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Alcohol Solutions Impedance and Equivalent Circuits

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Abstract: **We measured the S-parameters of six different types of liquid samples, such as aqueous alcohol solutions, NaCl ionic solutions, alcoholic beverages, and fruit juices in the 1 to 100 MHz frequency range, and calculated their impedance and admittance. Equivalent circuits of the liquid samples were synthesized by curve fitting on a Smith chart and Cartesian coordinates. The relationship between the impedance, admittance, and circuit element values of the synthesized equivalent circuit and the ethanol C2H5OH, polar water molecule H2O, and cation (K+ ion) that constitute the liquid sample was analyzed. Distilled alcoholic beverages showed a high impedance, but the impedance decreased after aging. Non-distilled alcoholic beverages showed a significant decrease in impedance due to cation (K+ ion). The impedance of the dehydrated reduced concentrated beverage increased significantly due to the reduction of cation (K+ ion).**

Keywords: **EIS, alcoholic beverage, S-parameter, equivalent circuit, polar water molecule**

I. INTRODUCTION

Electrochemical impedance spectroscopy (EIS) is a method for analyzing the electrical properties of plant organisms, such as vegetables and fruits. It has been widely studied because it provides useful electrical information about the organisms and the dielectric materials [1-12]. A common research method is to measure the impedance of a sample using an LCR meter or an impedance analyzer, display the measurement results on Nyquist plots (Cole-Cole plots), and analyze the frequency characteristics of the dielectric constant and equivalent circuit. However, there are issues such as low measurement frequency, large test fixtures using the four-terminal method, the capsule's large size, difficulty synthesizing equivalent circuits, etc. The number of cases of analyzing the electrical properties of liquids using EIS is increasing [13-17]. For example, the impedance characteristics of aqueous NaCl solutions with different concentrations were measured by impedance analyzers in the frequency range from 1 kHz to 1 MHz because of the influence of the electrical double layer at the electrodes in the range from 1 Hz to 1 kHz [17].

We focused on studying the electrical properties of alcoholic beverages, which are made from various raw materials and undergo complex processing steps. In studies using EIS, dielectric constants are primarily measured using an impedance analyzer [9,11]. We are conducting studies using a small probe that can measure small amounts of liquid samples and a network analyzer (VNA) suitable for measurement in the high-frequency range [18,19]. In this study, we measured the S-parameters of liquid samples such as alcohol (ethanol) solution, NaCl ion solution, and fruit juice using VNA, synthesized an equivalent circuit of the liquid samples from the impedance and admittance calculated from the S-parameters, [18] and analyzed the relationship between the element values in the equivalent circuit and the impedance characteristics of the liquid. We analyzed the relationship between the values of the equivalent circuit's elements and the liquid's impedance characteristics.

II. S-PARAMETER MEASUREMENTS OF AQUEOUS SOLUTIONS USING A PORTABLE VNA AND A SMALL SMA PROBE

The S-parameter was measured using the small SMA (sub-miniature type A) probe shown in Fig. 1 to investigate the impedance of liquids such as aqueous alcohol (ethanol), alcoholic beverages, and aqueous NaCl solutions. The SMA probe consists of three corrosion-resistant pins: a central signal pin (gold-plated copper, 0.8 mm diameter, and 4 mm length) surrounded by PTFE (polytetrafluoroethylene) and two ground pins (gold-plated brass, 0.8 mm diameter, and 4 mm length) on the left and right, spaced 4 mm apart. We don't use the large test fixtures using the four-terminal method. The reflection coefficient of the S-parameter, S_{11}, was measured in the frequency range from 1 to 100 MHz using a portable vector network analyzer (VNA) connected to an SMA probe. The S-parameter S_{11} was calculated from the ratio of the transmitted forward signal voltage V_f^+, sent from the VNA to the aqueous solution in the glass container, and the reflected signal voltage V_r^- for the magnitude and the phase at each frequency. The impedance Z and the admittance Y were calculated from the S-parameter S_{11} using two RF (radio - frequency) simulators, QucsStudio and AWR-MWO [20], [21]. The small SMA probe reduced the volume of the aqueous solution sample required for the measurement to approximately ten mL [9]. SOLT (short, open, load, through) SMA terminals were used to calibrate the measurement system. Calibration was verified by measuring and comparing the resistance of 1608(in mm) size 100-Ω and 1200-Ω SMDs (surface mount devices) soldered between the signal and ground pins of the SMA probe in the frequency range from 1 to 100 MHz.

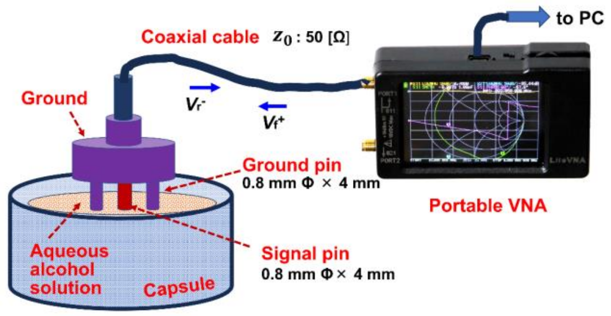

Fig. 1. S-parameter S_{11} of aqueous solution samples measured at frequencies from 1 to 100 MHz using a portable VNA

