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Review Article

Electrical Impedance Spectroscopy for Quality Assessment of Meat and Fish: A Review on Basic Principles, Measurement Methods, and Recent Advances

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Electrical impedance spectroscopy (EIS), as an effective analytical technique for electrochemical system, has shown a wide application for food quality and safety assessment recently. Individual differences of livestock cause high variation in quality of raw meat and fish and their commercialized products. Therefore, in order to obtain the definite quality information and ensure the quality of each product, a fast and on-line detection technology is demanded to be developed to monitor product processing. EIS has advantages of being fast, nondestructive, inexpensive, and easily implemented and shows potential to develop on-line detecting instrument to replace traditional methods to realize time, cost, skilled persons saving and further quality grading. This review outlines the fundamental theories and two common measurement methods of EIS applied to biological tissue, summarizes its application specifically for quality assessment of meat and fish, and discusses challenges and future trends of EIS technology applied for meat and fish quality assessment.

1. Introduction

Electrical impedance spectroscopy (EIS) is a method to analyze electrical properties of materials and systems by inducing alternating electrical signals at different frequencies into them and measuring the responding signals [1]. A function of impedance according to frequencies is established and further correlated with physical parameters or properties of materials and systems, for the aim of analysis and evaluation. EIS was originally applied in research on electrochemical system, and, from 1920s, it began to be used for biological systems. Until now EIS has had an extensive application in biological research. According to the biological objects, application of EIS can be divided into three aspects, that is, electrical impedance tomography in medical imaging [2–4], quality and safety assessment in food industry, and phytophysiology in agronomy [5–7]. Research objects and targets of EIS applied in food are abundant and extensive, including for fruits, such as study on dry matter content of durian [8] and ripening of banana [9], for vegetables, such as changes in potato and spinach tissues during or after heating [10, 11] and moisture content of carrot slices during drying [12], for meat, such as quality evaluation of pork meat during storage [13] and investigation of beef meat behavior during ageing [14], for chicken, such as discrimination of fresh and frozen-thawed chicken breast muscles [15], for fish, such as salt and moisture content determination of salted rainbow trout [16] and freshness estimation of carp [17], for dairy products, such as real-time detection of bovine milk adulteration [18], and moreover for determination of the additives content in natural juices [19], fermentation process of bread dough [20], and quality assessment of cooking oil [21].

Table 1: Comparison of four new technologies.

Technologies	Fast	Nondestructive	Easily implemented	Inexpensive
Near infrared spectroscopy	√	√	√	×
Hyperspectral image	√	√	√	×
Electronic nose technology	√	√	×	×
EIS	√	√	√	√

Nowadays customers pay more attentions on quality attributes of meat products, such as appearance, flavor, and nutrients. However due to individual differences of livestock, there is a broad-ranging variability in quality of the raw meat, which also causes high variation in the commercialized end products. Customers and manufacturers expect that products can be further graded according to quality, in order to gain more benefit. Thus there is a strong demand for manufacturers to assess the quality of every product on-line to monitor processing, in order to obtain reliable and definite quality information for customers and further processing manufacturers [22]. It also can help to determine the best destination for meat carcasses and to reduce economic losses for industries and customers [23]. There are similar requirements for fish industry as well.

Traditional methods for quality assessments of both meat and fish are precise but destructive, time-consuming, complicated for experiments, and requiring skilled operators. Hence quality information for every individual product cannot be easily collected on-line and nondestructively. In addition to EIS, other new alternative technologies for on-line quality detection also have been investigated, such as near infrared spectroscopy [24–26], hyperspectral image [27–29], and electronic nose technology [30–32]. The comparison of the four technologies was showed in Table 1. All of the technologies are fast, nondestructive, and suitable for development of on-line detecting instrument. However, near infrared spectroscopy and hyperspectral image demand expensive equipment, and electronic nose technology requires specific environmental conditions for measurement [33]. Compared with other new technologies, EIS shows outstanding advantages of being inexpensive and low requirement to the operation [14, 17].

The review mainly introduced principles of EIS applied to biological tissue and summarized its application for quality assessment of meat and fish. Specifically, the article consisted of four sections: (i) the fundamental theories and principles, (ii) two common measurement methods and corresponding probes with diverse configurations, (iii) the latest development in application for quality assessments of meat and fish, and (iv) challenges and future trends of using EIS for quality assessment of meat and fish.

2. Three Important Fundamental Theories

EIS began to be tested on biological system in the 1920s [34, 35]. Some classic theories about principles of EIS applied to biological system were proposed in later study. They were Fricke model, an equivalent circuit diagram of biological tissue [36–38], Schwan's dispersion theory, which proposed three main dispersions occurring in biological tissue [14, 39], and Cole-Cole equation, an empirical formula describing the dispersions [40].

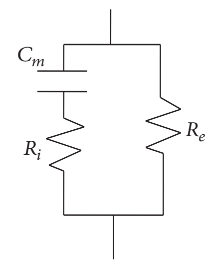

Figure 1: Fricke model.

2.1. Fricke Equivalent Circuit Model. Fricke model [36–38], shown in Figure 1, is an elementary and excellent method to simulate biological system at microscopic level by electronic components [17, 41, 42]. It considers biological tissue as a homogeneous suspension of cells in an ionized liquid medium and simulates biological tissue components, such as membranes, intracellular (ICF) and extracellular fluids (ECF), with passive electrical elements, such as resistor and capacitor, connected in series and in parallel.

The model consists of three elements (R_e, R_i, C_m), so it is also called three-element circuit model. The three elements R_e, R_i, and C_m represent resistance of ECF, resistance of ICF, and capacitance of membrane, respectively. Na^+ and Cl^- ions exist in ECF. In ICF, major cation is K^+, while major anions are phosphate and proteins. Therefore, ICF and ECF can be regarded as electrolytes. Cell membrane performs similar to capacitance. At low frequencies, the current cannot pass through the cells membrane because of its high resistance, while, at higher frequencies, the current passes through ECF, membrane, and ICF. Parameters of the three electrical elements depend on ions concentration and mobility during metabolism of cells, which reflect on physicochemical properties of biological tissue [41]. The model has been widely used in cells, microorganisms' suspensions in a liquid medium, and homogeneous media [41, 42].

2.2. Schwan's Dispersion Theory. A phenomenon that electrical parameters have dramatical changes in a certain frequency range is called frequency scattering, referred to as dispersion, which is due to corresponding relaxation phenomena [43]. Schwan [39] proposed that there are three main dispersions (α, β, γ) in biological system occurring at three frequency

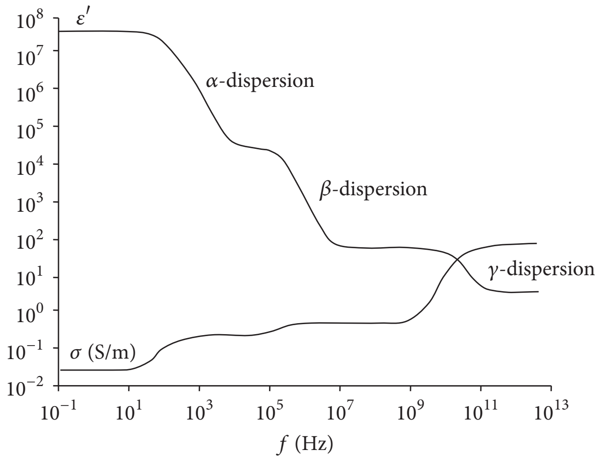

Figure 2: Three dispersions in biological system [σ (S/m) represents electric conductivity and ε' represents dielectric constant] [23].

bands (Figure 2). The α-dispersion, from few Hz to few KHz, is caused by the polarization phenomena in the electrical double layer of the tissue and is a relaxation of "nonpermanent" dipoles, which is formed during free counterions laterally moving along the insulating cell membrane or large molecules [14]. The α-dispersion has been extensively studied in biomedical applications on monitoring tissue or organ vitality for transplantation [41].

The β-dispersion, at radio frequencies ranging from few KHz to MHz, is mainly due to the Maxwell-Wagner effect, which is related to interface polarization occurring in systems where the electric current passes at the interface between two different materials. The β-dispersion is associated with the dielectric properties of the cell membranes, as well as the interactions between membranes and the extracellular or intracellular electrolytes [14]. The β-dispersion is directly associated with the cell membranes behavior and could serve in study of meat ageing based on membrane integrity, as oxidation of the phospholipid membrane layers and lysis occurring during ageing make the membrane porous, which causes insulating properties of membrane to decrease [14, 44].

The γ-dispersion, at microwave frequencies above 100 MHz, is mainly a result of the permanent dipole relaxation of small molecules, mainly water molecules in biological tissues [14, 23].

In general, the α- and β-dispersions are more relevant to the cells states compared with γ-dispersion and commonly used in impedance measurements for study on biological tissues.

2.3. The Cole-Cole Theory. The Cole-Cole equation (shown in (1)) derived based on a considerable amount of experimental data can be used to fit the dispersion processes [40, 45]. In (1), Z^* is complex impedance. R_0 and R_∞ are the impedances at the "static" and "infinite frequency." $\omega = 2\pi f$. τ is a characteristic constant which may be called the relaxation time. α is a dimensionless exponent parameter, which is a constant reflecting distribution in dispersion and is used for

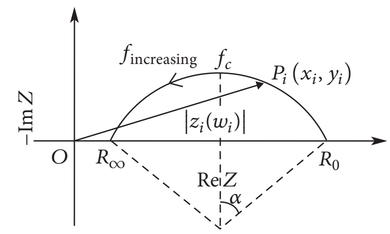

Figure 3: The Cole-Cole plot [45].

correcting the nonstrict capacitive behavior of membranes in biological tissues caused by dielectric losses [14, 41]:

$$Z^* = R_\infty + \frac{(R_0 - R_\infty)}{1 + (i\omega\tau)^\alpha} = z_{\text{Re}} + iz_{\text{Im}}. \quad (1)$$

As shown in Figure 3, locus of (1) in complex plane is an arc with its center below the horizontal axis, which is consistent with the measured bioimpedance data plotted in the complex impedance plane. This is called Cole-Cole plot [40].

