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Application of acoustic emission sensing to the evaluation of cookie texture under varying moisture and structural conditions

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Acoustic emission
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Frequency analysis
Short-time Fourier transform
Food texture
Moisture content
Cookies
Measurements
Crack propagation
Interparticle friction

ABSTRACT

The evaluation of food texture (tribological phenomena between the oral cavity and foods) is primarily based on the analysis of force, vibration, and sound. However, inherent limitations in measuring and evaluating the sensory characteristics of complex foods must be acknowledged. To bridge the gap between theoretical and actual sensory perception, new measurement and evaluation methods must be utilized. In the present study, acoustic emission (AE) sensing, which quantifies elastic stress waves generated during deformation and fracture of materials, was used to evaluate food texture. In the experiments, cookies were used as the object of study and AE signals were measured during compressive deformation and fracture of the food to examine the effects of food structure and moisture content. The findings indicated a correlation between the AE signal amplitude and the moisture content of the foodstuffs. A frequency analysis of the AE signal waveforms revealed a correlation between the state of the food structure and the AE frequency component. Therefore, the present study has demonstrated that alterations in food texture that are not quantifiable through stress measurement systems, such as texture analyzers, can be visually manifested and appraised through the implementation of short-time Fourier transform of AE signal waveforms.

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1.0 INTRODUCTION

Chewing is a fundamental bodily function that governs ingestion and strongly affects the brain, mind, and body. During the mastication process, food texture (i.e., mouthfeel, tongue feel, and tooth feel) plays a role, which can be described as "tribology (the study of friction, wear, and lubrication) (Jost, 1966)" occurring in the mouth. This involves highly complex phenomena. The texture of food is a critical factor in the perception of its gustatory qualities during mastication. The assessment of food texture is predominantly conducted through the measurement of physical parameters such as force, vibration, and sound. In addition, observations of food cross-sections complement the quantitative evaluations. However, these physical methods have limitations in measuring and evaluating the complex sensory characteristics of food. Currently, texture analyzers and rheometers are the tools of choice for evaluating the texture of various foods. However, a substantial gap exists between these evaluations and sensory evaluations, which is a matter of concern. To address this discrepancy between sensory perception and evaluation, the development of novel measurement methods and the establishment of evaluation parameters are imperative.

The objective of this study is to quantitatively evaluate food texture, i.e., mouthfeel, using acoustic emission (AE) sensing (ASTM E1316-07). AE sensing involves measuring elastic stress waves generated during material deformation and fracture. Prior studies have covered quality and safety control in food processing (Zadeike and Degutyte, 2023), as well as mouthfeel evaluation through acoustic vibration methods (Acosta-Ramírez et al., 2024; Zhu et al., 2024; Taniwaki et al., 2006; Sakurai et al., 2005) and AE-based evaluation of confections and fresh produce (Zdunek et al., 2010; Makino et al., 2002). These studies have consistently focused on AE waves within the audible range (20 kHz or below), whereas the inaudible range (above 20 kHz) has not been addressed. As demonstrated in previous studies, discrepancies in the deformation and fracture modes of industrial materials result in variations in AE waves within the inaudible range (Hase et al., 2012; Hase, 2020). Consequently, measuring and evaluating AE waves in the inaudible range for food is also imperative. This approach holds potential for assessing food texture in diverse foodstuffs. In the present study, AE signals were measured and evaluated, with emphasis on frequency components above 20 kHz, during the compression and fracture of cookies. Regarding cookies, the effects of raw materials and additives on quality and texture (Fustier et al., 2009; Pareyt et al., 2009; Jacob et al., 2007), as well as the influence of temperature on moisture absorption (Palou et al., 1997), have been investigated. To improve food quality and conduct detailed evaluations of texture, it is necessary to clarify the relationship between food state, texture, and AE signals. In this paper, the results of an investigation into the effects of cookie type and moisture content on AE signals are presented.

This study elucidated the relationship between AE signal characteristics and the physical properties of cookies during compression testing. It demonstrated that AE amplitude and frequency vary with cookie type, internal structure, and moisture content, reflecting distinct fracture and friction mechanisms. These findings highlight the potential of AE sensing as an effective tool for evaluating the texture and structural properties of food products. Starting with this study on texture evaluation of cookies, if quantitative food texture assessment using AE sensing becomes feasible, it will reduce the burden of sensory evaluation previously reliant on human judges and eliminate the impact of variability. This will accelerate food development tailored to consumer demands.