III. IMPEDANCE MEASUREMENTS OF AQUEOUS ALCOHOL (ETHANOL) SOLUTIONS

The reflection coefficient S_{11} of the S-parameter was obtained from the ratio of the reflected signal V_r^- from the aqueous solution to the transmitted signal voltage V_f^+transmitted from the VNA. Equations (1) and (2) were used to obtain the input impedance Z from the reflection coefficient S_{11} , where Z_0 : characteristic impedance (usually 50 Ω), γ : propagation constant (= α+ jβ), α: loss term, β : phase term, A, B : constants, x: distance from the VNA. Since the reflection coefficient S_{11} is expressed in complex numbers or polar coordinates, the impedance is expressed in complex numbers $Z = Z$ (Re) + Z (Im) or polar coordinates $Z = |Z| \angle \theta$.The admittance Y is the reciprocal of the impedance Z and is expressed by (3), where G is the conductance, and B is the susceptance. Plotting the admittance Y calculated from the measured S-parameters S_{11} for different alcohol (ethanol) concentrations (5, 25, 40, 50, and 99.5%) in aqueous alcohol solutions on the Smith chart admittance grid. Figure 2 shows that for most alcohol (ethanol) concentrations, the conductance of the ethanol concentration was $G \simeq 0$. To enlarge the graph for the high-impedance aqueous alcohol solution, we set the characteristic impedance Z_0 to 2500 Ω and recalculated the S-parameters S_{11} measured at $Z_0 = 50$ Ω. When the admittance Y was divided into conductance G and susceptance jB and plotted in Cartesian coordinates, the change in susceptance jB became apparent, as shown in Fig. 3. Since $G \simeq 0$, we can consider $Y \simeq$ jB. The susceptance jB increases as the alcohol concentration decreases. Therefore, this jB indicates the electrical properties due to water. Figure 4 shows the change in impedance Z of aqueous alcohol (ethanol) solutions with alcohol concentration K as the parameter. For comparison, the changes in impedance Z of pure water and NaCl solutions are also shown [18]. The pure water was purified by an ion exchange resin and reverse osmosis membrane. As the alcohol concentration K decreases, impedance Z decreases and approaches the impedance Z of pure water; the impedance Z of the NaCl solution is lower than the impedance curve of pure water, and the impedance Z decreases as the NaCl molar concentration M increases.

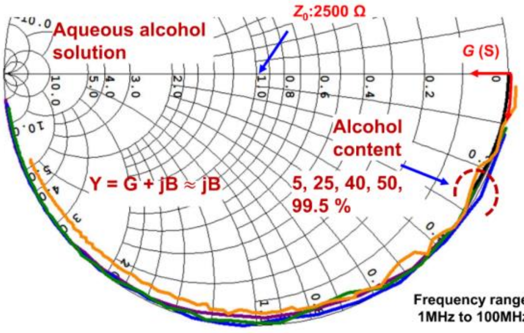

Fig. 2. S-parameter S_{11} measured for aqueous alcohol solutions at different alcohol (ethanol) concentrations and admittance Y plotted on a Smith chart. The characteristic impedance is set at 2500 Ω.

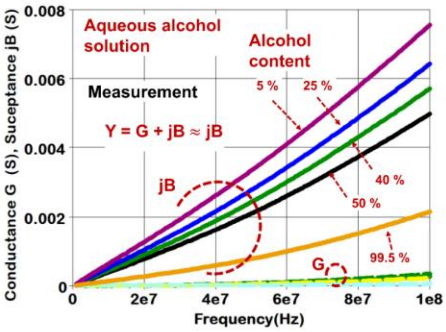

Fig. 3. Conductance G and susceptance jB of admittance Y measured for aqueous alcohol solutions with different alcohol (ethanol) concentrations. The coordinate notation is 4e7 = 4×10^7. Synthesis of equivalent circuits of aqueous alcohol solutions

$$Z = \frac{v_{in}(x)}{i_{in}(x)} = Z_0 \frac{A\varepsilon^{-\gamma x} + B\varepsilon^{\gamma x}}{A\varepsilon^{-\gamma x} - B\varepsilon^{\gamma x}} = Z_0 \frac{1 + S_{11}}{1 - S_{11}}$$

$$= Z_0 \frac{\sqrt{\left(1 + S_{11}(Re)\right)^2 + S_{11}(Im)^2}}{\sqrt{\left(1 - S_{11}(Re)\right)^2 + S_{11}(Im)^2}} \varepsilon^{j(\theta_{11} - \theta_{12})} \tag{1}$$

$$\theta_{11} = \tan^{-1} \frac{-S_{11}(Im)}{1 - S_{11}(Re)} , \quad \theta_{12} = \tan^{-1} \frac{S_{11}(Im)}{1 + S_{11}(Re)} \tag{2}$$

$$Y = \frac{1}{z} = G + jB \tag{3}$$

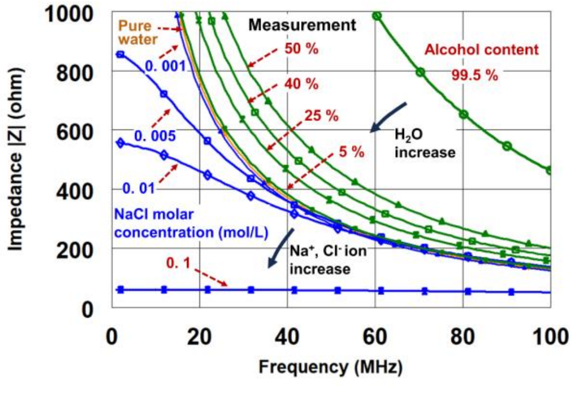

Fig. 4. Measurement results of impedance Z of aqueous alcohol solutions with different alcohol (ethanol) concentrations and aqueous NaCl solutions with different NaCl molar concentrations M at frequencies from 1 to 100 MHz.

