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Review Article

Review on Electrical Conductivity in Food, the Case in Fruits and Vegetables

Misgana Banti

Ethiopian Institute of Agricultural Research, Jimma Agricultural Research Centre, Jimma, Ethiopia

Email address:
misganabanti2013@gmail.com

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Abstract: Electrical conductivity in food and agricultural products is gaining attentions in response to ohmic heating and pulsed electric field processing, the newly emerging food processing technologies. Electrical conductivity of agricultural product is the ability of the products to conduct electric current. This paper is intended to review the electrical conductivity in foods in general and fruits and vegetables in particular. For this review to take its form, different articles, books and other possible sources have been reviewed, cited and acknowledged. So, this paper has been enriched by composition of the finding of different authors and researcher. Since measurement of electrical conductivity has number of application in agricultural products and food processing, methods of measuring this property is important. Measurement of electrical conductivity can be through dielectric analysis and electrical impendence spectroscopy measurement. In dielectric analysis high frequency area (100 MHz - 10 GHz) is used and this has an application in moisture determination and bulk density measurement. In electrical impendence spectroscopy, the range of frequency is from 100Hz to 10MHZ and is simple and easier techniques used to evaluate physiological status of various biological tissues. There are factors affecting electrical conductivity of agricultural products; electrical conductivity is reported by different authors to be increasing with temperature, field strength, and storage duration until the product is over ripe in case of fruits and vegetables. Plus, conductivity also found decreasing with increasing sugar content. The decrease in firmness of fruits and vegetables is related to increase in its conductivity. The nature of product and way of applying electricity is also other factors affecting conductivity. Electrical conductivity has number of application in foods, fruits and vegetable industries. However, still much work is expected for the utilization of its high potentials application.

Keywords: Conductivity, Dielectric Analysis, Impendence, Ohmic Heating, Pulsed Electric Field

1. Introduction

Electrical conductivity in food is the measure of how well the electric current flows through the food of cross-sectional area A, unit length L, and resistance R. It is the inverse value of electrical resistivity (measure of resistance to the electric flow) and is expressed in Siemens per meter (S/m) as SI unit. Electrical conductivity of food and an agricultural product is attracting the attention of researchers relatively very recently. Thus, little literatures are available related to the electrical conductivity of foods and food products since electrical conductivity was not critically important in food companies until 1980. The increase in interests of electrical conductivity which was immerged in recent years is mostly the response to the development of commonly two food processing technology; ohmic heating and pulsed electric field processing technologies [1].

Ohmic heating relies on flow of alternate current in food materials and this electricity in the form of wave is transformed to thermal energy and heat in the food by internal generation. In other word, ohmic heating also called electric resistance heating, joule heating or electro conductive heating is an advanced thermal food processing techniques, where heat is internally generated in sample due to electrical resistance when electric current is passed through it. Whereas pulsed electric field (PEF) processing applies high intensity electric field pulses for short duration of time (two to 10 micro second) to cause microbial inactivation via membrane rupture [2]. Ohmic heating can be the consequence of pulsed electric field heating methods. The concept of Ohmic heating is simple. A passage of electric current trough electrically conductive food materials obeys Ohm's law and heat generation due to the electrical resistance of foods is determined as the product of square of current and resistance [3].

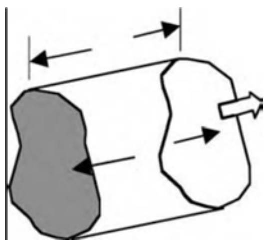
There are different factors which influence the electrical conductivity of foods. Among these factors, temperatures, water content, ionic content, fat content, porosity and the like are more common factors. The starch transition and cell structural changes also affect electrical conductivity in food. Electrical conductivity decreased about 40 to 56% depending upon the temperature when total soluble solid TSS increased from 0 to 1% on dry weight basis in case of tomato juice.

Fruits and vegetables show decline in their firmness after harvest on the way to ripening at 20°C and this has positive relation with increase in electrical conductivity in fruits and this also related to loss in membrane integrity. The firmness of avocado fruit decreases with increase in ripening process; and electrical conductivity increase attributing the loss of tissue integrity as reported in as study [4].