2.0 EXPERIMENTAL PROCEDURE

2.1 Experimental Setup and Measurement Conditions

This study measured AE signals during cookie compression and investigated the relationship between cookie condition and the results of signal analysis. Figure 1 shows the experimental setup and the measuring system used in this study. This compression testing machine was specially built and is not commercially available. An experiment was performed in which food was placed on a sample stage and compressed and crushed by dropping a metal plate located above it. The dropping speed was set to 2 mm/s, which is equivalent to the speed of slow chewing. Note that this experiment did not take chewing into consideration and that only one compression was applied.

The elastic stress waves (AE waves) generated during the deformation and fracture of the food were converted into AE signals using an AE sensor (AE-900M-WB: NF Corp., Kanagawa, Japan) installed inside the sample stage. Because the output signals from the AE sensors are very weak, they were amplified by a preamplifier (AE-912: NF Corp., Kanagawa, Japan) and then filtered and amplified again using an AE signal processing unit (AE9922: NF Corp.). Table 1 shows the AE measurement conditions. The AE signal amplification rate was set to a total gain of 70–80 dB, and a 20 kHz high-pass filter was used for the AE signal filter. The AE signals were primarily evaluated on the basis of changes in signal amplitude (signals obtained after full-wave rectification and envelope detection).

In addition to the AE signals under study, vertical displacement was measured using an eddy current displacement sensor (PU-14: Applied Electronics Corp., Kanagawa, Japan), vertical force was measured using a load cell (LSM-100K-B: MinebeaMitsumi Inc., Tokyo, Japan), and vertical vibration was measured using a single-axis vibration accelerometer (352C22: PCB Piezotronics Inc., New York, USA). All signals were input into a data logger (NR-500, NR-HV04, NR-ST04 and NR-CA04: KEYENCE Corp., Osaka, Japan) and measured using a computer. For detailed analysis of the AE signal waveforms, the AE signals were measured separately using a high-speed waveform digitizer (PicoScope5203: Pico Technology Ltd., Cambridgeshire, UK) with a sampling rate of 4 MHz.

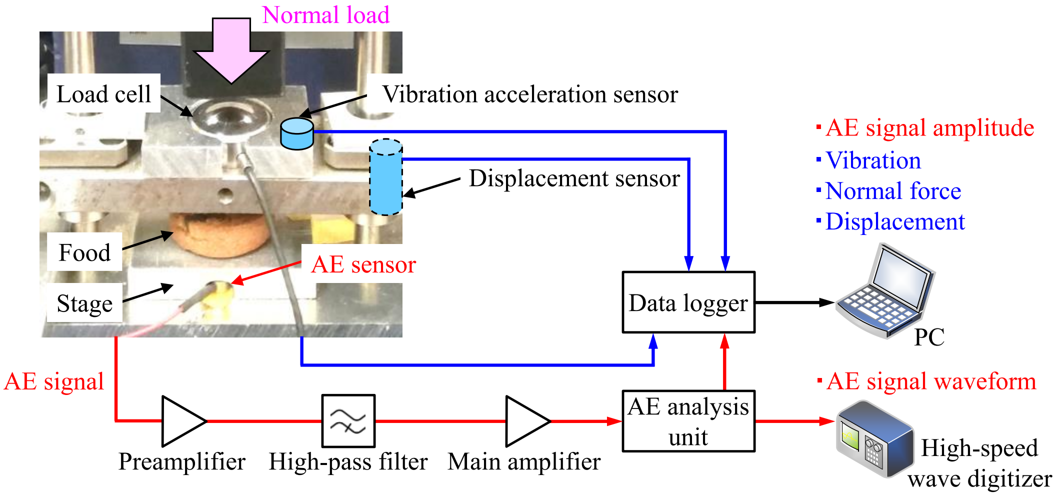


Figure 1: Schematic of the experimental setup and the measurement system.

Table 1: Summary of the AE measurement conditions.