IV. SYNTHESIS OF EQUIVALENT CIRCUITS OF AQUEOUS ALCOHOLIC SOLUTIONS

We synthesized equivalent circuits of aqueous alcohol (ethanol) and NaCl solutions by curve fitting of the measured value curves on a Smith chart and Cartesian coordinates. The synthesized equivalent circuit is based on a parallel circuit of capacitor C_1 and resistor R_2 (see Fig. 5 [18]). There are resistors R_1 and R_3 as complementary elements to the capacitor C_1 and resistor R_2, but they do not significantly affect the overall impedance value. The values of the synthesized circuit elements are listed in Table I.

TABLE I. VALUES OF EQUIVALENT CIRCUIT AND CIRCUIT ELEMENTS SYNTHESIZED FROM IMPEDANCE Z MEASUREMENT RESULTS OF AQUEOUS ALCOHOL SOLUTIONS WITH DIFFERENT ALCOHOL (ETHANOL) CONCENTRATIONS. THE NUMBER NOTATION IS 6E4 = 6 ×10^4.

Aqueous alcohol solution	C_1	R_1	R_2	R_3
alc. 99.5%	2.7	0	6E4	0
alc. 50%	6.4	0	6E4	0
alc. 40%	7.3	0	6E4	0
alc. 25%	8.3	0	6E4	20
alc. 15%	9.2	0	6E4	20
alc. 5%	10.1	0	6E4	20
Unit	pF	Ω	Ω	Ω

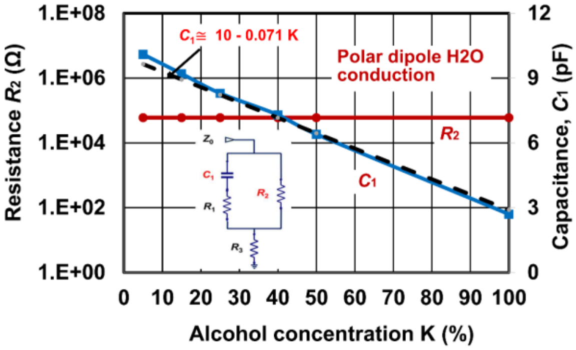

Fig. 5. Equivalent circuit synthesized from the measurement results of impedance Z of aqueous alcohol solutions with different alcohol (ethanol) concentrations and the values of circuit elements R_2 and C_1.

The impedance Z can be calculated using Kirchhoff 's law from the equivalent circuit of the synthesized aqueous solution. The calculation formulas are given in (4) and (5). Figure 5 shows the resistance R_2 and C_1 values measured at different alcohol concentrations K in aqueous alcohol (ethanol) solutions. The resistance R_2 is constant with alcohol concentration, and the capacitor C_1 decreases with concentration K and can be expressed by the approximate formula $C_1 \cong 10 - 0.071K$. This change in the capacitor C_1 is related to the polar molecule H_2O. The susceptance jB at high-frequency signals (1 to 100 MHz) of aqueous alcohol solutions is due to the vibration and rotation of the polar molecule H_2O, and C_1 also increases as the ratio of H_2O increases [22].

$$Z = R_3 + \frac{K_1(\cos\theta_1 + \frac{1}{R_2}K_1)}{K_2} - j\frac{K_1 \sin\theta_1}{K_2} \tag{4}$$

$$K_1 = \sqrt{{R_1}^2 + \left(\frac{1}{\omega C_1}\right)^2}\ , \quad K_2 = (\cos\theta_1 + \frac{K_1}{R_2})^2 + (\sin\theta_1)^2 \tag{5}$$

$$Y = j\omega C = j\omega C_0\varepsilon^* = j\omega C_0\varepsilon' + \omega C_0\varepsilon'' = j\omega C_1 + \frac{1}{R_2}$$
$$\varepsilon' = \frac{C_1}{C_0}\ , \qquad \varepsilon'' = \frac{1}{\omega C_0 R_2} \tag{6}$$

Since the combined equivalent circuit is considered as a capacitor C and the capacitor C can be expressed as a parallel circuit of C_1 and resistor R_2, the admittance Y of the capacitor C can be approximated by (6), where $*$ is the complex permittivity $\varepsilon' - j\varepsilon''$. The imaginary part is the loss term. Since R_2 is very large in aqueous alcohol solutions, there is almost no dielectric loss. The equivalent circuit of the synthesized NaCl solution is based on a parallel circuit of capacitor C_1 and resistor R_2, as in the aqueous alcohol solution. The values of the synthesized elements are listed in Table I. The other circuit elements, resistors R_1 and R_3, do not significantly affect the overall impedance and admittance values.

The values of the resistor R_2 and the capacitor C_1 with NaCl concentration M as a variable are shown in Fig. 6. The capacitor C_1 is constant with NaCl concentration M, while the resistance R_2 decreases with NaCl concentration M and can be expressed by the approximate equation $R_2 \simeq 4.5/M$ [13], [15,16]. Changes influence the change in resistance R_2 in the concentration of ionized ions Na^+ and Cl^-. The change in resistance R_2 is due to the change in concentration of ionized Na^+ and Cl^-. The admittance Y at high-frequency signals (1 to 100 MHz) of aqueous NaCl solution is mainly due to electrical conduction by dissociated ions Na^+ and Cl^-. The vibration of polar molecules H_2O in aqueous NaCl solution is the substantial cause of the resistance R_2. The fraction of admittance Y in the high-frequency signal (1 to 100 MHz) is small due to the vibration and rotation of the polar molecule H_2O in NaCl solution.