As it was raised, the interest of electrical conductivity of food is increasing greatly as advancement in food processing technology, food quality evaluation and food preservation is increasing to its greatest extent. Despite this growing interest in electrical conductivity, limited and dispersed literatures are available related to electrical conductivity of fruits and vegetables. Hence, it needs reviewing, compiling and writing the available information and pointing the future line of work concerning the issue of electrical conductivity in food in general and fruits and vegetables including their juices in particular. Thus, the purpose of this review is to review as much available literature as possible and to identify the future research gap concerning these electrical properties of foods in general and fruits and vegetables in particular.

2. The Concept of Electrical Properties

There are two main electrical properties in food engineering. These two electrical properties are electrical conductivity and electrical permittivity. These properties of foods are important in different food processing technology which involves flow of electric current conduction, electric field, or food processing or heating through electromagnetic waves and detection of processing conditions or the qualities in food [5].



Source: [6]

__Figure 1.__ Sample conductor of length L, cross-sectional area A, with a voltage V applied across the faces. A current I flows perpendicular to the parallel faces.

2.1. Electrical Conductivity

Electrical conductivity is how well the substance transmits electric current in its structure. The SI unit for the parameter electrical conductivity is Siemens per meter (S/m^2). Electrical conductivity is the ratio of substance density to electric field strength and is affected by chemical composition of materials and tissue structure [6].

Electrical conductivity also called specific conductance is the property of materials; in case of this review, it is the property of the food product which measures the ability of the foods to conduct electric current. Electrical conductivity of food is the measure of how well electric current flows through the food matrix having cross sectional area A, length L and resistance R. The electrical conductivity of foods is of comparatively recent interest to scientists. Zhang, H. in his book entitled FOOD ENGINEERING – Vol. I stated electrical conductivity is a critical parameter for both the Ohmic heating and pulsed electrical field processes [7]. The knowledge of foods electrical conductivities while under Ohmic heating or pulsed electrical field condition is essential for foods quality evaluation, process design and improving processing technology.

$$\mathrm{EC}=\frac{L}{AR}$$

Electrical conductivity of the food material has an influence on Ohmic heating process in a number of ways.

Firstly, the electrical conductivity determines the local rate of heat generation as $Q=\sigma E^2$, where, Q=the heat generated, E=the local electric field strength, and

Secondly, the global distribution of electrical conductivity governs the field distribution, and hence, the local heating rate [8, 9].

Determination of moisture content is of vital interest to a wide range of disciplines and industries. In food industry, the moisture determination can be considered as one of the most important daily activity because of different factors ranging from food quality, safety and process design. The range of food and agricultural materials is also diverse and includes horticultural, cereals, dairy products, beverage and juice. Majority of the methods available for determination of moisture are destructive and thus, methods for non-invasive, non-destructive measurement of moisture profiles would find wide application. Therefore, it is necessary to look for non destructive moisture determination that involves the change of the electric conductivity of food at transition of the electric current through the biological material. It is obvious that inside of the cell has the ionic conductivity. The electric current in a cellular membrane travels as displacement current. The density of the electric current 'I' is defined as:

$$\mathrm{I}=\frac{1}{S}\frac{dQ}{dT}$$

Where, Q=Charge, T=time, S=surface

The relationship between the density of the current and electric field intensity is [4]

$$i = \sigma E = -\sigma\, grad\, U$$

Where: σ – electric conductivity (S/m), *grad U* – gradient of the electric voltage (V/m),

E – Intensity of the electric field (V/m).