AE measurement	**Values**
AE sensor (frequency band)	Wideband-type (0.5–4.0 MHz)
AE amplification factor	70–80 dB
AE band-pass filter	High-pass filter: 20 kHz Low-pass filter: through

2.2 Food Samples and Experimental Conditions

In this experiment, commercially available butter cookies and chocolate chip cookies manufactured in a factory were examined. The main ingredients of the butter cookies are wheat flour, sugar, shortening, butter, liquid whole eggs, salt/emulsifier (soy-derived), leavening agents, flavoring (milk-derived), and coloring (carotene). The main ingredients of the chocolate chip cookies are wheat flour, sugar, shortening, cocoa mass, margarine (containing milk components), cocoa powder, vegetable oil, processed oil products (containing milk components), liquid whole eggs, lactose, salt, cinnamon powder/emulsifier (soybean-derived), leavening agents, flavorings, and sodium caseinate (milk-derived). Table 2 shows the main nutrients in the cookies used in this experiment. Here, the size and thickness of the cookies were selected so that they would be equivalent, with a diameter of approximately 30 mm and a thickness of approximately 10 mm. In addition, comparative experiments were conducted to examine differences in moisture content between a dry state (moisture content of 9% or less) and a moist state (moisture content of 9% or more). The moisture content was applied randomly using a spray bottle. Moisture content was measured using a moisture meter immediately before the experiment. All experiments were conducted at room temperature (temperature: 25°C; relative humidity: approximately 50%). For each of the two types of cookies, experiments were conducted on at least 10 samples. The reproducibility under each condition has been confirmed. Also, some of the cookies were examined using an optical microscope to observe and compare the fracture surfaces after the experiment.

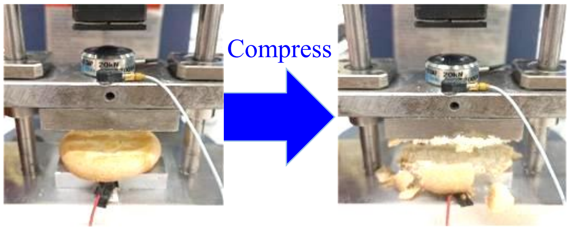
Table 2: List of the main nutrients in the cookies used in this experiment.

	Butter cookies [per 1 bag (42 g)]	**Chocolate chip cookies [per 1 bag (47 g)]**
Protein	2.5 g	3.1 g
Fat	10.3 g	11.8 g
Saturated fat	5.1 g	5.2 g
Carbohydrates	27.6 g	30.5 g
Sugars	27.0 g	28.9 g
Dietary fiber	0.6 g	1.6 g
Sodium	0.4 g	0.2 g

3.0 RESULTS AND DISCUSSION

3.1 Change in AE Signal Amplitude during Cookie Compression and Crushing

Figure 2 shows examples of observations and measurement data obtained from a series of experiments ranging from cookie compression to crushing. These results show that changes in the AE signal amplitude are similar to the changes in vibration. However, the AE measurements are highly sensitive and have dense waveforms, enabling the detection of microscopic and rapid deformation and fracture phenomena. These phenomena cannot be detected by vibration measurements (Hase, 2020). In addition, vibration measurements are not straightforward because they can be affected by outside factors, which makes determining whether vibrations are due to food changes or other factors difficult. After unloading, vibrations from the equipment can strongly affect the measurements.



