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# Potential application of electrical conductivity measurement for freshness assessment of tofu

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A B S T R A C T

The potential of using electrical conductivity measurements to evaluate the freshness of tofu during storage was studied. Changes in the electrical conductivity of tofu were measured using a custom system under refrigerated (5 °C) and room temperature conditions (20 °C). The electrical conductivity of tofu stored at room temperature rapidly increased from 0.46 to 0.81 S/m within 9 days. During refrigerated storage, the conductivity slowly increased from 0.30 to 0.41 S/m over 24 days. The electrical conductivity data were converted into an electrical conductivity freshness index ($EF_i$) to develop an empirical model for physicochemical qualities (pH and texture) and microbial growth. In the pH analysis, $EF_i$ could well predicted the pH reduction following spoilage during both refrigerated and room-temperature storage. For example, the $EF_i$ empirical model showed ß$_2$ coefficient and $R^2$ values of − 2.553 and 0.976, respectively, for pH estimation of refrigerated tofu. Microbial growth could be precisely predicted using electrical conductivity measurements since the empirical parameter of $EF_i$ showed positive values. The results of this study suggest that *in situ* electrical conductivity measurements can be used for the rapid estimation of tofu freshness during storage.

## 1. Introduction

Tofu is a soybean (*Glycine max*) curd prepared by curdling fresh hot soymilk with a coagulant that is an inexpensive source of highly digestible protein and isoflavones [3,4,13,21]. The global market value of tofu was estimated to be USD 2.31 billion in 2018 and is expected to increase at an annual growth rate of 5.2% from 2019 to 2025 [1,20]. Its high nutritional content makes tofu a good medium for bacterial growth during manufacture, distribution, and storage. Tofu is a perishable product with a shelf life much shorter than that of other soybean products; its shelf life is influenced by various environmental factors such as bacterial load, storage temperature, air composition, and manufacturing process [2,9,12]. Hence, tofu should be refrigerated during storage; the shelf life of unpasteurized tofu is three days [8]. Tofu contains various potential spoilage and pathogenic bacteria such *as Escherichia coli* and other *coliforms*, *Bacillus cereus*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Salmonella* spp. [12]. Therefore, most manufacturers pasteurize tofu, which is distributed and consumed through a cold-chain system. Despite the use of such a system, there is a chance of temperature abuse during distribution and storage. Inappropriate control of the tofu temperature can result in bacterial growth and subsequent spoilage. The freshness of tofu can be estimated by the presence of odors and discoloration, but other more precise methods should be used to prevent foodborne illnesses. The measurement of pH is typically employed in the analysis of tofu freshness because it decreases in spoiled tofu due to the formation of lactic acid [15]. However, pH measurement cannot be easily used in cold-chain systems because it requires a homogenization process, distilled water, and experimental equipment. Another method for determining tofu freshness is microbial analysis; however, it also requires labor, a laboratory environment, trained personnel, and an incubation period.

Therefore, a new freshness evaluation method should be developed to rapidly determine the state of tofu in real time. A previous study [5] showed the potential of using electrical conductivity to rapidly evaluate the freshness of milk. In this study, we report on the potential use of *in situ* electrical conductivity measurements to assess tofu quality and spoilage. Changes in the electrical conductivity of tofu are correlated with physicochemical freshness parameters (pH, color, and texture) and microbial growth. This method of electrical evaluation of tofu freshness would be useful for the rapid testing of spoilage in real time.

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## 2. Materials and methods

### 2.1. Sample preparation

Commercial pasteurized tofu (Pulmuone Danone Co. Ltd., Seoul, Korea) was purchased from a local market within three days of production. The samples were cut into rectangular shapes (30 mm × 53 mm × 30 mm) in a biosafety cabinet (Samin Science Co. Ltd., Ansan-si, Korea) to ensure aseptic conditions. A customized electrical conductivity cell was fabricated using an acrylic container equipped with titanium electrodes (55 × 30 mm) at both ends. Each sample was loaded between the electrodes in a conductivity cell. Ethyl alcohol (70%) was used to sanitize the electrodes and conductive cells to prevent contamination by microorganisms before the experiment. The top of the electrical conductivity cell was hermetically sealed with Parafilm (Millipore-Sigma, Burlington, MA, USA) to prevent contamination during storage.