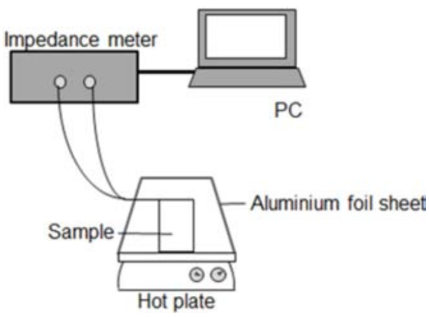
2.2. Electrical Permittivity

Electrical permittivity of foods determines the interaction of foods with dielectric field. In fruits and vegetable and other agricultural products, permittivity is related to the integrity of cell, chemical composition, moisture content, ion content, frequency and the like. It determines the relations of electromagnetic waves with matter and defines the charge density under an electric field. In the solids, liquid, and gases the permittivity depends on two values [5]:

1. The dielectric constant, related to the capacitance of a substance and its ability to store electrical energy.
2. The dielectric loss factor, related to energy losses when the food is subjected to an alternating electrical field (i.e., dielectric relaxation and ionic conduction).

3. Measurement Methods of Electrical Conductivity

The measurement methods of electrical conductivity include dielectric analysis and electrical impendence spectroscopy.



Source: [11]

Figure 2. *The system of non-destructive impedance measurement.*

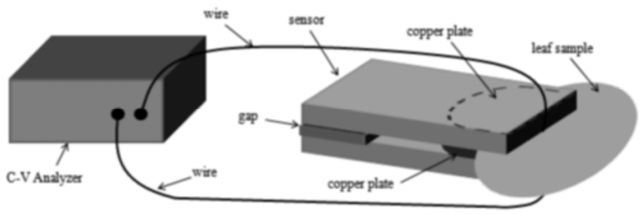
3.1. Electric Impendence Spectroscopy

In electrical impendence spectroscopy, the physical state of a material is measured as a function of frequency which ranges from 100Hz to 10MHZ. This electrical impendence spectroscopy is the simple and easier techniques used to evaluate physiological status of various biological tissues. EIS in which a sinusoidal test voltage or current is applied to the sample under test to measure its impedance over a suitable frequency range, is a powerful technique to investigate the electrical properties of a large variety of materials. In practice, the measured impedance spectra, usually fitted with an equivalent electrical model, represent an electrical fingerprint of the sample providing an insight into its properties and behavior. EIS is used in a broad range of applications as a quick, non invasive, non destructive and easily automated technique to characterize solid, liquid, semi-liquid, organic as well as inorganic materials [10]. In fruits and vegetables, EIS has been widely used to estimate the ripening state as well as to detect defects (such as fruit bruising).

As a first approximation, the (complex) structure of fruits and vegetables can be modeled with the simplified structure [10] where the plant cells are all surrounded by the extracellular cell wall and delimited by a phospholipid bilayer membrane (plasmalemma).

3.2. Dielectric Analysis

DEA measurement is used in high frequency areas, generally 100 MHz - 10 GHz and is used in moisture estimation and bulk density determination. The dielectric properties (permittivity) point out the relations of material with electric fields. The measurement of dielectric properties can be by several methods which range from direct current to microwaves. The most commonly used devices and instruments to measure dielectric properties of food materials encompass the parallel plate capacitor, coaxial probe, waveguide, resonant structure, inductance, capacitance- resistance meter (LCR meter), impedance analyzer, and scalar and vector network analyzer [12]. This dielectric measurement is applicable in different process and quality inspection. For example, the estimated leaf moisture content by measuring the dielectric constant of leaves in five different types of crops was reported in literature [13]. This dielectric measuring device as an example composed of two semi-oval isolated copper plates and a Keithly 590 C-V Analyzer as the capacitance measuring device, which had the capability of measuring capacitance at two frequencies of 100 kHz and 1 MHz (Figure 1).



Source: http://www.sciencepub.net/nature [13]

Figure 3. *Schematic of the capacitance measuring system*

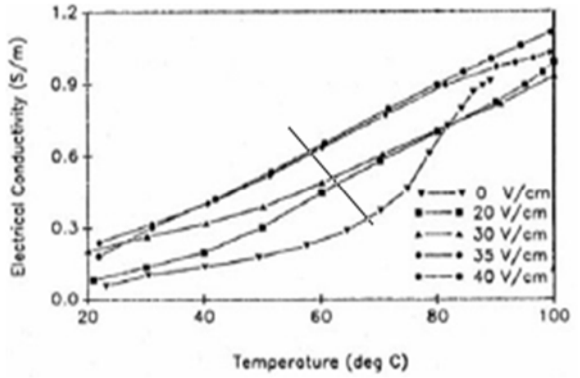
3.3. Factors Affecting Electrical Properties of Fruits and Vegetable

