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Influence of calcium sulfate incorporated with gluconolactone coagulant on the quality of whole soybean flour tofu

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A R T I C L E I N F O

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A B S T R A C T

This work proposes a novel method for whole soybean flour tofu preparation by combining calcium sulfate (CS) and glucose-delta-lactone (GDL) coagulation. Importantly, the characteristics of the synthesized gel and the quality were studied. MRI and SEM results showed that the whole soybean flour tofu possessed satisfactory water holding capacity and water content at a CS to GDL ratio of 3:2, significantly improving the cross-linking network gel in tofu and accounting for its similar color to soybeans. Furthermore, GC-IMS analysis showed that the whole soybean flour tofu prepared at a 3:2 ratio had more flavor components (51 types) than commercially available ones (CS or GDL tofu) and exhibited satisfactory results during consumer sensory evaluation. Overall, this method is effective and applicable for the industrial preparation of whole soybean flour tofu.

1. Introduction

Tofu originated in China and is becoming increasingly popular across the world. It is a valuable protein source, comparable to meat, fish, and cheese, especially for Asians and vegetarians (Li et al., 2015). Given its high nutritional value, nice texture, and distinctive taste ingredients, tofu has recently attracted significant interest from Westerners (Guo et al., 2018). Furthermore, compared to animal-source proteins such as meat and milk, tofu is cholesterol-free and contains less saturated fat (Liu, 1997), with health-promoting properties, leading to decreased incidence of various malignancies (Messina, Persky, Setchell, & Barnes, 1994). The traditional tofu preparation process usually involves soaking and grinding soybeans, filtering, boiling, and coagulating the resultant soymilk, then pressing the curd results in tofu (Shen & Kuo, 2017; Guo et al., 2018). Indeed, the coagulant used directly impacts the coagulation process, influencing tofu quality and consumer acceptance (Shi et al., 2020).

Coagulants are mainly divided into two types: salts and acids (Shi et al., 2020). Calcium sulfate (CS) has been extensively utilized as a salt coagulant, generating a three-dimensional network structure by building a Ca bridge to cross-connect protein molecules (Li et al., 2015; Zuo et al., 2016). The Ca^{2+}- induced coagulation of soymilk is typically defined as a three-stage process. First, phytic acids bind with Ca^{2+} and generate non-ionizing products that decrease the electrostatic screening effects of ions on protein molecules, allowing Ca^{2+} and proteins to interact. Next, Ca^{2+} binds preferentially with non-particulate proteins, resulting in the formation of new protein particles. Finally, protein particles interact with one another to form the gel network, culminating in the formation of tofu (Shun-Tang, Ono, & Mikami, 1999; Wang, Xie, & Guo, 2015). However, it has been established that CS dissociates quickly at low temperatures. The shorter gelation interval results in a weaker and more discontinuous curd (Liu & Kuo, 2011). Glucose-delta-lactone (GDL) is a widely used acidic coagulant based on isoelectric precipitation and the interplay of intermolecular hydrophobicity, hydrogen bonding, and Van der Waals forces (Cao et al., 2017). GDL is commonly used in the production of silken tofu. The delayed release of protons by the GDL in soymilk results in the appropriate gelation of soy proteins but is time-consuming (Shen & Kuo, 2017).

This study sought to investigate the effects of CS and GDL on the moisture content, textural characteristics, and aroma composition of high-fiber tofu. The results of this study provide useful information for the application of coagulants in tofu production.

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2. Materials and methods

2.1. Materials

Soybeans were bought from Heilongjiang Province, China. The analytical grade chemical reagents utilized in this work were bought from the LingFeng Reagent Distribution Department (Shanghai, China).

2.2. Whole soybean flour tofu production

The tofu was prepared as described by Li et al., (2014) with minor modifications. To begin, soybeans were dried in an oven at 55 °C for 48 h due to moisture. The dried soybeans were crushed at high-speed for varying durations at 34,000 r min^{-1}, 3000 W (High-speed multifunctional grinder, ThermoScientific, Germany) and then sheared for 20 min using a high-speed shear (ThermoScientific, Germany) at a water-to-soybean powder ratio of 9:1. Next, the slurry was heated to boiling and cooked for another 3 min after being poured into a soymilk grinder (JiuYang Soymilk grinder, China). After naturally cooling to 90 °C, a coagulant (CS or GDL) corresponding to 3 % of the soybean mass was added, and the mixture was put in a 90 °C water bath for 35 min to maintain the slurry solidified, followed by split cooling for second gel maturation. Finally, the concretion was gently stirred to remove any remaining liquid before being pressed into a mold and the samples were kept in a 4 °C refrigerator for one day for further study.