### 2.2. Experimental set-up of the electrical conductivity cell

Fig. 1 shows the custom-developed electrical conductivity measurement system used in our previous study to determine food freshness [5]. It comprises a function generator (Keysight Technologies, Santa Rosa, CA, USA), electrical conductivity cell, and current measurement sensor (50 Ω resistor; Jeil Electronics Co., Ltd., Gwangju, Korea). The electrical conductivity cell was equipped with two titanium electrodes (55 × 30 mm) at both ends of a rectangular acrylic container that maintained an electrode distance of 53 mm. A waveform generator applied an electric field strength of 0.87 V/cm across each tofu sample. In the preliminary experiment, this level of electric field strength did not induce any ohmic heating of tofu. In the preliminary experiment, the gel stability did not change when a 0.87 V/cm electric field was applied to tofu for 24 h at 5 °C or 20 °C. The stability of tofu was tested hourly for changes in hardness and moisture exudation. A data acquisition system (DAQ; Keysight Technologies) was used to monitor and record the current and voltage across the sample every 5 min during the storage period. These data were used to calculate the changes in the electrical conductivity of tofu.

### 2.3. In situ electrical conductivity measurements

The electrical conductivity of the tofu was calculated from the voltage and current flows across the sample, as indicated in Eq. (1):

$$\sigma = \frac{L \cdot I}{A \cdot V} = k \cdot \frac{I}{V} \quad (1)$$

where $L$ is the distance (m) between the electrodes, $A$ is the cross-sectional area ($m^2$) of the sample, $I$ is the current flow ($A$) across the sample, $V$ is the measured electric potential ($V$) across the sample, and $k$ is the cell constant ($m^{-1}$) of the conductivity cell. The constant, $k$, considers the volumetric dimension of the sample for electric current flow, which is determined from the cross-sectional area ($m^2$) of the sample and its length (m). This equation has been used previously to estimate the electrical conductivity of food [14,16,18].

The value of $k$ for tofu was calculated to be 59 $m^{-1}$. Changes in the electrical conductivity were recorded by the DAQ system every 5 min under refrigerated (5 °C) and room temperature (20 °C) conditions for 24 days. Under refrigeration, tofu was stored at 5 °C in a refrigerator (Infobiotech, Daedeok-gu, Korea). Room temperature samples were stored at 20 °C in an incubator (Changshin Science, Seoul, Korea).

### 2.4. Calculation of the in situ electrical conductivity freshness index

In previous studies [5,16], the *in situ* electrical conductivity freshness index ($EF_i$) has been used to evaluate the freshness and quality attributes of foods during processing and storage. $EF_i$ was calculated from the logged *in situ* electrical conductivity data, as in a previous study [5].

$$EF_i = \frac{\sigma_{is} - \sigma_{fs}}{\sigma_{sp} - \sigma_{fs}} \quad (2)$$

where $\sigma_{is}$ is the *in situ* electrical conductivity of tofu, $\sigma_{fs}$ is the electrical conductivity of fresh tofu, and $\sigma_{sp}$ is the electrical conductivity of spoiled tofu during storage at the given temperature. An $EF_i$ value of 0 indicated fresh tofu, whereas a value of 1 indicated spoiled tofu.

### 2.5. Changes in the pH

Changes in the pH of tofu stored at 5 °C and 20 °C were evaluated using a glass electrode pH meter (Orion Star A211, Thermo Fisher Scientific Inc., Waltham, MA, USA). Tofu was homogenized in distilled water (tofu:distilled water equal 1:2) at 200 rpm using a homogenizer (SR30, Mtops, Seoul, Korea). The homogenized tofu mixture was transferred into a 50 mL conical tube and pH measurements were