Moreover, there is another similar equation described by Foster and Schwan [46] and shown as (2) [47], where $f_c = 1/2\pi\tau$ (shown in Figure 3) is the characteristic frequency, at which the imaginary part of impedance is the largest in absolute value among other frequencies [47].

$$Z^* = R_\infty + \frac{(R_0 - R_\infty)}{1 + (i(f/f_c))^\alpha} = z_{\text{Re}} + iz_{\text{Im}}. \quad (2)$$

Furthermore, the Cole-Cole equation can be related to Fricke model by following equations shown in (3) [41, 45]. Electric parameters in the fitting equations reflect physical and chemical properties of biological tissues. Prediction models for quality parameters are established with the electric parameter data as input, which is the principle of EIS applied to quality assessment of food.

$$\tau = (R_i + R_e) C_m,$$
$$R_0 = R_e, \quad (3)$$
$$R_\infty = \frac{R_e R_i}{R_e + R_i}.$$

2.4. Progress of Equivalent Circuit Model. EIS technology is able to deduce elementary reactions steps and extract the kinetic parameters characterizing the reaction steps of a total electrochemical reaction system, by using equivalent circuits or functions derived from the known mechanism [48]. However, for biological tissues, although Fricke model and Cole-Cole equation have made some contributions to theoretical analysis, there are still a lot of complicated unknown reactions and transformations in biological system needed to be discovered and explored. Therefore, equivalent circuit model plays an important role in EIS analysis, and more effective ones are still expected to be developed for application in food quality detection.

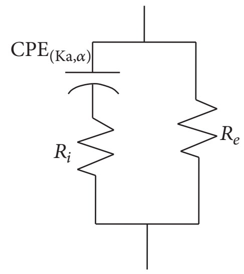

Figure 4: Modified Fricke model.

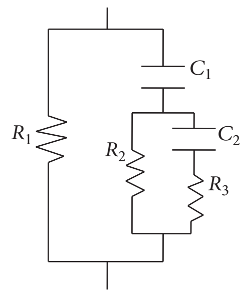

Figure 5: Equivalent circuit model proposed by Zhang et al. [51].

In (1), when α is 1, the equation mathematically describes the Fricke model. However, it was observed that the Fricke model was not accurate enough to fit the experimental results [14, 40], as cell membrane performs different with capacitance. According to Cole-Cole equation, a constant phase element (CPE), which is used to describe cell membrane with modified capacitive performance, is defined as $Z_{\text{CPE}} = 1/K_a(j \cdot \omega)^{\alpha}$. Guermazi et al. [14] used a modified Fricke model (shown in Figure 4) to investigate the ageing state of beef meat during 14 days. Results indicated that the modified Fricke model led to a good fitting performance with the expected behavior of muscle during ageing.

Fricke model and modified Fricke model are the most classic equivalent circuit models for biological tissue and are still used in recent research on animal or plant tissue, such as estimating freshness of carp [17], preliminary analysis to predict breast cancer [49], detecting phosphorus nutrition level for *Solanum lycopersicum* [7], and changes of potato tissues during drying [50].

Additionally, there is also an equivalent circuit model used to simulate plant tissue. As shown in Figure 5, the model was developed by Zhang et al. (1990) [51] during study on parenchymatous plant tissues. It takes into account cell wall, vacuole, and tonoplast. In Figure 5, the components R_1, R_2, and R_3 represent the cell wall resistance, cytoplasm resistance, and vacuole resistance. C_1 and C_2 represent plasma membrane capacitance and tonoplast capacitance, respectively.

Although the model contains more detailed cell structure, the fitting performance of the model to the measured impedance data was worse than that of the modified Fricke model according to research of Wu et al. [52] on eggplant pulp. Harker and Maindonald [53] also used the model to study nectarine during ripening. The results showed that the model was not able to predict all of the changes during ripening, but it helped to improve the understanding of nectarine ripening.

Recently, a new electrical model of a biological cell with nucleus was developed and simulated [54, 55]. The simulation results of the model were compared well with published data, which indicated the promising utilization to serve as an aid to further understand behavior of cells over frequency range.

3. Bipolar and Tetrapolar Measurement Methods

3.1. Bipolar Measurement Method. The mathematical principle of electrical impedance measurement is Ohm's law, $Z = U/I$. Thus the most fundamental measuring method is using two electrodes to induce the current (I) and to measure the voltage (V). However, in this bipolar measurement method, because of the existence of electrode polarization, the measured impedance consists of two parts, that is, impedance of measured object and parasitic capacitive impedance on the interface of the electrode-sample ohmic contacts [22, 56]. The parasitic impedance decreases with frequency increasing; thus it can be ignored when frequency is high in bipolar measurement system [17]. Material and configuration of electrodes have an impact on electric field loaded on the tested biological tissue and are important factors in EIS measurements [57, 58].

Five common configurations of two-electrode probes used in research of meat are introduced as follows, and the corresponding schematic diagrams are shown in Figure 6. Sun et al. [17] estimated freshness of carp based on EIS morphological characteristic with a pair of platinum (Pt) electrodes (Figure 6(a)). Masot et al. [57] used a coaxial needle electrode (Figure 6(b)) in measurement to predict salt content in cured ham or pork loin. The electrode was made of a hollow needle and an isolated wire inside the needle, which were both made of stainless steel. A dielectric material, an epoxy resin, was between them. The needle is used for electromyography in medical applications. Damez et al. [59] used a cylindrical probe (Figure 6(c)) to measure electrical anisotropy of meat to assess ageing state. The probe was made of 20 stainless steel needles electrodes equally arranged on a periphery with 8 cm in diameter. Each pair of electrodes that are diametrically opposite was a bipolar system. The ten electrodes pairs were able to measure impedances at radial directions. Ćurić et al. [16] tested the applicability of needle-type multielectrode array (Figure 6(d)) in evaluating salt and moisture content of structurally heterogeneous fish samples. The needle-type multielectrode array arranged in bipolar configuration was comprised of two rows of 6 parallel, electrically connected, and gold-plated needles and was considered able for more accurate measurements for electrical properties. Guermazi et al. [14] measured the impedance of beef meat during ageing period with circular penetrating multielectrodes (Figure 6(e)). The circular penetrating probe consisted of one central electrode and eight surrounding electrodes. All electrodes were made of gold-plated steel. The

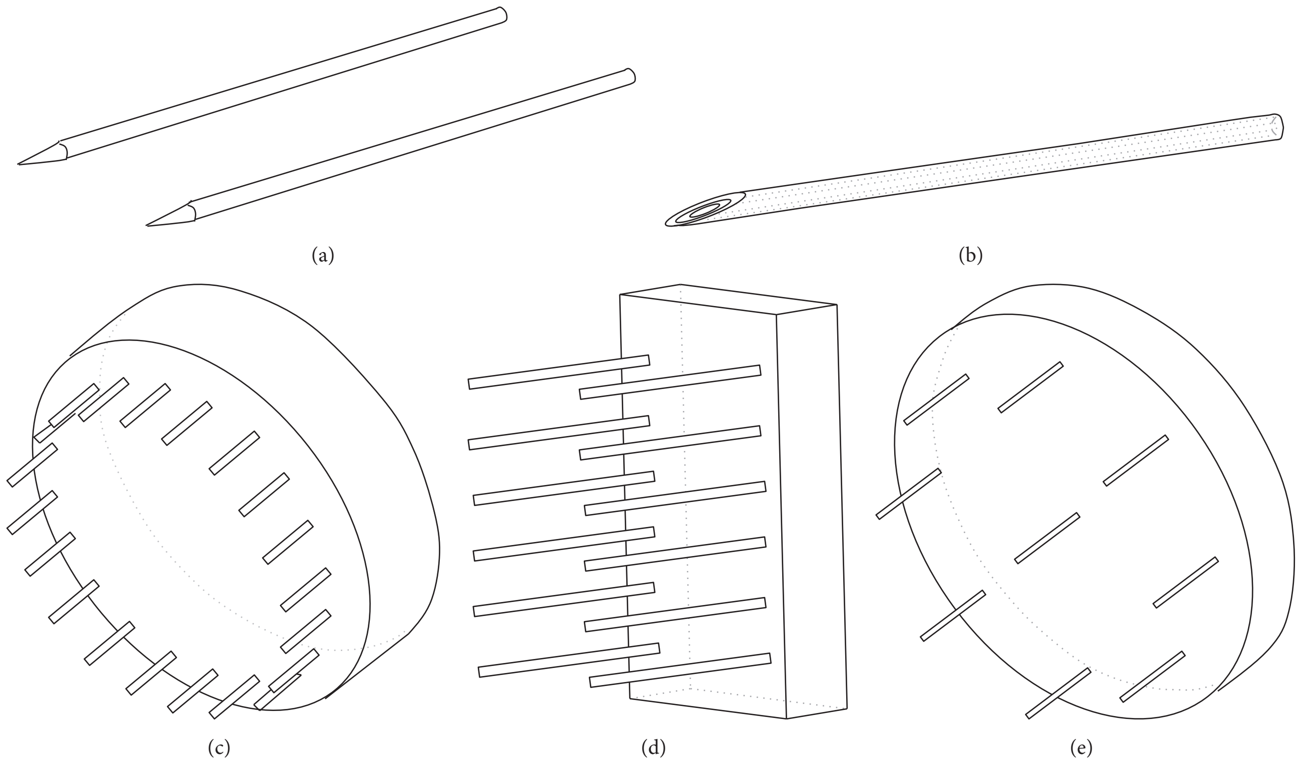

Figure 6: Schematic diagrams of five configurations of bipolar probe.

excitation signal was delivered from the inner electrode to the meat and the surrounding electrodes were grounded. This provided information about the distribution of the electric field in meat independent of anisotropy effects [14]. It was found that measured data had higher reliability and the instrument was more stable, when using two rows of pairs of needles electrodes than using circular probe with needles electrodes equally arranged on a periphery [60].