(i) Before the experiment (ii) After the experiment

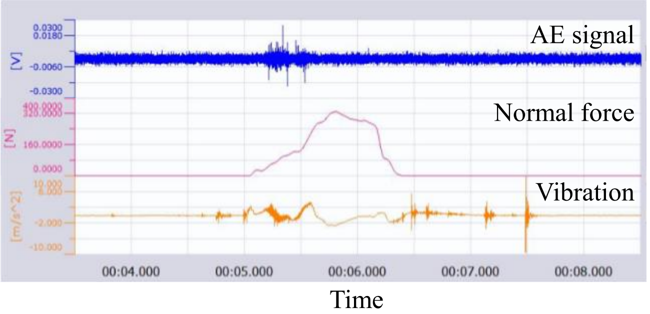
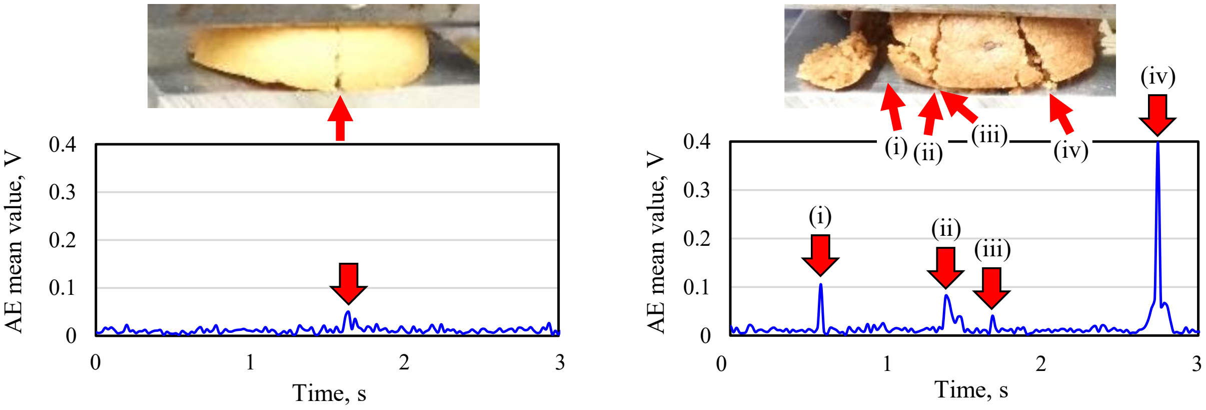


Figure 2: An example of the state observations and the acquired data for the compression experiments on a cookie.

Figure 3 shows an example of the change in the AE signal amplitude (AE mean value voltage) from the start of load application to cookie crushing. The results for the butter cookie [Figure 3(a)] and the chocolate chip cookie [Figure 3(b)] are shown here. The top part of the graph shows the crack locations observed on the cookie sides. These results show that the changes in the AE signal amplitude depend on the type of cookie. In both cases, burst-type AE signals were detected as cracks grew. The amplitude at the time of fracture was clearly smaller for the butter cookies. However, for the chocolate chip cookies, the amplitude values were approximately 10 times larger and multiple burst-type AE signals were detected. The amplitude values are thought to be related to the hardness of the food and its microscopic structure, which will be discussed later. In addition, the number of main cracks is related to the number of burst-type AE signals detected, as shown by the observation results for the cookie sides.



(a) Butter cookie

(b) Chocolate chip cookie

Figure 3: Relationship between the locations of cracks and the corresponding changes in the AE mean value for the compression experiment on different types of cookies: (a) butter cookie and (b) chocolate chip cookie.

3.2 Influence of the Moisture Content in Cookies on their AE Signals

Figure 4 shows the relationship between the maximum intensity of the AE signal waveform (AE signal amplitude) and the moisture content of butter cookies and chocolate chip cookies. Here, because the moisture content in the dry state (moisture content of 9% or less) was unclear, only the results for the moist state (moisture content of 9% or more) were used. The results show that a correlation exists between the magnitude of the AE signal and the cookies' moisture content. This correlation is observed because the cookies soften when they are moist. In addition, the AE signal amplitude of the butter cookies, which have a softer texture, tends to be slightly lower than that of the chocolate chip cookies. In any case, as can be seen from the figure, a good correlation was obtained, with an R^2 coefficient of approximately 0.6–0.7.

The results from the perspective of food texture are discussed here. Figure 5 shows the optical microscope observations of the cookie fracture surfaces after the experiment in two states: (i) dry and (ii) moist. In the dry state, the chocolate chip cookies contained many pores, as evident in the center of Figure 5(i-b). Coarse particles were also observed in the cookies. However, no pores were observed in the dry butter cookies or wet butter cookies. These differences in internal structure led to major changes in how the materials deformed and fractured. The moisture content of cookies and the relative humidity during storage change over time, causing fluctuations in hardness and crispness. It has been reported that high humidity causes moisture adsorption, softening the binding components and leading to a decrease in hardness (Zabik et al., 1979). Therefore, these structural changes can be evaluated using AE sensing.