2.3. Moisture content of tofu

2.3.1. Water-holding capacity (WHC) of tofu

The WHC of tofu was determined based on the method described by Puppo and Anon (1998) with slight modification. Approximately 2.0 g of tofu (m_0) was placed into a centrifuge tube, its mass was weighed to obtain m_1 (g), and 30 mL of deionized water was added. After centrifugation at 4500 rpm for 15 min, the supernatants were discarded, and residual liquids were carefully removed. Then, the remained sample was weighed as m_2 (g). The WHC of tofu was calculated using as the following equation:

$$\mathbf{WHC = (m_2 - m_1)/m_0 \times 100\ \%.}$$

2.3.2. Water distribution of tofu

The density and distribution of hydrogen protons inside the sample were obtained using a nuclear magnetic resonance (NMR) hydrogen spectroscopy (MesoMR23-060H-I, China) pseudo-color map to depict the sample's moisture content and distribution (Bian, Cao, Zhao, Liu, & Ren, 2017; Li et al., 2014). The brightness and darkness of the proton density images were used to describe the internal moisture content of the three different tofu production processes, and the higher brightness of the proton density-weighted images indicated greater density of hydrogen protons and higher moisture content of the sample (Song et al., 2016). Coronal pictures were taken during the test with the following settings:

FOV Read = 60 mm, Offset Read = 0 mm, FOV Phase = 60 mm, GxOffset = − 30, GyOffset = 50, GzOffset = –480, RFA90% = 1, RFA180% = 2, TR = 120 ms, TE = 5.885 ms, Averages = 256.

2.4. Texture profile analysis

Tofu samples were cut into 1 × 1 × 1 cm cubes with a razor blade and analyzed on a TA-XT2 texture analyzer (Stable Micro Systems, Surrey, UK), as previously documented by Zhang et al. (2013). The samples were compressed twice to 45 % deformation using a P/36R probe, pretest speed 2.0 mm s^{-1}, test speed 1.0 mm s^{-1}, and post-test speed 2.0 mm s^{-1}. The following texture parameters of the samples were measured: hardness, springiness, cohesiveness, gumminess, and chewiness.

2.5. Chroma analysis

Color analysis of tofu samples with different coagulant ratios was performed with a handheld colorimeter (UltraScan Pro, HunterLab, Reston, VA, USA) as previous described (Kim et al., 2019). Three parts of each sample were measured and averaged (surface, side, and profile). Before sample analysis, the colorimeter was calibrated with a standard whiteboard (with a diameter of 42 mm, Diffuse surface ceramic series standard whiteboard, Zhejiang Institute of Metrology and Technology), and the tofu samples were measured. b^* (yellowness value, the yellow color indicates a positive number, while the blue color indicates a negative number), a^* value (redness value, responding to the degree of redness of the sample; the positive number represents red, while the negative number represents green), L^* (brightness value, responding to the brightness of the color).

2.6. Microstructure of tofu

A scanning electron microscope was utilized to analyze the microstructure of tofu (SEM, TM3000, Hitachi Science Systems, Tokyo, Japan). The sample preparation for SEM was conducted as previous described (Shen & Kuo, 2017) with some modifications. The tofu was cut into several 2 × 2 × 2 mm cubes with a razor blade and then immersed in 2.5 % glutaraldehyde (10 times higher than the sample volume) overnight at 4 ℃ and rinsed thrice with phosphate buffer solution (0.1 M, pH 7.0). The sample was then fixed with a 1 % citric acid solution for 1–2 h before the fixative solution was drained out, followed by stepwise dehydration using 50 %, 70 %, 80 %, 90 %, 95 %, and 100 % (v/v) ethanol. After that, the samples were treated with a mixture of ethanol and isoamyl acetate ($v/v = 1/1$) for 30 min and then treated with pure isoamyl acetate for 2 h. The treated samples were then dried at the critical point. The dried samples were then fixed to the sample stage with conductive double-sided adhesive. The gold sputter was then used to overlay the dried samples (Desk-2, Denton quorum, Moorestown, NJ, USA). The SEM pictures were captured at a 15 kV accelerating voltage. The instrument parameters were as follows.

Inherent Parameters: SF = 21 MHz, O1 = 238762 Hz, $P1$ = 5.4 us, $P2$ = 10.8 us; Adjusting parameters: SW = 250 KHz, TW = 6000 ms, RFD = 0.15 ms , RG1 = 20 , DRG1 = 3, NS = 4, DR = 1, PRG = 1, NECH = 18000, TE = 0.8 ms.

2.7. GC-IMS analysis

Instrumentation and software studies of volatile chemicals were conducted using FlavourSpec ®Static Headspace (SHS) Gas chromatography-ion mobility spectrometry (GC-IMS) equipment with a heated splitless injector (Gesellschaft für Analytische Sensorsysteme mbH (G.A.S.), Dortmund, Germany). The IMS's ionization source was tritium 3H. The apparatus included an autosampler (PAL RSI, CTC Analytics AG, Zwingen, Switzerland) and a WAX-30 m × 0.53 mm ID capillary column (CS-Chromatographie Service GmbH, Düren, Germany). Data from IMS instruments were collected in the positive mode and analyzed with LAV® software (G.A.S.) that included the Reporter, Gallery Plot, and Dynamic PCA plugins. Furthermore, the GC-IMS Library Search ®software (G.A.S.) was used to identify chemicals. The instrument parameters and gas chromatographic conditions were set as described in in Table S1 & Table S2.