Electrode distance variation technique can be used for electrode polarization correction in bipolar measurement system. Some researches thought that capacitive gap contact between electrode and sample reflected the feature of the samples [22, 56]. Based on electrode distance variation technique, Damez et al. [61] investigated contact impedance as a parameter of interest for assessment of meat ageing. The probe used in measurement composed of eight stainless needles aligned and spaced 15 mm apart ($\phi = 0.6$ mm; $L = 5$ mm). Any pair of electrodes was a bipolar system, and 28 data points were obtained from these pairs of electrodes. Some data were used to plot a figure of average impedance against distance between electrodes at several frequencies. It showed linear relation between impedance and distance, and the slope of line corresponded to impedance per unit length of the sample, while the y-intercept represented contact impedance. Contact impedance was found to be related to meat fibers strength and reflected conductive properties of the extracellular spaces [61]. Limitation of the technique is that the polarization impedance becomes large in comparison with the sample impedances at low frequencies. Therefore, the spacing between electrodes should be as large as possible in order to increase the weight of the sample impedance [56].

3.2. Tetrapolar Measurement Method. To eliminate the electrode polarization for more accurate measurement of impedance, a tetrapolar measurement method was proposed. The parasitic voltage is caused when a current flows through the interface of electrode sample. In tetrapolar system, current inducing and voltage measurement are via two separate electrodes pairs [22]; thus current is not introduced in the voltage measurement circuit and the parasitic impedance is eliminated. However, in practical terms, electrodes with uniform specific polarization impedance (per unit surface area) over the entire electrode surface are difficult to obtain, which causes the electrode on a potential level different from the one it ought to register [56].

The simplest configuration of four-electrode probe is four metal electrodes arrayed in line. Yang et al. [45] used four stainless steel electrodes (Figure 7(a)) to measure impedance of porcine meat for moisture content prediction. Furthermore, Altmann and Pliquett [62] carried on an impedance measurement using Purdue Tetrapolar probe (PTP) (Figure 7(b)) on the M. longissimus dorsi in pork and beef. The configuration of PTP was a steel shaft with four ring electrodes mounted in a line along it. The electrodes were insulated from each other, and the outer pair of electrodes was used for inducing a current into system while the inner pair of electrodes was for voltage measurement. Similar to the cylindrical bipolar probe mentioned above, Damez et al. [59]

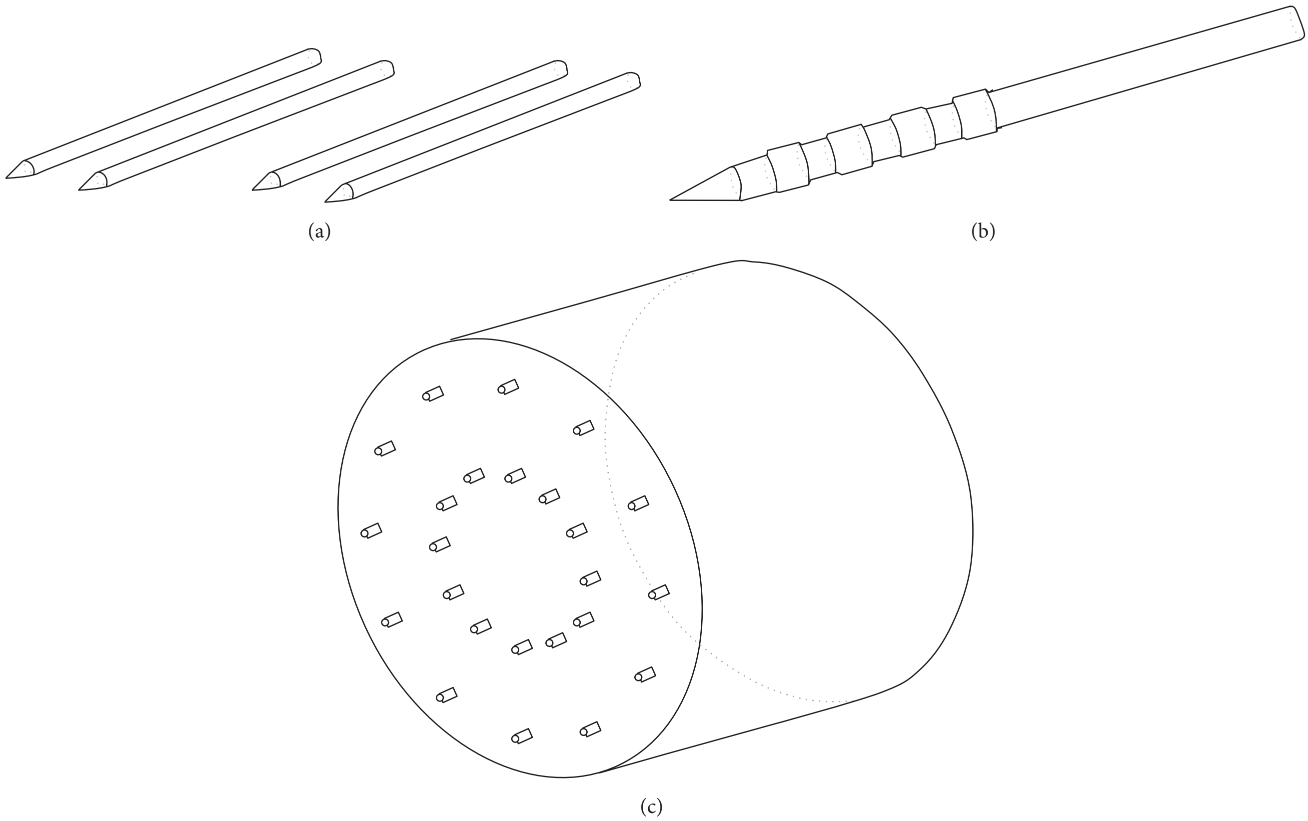

Figure 7: Schematic diagrams of three configurations of tetrapolar probe.

also used a cylindrical tetrapolar probe (Figure 7(c)). The probe consisted of 24 noninvasive electrodes which were equally spaced on a periphery in two concentric circles. Each four electrodes arrayed along diameter were a tetrapolar system. The advantage of this probe was that the impedances of six directions could be obtained in a single application. There is also a three-point measurement method, which is the simplification of tetrapolar method with one electrode working to induce current and to measure voltage. However, this method is rarely used in measurement for biological system and is not introduced in detail in this paper.

4. Quality Assessments of Meat and Fish

This section summarized recent development in quality assessments of meat and fish using EIS. The published research was summarized on two aspects of quality assessments: (i) physicochemical properties of raw meat and fish and (ii) chemical compositions of both raw meat and fish and their products. For physicochemical properties evaluation, four common quality issues, ageing state of beef, PSE and DFD of pork, freshness of fish, and defrosting of fish and chicken, were discussed, respectively. For chemical compositions evaluation, salt and water are the main evaluated ingredients, and the discussions are separated into two parts, meat and fish, depending on distinct features between them. Specific framework of the summary is shown in Figure 8. The general information of all studies reviewed is given in Table 2.

4.1. Physicochemical Properties. Physicochemical properties of raw meat and fish include color, pH, water-holding capacity (WHC), Warner-Bratzler shear force (WBSF), and total volatile basic nitrogen (TVB-N). These properties are the indicators for diverse quality issues, which draw attention of customers and manufacturers. EIS has been studied to realize prediction of physicochemical properties in order to solve the appropriate quality issues.

4.1.1. Ageing State: Beef. One of the most important factors of beef palatability or quality is tenderness that is closely related to meat ageing state [59]. Meat after slaughter undergoes two periods, rigor mortis and ageing. Then it is either further processed or sold in the retail markets. During ageing, connective proteins break down, causing structural changes of fragmentation of myofibrils and degradation of cytoskeletons. Well-aged meat is tender with improved flavor. Assessment of meat tenderness optimizes refrigerated storage time and the ageing state for sale [61]. Ageing results in changes in membrane and intracellular and extracellular electrolytes. These can impact electrical properties and can be reflected by impedances with increasing frequencies [83]. During post-rigor-mortis ageing, impedance of meat decreases more slowly than prerigor period [84] and there is no convincing explanation of the mechanisms.

It was found that ratio $Z_{1\,\text{kHz}}/Z_{100\,\text{kHz}}$ decreased free from the impact of fat level during ageing [85, 86]. Therefore, the ratio was suggested as an indicator for meat ageing

Table 2: Application of EIS for quality assessments of meat and fish.