Electrical conductivity in general and that of agricultural products in particular is dependent on numbers of factors [14]. To list among these factors, temperature, applied voltage gradient, frequency, particle size; and concentration of electrolyte are found to affect the rate of ohmic heating in fruits and vegetables and hence, the electrical conductivity of fruits and vegetables [1]. The writers farther state that the rate of ohmic heating linearly increase with temperature, voltage gradient and concentration of ionic constituent while getting decreased with increase in particle size, frequency and heating rate. Electrical conductivity of food and agricultural products has been found to be increasing with temperature, moisture content and ionic content of the product under investigation [15].

3.3.1. Temperature

The electrical conductivity for tomato and orange juices has linear correlation with temperature. In strawberry the electrical conductivity value was increased following the increase in temperature [16]. From the experiment on six different fruits (red apple, golden apple, peach, pear, pineapple and strawberry), it has been indicated that the electrical conductivity increases linearly with increase in temperature [2]. The electrical conductivity of apple and sour cherry juices were also found significantly increased with temperature and concentration as reported in literature [18]. In similar manner, the electrical conductivity increased almost linearly with temperature [19]. Authors further justified that, when heat is applied to agricultural product or biological tissues, electrical conductivity increase due to increase in ionic mobility. The literatures, it has been found the increasing electrical conductivity of mango fruit with increasing temperature [20]. These researchers evaluated the electrical conductivity at different ranges of temperatures and compared it at 20°C and 60°C and reported that it was as large as twice at 60°C as at 20°C. This phenomenon occurs due to structural changes in the tissue like cell wall proto-pectin breakdown, expulsion of non conductive gas bubbles, softening, and lowering in aqueous phase viscosity.

The decreasing of electrical conductivity of tomato juice with increasing of TSS from zero to one percent degree brix on dry weight bases is found to be dependent on temperature [21]. This result also indicates that the electrical conductivity of fruit juice is dependent on the temperature. It can also extended to other agricultural products than limited to fruit juice only because, other authors also found the same trend of increasing conductivity with increasing temperature in different foods and agricultural products.



Source: [22]

Figure 4. *Electrical conductivity of carrot (parallel to stem axis) subjected to various electric field strengths and temperature.*

3.3.2. Firmness

Firmness is also another factor to influence the electrical conductivity in biological materials. It is obvious that the firmness of fruits will decline after harvest. The decrease in firmness of fruits and vegetables are related to the increase in electrical conductivity in one or another ways. It has also found that positive correlation between the decrease of firmness and the increase of electrical conductivity of fruit tissues exist suggesting that a gradual loss of cell membrane integrity during ripening [4]. Thus, ripening processes induce the increment of electrical conductivity in their experiment on avocado fruits. Therefore, it can be concluded that in avocado fruit, electrical conductivity can be good indicator for membrane permeability that it is highly correlated with ethylene production, softening and also demonstrate the relationship between firmness and electrical conductivity.

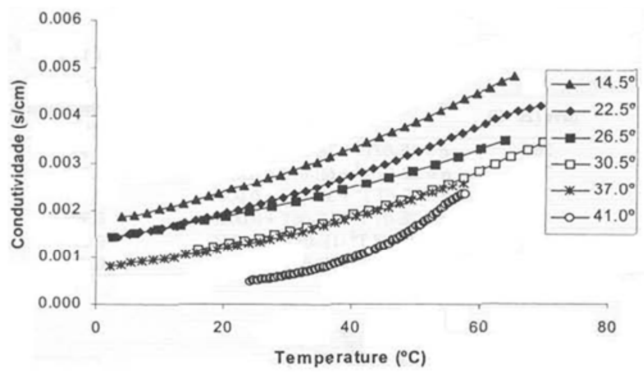
Table 1. *Firmness and electrical conductivity of Fuerte avocado fruits during ripening at 20°C.*