Several parameters for analyzing the volatile components of greengage wine were adjusted as described by Yang (2021) and Arroyo-Manzanares et al. (2018). The headspace (100 μL) was collected and automatically injected using an 85 °C heated syringe. The sample was injected into the capillary column after the carrier gas (N_2 at 3 bar input pressure) was passed through the GC-IMS syringe. The analytes were then eluted at 60 °C and transported to the ionization chamber. The 3H source ionized compounds at atmospheric pressure, producing product ions (protonated monomers or proton-bound dimers) depending on the concentration and chemical type of the analytes. The ions were then driven into a 9.8 cm long drift tube through the shutter grid, which was set to a constant voltage (500 V cm^{-1}) and temperature (45 °C). The drift

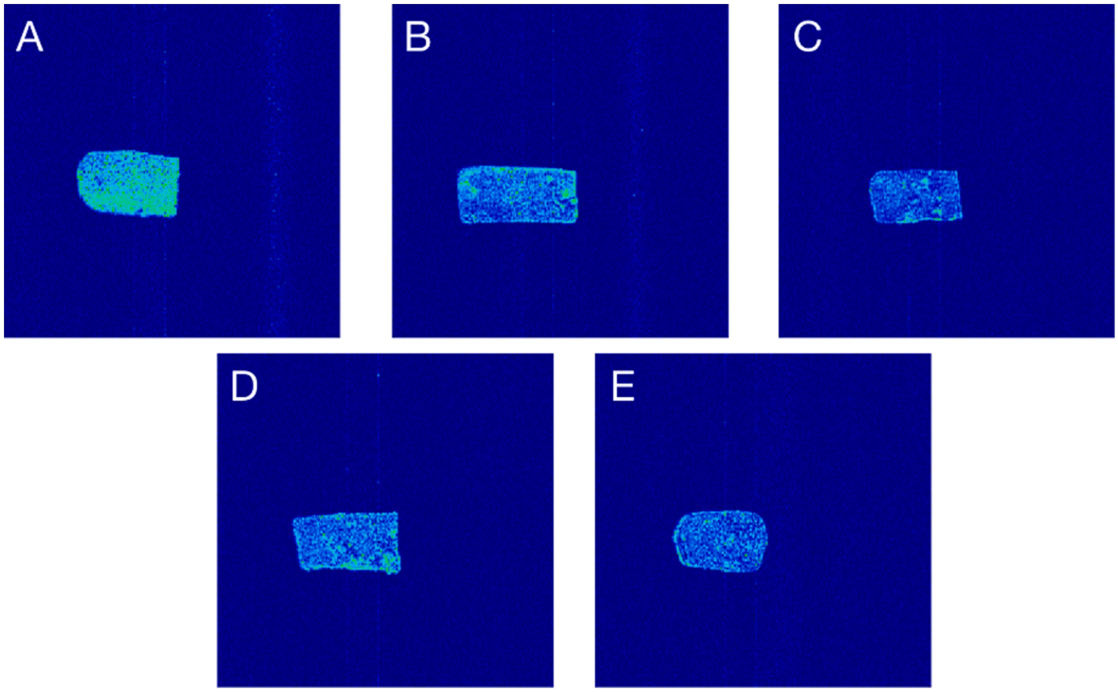

Fig. 1. Pseudo-color images of tofu with different coagulant ratios. (A) CS tofu, (B) GDL tofu, (C, D, and E) tofu with coagulant ratios CS / GDL of 1:1, 2:3, and 3:2, respectively.

gas (N_2) flow rate was set at 150 mL min^{-1}. Each spectrum had an average of 16 scans with a 30 ms repetition rate. The twofold separation obtained in the GC column and the IMS drift tube was depicted in a topographic map, including the retention duration, drift time, and intensity value.

2.8. Sensory analysis

This experiment was conducted to evaluate the effect of different ratios of coagulants on the market acceptance of high-fiber tofu through sensory analysis. As a result, the methodology described by Choi et al. (2006) was slightly adjusted for the sensory evaluation of the tofu samples. Ten trained panelists (five male and five female, aged 20 to 50) were required to identify and rank the sensory features of several tofu samples. Surface, taste, texture, mouthfeel, and overall acceptability were among the sensory indications assessed. The outcomes of each attribute were recorded on a 5-point scale, with 1 denoting very dissatisfied and 5 reflecting very satisfied. Detailed definition was indicated in the Table S5. Commercial GDL tofu, commercial CS tofu, and tofu with different CS and GDL compounding ratios were used in the study. Refer to Supplementary Material 2 for details of the results.

2.9. Data analysis

Graphpad prism 9.3.1 statistical software was used to perform one-way ANOVA and multiple comparisons were made using the LSD methodology. Data were analyzed for significance by SPSS software ($p < 0.05$, significant difference). The GC-IMS Library search program employed NIST and IMS databases for qualitative analysis of volatile organic compounds (VOCs). At least triplicates of the data were used to calculate the mean value and standard deviation (SD).

3. Results and discussion

3.1. Water holding capacity (WHC) and distribution of tofu with different coagulant ratios

It is well-established that water in a gel system may bind to the functional groups of protein and polysaccharides, or is trapped in the gel network's pores. Indeed, tofu's water-holding capacity has a direct impact on its texture and acceptance (Liu et al., 2013; Shen & Kuo, 2017). The release or passive diffusion of water from tofu during storage is termed to as syneresis. Moisture that can be removed from tofu by centrifugation is referred to as expressible water, while the remaining water is described as entrapped water (Shen & Kuo, 2017). In the present study, under the same processing conditions, the highest equilibrium moisture (94.24 %) was observed for the soybeans that used GDL only as a coagulant (Fig. S1), and the water distribution was more uniform than that of tofu prepared with CS alone (Fig. 1). Besides, the WHC of tofu when CS was incorporated with GDL was not significantly different from CS tofu, which validated that tofu with different coagulant ratios exhibited satisfactory WHC.