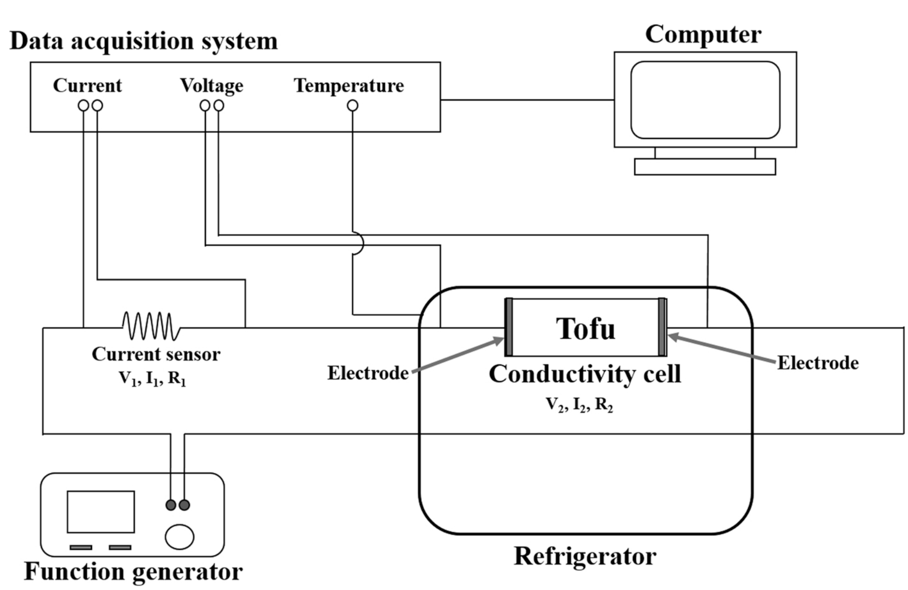


**Fig. 1.** Schematic diagram of electrical conductivity system for tofu
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conducted every 1 and 3 d at 5 °C and 20 °C, respectively.

### 2.6. Microbial growth

The total aerobic bacteria (TAB) count was used to monitor microbial growth. Tofu (10 g) was aseptically transferred to a bag filter (BagFilter P 400, Interscience, France), and 90 mL of sterilized distilled water was added. The mixture was macerated for 2 min using a stomacher (Bagmixer 400, Interscience) and then a 1 mL sample was sequentially diluted 10-fold with sterilized 0.85% saline solution. The diluted sample (100 μL) was aseptically spread on standard methods agar (247940, Becton Dickinson and Company, Franklin Lake, NJ, USA) and incubated at 37 °C for 48 h before counting. TAB count was determined every 1 and 3 d for refrigerated and room temperature storage samples, respectively.

### 2.7. Color measurement

The color of the tofu was measured using a colorimeter (CR-10; Konica Minolta Sensing Inc., Sakai, Japan). The color of the tofu surface was evaluated and described with the attributes of lightness ($L^*$), redness ($a^*$), and brightness ($b^*$) every 1 and 3 d at 5 °C and 20 °C, respectively.

### 2.8. Textural profile analysis

Textural profile analysis (TPA) of the tofu was conducted *via* a puncture test using a texture analyzer (Stable Micro Systems, Surrey, UK). A cylindrical probe (diameter: 5 mm) was used to puncture the sample to a depth of 40% of the original height at a constant speed (pre-test: 2 mm/s; test: 0.80 mm/s; post-test: 2 mm/s). The maximum puncture force was determined as the hardness (N). The analysis intervals were 1 and 3 d at 5 °C and 20 °C, respectively.

### 2.9. Mathematical model of electrical conductivity and freshness

An empirical model of $EF_i$ was developed to estimate changes in pH, TAB count, and TPA of tofu, as suggested in a previous study [5]. The first and second polynomial regression models are interrelated as follows:

$$pH = \beta_0 + \beta_1 \cdot EF_i + \beta_2 \cdot EF_i^{\,2} \pm \varepsilon \tag{3}$$

$$TAB = \beta_0 + \beta_1 \cdot EF_i + \beta_2 \cdot EF_i^{\,2} \pm \varepsilon \tag{4}$$

$$TPA = \beta_0 + \beta_1 \cdot EF_i + \beta_2 \cdot EF_i^{\,2} \pm \varepsilon \tag{5}$$

where $EF_i$ is the *in situ* electrical conductivity freshness index, $\beta_0$ is the intercept coefficient of the polynomial regression, $\beta_1$ is the slope coefficient of the first-order term, $\beta_2$ is the slope coefficient of the second-order term, and ε is the standard error in Y.