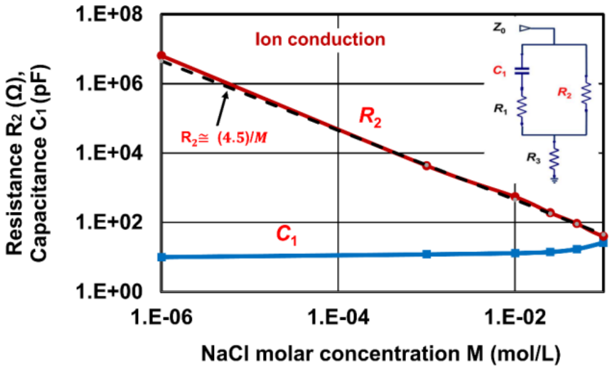

Fig. 6. Equivalent circuit synthesized from impedance Z measurements of NaCl solutions with different molar concentrations of NaCl and values of circuit elements R_2 and C_1. The notation of the coordinates is 1.E04=1×10^{-04}.

V. IMPEDANCE AND EQUIVALENT CIRCUIT OF ALCOHOLIC BEVERAGES

We measured the impedance *Z* of five alcoholic beverages and synthesized equivalent circuits for each. Table II shows an overview of the five alcoholic beverages: Vodka is a colourless, odourless liquor made by saccharifying and fermenting grain and distilling it; Whisky (Scotch whisky) is produced by saccharifying and fermenting barley, distilling it, and aging it in oak barrels for more than three years; Awamori is made by saccharifying and fermenting rice (Thai rice) and distilling it; and Kura is aged in oak barrels for more than three years. Sake is made by simultaneously saccharifying and fermenting Japanese rice and filtering it; Wine is made by fermenting grapes and filtering them.

We measured the S-parameters S_{11} of five alcoholic beverages, calculated impedance *Z* and admittance *Y*, and plotted on a Smith chart (see Fig. 7). Because alcoholic beverages have very large impedances, we set the characteristic impedance Z_0 to 2500 Ω and recalculated the data measured at $Z_0 = 50$ Ω. Conductance *G* increased in the order of vodka (alc. 50%), Scotch whisky (alc. 40%), awamori (alc. 25%), sake (alc. 15%), and wine (alc. 12%). Sake (alc. 15%) and wine (alc. 12%), which did not undergo distillation, showed a significant increase in conductance *G*.

TABLE II. SUMMARY OF FIVE ALCOHOLIC BEVERAGES WITH DIFFERENT ALCOHOL CONCENTRATIONS AND PRODUCTION METHODS

Alcoholic beverage	**Production method**	**Production place**
Vodka (alc. 40%)	fermenting grains and distilling	Chiba Japan
Whisky (alc. 40%)	Fermenting barley, distilling and aging	Scotland, UK
Awamori (alc. 25%)	fermenting rice, distilling, and aging	Okinawa, Japan
Sake (alc. 15%)	fermenting rice and filtering	Akita, Japan
Wine (alc. 12%)	fermenting grape and filtering	France

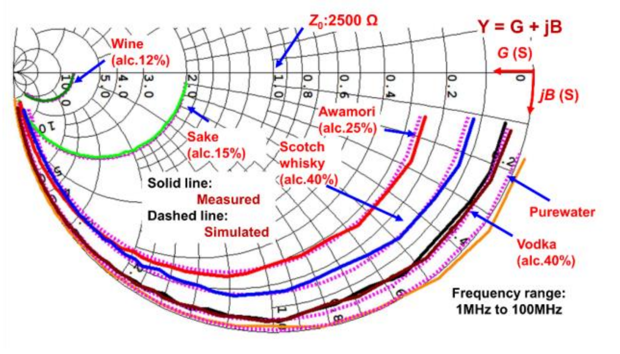

Fig. 7. S-parameters S_{11} of five alcoholic beverages with different alcohol concentrations and production methods were measured, and the admittance *Y* was plotted on a Smith chart. The characteristic impedance Z_0 is set to 2500 Ω.

Comparing the impedance *Z* on the Cartesian coordinate as shown in Fig. 8, the impedance *Z* decreased with decreasing alcohol concentration for vodka (alc. 40%), Scotch whisky (alc. 40%), and awamori (alc. 25%), indicating a relationship between the change in alcohol concentration and impedance *Z*. The trend was similar to that shown in Fig. 4, which shows the relationship between alcohol concentration and impedance *Z*. Scotch whisky (alc. 40%) and awamori (alc. 40%) (Kura) were aged in oak barrels for more than three years after distillation, which is considered to have relatively low impedance *Z*. Sake (alc. 15%) and wine (alc. 12%) did not undergo distillation, and therefore showed similar impedance changes to the NaCl solutions shown in Fig. 4. The impedance of Sake (alc. 15%) and wine (alc. 12%) showed a similar change in impedance to that of the NaCl solution shown in Fig. 4 because they were not distilled.

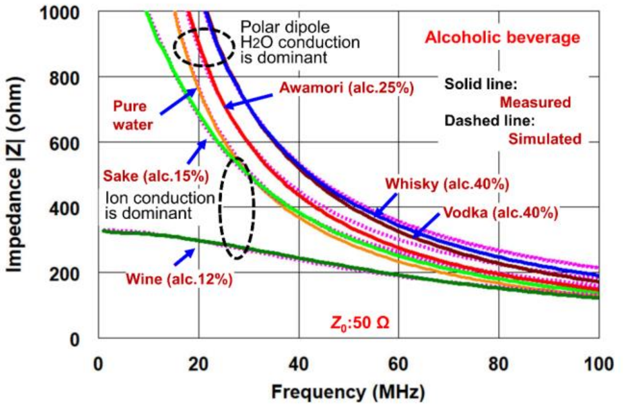

Fig. 8. Measured S-parameters S_{11} of five alcoholic beverages with different alcohol concentrations and production methods and plotted the impedance *Z*. The characteristic impedance is set to 50 Ω.