The MRI pseudo-color map in the NMR hydrogen spectrum was employed to demonstrate the hydrogen content and density distribution to assess the moisture content and distribution image in the tofu samples. Indeed, a brighter color indicates higher moisture content, and a more uniform density reflects a more uniform moisture distribution. As shown in Fig. 1A, the GDL tofu exhibited the highest moisture content, and the remaining samples exhibited comparable moisture content consistent with the WHC results, suggesting that the WHC of tofu was positively correlated with the moisture content. These findings were consistent with a previous study (Cai, Chang, Shih, Hou, & Ji, 1997), which found that tofu with a high percentage of solids had a low water content instead. Therefore, when different proportions of coagulants were used, soymilk proteins were coagulated to different uniform degrees and different levels of water were trapped in the gel network, which affected the protein or solids recovery in tofu and tofu yield. Moreover, when CS and GDL were used at a 3:2 ratio, the density distribution of water distribution was more uniform than other ratios.

In summary, the moisture content of tofu prepared by coagulant compounding was lower than that of tofu prepared by a single coagulant. While tofu with a CS / GDL ratio of 3:2 exhibited a uniform moisture distribution.

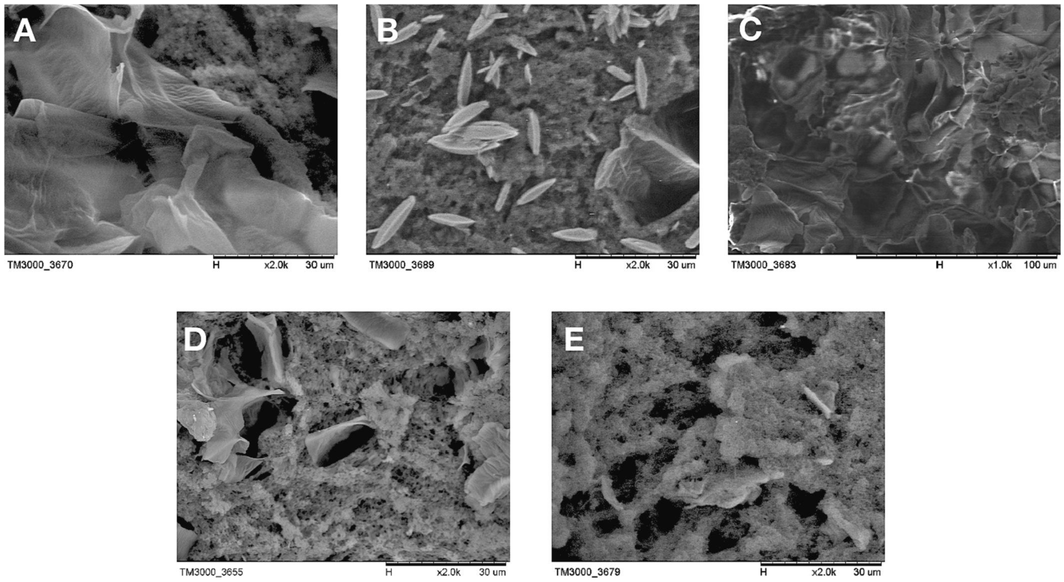

Fig. 2. SEM images of whole soybean flour tofu with different coagulant ratios. (A) CS tofu, (B) GDL tofu, (C, D, and E) tofu with coagulant ratios CS / GDL of 1:1, 2:3, and 3:2, respectively. SEM images were taken at 2,000 × magnification.

3.2. Texture profile analysis of tofu with different coagulant ratios

The texture, comprising hardness, springiness, cohesiveness, gumminess, and chewiness, was determined to understand the final qualities of tofu made with various ratios of coagulants, as analyzed and shown in Table S3 (Zhang et al., 2013).

Hardness refers to the ability of tofu to resist destructive forces during processing and application. Additionally, chewiness indicates the degree of gel binding, and simulates the ease of swallowing in the mouth (Liu et al., 2013 & Obatolu, 2008). As seen in Table S3, the chewiness value of the tofu samples made with the composite coagulant was the highest when the ratio of CS to GDL was 3:2, and was second to CS tofu when compared with the other coagulant ratios ($p < 0.05$). Moreover, a higher content of CS in the coagulant could significantly improve the hardness and chewiness values of tofu, causing a harder texture, indicating that CS could enhance the ability of tofu to resist external forces during processing. Of note, many large insoluble particles in the soy flour suspension (Fig. 2E) were involved in tofu gelation. These particles are widely thought to adversely affect the formation of the gelation network (Liu et al., 2013). When combined with different ratios of gelling agents, these particles were more agglutinated with each other, leading to fewer adverse effects and improving the hardness characteristic of the tofu.

Other texture properties such as springiness, cohesiveness and gumminess of tofu with different coagulant ratios showed a similar tendency. Soymilk coagulation transformed the protein molecules into a gel, increasing the springiness values, which can be used to investigate the process of coagulant action. Given that the magnitude of the springiness represents the ability of tofu to rebound during chewing, it is an important parameter during the quality of assessment of tofu. Cohesiveness refers to the ability of a product to withstand a second deformation relative to the first. In this study, there was no significant difference ($p > 0.05$) in the springiness, cohesiveness and gumminess values of the tofu prepared with the compound coagulant and all were lower than the single coagulant (CS or GDL) tofu, validating that CS and GDL at a 3:2 ratio yielded optimal textural characteristics.