Fruits quality characteristics	Ripening day at 20°C						
	0	3	6	9	12	15	LSD (0.05)
Firmness (n)	77.24a±1.24	75.61a±1.94	45.09b±0.98	14.82c±1.24	12.30d±0.75	10.75±0.90	2.203
Electrical conductivity (ms/cm)	0.63f±0.067	0.89e±0.060	1.63d±0.141	2.98c±0.156	3.51b±0.104	3.89a±0.62	0.1949

Source: [4]

3.3.3. Sugar Content

The electrical conductivity decreases with the increase of solid content and sugar as indicated in literature [16]. The authors conclude that a different design of ohmic heater is necessary because of low value of electrical conductivity for some of formulation they have tested (solid content of 20 w/w and over 40°Brix). Brix gradient (sugar content) of strawberry is experimentally determined to lower the electrical conductivity of the fruit in an experiment by literature [16]. They explained that the phenomenon to be related to the presence of fats, oils and sugar components which can reduce the electrical conductivity. They supported their result by citing the work in literature which is in line with their finding [22]. The literature found that electrical conductivity decreased at about 40 to 56% depending upon the temperature when TSS increased from 0 to 1% on dry weight basis in case of tomato juice [21]. They also conclude the same phenomenon for orange and pineapple showing decrease of about 30-32% and 40-48% respectively.

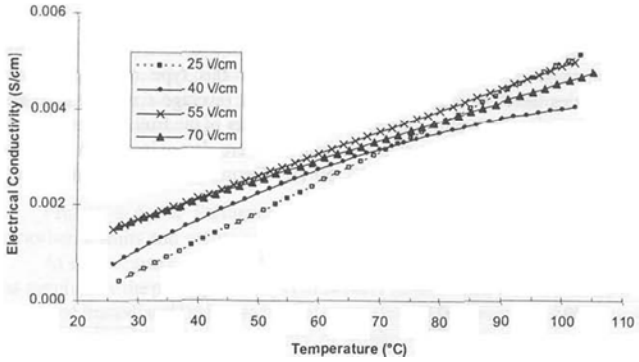


Source: [16]

Figure 5. *Electrical conductivity curves of strawberry pulp p1 with different brix, during ohmic heating.*

3.3.4. Storage Duration

The other possible factor to influence electrical conductivity of fruits and vegetables is storage duration. Literature reported that the electrical conductivity increase with extended storage day until day eight of storage and after eighth day, the difference in electrical conductivity is negligible at each temperature [20]. It has been reported that, the electrical conductivity of avocado increase during the first five days and rapidly grow and reached maximum on the seventh day [24]. But the writer also reported that, this pick conductivity of electricity is followed by softening of the fruit tissue and color change and also drop in electric conductivity when the fruit overripe by about 10 days.



Source: [16]

Figure 6. *Electrical conductivity of fresh, whole strawberry for different field strength.*

3.3.5. Field Strength or Voltage Gradient

Field strength or voltage gradient is another factor to influence the electrical conductivity of fruits and vegetables. The increase in field strength seems increase the electrical conductivity of materials, in our case agricultural products [16]. The increase in voltage gradient will lead to the increased in the current passing through the sample and increased heat generation as is reported in literatures [25]. The electrical conductivity of guava pulp during ohmic heating showed a general increase in trend with increasing in concentration and voltage gradient. According to the finding in a literature, the increase of electrical conductivity with field strength was also obvious for fresh strawberry and strawberry jelly but not for the pulp; and the relationship of conductivity and field strength is linear [16]. In one of the graph of the finding however, one of the curves (40 V/cm) curves downwards. The writers suggest for the graph that the sample used at these experiments to differ from the others in terms of maturity stages. The graph is shown below.