Figure 9 shows the results of synthesizing the equivalent circuits of five alcoholic beverages and comparing R_2 and C_1, which significantly affect impedance *Z*. The value of C_1 changes almost nothing, and the change in R_2 is significant. Sake (alc. 15%) and wine (alc. 12%) showed low R_2. The impedances *Z* of Vodka (alc. 40%), Scotch whisky (alc. 40%), and awamori (alc. 25%) were affected by the polar water molecules H_2O showing large R_2. Sake (alc. 15%) and wine (alc. 12%) showed low R_2, mainly influenced by the cations (e.g., K^+) contained in the raw materials [23].

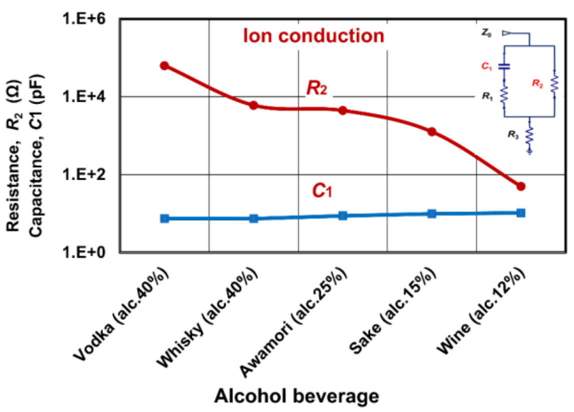

Fig. 9. Equivalent circuit synthesized from S-parameter S_{11} measurements of five alcoholic beverages with different alcohol concentrations and production methods, and the values of the circuit elements R_2 and C_1.

In manufacturing, K^+ ions are significantly reduced when distillation is used. Scotch whisky (alc. 40%) has an increase in K+ ions and a decrease in R_2 compared to vodka (alc. 40%), which does not undergo the aging process due to ion exudation from oak barrels during the aging process and ion formation from oak barrels and organic acids in awamori. Undistilled Sake (alc. 15%) and wine (alc. 12%) showed a decrease in impedance due to residual K^+ ions in the raw material. Sake (alc. 15%), to which water is added after aging, contains more K^+ ions than wine (alc. 12%), to which no water is added.

VI. IMPEDANCE AND EQUIVALENT CIRCUIT OF ALCOHOLIC WINE

We investigated the characteristics of impedance Z for different grape processing methods. Figure 10 shows the measured impedance Z of an untreated sample (grapes), a grated and filtered grape sample, a concentrated juice sample, and a sample after alcoholic fermentation (wine). The synthesized equivalent circuit is shown in Fig. 11. Wine (alc. 12%) produced by alcoholic fermentation has the highest impedance Z. Wine (alc. 12%) is fermented after the grapes are grated and filtered, so the main components are alcohol (ethanol), polar water molecules, and K^+ ions in the grape vacuoles. The alcohol increases the impedance Z. Among alcoholic beverages, wine has the lowest impedance Z because it contains the most significant proportion of K^+ ions (see Fig. 8) [23]. The next highest beverage impedance is concentrated reduced fruit juice. In the concentrated and reduced fruit juice manufacturing process, the grape is grated, filtered, and dehydrated, so the K^+ ions in the grape vacuole are removed in the dehydration process, resulting in a high impedance Z.

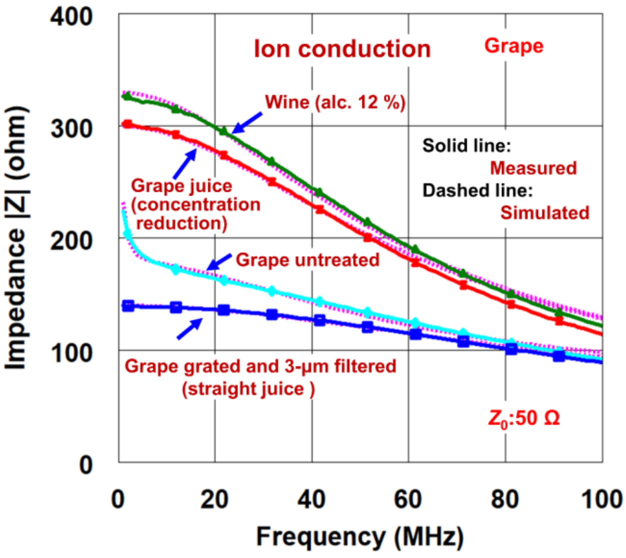

Fig. 10. Values of impedance Z at 1 to 100 MHz frequencies for samples with different grape processing methods.

The concentrated and reduced fruit juice analysis of S_{21} measured on fruit and vegetables filtered through a 3-µm filter showed no change in impedance due to the absence of cell walls and K^+ ions. Untreated grape (fruit) juice showed a lower impedance Z due to K^+ ions in the vacuole. Straight juice, produced by grating grape and filtering through a 3-µm filter, showed a lower impedance than grape (fruit) because the cell walls of the plant cells, which have a high impedance, were removed, and most of the K^+ ions remained in the vacuole [24,25]. The equivalent circuit element R_2 decreased in the order of wine, concentrated reduced juice, and straight juice, indicating that the increase in K^+ ions caused the decrease in R_2 (see Table III).