The model was generated using statistical analysis software (SAS version 9.1.3, SAS Institute Inc., Cary, NC, USA).

### 2.10. Statistical analysis

The electrical conductivity, pH, TAB count, and TPA were measured in triplicate. The statistical significance of the results was determined using an ANOVA. Fisher's least significant difference was adopted at a 95% confidence interval using SAS (version 9.1.3).

## 3. Results and discussion

### 3.1. In situ electrical conductivity and in situ freshness index of tofu

The evolution of the *in situ* electrical conductivity and $EF_i$ of tofu stored at 5 °C and 20 °C is shown in Fig. 2. The initial *in situ* electrical conductivities of tofu were 0.30 ± 0.01 S/m and 0.46 ± 0.03 S/m at 5 °C and 20 °C, respectively. The electrical conductivity of foods is temperature-sensitive because ion movement is temperature dependent [5–7]. At 5 °C the *in situ* electrical conductivity slowly increased from 0.30 ± 0.10–0.41 ± 0.01 S/m over 24 days. The freshness of refrigerated tofu degrades from day 8 of storage [19]. In this study, the *in situ* electrical conductivity of refrigerated tofu increased slightly from day 9 of storage. When tofu spoils, low-molecular-weight electrolytes (peptides and amino acids) are formed [15]. These electrolytes increase the *in situ* electrical conductivity of tofu. In a previous study, the *in situ* electrical conductivity of cow's milk was found to increase with spoilage [5]. The *in situ* electrical conductivity of tofu stored at 20 °C rapidly increased from 0.46 ± 0.03–0.87 ± 0.10 S/m in 12 days. This increase was attributed to the faster initiation of tofu spoilage. Acid and peroxide levels increase when tofu is spoiled [13]. The initial $EF_i$ of tofu stored at either 5 °C or 20 °C was 0 on day 0. Refrigerated tofu maintained this $EF_i$ until day 6, after which a sharp increase was observed from day 9 onward. Based on $EF_i$, the shelf life of refrigerated tofu is 9 days, which corresponds to the shelf life of tofu estimated by microbial analysis [10]. At room temperature, $EF_i$ increased from day 1 of storage, indicating the initiation of spoilage.