3.3.6. Nature of the Product

Nature of the product is also one of the factors which influence the electrical conductivity of biological materials [1]. The electric conductance alongside the stem is higher than the electric conductance crosswise the stem in bamboo shoots and sugarcane, while the reverse is true in lettuce stem and mustard stem [23, 27]. As they explained further, orientation of vascular bundles and the shape of parenchyma cells are proposed to account for the different conductance readings from the same vegetable in different directions. The orientations of vascular bundles appear to influence electric conductance more than the shape of parenchyma cells when both factors are present in the same time. After comparing the conductivity of six different fruits, it has been reported that the conductivity of peach and strawberry is larger than that of pears, apple and pineapple [2]. This is due to the fact that these fruits differ in their internal tissue structural make ups and porosities.

4. Applications of Electrical Conductivity

The electrical properties have important application in different types of food processing; for example, pulsed electric fields, ohmic heating, induction heating, radio frequency, and microwave heating [1, 6, 17]. Thus electrical conductivity is the basic element in both Ohmic heating where thermal energy is produced from electric under flow of an alternating current through food, and also in pulsed electric field in which high intensity electric current is applied to the given food product for only short time [6]. Based on the fact that the interest in electrical conductivity in food increase in response to the development of food ohmic heating and pulsed electric field processing technology, these two processing techniques are reviewed below. Electrical conductivity has also an application in quality evaluation of the different agricultural products. Measuring electrical conductivity can be applicable in determining the different characteristics of agricultural materials and food like frost sensitivity, chilling and freezing tolerance [27, 28].

4.1. Ohmic Heating

Ohmic heating has electrical conductivity as its component and it is processing technology in which thermal energy is produced from the flowing electric current through the food matrix. In this heating process, there is no need of transferring heat through solid liquid interfaces or inside the solid particles once the heat is dissipated directly into foods. Ohmic heating is applicable in numbers of processing techniques like pasteurization, blanching, evaporation, dehydration, fermentation, extraction, sterilization and heating of foods to serving temperature, including in the military field or long-duration space missions.

Ohmic heating is the special system in which particulate material is pumped through a non conducting tube in which electrodes are placed. In ohmic heating technique, electric current is passed through the material and the heating effect is caused by resistive heating and is determined by the electrical conductivity of the food as well as the applied voltage. In ohmic heating the resistance of the given material obeys ohms low in which voltage v is directly proportional to resistance and current. If the solid particles are the same conductivity as the liquid, there should be no difference in heating rates between them [4]. Unfortunately there is no rapid cooling process to accompany it and little scope for energy regeneration.

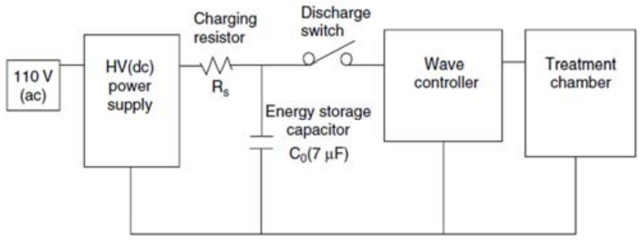
Ohm's low, $V=RI$

The rate of ohmic heating as reviewed in different sources are dependent on numbers of factors; of which applied voltage gradient, frequency, particle size, concentration and the like are reported to influence it. As it has been stated in different articles, electrical conductivity increases with temperature and hence, ohmic heating becomes more effective at higher temperatures [22]. During ohmic heating the applied electrical field heating leads to faster deactivation of enzymes and microorganisms. The phenomenon of electro-poration is dominant at low frequencies which lead to membrane rupture and ultimately a significant rise in tissue electrical conductivity [1]. In more up to date experimental study, it has been confirmed that a mild electroporation type of mechanisms may happen during the process of ohmic heating and PEF heating process. The presence of pore forming mechanisms during ohmic heating on cellular tissue has been confirmed in works by [22]. According this author, it has been indicated that the kinetics of inactivation of *Bacillus subtilis* spores can be accelerated with ohmic heat treatment. He further explained that, a two-stage ohmic heat treatment (ohmic treatment, followed by a holding time prior to a second heat treatment) was found to accelerate death rates further. According to this author, leakage of electrolyte, the intracellular constituents of *Saccharomyces cerevisiae* was found to be enhanced under ohmic heating, compared with conventional heating in boiling water.