Object	Quality indicator	Predictor variable	Frequency	Algorithm	Accuracy	Reference
Ageing state: beef						
Heifers	WBSF	Electrical impedance(EI), conductivity(EC)	A wide range for EI, 1 KHz for EC	CA	$R = 0.68$ (EI), and -0.65 (EC)	[63]
beef	Mechanical resistance	$Z_{1\,\text{kHz}}/Z_{100\,\text{kHz}}$	1,100 kHz	LRA	$0.73 \le R^2 \le 0.98$	[64]
beef	Mechanical resistance	Lineic impedance index (I); contact impedance (CI)	100 Hz	LRA	$R^2 = 0.79$ (I); $0.77 \le R^2 \le 0.95$ (CI)	[61]
Cull cows	Mechanical resistance	8 selected parameters related to complex impedance	100 Hz–1.5 MHz	LRA	$R^2 = 0.71$	[59]
Beef and veal	Time of postmortem period	R_e, R_i, C derived from the modified Fricke model	40 Hz–110 MHz	TA	—[a]	[14]
PSE, DFD, and RFN: pork						
Porcine muscle	pH_{45}	Changes in phase angle	1 kHz	CA	$R = 0.73$	[65]
Pig carcass	Drip loss at 24 h	Electrical impedance	1000 Hz	PLS	$R = 0.50$, RMSEP = 2.53%	[66]
Green ham	pH_{45}	R_∞/R_0, α, and f_c	8 kHz–1 MHz	MRA	$R^2 = 0.50$	[47]
Lean pork tenderloins	TAC, TVB-N	$Z = (Z_0 - Z_t)/Z_0$ (Z_0, impedance at day 0; Z_t, impedance at a given storage interval)	20, 200 Hz, 2, 20, 200 kHz	NRA	$0.758 \le R^2 \le 0.992$, $0.11 \le \text{RMSE} \le 0.57$ for TAC; $0.636 \le R^2 \le 0.989$, $0.29 \le \text{RMSE} \le 1.68$ for TVB-N	[13]
Freshness: fish						
Carp, herring and sea bass	Hypoxanthine content	Phase angle	2.5 kHz	LRA	$R^2 = 0.92$ for carp; 0.87 for herring; 0.86 for sea bass	[67]
Grass carps	TAC, K value, TVB-N, sensory assessment (SA)	$Q = (Z_{1\,\text{kHz}} - Z_{16\,\text{kHz}}) \times 100/Z_{16\,\text{kHz}}$	1 kHz, 16 kHz	CA	$R = 0.943$ for TAC, 0.996 for k value, 0.951 for TVB-N, 0.968 for SA	[68]
Bighead carp	pH, texture, TVB-N, K value, drop loss, SA and TAC	$Q = (Z_{1\,\text{kHz}} - Z_{20\,\text{kHz}}) \times 100/Z_{20\,\text{kHz}}$	1 kHz, 20 kHz	CA	$R \ge 0.919$ for pH and texture, ≥ 0.955 for TVB-N, K value, drop loss, SA and TAC	[69]
Sea bream	TVB-N	Impedance modulus and phase	1 Hz–1 MHz	PLS	$R^2 = 0.72$	[70]
Carp	Storage time (ST), SA	Morphological characteristic parameter, impedance modulus, phase	1 Hz–1 MHz	LRA	$R^2 = 0.69$ for ST, 0.66 for SA	[17]

Table 2: Continued.

Object	Quality indicator	Predictor variable	Frequency	Algorithm	Accuracy	Reference
Defrosting: fish and chicken						
Sea bass	Slow-frozen in 1 and 2 cycles, Fast-frozen in 1 and 2 cycles	Resistance, reactance, water, fat content, WHC and pH	1 Hz–1 MHz	PCA, DA	78% for total samples, 100% for the unfrozen	[71]
Salmon	Frozen and stored for 15, 30 and 60 days, frozen in 1 and 2 cycles	Impedance modulus and phase	1 Hz–1 MHz	PCA, DA	71.93%	[72]
Sea bream	Frozen and stored for 15, 30 and 60 days, frozen in 1 and 2 cycles	Impedance modulus and phase	1 Hz–1 MHz	PCA, DA	70.24%	[73]
Sea bass	Frozen for 1 month with and without temperature fluctuations (TF), frozen for 4 months with and without TF	Impedance modulus and phase	0.1–1000 kHz	ANOVA, LRA	$R^2 = 0.918$ between phase angle and protein solubility	[74]
Atlantic chub mackerel	Slow-frozen in 1 and 2 cycles, Fast-frozen in 1 and 2 cycles	Resistance, reactance	1 Hz–1 MHz	ANOVA	—[a]	[75]
Chicken breast meat	1 and 2 frozen-thawed cycles	Impedance modulus and phase	50–200 kHz	LVQNN	100% for fresh, >90% for one cycle, >88% for two cycles	[60]
Chicken breast meat	1, 2, and 3 frozen-thawed cycles	$(Z_{50\,\mathrm{Hz}} - Z_{200\,\mathrm{kHz}})/Z_{200\,\mathrm{kHz}}$, $(\mathrm{Ph}_{50\,\mathrm{Hz}} - \mathrm{Ph}_{200\,\mathrm{kHz}})/\mathrm{Ph}_{200\,\mathrm{kHz}}$, chewiness, hardness, expressible loss (*Z* is the modulus; Ph is the phase angles)	50 Hz, 200 kHz	LVQNN	100%, 97.5%, 87.5%, and 77.5% for 0, 1, 2, and 3 cycles samples, respectively	[15]
Water, fat, and salt: meat						
Potted minced pork products	Water (W), lipid (L)	Impedance modulus and phase	5 kHz–2 MHz	PLS	A standard deviation of the residues of 0.66% for W and 1.08% for L	[76]
Porcine meat	Water	R_∞	1–250 kHz	LRA	$R^2 = 0.879$, RMSEP = 0.00566, RSD = 0.73%	[45]
Chicken breast meat	Water	Impedance module and phase	1 Hz–1 MHz	PLS	$R^2 = 0.9388$, predictive residual sum of squares of 1.9242	[58]
Green ham	Visual fatness	R_∞, α, conformation, ham weight	8 kHz–1 MHz	MRA	$R^2 = 0.59$	[47]
Beef and pork from different size grinds	Fat	Resistance, temperature, weight	50 kHz	—[a]	$R^2 = 0.36, 0.60, 0.86$ for beef trim, 0.95-, 0.32 cm ground; $R^2 = 0.64, 0.66, 0.92$ for pork trim, 0.95, 0.32 cm ground	[77]

Table 2: Continued.

Object	Quality indicator	Predictor variable	Frequency	Algorithm	Accuracy	Reference
Pig of various breeds and cattle	Intramuscular fat	R_u, resistance at high frequencies immediately after the change of current signal; R_0, derived for the voltage extrapolated to infinite time	500 Hz–100 kHz	SFR, CA	$R = 0.34$ for total pork, $R = 0.69$ for beef	[62]
Minced pork loin	Salt	Impedance modulus and phase	100 Hz–1 MHz	PLS	$R^2 = 0.934$	[57]
Minced pork loin	Sodium chloride, sodium nitrite, sodium nitrate content	Impedance modulus and phase	1 kHz–1 MHz	PLS	p1 = 0.985, NR = 0.388 for chloride; p1 = 0.709, NR = 1.436 for nitrite; p1 = 0.648, NR = 1.511 for nitrate[b]	[78]
Dry-cured hams of three qualities (deep spoilage, spoiled swollen, and unaltered)	Salt	Impedance modulus and phase	100 Hz–1 kHz	PLS	$0.72 \le R^2 \le 0.78$	[79]
Salt and water: fish						
Fresh salted Atlantic salmon	Salt, water, water phase salt (WPS)	Conductance at 1 MHz, capacitance increment ($Cap_{10\,MHz} - Cap_{1\,MHz}$)	1, 10 MHz	LRA	$0.822 \le R^2 \le 0.926$ for salt, $0.488 \le R^2 \le 0.534$ for water, $0.732 \le R^2 \le 0.890$ for WPS	[80]
Fresh salted rainbow trout	Salt, water, WPS	Impedance modulus and phase	50 kHz	LRA, MRA	$R^2 = 0.864$ for WPS, 0.844 for water, 0.853 for salt	[16]
Salmon during salting-smoking process	Salt, water, water activity (a_w)	Impedance modulus and phase	1 Hz–1 MHz	PLS	RMSEP = 0.685 for salt, 0.006 for a_w, 3.579 for water	[81]
Smoked salmon and cod products (of different brands and batches)	Salt, water, lipid, a_w	Impedance modulus and phase	1 Hz–1 MHz	PLS	$0.701 \le R^2 \le 0.823$ for a_w, $0.351 \le R^2 \le 0.640$ for lipid, $0.564 \le R^2 \le 0.851$ for water, $0.600 \le R^2 \le 0.761$ for salt	[82]

Correlation analysis: CA; Linear regression analysis: LRA; Trend analysis: TA; Multiple regression analysis: MRA; Nonlinear regression analysis: NRA; Analysis of variance: ANOVA; Learning vector quantization neural network: LVQNN; Stepwise forward regression: SFR; [a]Accuracy was not available; [b]The parameters of p1 (slope of the fitting line) and norm of residuals (NR) were obtained from the fitting line of predicted and measured salt content, and were used as indicators of performance of the PLS model.

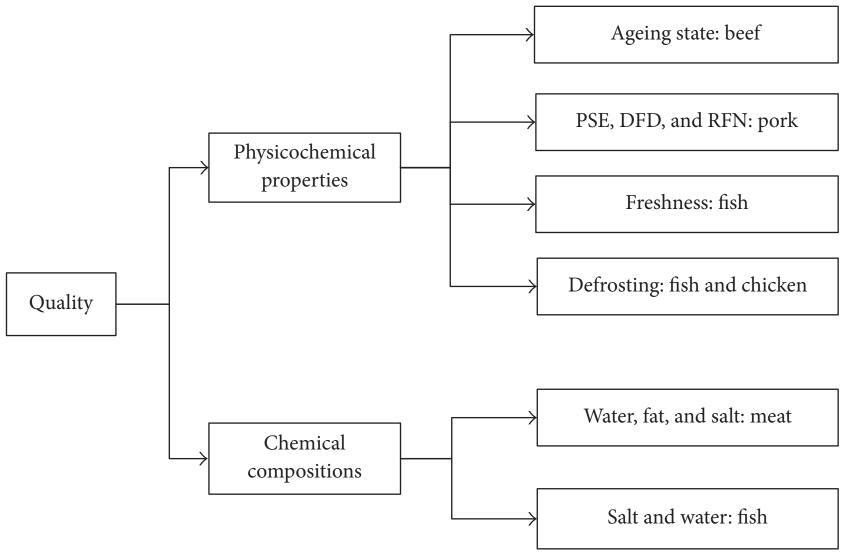

Figure 8: Framework of overview.