3.3. Chroma analysis of tofu with different coagulant ratios

Tofu is usually recognized as being creamy white/milky in color (Hou & Chang, 2004; Noh et al., 2005). Fig. S2 depicts the color properties of tofu with various coagulant levels. The colors of tofu created with various coagulant ratios were compared to tofu made with only one coagulant (CS or GDL). Accordingly, the highest brightness value (L^*) was obtained when the ratio of CS and GDL was 3:2, while a^* and b^* valuables were the lowest ($p < 0.05$), attributed to the high moisture content of tofu, which accounted for the greenish colour of soybeans, resulting in a decline in a value (Kong et al., 2008). However, the opposite trend was observed when the tofu sample was made by GDL only, which yielded the lowest value of L^*, and the highest a^* and b^* values. Additionally, it has been substantiated that different coagulant ratios could yield tofu samples of varying colors ($p < 0.05$).

3.4. Microstructure of tofu with different coagulant ratios

It has been suggested that a better understanding of the changes in tofu microstructure related to coagulation conditions would provide a more reasonable foundation for determining the appropriate coagulant ratios (Kao et al., 2003). In this study, SEM images were taken to observe the microstructures of tofu prepared with different ratios of CS and GDL (Fig. 2), and the results showed significantly different delicate structures. When CS or GDL was used alone, the obtained gel networks contained discontinuous fractals aggregates and relatively large interspaces (Fig. 2A and 2B). This microstructure caused the discharge of water, uncoagulated proteins, and other soluble substances from the gel during the tofu compressing process, reducing tofu yield. On the other hand, tofu gels generated from CS incorporating the GDL coagulant displayed more continuous, homogenous, and denser networks (Fig. 2C–E). Of note, when the CS content in composite coagulant was increased to 60 % (the ratio of CS to GDL was 3:2), pore size exhibited a propensity to decrease and with a more homogeneous arrangement (Fig. 2E), accounting for the optimal WHC as shown in Fig. S1. These findings were consistent with findings reported by Puppo and Anon (1998), who documented a protein gel with a homogenous and tiny structure yielded better WHC than a gel with a nonhomogeneous structure, which had a significant degree of syneresis.

3.5. Volatile organic compounds analysis of tofu with different coagulant ratios

Three major indices of food quality are aroma, taste, and appearance. Volatile aroma compounds substantially impact food flavor, which

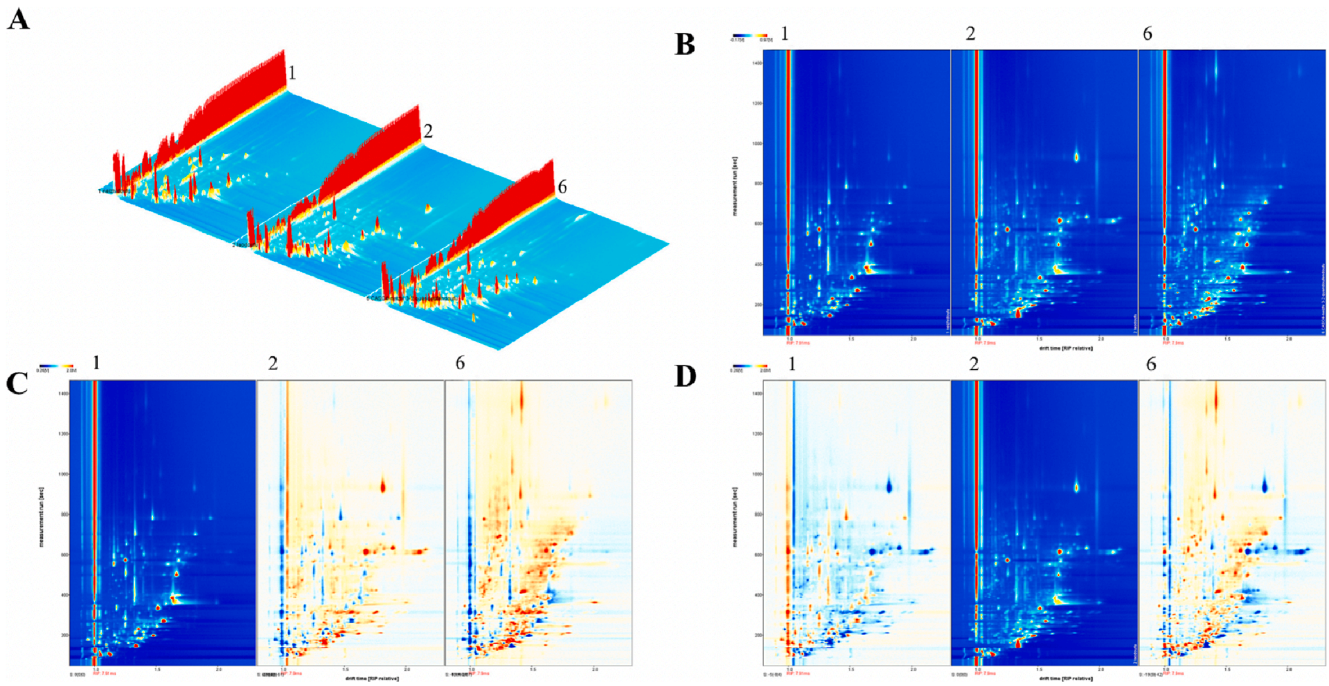

Fig. 3. 3D-topographic plot of whole soybean flour tofu prepared with different coagulant ratios. The vertical coordinate indicates the retention time of gas chromatography, and the horizontal coordinate indicates the ion migration time. Samples 1,2,6 represent GDL tofu, CS tofu and coagulant compound (CS / GDL = 3:2) tofu, respectively.