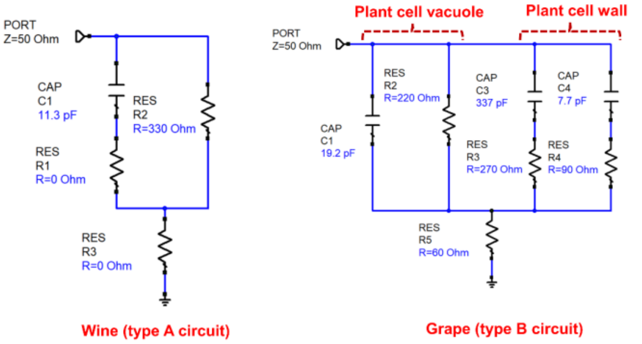

Fig. 11. Equivalent circuits synthesized from S-parameter S_{11} measurements of beverages and fruits with different grape processing methods; Type A circuit represents beverages, and Type B circuit represents fruits.

TABLE III. VALUES OF THE CIRCUIT ELEMENTS OF THE EQUIVALENT CIRCUIT SYNTHESIZED FROM THE S-PARAMETER S_{11} MEASUREMENTS OF SAMPLES WITH DIFFERENT GRAPE PROCESSING METHODSS

Grape beverage	C_1	R_1	R_2	R_3
Wine (alc. 12%)	11.3	0	330	0
Concentrated juice	11.2	0	300	0
3-µm filtered juice	13.2	30	120	20
Unit	pF	Ω	Ω	Ω

VII. RELATIONSHIP BETWEEN IMPEDANCE AND THE VONSTITUENT MOLECULES AND IONIZED IONS OF IQUEOUS IOLUTIONS

Consider the relationship between the molecules and ionized ions constituting aqueous alcohol (ethanol) solution and the impedance Z. Figure 12 shows an aqueous alcohol (ethanol) solution consisting of the ethanol molecule C_2H_5OH and the polar water molecule H_2O. The ethanol molecule C_2H_5OH has the same polarity as the polar water molecule H_2O. Still, in the admittance Y measurement (see Fig. 3) of the alcohol solution at 99.55 % concentration, the conductance G was almost zero, the susceptance jB was very small, and no response due to electrical polarity was observed in the frequency range from 1 to 100 MHz. Therefore, the polarity of the ethanol molecule C_2H_5OH has almost no function. Due to the significant molecular weight of the ethanol molecule C_2H_5OH, it is thought that it cannot respond by rotation or vibration in the frequency range of 1 to 100 MHz. Therefore, as the concentration of the ethanol molecule C_2H_5OH decreases, the polar water molecule H_2O reacts, causing conductance G to increase (see Fig. 3) and impedance Z to decrease (see Fig. 4).

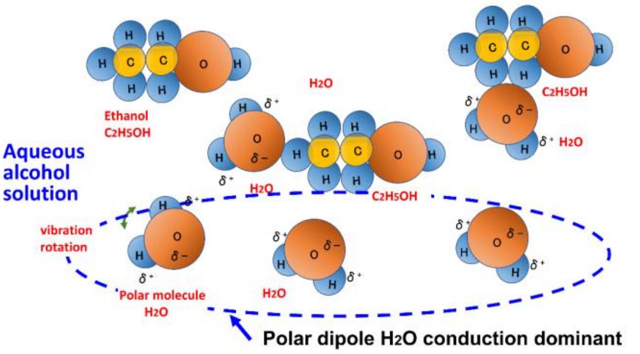

Fig. 12. Types of constituent molecules in aqueous alcohol(ethanol) solutions and the main molecules that respond to high-frequency signals.

As shown in Fig. 13, the aqueous NaCl solution has a large amount of ionized Na^+ and Cl^- ions, which are almost 100 % ionized below 0.1 mole, and the impedance Z decreases in proportion to the molar concentration M of NaCl in the frequency range from 1 to 100 MHz (see Fig. 4).

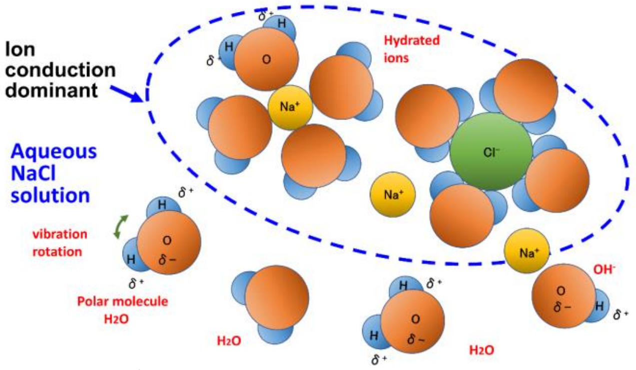

Fig. 13. Types of constituent molecules in aqueous NaCl solution and main molecules that respond to high-frequency signals.

The polar water molecule H_2O assembles around the Na^+ and Cl^- ions to form a high-molecular-weight hydrate. Unlike the ethanol molecule C_2H_5OH, the hydrated ions fully respond to high-frequency signals. At molar concentrations of 0.5 mol or higher, impedance Z increases due to the decreased ionization coefficients of Na^+ and Cl^- ions and friction between hydrated ions. Below 0.5 molar concentration, an increase in admittance Y is observed due to the rotation and vibration of the polar water molecule H_2O at higher frequencies [18].

In alcoholic beverages containing alcohol (ethanol) C_2H_5OH, polar water molecules H_2O, and cations, the polar water molecules H_2O and cations (K^+ ions) contribute significantly to the increase in admittance Y (see Fig. 7) and decrease in impedance Z (see Fig. 8), as shown in Fig. 14 [23]. The admittance Y of non-distilled sake and wine is very high due to the large amount of cations (K^+, Ca^+, etc.) and anions (Cl^-, PO_4^-, etc.) exuded from the vacuoles of grains and fruits. Because cations (such as K^+ ions) are removed from vodka during the distillation process, the impedance characteristics of vodka are similar to those of aqueous alcohol solutions without ions (see Fig. 8). Whisky and awamori are aged for over three years, so the cations and anions are produced in small amounts from the barrels and organic acids, which slightly reduces the impedance. The impedance is somewhat lower. Concentrated and reduced juice, which does not contain alcohol, has a higher impedance due to the removal of K^+ ions during dehydration. In straight juice, the high-impedance cell walls are removed, and K^+ ions in the vacuole remain almost intact, resulting in a lower impedance Z than fruit with cell walls with high impedance Z (see Fig. 10).