### 3.2. Changes in the pH of refrigerated and room-temperature tofu

Table 1 presents the changes in the pH values of tofu stored at 5 °C

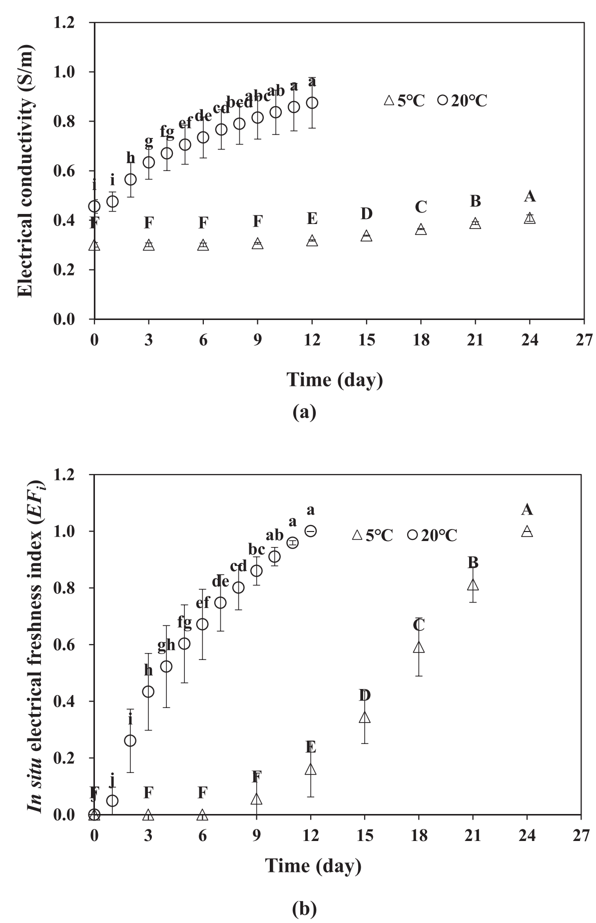


**Fig. 2.** Evolution of (a) electrical conductivity and (b) *in situ* electrical freshness index ($EF_i$) of tofu stored during refrigerated (5 ℃) and room temperature (20 ℃) storage. [A-F]Means ( ± Standard deviation) with a different letter are significantly different at 5 ℃ ($P < 0.05$). [a-j]Means ( ± Standard deviation) with a different letter are significantly different at 20 ℃ ($P < 0.05$).

**Table 1**
pH values of tofu during refrigerated storage at 5 ℃ and room temperature storage at 20 ℃.

| pH | | | |
|---|---|---|---|
| Time (day) | 5 ℃ | Time (day) | 20 ℃ |
| 0 | 6.99 ± 0.03 [A] | 0 | 6.99 ± 0.03[a] |
| • | • | 1 | 6.73 ± 0.02[b] |
| • | • | 2 | 6.42 ± 0.03[c] |
| 3 | 6.93 ± 0.03[BC] | 3 | 6.23 ± 0.03[d] |
| • | • | 4 | 5.97 ± 0.08[e] |
| • | • | 5 | 5.86 ± 0.01[f] |
| 6 | 6.94 ± 0.02[B] | 6 | 5.74 ± 0.09[g] |
| • | • | 7 | 5.73 ± 0.01[gh] |
| • | • | 8 | 5.72 ± 0.04[gh] |
| 9 | 6.89 ± 0.04 [C] | 9 | 5.70 ± 0.05[gh] |
| • | • | 10 | 5.66 ± 0.02[h] |
| • | • | 11 | 5.68 ± 0.02[gh] |
| 12 | 6.49 ± 0.02[D] | 12 | 5.67 ± 0.02[h] |
| • | • | • | • |
| • | • | • | • |
| 15 | 6.21 ± 0.04[E] | • | • |
| • | • | • | • |
| • | • | • | • |
| 18 | 6.09 ± 0.01 [F] | • | • |
| • | • | • | • |
| • | • | • | • |
| 21 | 6.10 ± 0.01 [F] | • | • |
| • | • | • | • |
| • | • | • | • |
| 24 | 6.07 ± 0.01 [F] | • | • |

[A-F]Means ( ± Standard deviation) with a different letter are significantly different at 5 ℃ ($P < 0.05$). [a-h]Means ( ± Standard deviation) with a different letter are significantly different at 20 ℃ ($P < 0.05$).

**Table 2**
Microbial growth in tofu during refrigerated storage at 5 ℃ and room temperature storage at 20 ℃.

| Total aerobic bacteria (TAB) (log cfu/g) | | | |
|---|---|---|---|
| Time (day) | 5 ℃ | Time (day) | 20 ℃ |
| 0 | ND[H] | 0 | ND[g] |
| • | • | 1 | 5.65 ± 0.14 [f] |
| • | • | 2 | 7.35 ± 0.04[e] |
| 3 | 2.30 ± 0.04 [G] | 3 | 8.20 ± 0.03[d] |
| • | • | 4 | 8.39 ± 0.06[c] |
| • | • | 5 | 8.93 ± 0.00[b] |
| 6 | 3.40 ± 0.04 [F] | 6 | 8.91 ± 0.03[b] |
| • | • | 7 | 8.93 ± 0.02[b] |
| • | • | 8 | 8.95 ± 0.04[b] |
| 9 | 4.79 ± 0.11[E] | 9 | 9.02 ± 0.03[a] |
| • | • | 10 | 9.06 ± 0.03[a] |
| • | • | 11 | 9.07 ± 0.01[a] |
| 12 | 7.19 ± 0.01 [C] | 12 | 9.09 ± 0.02[a] |
| • | • | • | • |
| • | • | • | • |
| 15 | 7.08 ± 0.06[D] | • | • |
| • | • | • | • |
| • | • | • | • |
| 18 | 7.89 ± 0.02[B] | • | • |
| • | • | • | • |
| • | • | • | • |
| 21 | 9.23 ± 0.03 [A] | • | • |
| • | • | • | • |
| • | • | • | • |
| 24 | 9.22 ± 0.05 [A] | • | • |