state. However, Lepetit et al. [64] found that the ratio $Z_{1\,\text{kHz}}/Z_{100\,\text{kHz}}$ and impedance (Z) tempted to decrease with ageing, but the slope of curves for the same muscle varied with different animals of Charolaise bulls. Thus these two parameters were not suitable for prediction of the ageing state. Meanwhile, they put forward electrical anisotropy as a new prediction parameter, since it decreased with ageing period and became almost isotropic after meat was fully aged. Based on this, Damez et al. [59] developed a circular probe, which was able to measure impedance at different directions of bovine meat. Ageing state evaluated by impedance measurement using the probe showed strong correlation with mechanical measurement for all muscles from three types ($R^2 = 0.71$). However the correlations showed great difference between the three muscle types (rectus abdominis: $R^2 = 0.83$; semimembranosus: $R^2 = 0.58$; semitendinosus: $R^2 = 0.18$). The results also showed that impedance measured parallel to muscle fibers is the minimum, while impedance measured across the muscle fibers is the maximum. Furthermore, Damez et al. [61] carried out impedance measurement only on the two directions for early assessment of beef meat ageing. The lineic impedance index was defined as the difference between the director coefficients of the regression lines of transversal and longitudinal impedance respectively against distance between electrodes. Higher correlation ($R^2 = 0.79$) based on the lineic index were obtained. Another parameter, contact impedance, was also tested. It was calculated as the y-intercept of impedance regression line against the distance, and high correlations with meat fibers strength were obtained for all tested muscle types ($0.77 \leq R^2 \leq 0.95$). Recently, Guermazi et al. [14] applied the modified Fricke model to characterize the ageing state of different muscles of beef and veal. The extracellular resistance R_e showed the highest sensitivity to ageing, with decreasing about 7% to 25% from day 6 to day 14 depending on the muscle type. These indicated that prediction ability of same model varied among different types of muscle.

4.1.2. PSE, DFD, and RFN: Pork. Pork meat can be divided into DFD (dark, firm, and dry), PSE (pale color, soft texture, and high exudation), and RFN (red, firm, and nonexudative) based on its color, pH, and drip loss. PSE meats are unsuitable for processing and DFD meats are perishable [61]. Both of them present unfavorable appearance for consumers and thus cause economic losses for meat industry [87]. In contrast, RFN meat is desirable meat and ideal for both producers and consumers. The benefits of identification of low quality meat for industry include reducing economic losses and distributing the best destination of meat carcasses [23].

Forrest et al. [66] used complex impedance (at 1000 Hz) to predict drip loss at 24 h of pig carcass at the slaughter line. The cross-validation showed a correlation of 0.50. The moderate results were thought to be due to a lack of temperature correction. Besides, the rate of changes in impedance and phase angle had a better performance of prediction for meat qualities than the absolute magnitude of impedance, which was concluded by Whitman et al. [65]. A better result was obtained by Oliver et al. [47] studying on green ham with Cole-Cole theory. Multiple regression model based on variables of ratio (R_∞/R_0), α, and f_c showed a result of $R^2 = 0.50$ to predict pH_{45} in the *semimembranosus* (SM) region. It was also found that ratio in SM region classified the technologically normal meat ($pH_{45} > 6.10$) from the PSE meat with 88.46% accuracy.

For DFD meat, the results were found not promising for the early detection based on electrical measurements [23, 61]. Besides, the detection for PSE meat was also difficult during the rigor mortis period, because pH, temperature, and metabolic modifications, which have influence on electrical properties of meat, are rapidly evolving at this period [88].

It was also concluded that discrimination of PSE, DFD, and RFN pork meat was more valid when the final pH has been reached, based on dielectric properties [23]. These indicated that detection time is also a significant factor in meat quality prediction.

H. B. Nguyen and L. T. Nguyen [13] used a new parameter of relative changes impedance [$Z = (Z_0 - Z_t)/Z_0$, Z_0, impedance at day 0; Z_t, impedance at a given storage interval] to evaluate TVB-N and total aerobic count (TAC) of lean pork tenderloins during storage. The results were promising, with $0.636 \leq R^2 \leq 0.989$ for TVB-N and $0.758 \leq R^2 \leq 0.992$ for TAC. This study can be used as a reference for other quality parameters prediction, such as pH and drop loss.

4.1.3. Freshness: Fish. Because of fish being highly perishable and significant impact of freshness on flavor, freshness is the primary quality attribute of fish for consumers and manufacture. EIS applied for freshness estimation of fish shows the promising results. Based on the phase angle and admittance changing with time, four stages of freshness (fresh, semifresh, semideteriorated, and deteriorated) of carp, herring, and sea bass can be easily defined. Furthermore, phase angle at 2.5 kHz had good linear relationship with hypoxanthine concentration which is used to estimate fish freshness ($R^2 \geq 0.86$ for carp, herring, and sea bass) [67]. Impedance change ratio (Q value), defined as $Q = (Z_{f1} - Z_{f2}) \times 100/Z_{f2}$, is also found to have high correlation ($R \geq 0.943$) with TAC, TVB-N, and sensory assessment (SA) of grass carps and bighead carp during storage [68, 69].

Although these impedance parameters demonstrated the ability as freshness indicators, the studies for practical application are in the preliminary stage and need to be confirmed in more situations [68]. Furthermore, it was found that impedance parameters to predict freshness of fish samples of different batches showed worse results than for the samples of same batches [70]. The reason was thought to be the difference in composition terms among the distinct batches. It was proved that growth environments and dietaries have an effect on body composition of fish [89, 90]. To eliminate the effect of different origins of fish, Sun et al. [17] defined a morphological characteristic parameter extracted from Bode plots to predict freshness. Compared with impedance module and phase angle, morphologic characteristic parameter showed highest correlations ($R^2 = 0.69$). The results were not outstanding due to 20 samples obtained from 20 different retailers.

4.1.4. Defrosting: Fish and Chicken. Due to perishability of fish and chicken, freezing is the common means to slow down meat quality deterioration during postharvest handling and storage. But in freezing, frozen storage, and thawing, the processes of protein denaturation and lipid oxidation take place, which not only cause tissue injury but also affect the sensory as well as nutritional quality of the products [72, 91]. Because of this, a lot of consumers prefer fresh products regardless of price. However in many cases, the difference between frozen-thawed products and fresh ones are too small to tell based upon their visual appearance [92]. Processes of freezing/thawing and frozen storage provoke protein denaturation and the destruction of cell membranes, which cause modification produced on the mobility of water and ion concentration and affect electrical impedance measured on fish and chicken [71, 93].

Fish samples of fresh and suffered with different freezing styles, frozen storage periods, and freezing cycles were investigated to be distinguished based on EIS at a frequency range of 1 Hz to 1 MHz [71–73]. Impedance data were analyzed with principal components analysis (PCA) and discriminant analysis (DA). Classification accuracy was above 70% (71.93% and 70.24%) for total samples [72, 73], while impedance data combined with physical and chemical parameters (water, fat content, WHC, and pH) as input had a higher accuracy of 78% [71]. The accuracies for fresh samples were up to 100%, while the results for the separation between freezing styles, storage periods, and freezing cycles were not good. This was considered caused by no significant difference between samples of different storage periods and freezing cycles in electrical impedance, which was the same as in other physicochemical parameters such as moisture content, TVB-N, $K1$ value (an indicator of ATP related compounds), pH, and microbial counts [72]. Moreover, it was found that reactance can be used to differentiate between different freezing styles and freezing cycles for sea bass at frequencies higher than 500 kHz [71]. And it seems that phase or reactance may be better indicator of the freezing history compared to impedance modulus or resistance [74, 75].

For chicken breast meat, the fresh samples and frozen samples with different freezing cycles were successfully distinguished (100% for fresh, >90% for one cycle, and >88% for two cycles), based on impedance magnitude and phase at frequencies from 50 to 200 kHz and a modeling method of learning vector quantization neural network (LVQNN) [60]. Furthermore, impedance modulus and phase angles measured at two frequencies (50 Hz and 200 kHz), combined with three physical properties (chewiness, hardness, and expressible loss), also showed the discrimination ability (100%, 97.5%, 87.5%, and 77.5% for the fresh samples, the one frozen-thawed cycles, two and three cycles, respectively) [15].

4.2. Chemical Compositions. There are many kinds of meat and fish products, such as meat floss, ham, bacon meat, and fish, which are deeply liked by customers in the market. The flavors of these products are affected not only by their physicochemical properties of the raw materials but also by chemical compositions in raw materials and end products as well as additives added in processes. Some of these compositions are moisture, lipid, and salt. Some research [94–97] has demonstrated that electrical properties of food are closely associated with their chemical compositions, which shows the possibility of EIS to assess component contents of food.

4.2.1. Water, Fat, and Salt Content: Meat. Prediction of water content of meat showed promising results, with EIS being applied to raw porcine meat [45] and potted minced pork products [76]. De Jesús et al. [79] studied dry-cured hams of three qualities (deep spoilage, spoiled swollen, and unaltered), and no good performance for water content prediction was obtained. This was due to no significant differences for water content among the all dry-cured ham samples. It was discovered that the moisture content differs from part to part and, even in one single piece of meat, moisture values vary from different detecting directions. Furthermore, meat muscles with fat uniformly distributed and low fat levels may obtain better accuracy for prediction [45]. Schmidt et al. [58] predicted moisture content of skinless deboned chicken breast meat, during cooking process with different heating time. Good prediction was obtained ($R^2 = 0.9388$), which indicated EIS can also be applied to chicken for moisture prediction.

The prediction of fat content of muscle meat based on EIS is not good [47, 62]. It was considered due to the fat concentrated in clustered adipose cells and inhomogeneously distributed within muscles [62]. This can be verified by the study of Marchello et al. [77], which assessed fat content of beef and pork from different size grinds based on impedance measurement. For the beef samples with fat percentage range of 4–35%, R^2 for the trim, 0.95, and 0.32 cm ground meat were 0.36, 0.60, and 0.86, respectively. For the pork samples with fat percentage range of 7.5–35%, R^2 for the pork samples of the trim, 0.95, and 0.32 cm ground were 0.64, 0.66, and 0.92, respectively. The results showed that the smaller the grind, the higher the accuracies of the prediction. These also demonstrated that fat content assessment for minced samples showed a better performance than for block samples.