The design of effective ohmic heaters depends on the electrical conductivities of a given food products [2]. The authors evaluated the electrical conductivities of six different fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and several different cuts of three types of meat (chicken, pork and beef) from room temperature through to the sterilization temperature range (25–140°C) found that electrical conductivity increasing with temperature. According to this finding peach and strawberries are more conductive than the rest of fruits and this may be due to difference in the tissue composition of each fruits.

4.2. Pulsed Electric Field

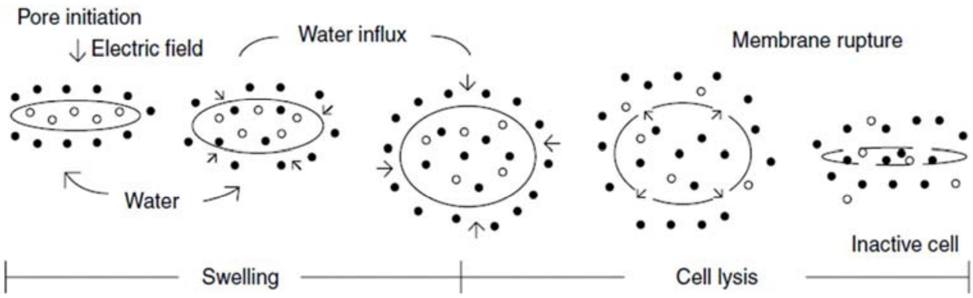
The principles in pulsed electric field power are simple. There is collection of electric energy at low power levels over an extended period and stored in a capacitor [26]. This stored energy can then be discharged almost instantaneously at very high levels of power. The generation of pulsed electric field requires two major devices: a pulsed power supply and a treatment chamber, which converts the pulsed voltage into pulsed electric field [30].



Source: [30]

Figure 7. *Major components of commercial electroporation genezapper.*

Application of PEF is gaining popularity in different food processing industries as it apply non-thermal type of heat treatment like non-thermal type of pasteurization and sterilization in which there is only less effect on natural properties of food to be expected if available [30]. The authors further stated that PEF is useful heat treatment for inactivation of enzyme.



Source: [30]

Figure 8. *Mechanism of cell inactivation.*

4.3. Electronic Noses: Gas Sensors Arrays

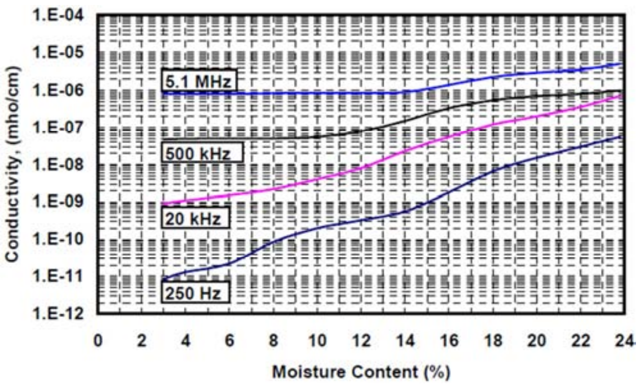
An electronic nose is instrument which try to mimic or simulate the human olfactory sense organ. There are different types of sensors made of an array of chemical and electronic sensors with partial specificity and of a system of pattern recognition, which, based on different principles, react with a change in their properties: metal oxide semiconductors of different types and conducting organic polymers change their electrical properties when absorbing volatile compounds which is measured [31].

4.4. Other Applications of Electrical Conductivity in Fruits and Vegetables

As said at the beginning, electrical properties are finding increasing application in food processing and agriculture in general. For example, knowledge of electrical properties as a function of moisture content and temperature is essential in designing and control of drying system [32]. Electrical conductivity property has also numbers of application in fruits and vegetable industry. For instance, electrical conductivity can be used in non destructivity quality inspection of fruits and vegetables, defect analysis, frost sensitivity evaluation, freezing tolerance evaluation and maturity index determination process. Total soluble solid, pH, firmness and hydrogen ion concentration are physiochemical parameters used as maturity and ripening indices in fruits and vegetables. In determining the quality and repining of any fruits by using any of these parameters as an index, it is a must to destroy the whole or at least part of the fruits for the analysis. But electrical conductivity when applicable is non destructive and non invasive unlike those stated above.