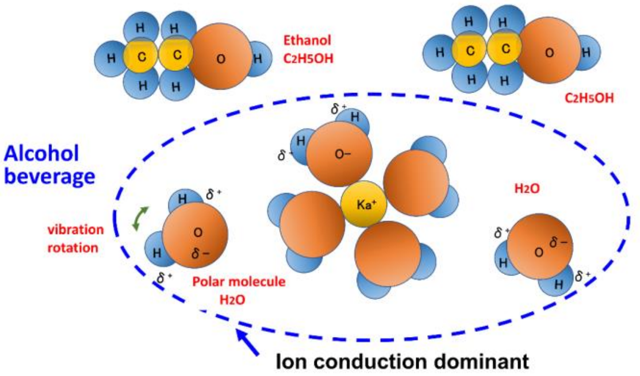

Fig. 14. Types of constituent molecules of alcoholic (ethanol) beverages and the main molecules that respond to high-frequency signals.

VIII. CONCLUSIONS

We measured the reflection coefficient S_{11} of the S-parameter in the frequency range of 1 to 100 MHz for solutions containing ethanol, water, and ions, such as aqueous alcohol solutions, aqueous NaCl solutions, alcoholic beverages, and fruit juices, using a portable VNA with a small SMA probe. The electrodes of the small SMA probe were gold-plated copper to enhance corrosion resistance, allowing measurement of minute amounts (approximately ten mL) of sample. We calculated impedance Z and admittance Y from the measured S-parameter S_{11}, plotted them on a Smith chart and Cartesian coordinates, and synthesized an equivalent circuit for the measured sample by curve fitting. The basic structure of the equivalent circuit of the solution was a parallel circuit of capacitor C_1 and resistor R_2. In aqueous alcohol solutions, the alcohol (methanol) C_2H_5OH did not contribute to electrical reflection in the 1 to 100 MHz frequency range, and the polar molecule H_2O determined the impedance Z of the alcohol solution. In aqueous NaCl solutions, ionic conduction by Na^+ and Cl^- determined the impedance Z. At low NaCl molar concentrations M, the polar water molecule H_2O determined the impedance Z at higher frequencies. The impedance Z of an alcoholic beverage containing alcohol (methanol) C_2H_5OH, cations (mainly K^+ ions), and polar water molecules H_2O was determined primarily by K^+ ions and polar water molecules H_2O. Alcoholic beverages that underwent distillation showed high impedance characteristics similar to those of aqueous alcohol solutions due to the absence of K^+ ions. Alcoholic beverages that were aged had a lower impedance Z due to the exudation and formation of small amounts of cations from the barrel and organic acids. Alcoholic beverages that did not undergo distillation showed significantly lower impedance due to the large amount of K^+ ions remaining in the beverage. In the synthesized equivalent circuit, capacitor C_1 was associated with the polar water molecule H_2O, and resistor R_2 was associated with K^+ ions.

Our research contributes significantly to quality control and product development in alcoholic beverages, food chemistry, chemical products, and bioelectronics.

REFERENCES

[1] X. Zhao, Hong Zhuang, S. Yoon, Y. Dong, W. Wang, and W. Zhao, “Electrical Impedance Spectroscopy for Quality Assessment of Meat, Fish: A Review on Basic Principles, Measurement Methods, and Recent Advances,” *Hindawi Journal of Food Quality*, 6370739, 16 pages, 2017. DOI:10.1155/2017/6370739.

[2] B. M. Aboalnaga, L. A. Said, A. H. Madian, A. S. Elwakil, A. G. Radwan,“Cole Bio-Impedance Model Variations in Daucus Carota Sativus Under Heating and Freezing Conditions,” *IEEE Open access*, vol. 7, pp. 113254-113263, 2019. DOI:10.1109/access.2019.2934322.

[3] I. Jocsak, G. Vegvari, E. Vozary, “Electrical impedance measurement on plants: a review with some insights to other fields,” *Theoretical and Experimental Plant Physiology*, vol. 31, pp. 359-375, 2019. DOI:10.1007/s40626-019-00152-y (0123456789).

[4] S. Ehosioke, F. Nguyen, S. R, T. Kremer, E. Placencia-Gomez, J. A. Huisman, A. Kemna, M. Javaux, S. Garre, “Sensing the electrical properties of roots: A review,” *Vadose Zone Journal*, vol. 19, no. 1, e20082. 2020. DOI:10.1002/vzj2.20082.

[5] M. R. Stoneman and V. Raicu, “Dielectric Spectroscopy Based Detection of Specific and Nonspecific Cellular Mechanisms,” *Sensors*, vol. 21, no. 3177, pp. 1-24, 2021. DOI:10.3390/s21093177.

[6] Y. Liu, D. Li, J. Qian, B. Di, G. Zhang, and Z. Ren, “Electrical impedance spectroscopy (EIS) in plant roots research: a review,” *Plant Methods*, vol. 17, no. 118, 2021. DOI:10.1186/s13007-021-00817-3

[7] M. I. Hussain, A. El-Keblawy, N. Akhtar, A. S. Elwakil, “Electrical Impedance Spectroscopy in Plant Biology,” *Sustainable Agriculture Reviews*, vol. 52, pp. 395-416, 2021. DOI: 0.1007/978-3-030-73245-5-12.