Good results were also obtained for salt content prediction of salted meat based on EIS [57, 78, 79]. It was also found that minced samples had better prediction accuracies than block samples, which indicated that salt homogeneously distributed within meat favorably impacts prediction accuracy. Furthermore, Labrador et al. [78] applied EIS to predict concentration levels of different salt types in minced meat. Precise prediction of chloride was obtained, whereas the predictions for nitrite and nitrate were moderate.

4.2.2. Salt and Water Content: Fish. Salt content and water phase salt (WPS) of fresh salted fish have good correlations with impedance parameters, even at two or single frequencies [16, 80]. These parameters include impedance modulus at 50 kHz, conductance at 1 MHz, and capacitance increment between 10 MHz and 1 MHz. Impedance modulus generally reflects changes of conductance. Conductance is thought to be related to ions capability of movement and capacitance which includes the information of the muscle state. For smoked product and during salting-smoking process, salt content prediction also showed good results based on impedance data at a frequency range of 1 Hz to 1 MHz [81, 82]. For both situations, prediction for water activity (a_w), a parameter closely related to microbial spoilage, obtained better results than for salt content. These indicated the feasibility to determine shelf life of smoked product based on EIS [82].

Studies showed different prediction performance for moisture content of fish [16, 80, 81]. In addition, it was found that prediction results for smoked products differed among brands and species, and the difference between species was greater [82]. Species with lower lipid content had better accuracies, which is consistent with prediction for meat. Moreover, configuration of electrode is also considered as an influence factor on moisture prediction accuracy [16]. This was indirectly verified by Fuentes et al. [73], who tested two types of electrode to separate the fresh fish from the frozen. One type of electrode was able to separate, while the other one failed. However, the failed electrode was found to be efficient to separate for another species of fish [72]. Effect caused by species is considered due to the different structures and compositions of fish muscle between species, while effect of electrode is the various electrical fields loaded on muscle tissue. Guermazi et al. [14] investigated electrode configuration by using Finite Element Methods to simulate the distribution of the electric field in meat sample.

4.3. Challenges and Future Trends. Although the above review shows a promising application of EIS in quality assessment/prediction of raw meat, fish, and/or its products, several challenges remain to be addressed before it can be applied in practical manufacturing process. The challenges are mainly from two aspects, that is, electrical impedance measurement and the tested meat or fish.

Electrode polarization presents one main challenge of EIS in impedance measurement and data exploration. Forced by the electric field, dissolved free ions existing in conductive systems tend to move towards the electrode/sample interface, leading to the formation of ionic double layers. The ionic double layers exhibit capacitive impedance character, producing voltage drops. This phenomenon is electrode polarization. The resultant spectra of electrode polarization overlay the relaxation process of the interested samples, impeding the interpretation of the data. Various approaches on both description of electric double layer using equivalent circuits and measurement setup configuration compensations are studied to correct the electrode polarization. However, effect of electrode polarization depends on impedance of the samples, the measuring temperature, the structure and materials of the electrode, and even the roughness of the electrode surface. These factors make it complicated and no correction technique can satisfy ideally in practical application [56].

Some challenges from the tested meat and/or fish are caused by variety of biological tissue. Diverse species, muscle types, and origins cause different muscle structure and/or composition, which produce various measurement results. Furthermore, in one muscle, anisotropic properties of tissues adversely impact prediction accuracy. These imply that predict model and/or electrode need be specialized for different application objects, and measurements should be performed on exact location of samples as well as control electrode orientation. Complexity of biological tissue also makes the difficulty in data interpretation and exploration. Although prediction of quality indicators performed promising results, the interpretations of relationships between EIS data and status of tested meat or fish samples are ambiguities.

Further research should focus on enhancing measurement system, which includes developing optimal electrode in suitable material and configuration, controlling or correcting temperature during measurement, and optimizing measurement setup configuration, in order to reduce effect of electrode polarization and muscle anisotropy to improve precision and stability. More effective equivalent circuit models and data processing methods need to be further studied to explore interpretation of the data with status and/or components of diverse tested meat or fish samples, in order to help extract the most important feature parameter for quality estimation accordingly and to help investigate the most suitable prediction model strategy with high precision, efficiency, and robustness for practical application.

5. Conclusions

EIS has been proved as a promising detection technology with advantages of being fast, nondestructive, inexpensive, and easily implemented and shows potential to replace traditional methods in order to save time, cost, and skilled persons. The reviewed studies above, including predictions of physicochemical properties and chemical compositions for raw meat and fish and their commercial products, illustrate that EIS has potential for application in quality assessments of meat and fish. Challenges of EIS lie on impact factors of impedance measurement, including electrode polarization, materials and structure of electrodes, and the measurement setup configuration, and lie on difficulty in data processing and interpretation for diverse and complex tested meat or fish tissue. These challenges still need to be carefully considered before moving this technology from the laboratories to the industrial real-time detection.

Conflicts of Interest

The authors declared that they have no conflict of interests.

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References

[1] M. Alcañiz, J.-L. Vivancos, R. Masot et al., "Design of an electronic system and its application to electronic tongues using variable amplitude pulse voltammetry and impedance spectroscopy," *Journal of Food Engineering*, vol. 111, no. 1, pp. 122–128, 2012.

[2] B. H. Brown, "Electrical impedance tomography (EIT): a review," *Journal of Medical Engineering & Technology*, vol. 27, no. 3, pp. 97–108, 2003.

[3] K. Y. Aristovich, B. C. Packham, H. Koo, G. S. D. Santos, A. McEvoy, and D. S. Holder, "Imaging fast electrical activity in the brain with electrical impedance tomography," *NeuroImage*, vol. 124, pp. 204–213, 2016.

[4] J. Karsten, T. Stueber, N. Voigt, E. Teschner, and H. Heinze, "Influence of different electrode belt positions on electrical impedance tomography imaging of regional ventilation: a prospective observational study," *Critical Care*, vol. 20, no. 1, article no. 3, 2016.

[5] R. F. Muñoz-Huerta, A. D. J. Ortiz-Melendez, R. G. Guevara-Gonzalez et al., "An analysis of electrical impedance measurements applied for plant N status estimation in lettuce (Lactuca sativa)," *Sensors*, vol. 14, no. 7, pp. 11492–11503, 2014.

[6] T. Repo, A. Korhonen, M. Laukkanen, T. Lehto, and R. Silvennoinen, "Detecting mycorrhizal colonisation in Scots pine roots using electrical impedance spectra," *Biosystems Engineering*, vol. 121, pp. 139–149, 2014.

[7] L. Meiqing, L. Jinyang, M. Hanping, and W. Yanyou, "Diagnosis and detection of phosphorus nutrition level for Solanum lycopersicum based on electrical impedance spectroscopy," *Biosystems Engineering*, vol. 143, pp. 108–118, 2016.

[8] P. Kuson and A. Terdwongworakul, "Minimally-destructive evaluation of durian maturity based on electrical impedance measurement," *Journal of Food Engineering*, vol. 116, no. 1, pp. 50–56, 2013.

[9] A. Chowdhury, T. K. Bera, D. Ghoshal, and B. Chakraborty, "Studying the electrical impedance variations in banana ripening using electrical impedance spectroscopy (EIS)," in *Proceedings of the 2015 3rd International Conference on Computer, Communication, Control and Information Technology (C3IT '15)*, pp. 1–4, February 2015.

[10] A. Fuentes, J. L. Vázquez-Gutiérrez, M. B. Pérez-Gago, E. Vonasek, N. Nitin, and D. M. Barrett, "Application of nondestructive impedance spectroscopy to determination of the effect of temperature on potato microstructure and texture," *Journal of Food Engineering*, vol. 133, pp. 16–22, 2014.

[11] T. Watanabe, Y. Ando, T. Orikasa, T. Shiina, and K. Kohyama, "Effect of short time heating on the mechanical fracture and electrical impedance properties of spinach (Spinacia oleracea L.)," *Journal of Food Engineering*, vol. 194, pp. 9–14, 2017.

[12] Á. Kertész, Z. Hlaváčová, E. Vozáry, and L. Staroňová, "Relationship between moisture content and Electrical impedance of carrot slices during drying," *International Agrophysics*, vol. 29, no. 1, pp. 61–66, 2015.

[13] H. B. Nguyen and L. T. Nguyen, "Rapid and non-invasive evaluation of pork meat quality during storage via impedance measurement," *International Journal of Food Science and Technology*, vol. 50, no. 8, pp. 1718–1725, 2015.

[14] M. Guermazi, O. Kanoun, and N. Derbel, "Investigation of long time beef and veal meat behavior by bioimpedance spectroscopy for meat monitoring," *IEEE Sensors Journal*, vol. 14, no. 10, pp. 3624–3630, 2014.

[15] T. Chen, Y. Zhu, M. Han et al., "Classification of chicken muscle with different freeze-thaw cycles using impedance and physicochemical properties," *Journal of Food Engineering*, vol. 196, pp. 94–100, 2017.

[16] T. Ćurić, N. M. Radovčić, T. Janči, I. Lacković, and S. Vidaček, "Salt and moisture content determination of fish by bioelectrical impedance and a needle-type multi-electrode array," *International Journal of Food Properties*, pp. 1–10, 2016.

[17] J. Sun, R. Zhang, Y. Zhang, G. Li, and Q. Liang, "Estimating freshness of carp based on EIS morphological characteristic," *Journal of Food Engineering*, vol. 193, pp. 58–67, 2017.

[18] G. Durante, W. Becari, F. A. S. Lima, and H. E. M. Peres, "Electrical impedance sensor for real-time detection of bovine milk adulteration," *IEEE Sensors Journal*, vol. 16, no. 4, pp. 861–865, 2016.

[19] A. Nakonieczna, B. Paszkowski, A. Wilczek, A. Szypłowska, and W. Skierucha, "Electrical impedance measurements for detecting artificial chemical additives in liquid food products," *Food Control*, vol. 66, pp. 116–129, 2016.