ND: Not detected
[A-H]Means ( ± Standard deviation) with a different letter are significantly different at 5 ℃ ($P < 0.05$). [a-h]Means ( ± Standard deviation) with a different letter are significantly different at 20 ℃ ($P < 0.05$).

and 20 °C. The pH of fresh tofu was 6.99 ± 0.03 on day 0. The pH of fresh tofu is approximately 6.54 [11]. Under refrigeration, the pH decreased slightly, to 6.89 ± 0.04, until day 9 and then drastically decreased to 6.49 ± 0.02. Based on electrical conductivity, the freshness of tofu changed suddenly after day 9 of refrigerated storage. The pH of tofu stored at room temperature rapidly decreased from day 1 of storage, to 5.67 ± 0.02 on day 12. This is consistent with a report that the pH of fresh tofu decreased from 6.30 to 5.85 after 9 h at room temperature [17]. Spoilage of tofu was initiated at 15–20 h at 30 °C, when its microbial count reaches 4–7 log CFU/g [8]. In this study, an off-flavor of tofu was observed from day 3 of storage at 20 °C when the pH decreased to 6.23 ± 0.03. The pH of tofu decreases with spoilage, because lactic acid is formed by the decomposition of carbohydrates during microbial growth. Therefore, the pH is an indicator of the freshness of tofu; its relation to electrical conductivity is discussed in Section 3.5.

### 3.3. Microbial growth in refrigerated and room temperature tofu

Table 2 presents the changes in TAB count over time in refrigerated and room-temperature tofu. No change in TAB count was detected in the tofu on day 0. The initial spoilage of tofu was previously determined to be at a TAB count of 6 log CFU/g [11]. In this study, the TAB count of refrigerated tofu reached 7.19 ± 0.01 log CFU/g on day 12 of storage, indicating that spoilage was initiated. The shelf life of pasteurized tofu is postulated to be 12 days at 5 °C. The recommended shelf life of pasteurized tofu is 15 d below 10 °C [11]. In this study, the packaging of pasteurized tofu was removed and the tofu was transferred to an electrical conductivity cell. Although care was taken to prevent contamination during the experiments, the storage conditions are different compared to the originally packaged tofu from the manufacturer. This difference may have caused the shorter shelf life of the tofu in the conductivity cell. The electrical conductivity of refrigerated tofu reached 9.22 ± 0.05 log CFU/g on day 24 of storage, which was postulated to be the time when bacterial population growth reached a limit.

At room temperature, the TAB count was 5.65 ± 0.14 log CFU/g on day 1 of storage and rose to 7.35 ± 0.04 log CFU/g, which implied that tofu spoilage had been initiated. Bacterial growth in the tofu stored at room temperature reached the limit of the population (9.02 ± 0.04 log CFU/g) on day 9 of storage. The shelf life of tofu at room temperature ranges from 1 to 2 days [15].

### 3.4. Textural changes of refrigerated and room temperature tofu

Table 3 presents the textural changes in tofu during refrigerated and room temperature storage. The hardness of fresh tofu ranged from 6.33 ± 0.34 N to 6.41 ± 0.09 N. During refrigerated storage, the hardness of tofu significantly increased to 7.25 ± 0.06 N on day 12 of storage ($P < 0.05$), and then slightly decreased but not significantly ($P > 0.05$). It was reported previously that the hardness of refrigerated tofu increased during the initial stage of storage and then decreased from day 9 onwards [15] but the changes in hardness were not significantly correlated with the freshness of the tofu.