influences the overall perception of food (Lu et al., 2022; Wang, Chen, & Sun, 2020). GC-IMS analysis has been used to quickly obtain information on VOCs in tofu, explore the effect of different coagulant ratios on the flavor of tofu, and help evaluate the consistency of the process (Yang et al., 2021). Based on the results of other indicators for assessing the quality of tofu, a ratio of CS to GDL of 3:2 was finally selected for comparative analysis in terms of aroma composition with tofu made from a single commercially available single coagulant (CS or GDL). This study employed the GC-IMS technique to detect and analyze the VOCs and characteristics of tofu prepared with a coagulant compound (3:2)

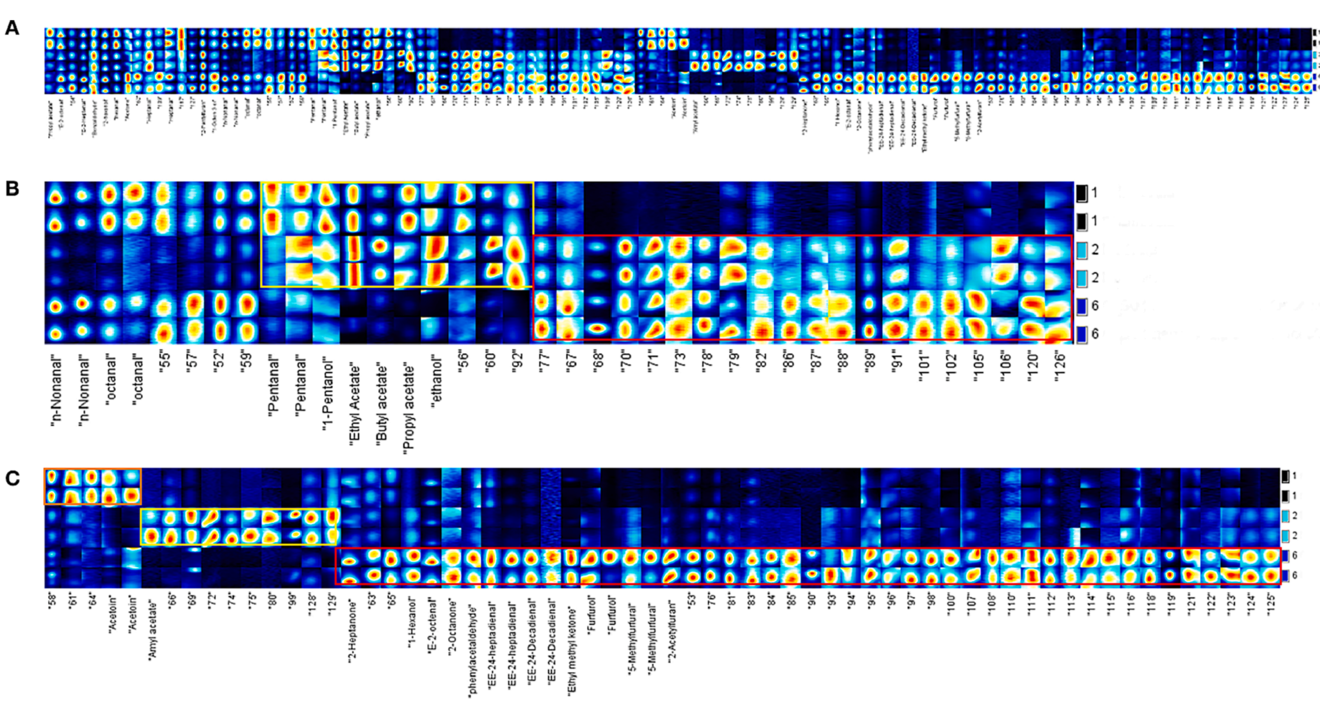

Fig. 4. Gallery plot of the selected signal peak areas obtained from whole soybean flour tofu prepared with different coagulant ratios. Because the above diagram (A) was too small, the following enlargement indicated the significantly different substances divided into the (B) and (C) parts. Each row in the figure represents all the peaks selected from one tofu sample. Each column in the graph represents the signal peaks of the same VOC in different tofu samples. The complete volatile information of each sample and the difference in VOCs between samples can be visualized in the graph. Samples 1,2,6 represent GDL tofu, CS tofu and coagulant compound (CS / GDL = 3:2) tofu, respectively.