[20] K. Toyoda, I. Ihara, Y. Tamaki, and M. Ohta, "Characterization of bread dough fermentation by electrical impedance spectroscopy," in *Proceedings of the 3rd International Symposium Food and Agricultural Products: Processing and Innovations*, Naples, Italy, 2007.

[21] A. Y. Khaled, S. A. Aziz, and F. Z. Rokhani, "Development and evaluation of an impedance spectroscopy sensor to assess cooking oil quality," *International Journal of Environmental Science and Development*, vol. 5, no. 3, pp. 299–302, 2014.

[22] J.-L. Damez and S. Clerjon, "Quantifying and predicting meat and meat products quality attributes using electromagnetic waves: an overview," *Meat Science*, vol. 95, no. 4, pp. 879–896, 2013.

[23] M. Castro-Giráldez, P. Botella, F. Toldrá, and P. Fito, "Low-frequency dielectric spectrum to determine pork meat quality," *Innovative Food Science and Emerging Technologies*, vol. 11, no. 2, pp. 376–386, 2010.

[24] M. De Marchi, C. L. Manuelian, S. Ton et al., "Prediction of sodium content in commercial processed meat products using near infrared spectroscopy," *Meat Science*, vol. 125, pp. 61–65, 2017.

[25] N. Prieto, Ó. López-Campos, J. L. Aalhus, M. E. R. Dugan, M. Juárez, and B. Uttaro, "Use of near infrared spectroscopy for estimating meat chemical composition, quality traits and fatty acid content from cattle fed sunflower or flaxseed," *Meat Science*, vol. 98, no. 2, pp. 279–288, 2014.

[26] D. F. Barbin, C. M. Kaminishikawahara, A. L. Soares et al., "Prediction of chicken quality attributes by near infrared spectroscopy," *Food Chemistry*, vol. 168, pp. 554–560, 2015.

[27] J. Ma, D.-W. Sun, and H. Pu, "Spectral absorption index in hyperspectral image analysis for predicting moisture contents in pork longissimus dorsi muscles," *Food Chemistry*, vol. 197, pp. 848–854, 2016.

[28] G. Konda Naganathan, K. Cluff, A. Samal et al., "A prototype on-line AOTF hyperspectral image acquisition system for tenderness assessment of beef carcasses," *Journal of Food Engineering*, vol. 154, pp. 1–9, 2015.

[29] M. Kamruzzaman, Y. Makino, and S. Oshita, "Parsimonious model development for real-time monitoring of moisture in red meat using hyperspectral imaging," *Food Chemistry*, vol. 196, pp. 1084–1091, 2015.

[30] W. YaLei, J. WenShen, P. LiGang, and R. Dong, "Application of electronic nose technology in the rapid assessment of meat quality," *Journal of Food Safety and Quality*, vol. 7, no. 2, pp. 419–424, 2016.

[31] Z. Haddi, N. El Barbri, K. Tahri et al., "Instrumental assessment of red meat origins and their storage time using electronic sensing systems," *Analytical Methods*, vol. 7, no. 12, pp. 5193–5203, 2015.

[32] V. Lippolis, M. Ferrara, S. Cervellieri et al., "Rapid prediction of ochratoxin A-producing strains of Penicillium on dry-cured meat by MOS-based electronic nose," *International Journal of Food Microbiology*, vol. 218, pp. 71–77, 2016.

[33] T. Miyasaki, M. Hamaguchi, and S. Yokoyama, "Change of volatile compounds in fresh fish meat during ice storage," *Journal of Food Science*, vol. 76, no. 9, pp. C1319–C1325, 2011.

[34] R. E. Remington, "The high frequency wheatstone bridge as a tool in cytological studies; with some observations on the resistance and capacity of the cells of the beet root," *Protoplasma*, vol. 5, no. 1, pp. 338–399, 1928.

[35] E. Bozler and K. S. Cole, "Electric impedance and phase angle of muscle in rigor," *Journal of Cellular and Comparative Physiology*, vol. 6, no. 2, pp. 229–241, 1935.

[36] H. Fricke, "A mathematical treatment of the electric conductivity and capacity of disperse systems I. The electric conductivity of a suspension of homogeneous spheroids," *Physical Review*, vol. 24, no. 5, pp. 575–587, 1924.

[37] H. Fricke, "A mathematical treatment of the electric conductivity and capacity of disperse systems II. The capacity of a suspension of conducting spheroids surrounded by a non-conducting membrane for a current of low frequency," *Physical Review*, vol. 26, no. 5, pp. 678–681, 1925.

[38] H. Fricke and S. Morse, "The electric capacity of tumors of the breast," *The Journal of Cancer Research*, vol. 10, no. 3, pp. 340–376, 1926.

[39] H. P. Schwan, "Electrical properties of tissue and cell suspensions," *Advances in Biological and Medical Physics*, vol. 5, pp. 147–209, 1956.

[40] K. S. Cole and R. H. Cole, "Dispersion and absorption in dielectrics I. Alternating current characteristics," *The Journal of Chemical Physics*, vol. 9, no. 4, pp. 341–351, 1941.

[41] J.-L. Damez, S. Clerjon, S. Abouelkaram, and J. Lepetit, "Dielectric behavior of beef meat in the 1-1500 kHz range: simulation with the fricke/cole-cole model," *Meat Science*, vol. 77, no. 4, pp. 512–519, 2007.

[42] D. T. Trung, N. P. Kien, T. D. Hung, D. C. Hieu, and T. A. Vu, "Electrical impedance measurement for assessment of the pork aging: a preliminary study," in *Proceedings of the 2016 International Conference on Biomedical Engineering (BME-HUST '16)*, pp. 95–99, Hanoi, Vietnam, October 2016.

[43] R. Pethig and D. B. Kell, "The passive electrical properties of biological systems: their significance in physiology, biophysics and biotechnology," *Physics in Medicine and Biology*, vol. 32, no. 8, pp. 933–970, 1987.

[44] U. Pliquett, M. Altmann, F. Pliquett, and L. Schöberlein, "Py—a parameter for meat quality," *Meat Science*, vol. 65, no. 4, pp. 1429–1437, 2003.

[45] Y. Yang, Z.-Y. Wang, Q. Ding, L. Huang, C. Wang, and D.-Z. Zhu, "Moisture content prediction of porcine meat by bioelectrical impedance spectroscopy," *Mathematical and Computer Modelling*, vol. 58, no. 3-4, pp. 813–819, 2013.

[46] K. R. Foster and H. P. Schwan, "Dielectric properties of tissues," *Handbook of Biological Effects of Electromagnetic Fields*, vol. 2, pp. 25–102, 1995.

[47] M. À. Oliver, I. Gobantes, J. Arnau et al., "Evaluation of the electrical impedance spectroscopy (EIS) equipment for ham meat quality selection," *Meat Science*, vol. 58, no. 3, pp. 305–312, 2001.

[48] D. A. Harrington and P. Van Den Driessche, "Mechanism and equivalent circuits in electrochemical impedance spectroscopy," *Electrochimica Acta*, vol. 56, no. 23, pp. 8005–8013, 2011.

[49] N. Amin, S. Rayhan, A. A. Anik, and R. Jameel, "Modelling and characterization of cell abnormality using electrical impedance spectroscopy (EIS) system for the preliminary analysis to predict breast cancer," in *Proceedings of the 2016 Second International Conference on Research in Computational Intelligence and Communication Networks (ICRCICN '16)*, pp. 147–152, Kolkata, India, September 2016.

[50] Y. Ando, K. Mizutani, and N. Wakatsuki, "Electrical impedance analysis of potato tissues during drying," *Journal of Food Engineering*, vol. 121, no. 1, pp. 24–31, 2014.

[51] M. Zhang, D. Stout, and J. Willison, "Electrical impedance analysis in plant tissues: symplasmic resistance and membrane capacitance in the haydon model," *Journal of Experimental Botany*, vol. 41, pp. 371–380, 1990.

[52] L. Wu, Y. Ogawa, and A. Tagawa, "Electrical impedance spectroscopy analysis of eggplant pulp and effects of drying and freezing-thawing treatments on its impedance characteristics," *Journal of Food Engineering*, vol. 87, no. 2, pp. 274–280, 2008.

[53] F. R. Harker and J. H. Maindonald, "Ripening of nectarine fruit. Changes in the cell wall, vacuole, and membranes detected using electrical impedance measurements," *Plant Physiology*, vol. 106, no. 1, pp. 165–171, 1994.

[54] K. H. Schoenbach, S. Katsuki, R. H. Stark, E. S. Buescher, and S. J. Beebe, "Bioelectrics-new applications for pulsed power technology," *IEEE Transactions on Plasma Science*, vol. 30, no. 1, pp. 293–300, 2002.

[55] P. Ellappan and R. Sundararajan, "A simulation study of the electrical model of a biological cell," *Journal of Electrostatics*, vol. 63, no. 3-4, pp. 297–307, 2005.

[56] P. B. Ishai, M. S. Talary, A. Caduff, E. Levy, and Y. Feldman, "Electrode polarization in dielectric measurements: A review," *Measurement Science and Technology*, vol. 24, no. 10, Article ID 102001, 2013.

[57] R. Masot, M. Alcañiz, A. Fuentes et al., "Design of a low-cost non-destructive system for punctual measurements of salt levels in food products using impedance spectroscopy," *Sensors and Actuators, A: Physical*, vol. 158, no. 2, pp. 217–223, 2010.

[58] F. C. Schmidt, A. Fuentes, R. Masot, M. Alcañiz, J. B. Laurindo, and J. M. Barat, "Assessing heat treatment of chicken breast cuts by impedance spectroscopy," *Food Science and Technology International*, vol. 23, no. 2, pp. 110–118, 2017.

[59] J.-L. Damez, S. Clerjon, S. Abouelkaram, and J. Lepetit, "Electrical impedance probing of the muscle food anisotropy for meat ageing control," *Food Control*, vol. 19, no. 10, pp. 931–939, 2008.