At room temperature, the hardness of the tofu continuously decreased. When the TAB count was higher than 6 log CFU/g on day 2, the hardness of the tofu significantly decreased to 5.77 ± 0.18 N. When tofu is stored at 23 °C, its hardness significantly decreases within 3 days owing to starch retrogradation [11]. In this study, the hardness of tofu was found to be inversely related to the degree of spoilage when stored at room temperature. However, the hardness of refrigerated tofu did not exhibit a close relationship with spoilage.

### 3.5. An empirical model of tofu quality and freshness

Table 4 lists the polynomial parameters of the empirical model to relate $EF_i$ to pH, TAB count, and TPA at the 95% confidence limits. The

**Table 3**
Texture profile analysis (TPA) of tofu during refrigerated storage at 5 ℃ and room temperature storage at 20 ℃.

| Hardness (N) | | | |
|---|---|---|---|
| Time (day) | 5 ℃ | Time (day) | 20 ℃ |
| 0 | 6.41 ± 0.09 $^{C}$ | 0 | 6.33 ± 0.34$^{a}$ |
| • | • | 1 | 6.26 ± 0.24$^{a}$ |
| • | • | 2 | 5.77 ± 0.18$^{b}$ |
| 3 | 6.69 ± 0.02$^{BC}$ | 3 | 5.09 ± 0.14$^{c}$ |
| • | • | 4 | 3.76 ± 0.12$^{d}$ |
| • | • | 5 | 3.31 ± 0.22$^{e}$ |
| 6 | 6.99 ± 0.09$^{AB}$ | 6 | 2.90 ± 0.28 $^{f}$ |
| • | • | 7 | 2.70 ± 0.13$^{fg}$ |
| • | • | 8 | 2.36 ± 0.26$^{gh}$ |
| 9 | 6.84 ± 0.29$^{B}$ | 9 | 2.18 ± 0.16 $^{h}$ |
| • | • | 10 | 1.81 ± 0.11$^{i}$ |
| • | • | 11 | 1.03 ± 0.11$^{j}$ |
| 12 | 7.25 ± 0.06 $^{A}$ | 12 | 0.70 ± 0.05$^{j}$ |
| • | • | • | • |
| • | • | • | • |
| 15 | 6.99 ± 0.17$^{AB}$ | • | • |
| • | • | • | • |
| • | • | • | • |
| 18 | 6.97 ± 0.11$^{AB}$ | • | • |
| • | • | • | • |
| • | • | • | • |
| 21 | 6.87 ± 0.06$^{AB}$ | • | • |
| • | • | • | • |
| • | • | • | • |
| 24 | 7.01 ± 0.53$^{AB}$ | • | • |

[A-C]Means ( ± Standard deviation) with a different letter are significantly different at 5 ℃ ($P < 0.05$). [a-j]Means ( ± Standard deviation) with a different letter are significantly different at 20 ℃ ($P < 0.05$).

**Table 4**
Estimated coefficients and probability test of the fitted second-order polynomial parameters between freshness parameters (pH, microbial counts and hardness) and electrical conductivity freshness index ($EF_i$) ($^{*}Y = \beta_0 + \beta_1 \cdot EF_i + \beta_2 \cdot EF_i^2 \pm \varepsilon$).

| | | 5 ℃ | | 20 ℃ | |
|---|---|---|---|---|---|
| | | Coefficients | Pr> \|t\| | Coefficients | Pr> \|t\| |
| **pH** | $\beta_0$ | 6.950 | < 0.0001 | 6.932 | < 0.0001 |
| | $\beta_1$ | -2.553 | < 0.0001 | -2.397 | < 0.0001 |
| | $\beta_2$ | 1.733 | 0.0008 | 1.110 | 0.0001 |
| | $R^2$ **values** | 0.976 | | 0.984 | |
| | **SSEY (ε)** | 0.075 | | 0.061 | |
| **TAB** | $\beta_0$ | 2.639 | 0.0157 | 2.483 | 0.0144 |
| | $\beta_1$ | 17.454 | 0.0195 | 18.174 | 0.0006 |
| | $\beta_2$ | -11.313 | 0.1006 | -12.066 | 0.0065 |
| | $R^2$ **values** | 0.824 | | 0.830 | |
| | **SSEY (ε)** | 1.567 | | 1.152 | |
| **Hardness** | $\beta_0$ | 6.771 | < 0.0001 | 6.463 | < 0.0001 |
| | $\beta_1$ | 1.001 | 0.2776 | -3.235 | 0.0063 |
| | $\beta_2$ | -0.877 | 0.3612 | -2.409 | 0.0232 |
| | $R^2$ **values** | 0.233 | | 0.980 | |
| | **SSEY (ε)** | 0.238 | | 0.294 | |