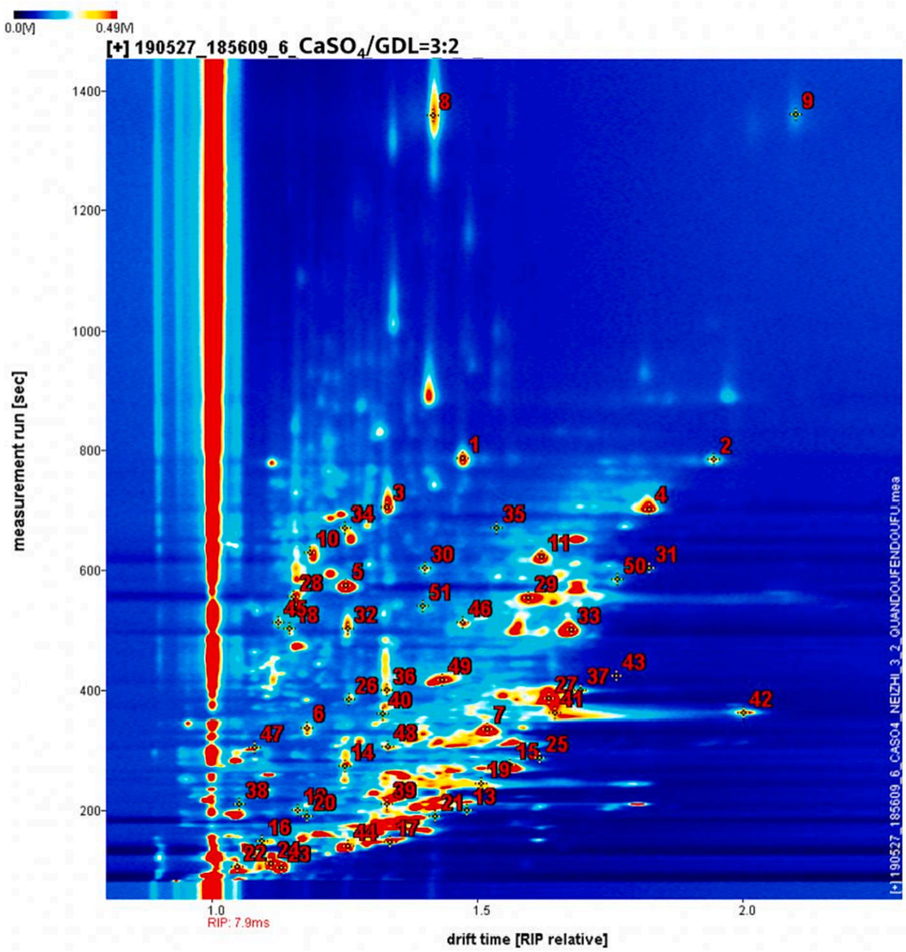

Fig. 5. Topographic plots of GC-IMS spectra with the selected markers obtained from whole soybean flour tofu prepared with different coagulant ratios.

versus a single coagulant (CS or GDL). Then tofu samples were subjected to principal component analysis to compare the flavor fingerprints of tofu prepared with the coagulation compound.

The three-dimensional spectrum results generated by GC-IMS are depicted in Fig. 3A, where the X-, Y-, and Z-axes reflect the ion migration time, GC retention time, and ion peak strength, respectively (Yang et al., 2021). The colors in the graph represent the signal intensities of the various chemicals. Red indicates strong intensity, whereas blue indicates low intensity. Intensity increases as the color darkness increases (Yang et al., 2021). In GC-IMS, GC separation was first conducted based on the strength of the force between the complex VOCs in the sample, followed by separation in the chromatographic column's stationary phase. The components eluted at varying retention durations were softly ionized in a gaseous form by the ion source to produce molecular ion groups. Due to variations in mass, collision section, charge, and periodic ion pulses, the ions sequentially entered the linear drift electric field under ambient air pressure and obtained various migration speeds for secondary separation. The ion drift time and ion peak strength were obtained for each component to undertake qualitative analysis (Yang et al., 2021).

The top-view plot of GC-IMS was generated by normalizing the ion migration time and reactive ion peak (RIP) position (Fig. 3B). The results suggest that most signals arrive at a holding time of 100–800 s and a drift time of 1.0–1.7 s. Herein, the topographic map of CS or GDL tofu was used as a reference. For VOCs with the same concentration in the reference and analyte, the background would appear white. Red indicates that the compound's concentration is higher than the reference value, while blue indicates that it is less than the reference value. As shown in Fig. 3B, most flavor ions had retention durations between 100 and 600 s and drift times between 1.0 and 1.7 s. Furthermore, 51 typical flavor compounds were identified from the topography by GC-IMS library search, with the largest number of species being aldehydes, followed by six alcohols, as well as four esters and ketones, two furans and one ethyl coupling (Fig. 5 and Table S4). Chung (1999) illustrated that 1-hexanol and 1-Octen-3-ol are essential VOCs that impart a grassy aroma. Moreover, Lee, Cho, and Lee (2014) highlighted that ethanol imparts an unpleasant aroma. Thereafter, Liu, Miao, Guan, and Sun (2012) and Lee et al. (2014) founded that alcohols were mainly produced by the fermentation of carbohydrates in soybean products. Benzaldehyde is an aromatic substance that imparts a pleasant flavor. In addition, hexanal contained in tofu yields a less attractive grassy flavor, but it is still an important flavoring component. Hexanal concentrations have been reported to decrease sharply during tofu preservation (Yang et al., 2021).

