protein glycosylation during heat treatment can lead to impairment of Ca absorption in these 2 components (Seiquer et al., 2010). It can be determined from the significant distribution changes of Ca in the aqueous phase and whey protein that the Ca ion balance is disrupted. As for the different Ca change trends, it may be caused by different processing conditions.

The Mg content of the fat and whey protein fractions reduced dramatically, whereas the Mg content of the casein fractions increased significantly following heat treatment. Heat treatment causes a decrease in the solubility of magnesium, which increases with the level of heat treatment. This is consistent with our result that the casein fraction has a greater Mg content. Additionally, Mg has been shown to bind to alkaline phosphatase on the milk fat globule membrane to activate it (Linden et al., 1977). As a result, the inactivation of alkaline phosphatase after heat treatment (Ritota et al., 2017) and the transfer may be to blame for the observed decrease in Mg concentration in the fat fractions. More research is needed on Mg content in whey protein fraction.

The Fe concentration in whey protein fraction decreased while the Fe content in the casein and aqueous phase of goat milk increased following heat treatment. The Fe content of fat fractions did not change much after 30 min of heat treatment at 65°C, but it decreased markedly after 10 min of heat treatment at 90°C. Heat treatment decreased the activity of xanthine oxidase, a Fe-binding enzyme, which could explain the variation in Fe content in fat fractions in our investigation (Ismail and Nielsen, 2011, Manoni et al., 2021). After heat treatment, whey protein associates with cystine-containing proteins (αs2-casein, κ-casein) via intermolecular thiol/disulfide exchange activities, resulting in an increase in Fe content in casein (Brisson et al., 2007). Because the bioavailability of different Fe-bound caseins varies, changes in casein Fe concentration may affect Fe absorption (Kibangou et al., 2005). Not only the binding of whey protein to casein will reduce the Fe content in whey protein, but the denaturation of Fe-binding proteins in the whey protein fraction will also affect the distribution of Fe. Heat treatment inhibits Fe-binding capacity of lactoferrin, decreases Fe content in the whey protein, and weakens lactoferrin’s antibacterial capability (Xiong et al., 2020), which could explain the drop in Fe concentration in the whey protein fraction.

The Cu content in fat and whey protein fractions decreased significantly while Cu content in casein fractions increased dramatically after heat treatment. Previous studies revealed that heat treatment transports Cu as a pro-oxidant to the milk fat globule membrane (Thum et al., 2023). Cu binds to ceruloplasmin and albumin in whey protein fraction (Puchkova et al., 2018), and after heat treatment, albumin in whey protein is denatured and forms a complex with casein, which is responsible for the decrease in Cu content in whey protein and increase in casein (Čurlej et al., 2022). Furthermore, based on the change in Cu level in whey protein fraction, heat treatment may potentially have a deleterious effect on ceruloplasmin, reducing its antibacterial action. Further investigation into the influence of heat treatment on the distribution of Cu in goat milk is required.

The Zn content in whey protein fraction and aqueous phase decreased significantly after heat treatment. Zn is coupled with albumin in the whey protein fraction (Fransson and Lönnernald, 1983), and heat treat-
ment causes aggregation of casein and whey protein, which reduces the Zn in whey protein. However, little is known about the shift in Zn distribution caused by heat treatment.

The Mo content in casein and aqueous phase increased significantly, but the Mo content in whey protein decreased significantly after heat treatment. Mo is an important factor that enables xanthine oxidase to function (Nishino et al., 2008). A study on the modification of xanthine oxidase activity in bovine milk after heat treatment found that xanthine oxidase was active after batch pasteurization and high-temperature short duration, but inactivated after heat treatment at 135°C (Ozturk et al., 2019). Therefore, the Mo concentration in fat fraction did not change significantly perhaps because the low level of heat treatment did not affect the activity of xanthine oxidase.

**CONCLUSION**

In our research, 2 regularly used processing techniques, homogenization and heat treatment, were utilized to analyze the distribution of mineral elements in fat, casein, whey protein, and aqueous fractions of goat milk. Mineral elements (such as Mg and Fe) are exceedingly low in fat fractions, whereas Ca, Zn, Fe, and Cu are widely diffused in casein fractions. Mineral element concentrations of K, Zn, Cu in fat and Na, K, Fe, Cr, Mn, Ni, Mo in the casein fraction rose after homogenization, but mineral elements such as Ca, Zn, Mo in whey protein fraction and Ca, Fe, Cu, Mo in aqueous phase dropped. When compared with raw milk, the element content in the fat fraction and casein fraction increased significantly after heat treatment. Based on the study of the distribution of mineral elements in goat milk, it is possible to support the future studies about the milk stability and element bioavailability of goat milk.

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