[8] M. Mohsen, L. A. Said, A. H. Madian, A. G. Radwan, A. S. Elwakil, “Fractional-Order Bio Impedance Modeling for Interdisciplinary Appli cations: A Review,” *IEEE access*, vol. 9, pp. 33158-33168, 2021. DOI:10.1109/access.2021.3059963.

[9] K. Kadan-Jamala, M. Sophocleousb, A. Jogc, D. Desaganic, O. Teig-Sussholzd, J. Georgioub, A. Avni, Y. Shacham-Diamand, “Electrical impedance spectroscopy of plant cells in aqueous buffer media over a wide frequency range of 4 Hz to 20 GHz,” Method Article, vol. 8, 101185, 2021. DOI:10.1016/j. mex.2020.101185.

[10] J. C. Nouaze, J. H. Kim, G. R. Jeon, J. H. Kim, “Monitoring of Indoor Farming of Lettuce Leaves for 16 Hours Using Electrical Impedance Spectroscopy (EIS) and Double-Shell Model (DSM),” *Sensors*, vol. 22, pp. 9671, 2022. DOI:10.3390/s22249671.

J. Cheng, P. Yu, Y. Huang, G. Zhang, C. Lu and X. Jiang,“Application Status and Prospect of Impedance Spectroscopy in Agricultural Product Quality Detection,” *Agriculture*, vol. 12, no. 1525, pp. 1-15, 2022. DOI:10.3390/agriculture12101525.

[11] M. V. Haeverbeke, M. Stock, and B. d. Baets,“Equivalent Electrical Circuits and Their Use Across Electrochemical Impedance Spectroscopy Application Domains,” *IEEE Access* vol.10, pp. 51363-51369, 2022. DOI:10.1109/ACCESS.2022.3174067.

[12] D.W. Scott and Y. Alseiha, “Determining detection limits of aqueous anions using electrochemical impedance spectroscopy,” *Journal of Analytical Science and Technology*, vol. 8, no. 17, 2017. DOI:10.1186/s40543-017-0126-9.

[13] T. K. Kataria, M. E. Sosa-Morales, J. L. OlveraCervantes, and A. Corona-Chavez, “Dielectric properties of tequila in the microwave frequency range (0.5-20 GHz) using coaxial probe,” *International Journal of Food Properties*, vol. 20:sup1, pp. S377-S384, 2017. DOI:10.1080/10942912.2017.129794.

K. Chinen, S. Nakamoto, I. Kinjo, “Two-port Equivalent Circuit Deduced from S-parameter Measurements of NaCl Solutions,” *IETE Journal of Research*, vol. 69, no. 12, pp. 9195-9203, 2022. DOI:10.1080/03772063.2022.2081264.

[14] D. Kustyanto, C. S. Widodo, D. R. Santoso, “Analysis of the Effect of NaCl Solution Concentration on the Properties of Impedance Solutions and Different Phases with a Gold Electrode Impedance Measurement System,” *International Research Journal of Advanced Engineering and Science*, vol. 4, no. 2, pp. 378-380, 2019.

[15] C. S. Widodo, H. Sela and D. R. Santosa, “The Effect of NaCl Concentration on the Ionic NaCl Solutions Electrical Impedance Value using Electrochemical Impedance Spectroscopy Methods,” *AIP Conf. Proc.*, vol. 2021, no. 1, p. 050003. DOI:10.1063/1.5062753.

[16] K. Chinen, S. Nakamoto, I. Kinjo, “RF Analysis of Fruit and Vegetables using Equivalent Circuits Deduced from S-parameters,” *International Journal of Electrical and Computer Engineering Research*, vol. 3, no. 2, pp. 18-24, 2023. DOI:10.53375/ijecer.2023.342.

[17] L. Zeng, A. Pernet, M. Cleroux, B. Bach, L. Froidevaux, and I. Preda, “Development of Distillation Sensors for Spirit Beverages Production Monitoring Based on Impedance Spectroscopy Measurement and Partial Least Squares Regression,” *ACS Omega*, vol. 8, no. 17, pp. 15323–15333, 2023. DOI:10.1021/acsomega.3c00481.

[18] https://qucsstudio.de

[19] https://www.awr.com

[20] K. Chinen, I. Kinjo, “A 3.5 GHz Band RF Wireless Signal Transmission Mechanism in Various Aqueous Solutions,” SSRG *International Journal of Electrical and Electronics Engineering*, vol. 10, no. 8, pp. 102-111, 2023. DOI:10.14445/23488379/IJEEE-V10I8P110.

[21] K. Chinen, S. Nakamoto, I. Kinjo, “Relationship between Impedance Transition Point and Cell Wall in Plant Tissue,” *Quest Journals, Journal of Electronics and Communication Engineering Research*, vol. 10, no. 3, pp. 9-18, 2024.

[22] I. M. Abramova, M. E. Medrish, V. B. Savelieva, A. G. Romanova, D.A. Gavrilova, and V. V. Zhirova, “The ionic composition of distilled beverages and its effect on their stability during storage,” *IOP Conf. Series: Earth and Environmental Science*, vol. 640, 062026, 2021. DOI:10.1088/1755-1315/640/6/062026.

[23] K. Chinen, S. Nakamoto, I. Kinjo, “Plant Cell Vacuolar Impedance and Equivalent Circuit,” *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*, vol. 19, no. 3:1, pp.18-26, 2024. DOI: 10.9790/2834-1903011826.