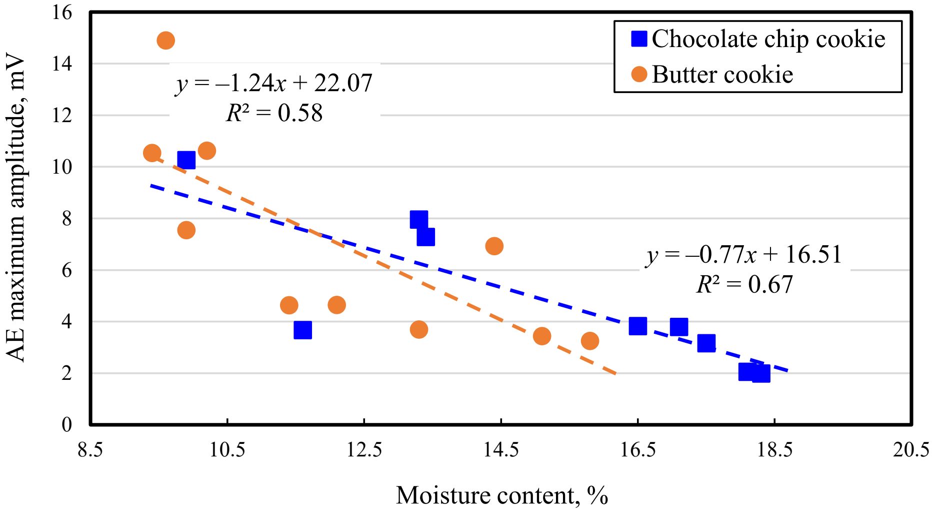
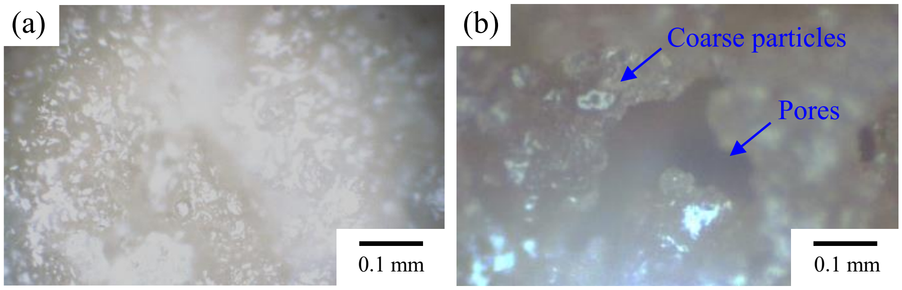
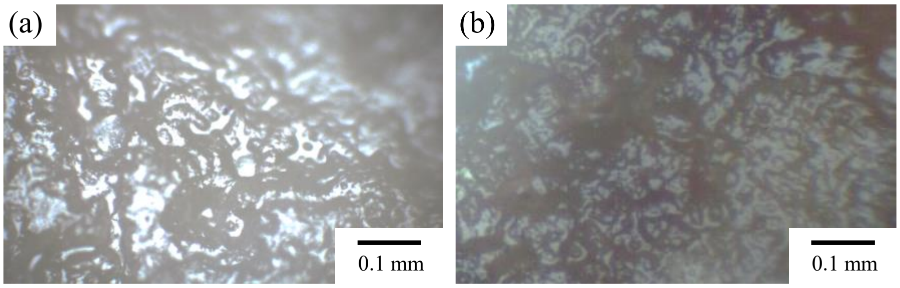


Figure 4: Relationship between the maximum magnitude of the AE signal waveforms and the moisture content of cookies under wet conditions.



(i) Dry condition

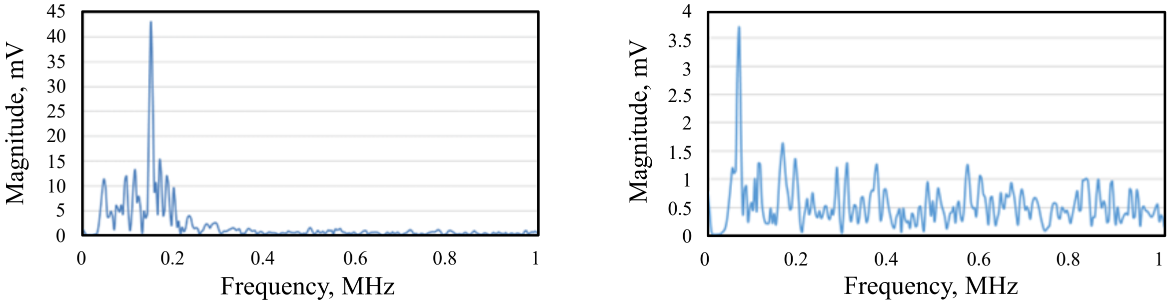


(ii) Wet condition

Figure 5: Comparison of structural conditions within the fracture surface after the compression experiment for (a) a butter cookie and (b) a chocolate chip cookie under (i) dry and (ii) wet conditions.