Accordingly, the substances in the red box of the fingerprint profile (Fig. 4B) were much higher in CS tofu and calcium sulfate lactone compounded tofu than in GDL tofu. In contrast, the substances in the yellow box, including valeraldehyde, 1-pentanol, ethanol, ethyl acetate, butyl acetate, and propyl acetate, were present in higher amounts in GDL tofu and CS tofu but in very low contents in CS and GDL compound tofu; other substances, including nonanal and octanal, were present in much higher concentrations in GDL tofu and calcium sulfate lactone compound tofu. Moreover, the substances in the red box of the fingerprint in Fig. 4C, including 2-heptanone, 1-hexanol, phenylethylaldehyde, 2-butanone, 2-octanone, *trans*-2-octenal, *trans*-2,4-decadienal, *trans*-2,4-heptadienal, 2-acetylfuran, furfural and 5-methylfuranal, were much higher in calcium sulfate lactone compound tofu than in CS tofu and GDL tofu. Besides, the substances in the yellow box,

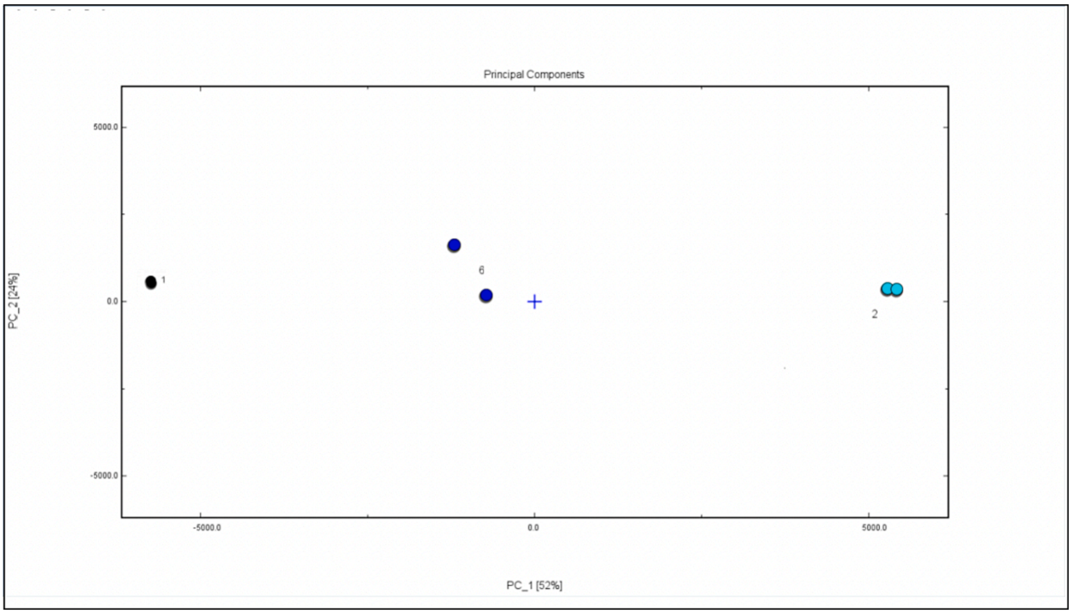

Fig. 6. PCA based on the signal intensity obtained from whole soybean flour tofu prepared with different coagulant ratios. Samples 1,2,6 represent GDL tofu, CS tofu and coagulant compound (CS / GDL = 3:2) tofu, respectively.

including acetate and pentyl acetate, were much higher in CS tofu than in GDL tofu and calcium sulfate lactone compound tofu. Finally, the substances in the orange box, including ethyl coupling, were much higher in GDL tofu than in CS tofu and calcium sulfate lactone compound tofu.

Principal Component Analysis (PCA) is a multivariate analysis-based detection method that emphasizes the differences between samples by utilizing the signal intensities of flavoring compounds (Eriksson, Johansson, Kettaneh-Wold, Trygg, & Wikstrom, 2006). The PCA findings for the flavor components in whole soybean flour tofu made with various coagulant ratios are shown in Fig. 6. It was found that the first two principal components accounted for 52 % and 24 % of the whole variance contribution ratio, respectively (Wu et al., 2015). The PCA results indicated that the samples from whole soybean flour tofu prepared with different coagulant ratios occupied comparatively independent spaces in the distribution map, which suggested significantly different flavors among the samples. Overall, the results confirmed that the unique flavor fingerprints of the samples from whole soybean flour tofu prepared with different coagulant ratios were successfully constructed using GC-IMS, providing novel insights into the mechanism of flavor development across different production stages.

4. Conclusion

Mixing different types and proportions of organic acid and salt as coagulants resulted in textural, color, flavor and microstructural differences in tofu. Tofu prepared with CS and GDL compounded in a ratio of 3:2 exhibited excellent physical properties, as evidenced by high energy storage modulus, unique color and flavor, uniform texture, WHC and high water content. Taken together, this findings suggest that tofu prepared by compounding CS and GDL has a texture close to CS tofu, and retains the water content and flavor of lactone tofu. Compounding CS and GDL not only improved the nutritional value of tofu while solving the problem of soybean residue resources, but also improved the texture and flavor quality of tofu. Overall, the results reveal that this ratio was optimal for producing whole soybean flour tofu.

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CRediT authorship contribution statement

Wenjing Lu: Conceptualization, Validation, Formal analysis, Writing – review & editing, Visualization, Supervision. **Yue Zhang:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Cen Zhang:** Formal analysis. **Di Chen:** Project administration. **Chaogeng Xiao:** Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2022.100527.

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