[*] $Y$ is either pH, TAB, TPA

pH correlated well with $EF_i$ at both refrigerated and room temperature storage. At 5 °C storage, $\beta_1$ (first-order coefficient) had a negative value of − 2.553 with statistical significance ($P < 0.05$). This implies that an increase in electrical conductivity represents a reduction in the pH of the tofu during refrigerated storage. Although $\beta_2$ (second-order coefficient) had a positive value of 1.733, its magnitude was low. Therefore, it had a negligible effect on pH changes. When tofu was stored at room temperature, it showed a negative $\beta_1$ value of − 2.397 with statistical significance ($P < 0.05$). Thus, $EF_i$ could predict the decrease in pH of tofu stored at room temperature. The coefficient of determination (COD, $R^2$) also indicated a good correlation between electrical conductivity and pH under both refrigerated and room temperature storage. A previous report showed that $EF_i$ and pH were negatively correlated during milk storage, similar to the results of this study [5].

A positive first-order coefficient ($\beta_1$) of 17.454 with significance ($P < 0.05$) was found between $EF_i$ and TAB count when tofu was refrigerated. The second-order coefficient ($\beta_2$) had a negative value (−11.313) that was not significant ($P > 0.05$). Under refrigerated storage of tofu, TAB count can be estimated based on $EF_i$ changes. Similarly, the $EF_i$ of milk can predict bacterial growth during refrigerated storage [5]. The empirical model of $EF_i$ could not clearly explain the growth of TAB count in tofu at room temperature, as both the positive and negative coefficients simultaneously showed statistical significance. The TAB count of tofu sharply increased to 5.65 ± 0.14 log CFU/g after 1 day of storage at room temperature; therefore, $EF_i$ and TAB count were not clearly correlated. Within the scope of this study, changes in electrical conductivity could predict microbial growth in tofu only under refrigerated conditions.

Textural qualities, such as the hardness of refrigerated tofu, could not be predicted using $EF_i$ because its COD was quite low (0.223). Hardness increased until day 12 of storage without spoilage and then slightly decreased upon the initiation of spoilage. Therefore, there was no constant trend in textural changes of tofu during refrigerated storage, consistent with a previous study wherein the hardness of refrigerated tofu increased during the initial stage of storage and then decreased from day 9, without a significant trend [15]. In contrast, tofu stored at room temperature exhibited a good correlation between $EF_i$ and hardness, with a COD value of 0.980. $\beta_1$ showed a significantly negative value (−3.235; $P < 0.05$). Therefore, $EF_i$ can predict a decrease in the hardness of tofu and is a more sensitive method to detect spoilage compared to texture profile analysis.

## 4. Conclusions

In this study, the potential of electrical conductivity measurements to predict the freshness of tofu during refrigerated and room temperature storage was evaluated. We developed an $EF_i$ that enabled the comparison of changes in electrical conductivity that occur between fresh and spoiled tofu. The $EF_i$ of room temperature tofu increases more rapidly than that of refrigerated tofu. This implies that physicochemical changes occur more actively in tofu at room temperature. When the changes in $EF_i$ were correlated with instrumental quality analyses (pH and texture) using an empirical model, it showed that changes in this index are predictive of the initiation of spoilage. Microbial growth also showed a good correlation with $EF_i$. This study suggests that *in situ* electrical conductivity measurements can be used to rapidly estimate the spoilage of tofu in real time.

## CRediT authorship contribution statement

**Seung Su Yu:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Han Soo Ahn:** Methodology, Writing – review & editing, Visualization. **Sung Hee Park:** Resources, Writing – review & editing, Visualization, 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

Data will be made available on request.

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