3.3 Food Texture Evaluation focusing on Frequencies of the AE Signal Waveforms

Analyzing the frequency components obtained from the frequency analysis of AE signal waveforms (hereafter referred to as "AE frequency") enables deformation and fracture modes to be identified and complex phenomena to be elucidated (Hase, 2022a). In this section, the characteristics of AE frequencies during the compression failure of cookies are discussed. Figure 6 shows the results of frequency analysis of AE signal waveforms for chocolate in (i) the dry state and (ii) the moist state of chocolate chip cookies. The results show a frequency peak at ~0.15 MHz for the cookies in the dry state (i). This AE frequency is attributed to crack propagation (Hase, 2020) and is speculated to be responsible for the crispy texture when the cookie breaks. By contrast, for the cookies in the (ii) moist state, not only does the signal intensity decrease but the frequency peak is observed below 0.1 MHz. As observed in Figure 5 (ii), the particles constituting the cookie swell because of moisture absorption, causing the pores to disappear. This observation suggests that crack propagation is suppressed and that fluidity arises, leading to AE frequencies less than 0.1 MHz caused by friction between particles (Wada et al., 1989). The friction state resembles that containing fine particles (i.e. mild wear particles), resulting in gentler wear and a smaller amplitude of the AE signal (Hase et al., 2008). At this point, the cookie's texture becomes crumbly and moist.