[60] T.-H. Chen, Y.-P. Zhu, P. Wang et al., "The use of the impedance measurements to distinguish between fresh and frozen-thawed chicken breast muscle," *Meat Science*, vol. 116, pp. 151–157, 2016.

[61] J.-L. Damez, S. Clerjon, S. Abouelkaram, and J. Lepetit, "Beef meat electrical impedance spectroscopy and anisotropy sensing for non-invasive early assessment of meat ageing," *Journal of Food Engineering*, vol. 85, no. 1, pp. 116–122, 2008.

[62] M. Altmann and U. Pliquett, "Prediction of intramuscular fat by impedance spectroscopy," *Meat Science*, vol. 72, no. 4, pp. 666–671, 2006.

[63] C. E. Byrne, D. J. Troy, and D. J. Buckley, "Postmortem changes in muscle electrical properties of bovine M. longissimus dorsi and their relationship to meat quality attributes and pH fall," *Meat Science*, vol. 54, no. 1, pp. 23–34, 2000.

[64] J. Lepetit, P. Salé, R. Favier, and R. Dalle, "Electrical impedance and tenderisation in bovine meat," *Meat Science*, vol. 60, no. 1, pp. 51–62, 2002.

[65] T. A. Whitman, J. C. Forrest, M. T. Morgan, and M. R. Okos, "Electrical measurement for detecting early postmortem changes in porcine muscle," *Journal of Animal Science*, vol. 74, no. 1, pp. 80–90, 1996.

[66] J. C. Forrest, M. T. Morgan, C. Borggaard, A. J. Rasmussen, B. L. Jespersen, and J. R. Andersen, "Development of technology for the early post mortem prediction of water holding capacity and drip loss in fresh pork," *Meat Science*, vol. 55, no. 1, pp. 115–122, 2000.

[67] J. Niu and J. Y. Lee, "A new approach for the determination of fish freshness by electrochemical impedance spectroscopy," *Journal of Food Science*, vol. 65, no. 5, pp. 780–785, 2000.

[68] L. Zhang, H. Shen, and Y. Luo, "A nondestructive method for estimating freshness of freshwater fish," *European Food Research and Technology*, vol. 232, no. 6, pp. 979–984, 2011.

[69] S. Zhu, Y. Luo, H. Hong, L. Feng, and H. Shen, "Correlation Between Electrical Conductivity of the Gutted Fish Body and the Quality of Bighead Carp (Aristichthys nobilis) Heads Stored at 0 and 3 ∘C," *Food and Bioprocess Technology*, vol. 6, no. 11, pp. 3068–3075, 2013.

[70] E. Pérez-Esteve, A. Fuentes, R. Grau et al., "Use of impedance spectroscopy for predicting freshness of sea bream (Sparus aurata)," *Food Control*, vol. 35, no. 1, pp. 360–365, 2014.

[71] S. Vidaček, H. Medić, K. Botka-Petrak, J. Nežak, and T. Petrak, "Bioelectrical impedance analysis of frozen sea bass (Dicentrarchus labrax)," *Journal of Food Engineering*, vol. 88, no. 2, pp. 263–271, 2008.

[72] I. Fernández-Segovia, A. Fuentes, M. Aliño, R. Masot, M. Alcañiz, and J. M. Barat, "Detection of frozen-thawed salmon (Salmo salar) by a rapid low-cost method," *Journal of Food Engineering*, vol. 113, no. 2, pp. 210–216, 2012.

[73] A. Fuentes, R. Masot, I. Fernández-Segovia, M. Ruiz-Rico, M. Alcañiz, and J. M. Barat, "Differentiation between fresh and frozen-thawed sea bream (Sparus aurata) using impedance spectroscopy techniques," *Innovative Food Science and Emerging Technologies*, vol. 19, pp. 210–217, 2013.

[74] S. Vidaček, T. Janči, Z. Brdek et al., "Differencing sea bass (Dicentrarchus labrax) fillets frozen in different conditions by impedance measurements," *International Journal of Food Science and Technology*, vol. 47, no. 8, pp. 1757–1764, 2012.

[75] S. Vidaček, H. Medić, N. Marušić, S. Tonković, and T. Petrak, "Influence of different freezing regimes on bioelectrical properties of Atlantic chub mackerel (Scomber colias)," *Journal of Food Process Engineering*, vol. 35, no. 5, pp. 735–741, 2012.

[76] M. Chanet, C. Rivière, and P. Eynard, "Electric impedance spectrometry for the control of manufacturing process of comminuted meat products," *Journal of Food Engineering*, vol. 42, no. 3, pp. 153–159, 1999.

[77] M. J. Marchello, W. D. Slanger, and J. K. Carlson, "Bioelectrical impedance: fat content of beef and pork from different size grinds," *Journal of Animal Science*, vol. 77, no. 9, pp. 2464–2468, 1999.

[78] R. H. Labrador, R. Masot, M. Alcañiz et al., "Prediction of NaCl, nitrate and nitrite contents in minced meat by using a voltammetric electronic tongue and an impedimetric sensor," *Food Chemistry*, vol. 122, no. 3, pp. 864–870, 2010.

[79] C. De Jesús, G. Hernández-Coronado, J. Girón et al., "Classification of unaltered and altered dry-cured ham by impedance spectroscopy: A preliminary study," *Meat Science*, vol. 98, no. 4, pp. 695–700, 2014.

[80] D. Chevalier, F. Ossart, and C. Ghommidh, "Development of a non-destructive salt and moisture measurement method in salmon (Salmo salar) fillets using impedance technology," *Food Control*, vol. 17, no. 5, pp. 342–347, 2006.

[81] A. Rizo, A. Fuentes, I. Fernández-Segovia, R. Masot, M. Alcañiz, and J. M. Barat, "Development of a new salmon salting-smoking method and process monitoring by impedance spectroscopy," *LWT-Food Science and Technology*, vol. 51, no. 1, pp. 218–224, 2013.

[82] P. Karásková, A. Fuentes, I. Fernández-Segovia, M. Alcañiz, R. Masot, and J. M. Barat, "Development of a low-cost non-destructive system for measuring moisture and salt content in smoked fish products," *Procedia Food Science*, vol. 1, pp. 1195–1201, 2011.

[83] J. L. Damez, S. Clerjon, and S. Abouelkaram, "Mesostructure assessed by alternaing current spectroscopy during meat ageing," in *Proceedings of the 51st International Congress of Meat Science and Technology*, pp. 327–330, 2005.

[84] P. Salé, "The electrical impedance of meat," *IIème Congrès International d'Impédance Bioélectrique*, pp. 347–355, 1976.

[85] J. Charpentier, R. Goutefongea, P. Salé, and A. Thomasset, "La discrimination des viands fraiches et congelees par measures d'impedance a deux frequencies," *Annales de Biologie Animale Biochimie Biophysique*, vol. 12, no. 1, pp. 173–178, 1972.

[86] N. Faure, C. Flachat, P. Jein, J. Lenoir, C. Roullet, and A. Thomasset, "Contribution a l'etude de la tendrete et de la maturation des viandes par la methode de la conductibilite electrique en basse et haute frequence," *Revue de medecine veterinaire*, vol. 123, pp. 1517–1527, 1972.

[87] A. J. Stetzer and F. K. McKeith, "Benchmarking value in the pork supply chain: Quantitative strategies and opportunities to improve quality Phase 1," *American Meat Science Association, Savoy, IL*, pp. 1–6, 2003.

[88] J. R. Bendall and H. J. Swatland, "A review of the relationships of pH with physical aspects of pork quality," *Meat Science*, vol. 24, no. 2, pp. 85–126, 1988.

[89] K. Overturf, F. T. Barrows, R. W. Hardy, A. Brezas, and A. Dumas, "Energy composition of diet affects muscle fiber recruitment, body composition, and growth trajectory in rainbow trout (Oncorhynchus mykiss)," *Aquaculture*, vol. 457, pp. 1–14, 2016.

[90] S. Zehra and M. A. Khan, "Dietary histidine requirement of fingerling Catla Catla (Hamilton) based on growth, protein gain, histidine gain, RNA/DNA ratio, haematological indices and carcass composition," *Aquaculture Research*, vol. 47, no. 4, pp. 1028–1039, 2016.

[91] A. Soyer, B. Özalp, Ü. Dalmiş, and V. Bilgin, "Effects of freezing temperature and duration of frozen storage on lipid and protein oxidation in chicken meat," *Food Chemistry*, vol. 120, no. 4, pp. 1025–1030, 2010.

[92] R. Karoui, E. Thomas, and E. Dufour, "Utilisation of a rapid technique based on front-face fluorescence spectroscopy for differentiating between fresh and frozen-thawed fish fillets," *Food Research International*, vol. 39, no. 3, pp. 349–355, 2006.

[93] S. Ali, W. Zhang, N. Rajput, M. A. Khan, C.-B. Li, and G.-H. Zhou, "Effect of multiple freeze-thaw cycles on the quality of chicken breast meat," *Food Chemistry*, vol. 173, pp. 808–814, 2015.

[94] R. E. Mudgett, "Electrical properties of foods," *Engineering Properties of Foods*, vol. 2, pp. 389–455, 1986.

[95] K. Toyoda, H. Kojima, S. Miyomoto, and R. Takeuchi, "Measurement and analysis of moisture changes in agricultural products using FFT noise impedance spectroscopy," *Drying Technology*, vol. 15, no. 6-8, pp. 2025–2035, 1997.

[96] E. P. Berg and M. J. Marchello, "Bioelectrical impedance analysis for the prediction of fat-free mass in lambs and lamb carcasses," *Journal of Animal Science*, vol. 72, no. 2, pp. 322–329, 1994.

[97] R. F. Kushner, "Bioelectrical impedance analysis: a review of principles and applications," *Journal of the American College of Nutrition*, vol. 11, no. 2, pp. 199–209, 1992.