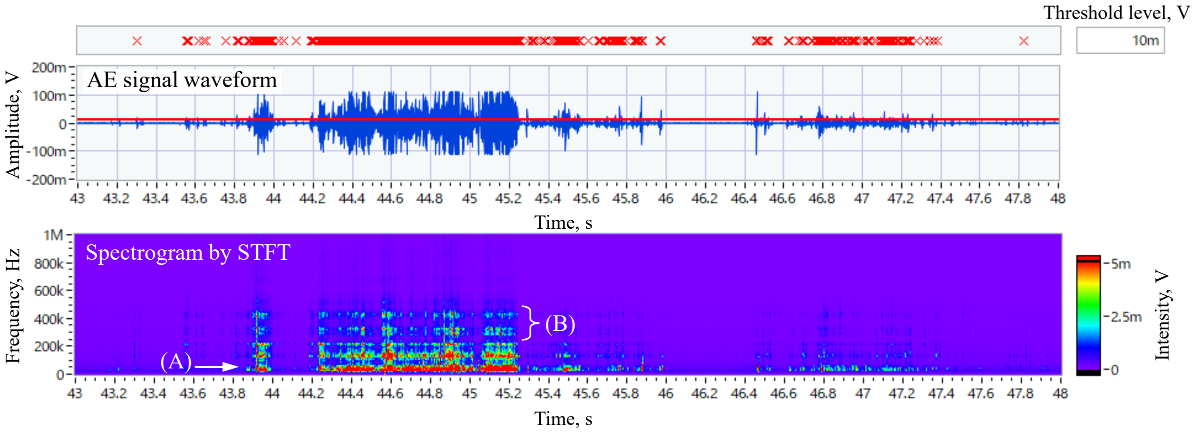


(i) Dry condition (ii) Wet condition

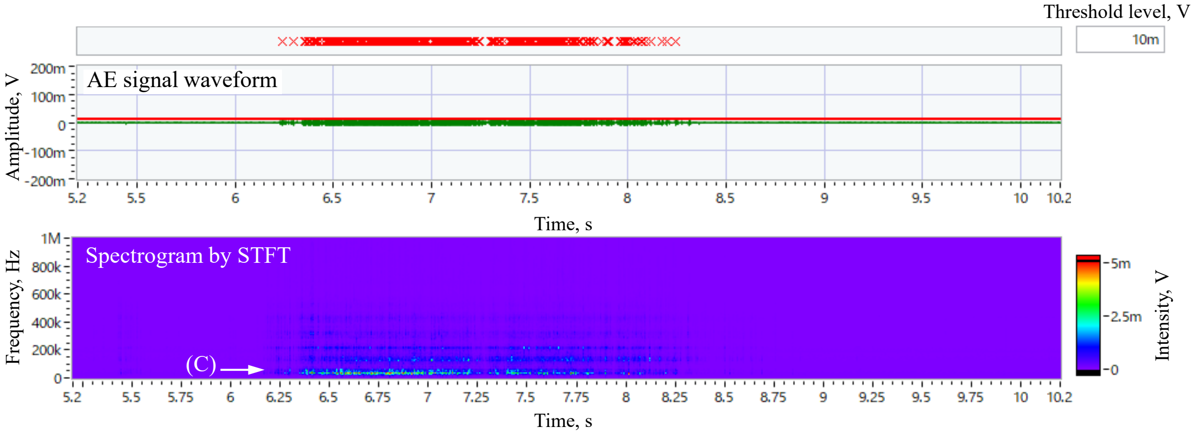
Figure 6: Typical frequency spectra of the AE signal waveforms for the compression experiment on a chocolate chip cookie under (i) dry and (ii) wet conditions.

Figure 7 shows an example of AE signal waveforms obtained for butter cookies in (i) the dry state and (ii) the moist state, along with spectrograms derived from short-time Fourier transform (STFT). As shown, changes in the AE frequencies during the compression and fracture of food can be visualized in real time as spectrograms, enabling the extraction of characteristic features. The results in Figure 6 show a frequency peak at ~0.15 MHz for the cookies in the dry state. In addition, strong frequency peaks are observed at frequencies below 0.1 MHz [frequency band (A) in Figure 7(i)]. These peaks are attributed to the difference in particle density between butter cookies and chocolate chip cookies, as shown in Figure 5 (i), which is a result of increased friction between particles at the fracture surface during crack propagation. This is similar to the propagation of cracks beneath the surface of brake friction materials, as well as the friction phenomenon at the surface of the cracks (Toyoda, 2025). In addition, AE frequency ripples were observed in the 0.25–0.5 MHz range [frequency band (B) in Figure 7(i)]. These AE frequencies correspond to digging friction (Hase et al., 2012) and are known to be detected when particles undergo sliding motion (Hase, 2022b). Therefore, whereas the butter cookies exhibited a crisp texture, the chocolate chip cookies exhibited a slightly gritty texture with a hint of crunchiness. However, for the cookies in the moist state, AE frequencies less than 0.1 MHz [frequency band (C) in Figure 7(ii)], which correspond to a crumbly texture, dominate.

This study demonstrates that changes in texture that cannot be obtained from stress measurements using texture analyzers can be visualized and evaluated through short-time frequency analysis of AE signal waveforms. The application of AE sensing is expected to enable future developments in the texture evaluation of foods that have been difficult to measure using texture analyzers (Ibañez et al., 2022; Kohyama, 2020).



(i) Dry condition



(ii) Wet condition

Figure 7: Typical AE signal waveforms and their spectrograms by STFT for the compression experiment on a butter cookie under (i) dry and (ii) wet conditions.

4.0 CONCLUSION

In this study, AE signals were measured during the compression crushing of cookies using AE sensing, and the effects of food type and moisture content were investigated. The following conclusions were obtained.

(1) The amplitude of AE signals during compression crushing was found to vary depending on the type of cookie. The magnitude of the amplitude values is related to the hardness and microscopic structure of the cookie, and the number of main cracks generated within the cookie is associated with the number of burst-type AE signals.
(2) A negative correlation exists between the amplitude of AE signals during cookie compression crushing and the cookie's moisture content.
(3) For cookies in the dry state, an AE signal frequency peak exists at 0.15 MHz (crack propagation is predominant); in some cases, another peak exists at ~0.5 MHz (excavation friction is predominant). For cookies in the moist state, peaks exist at frequencies less than 0.1 MHz (particle-to-particle friction is predominant).
(4) Differences in the microscopic structure of the cookie interior lead to substantial changes in deformation and fracture patterns, resulting in differences in the AE signal amplitude and frequency components.

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