The use of non destructive methods of quality inspection and maturity determinations are recent in fruits and vegetables. Different types of research activity have been done by different researchers on the possible use of electrical conductivity concept in fruits and vegetables. The values of impendence, reactance and resistance decrease during citrus fruit maturation. Authors measure in their experiment that the resistance values of the parts of citrus fruits, i.e., seed, segment, segment wall, and outer shell, and were decreased during maturation [33]. Hence, from this finding, it can be concluded that electrical conductivity measurement can be use as a good maturity indices.

The electrical properties of biological materials and food including agricultural products have long been utilized for rapid, non-destructive measurement of moisture content. The moisture content of agricultural products on the other hand are randomly determined for the fact that they are important in decision making about drying, storing, and even marketing [34]. The writers also stated the fact that, moisture is primary quality factor in trading of agricultural product. This is related to the fact that electrical conductance and resistance of water differs significantly from dry matter so that the property can be utilized in determining moisture content in food materials. This phenomenon is indicated with an example in the figure 3 below. Knowing this property provides rapid assessment of current quality and storage potential in the modern marketing system [34].



Source: [34]

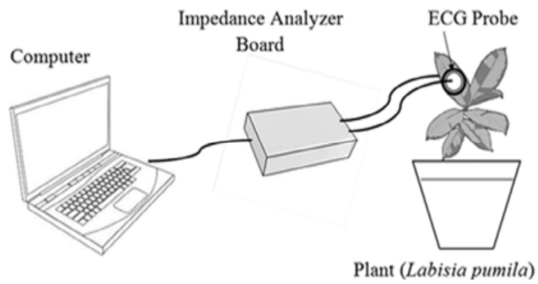
Figure 9. *Example of the dependence of dielectric properties upon moisture content.*

As reviewed authors, the measurement of electrical properties in general and electrical conductivities in particular has an application in determination of different agricultural products and food properties [35]. The writer explains further that the determination of conductivity is of vital interest in the cell membrane techniques. Authors have reported from their study on chicory roots by observing frost sensitiveness, chilling and freezing tolerance [29]. By measuring plant electric resistances, frost damage in chicory roots can be demonstrated clearly while visible symptoms are not convincing. Thus, measuring electrical resistance can be used to predict frost damage. As a result of enhanced membrane permeability, electrolyte leakage to extracellular space causes an increase in extracellular electrical conductivity (i.e. a decrease in resistance). Chicory roots with lower dry weight reached their significantly lowest electrical resistance after storage at the lowest temperature. He explained further that, the decrease in electrical resistance is observed before the happening of visible frost damage. This result indicates that, measuring electrical resistance of root tissues can be used to predict frost damage.

In literature, a study on olive tree observed freezing tolerance in the trees [32]. The occurrence of electrical resistance changes in the tissues of the olive trees exposed to low temperature suggests the use of this experimental procedure as a quick, easy and non-destructive tool to screen plant tissues for chilling tolerance. Therefore, the measurement of the electrical resistance changes in plants exposed to low temperature appears to be useful index for estimating chilling sensitivity and provides easy, quick and nondestructive methods of analysis.

Conductivity is the basic element in Ohmic heating where thermal energy is produced from electric under flow of an alternating current through food. The qualities of agricultural products are measured by various number of characteristic like moisture, freshness, maturity, insect control, frost sensitivity and tolerance to freezing. These characteristics can be determined through the conductive measurement, which is the inverse of resistivity, resistance to electric flow [33].

The water status of plant tissue can also be measured using electrical impendence analysis using electrocardiogram (ECG) electrode connected to an impedance analyzer board which is used to measure the impedance value of the leaf samples noninvasive and non destructively. This can even be done when the plant tissue is attached to their mother plant (Figure 10 below).



Source: [34]

Figure 10. *Layout of instrumentation for impedance measurement of Labisia pumila leaves using electrocardiogram (ECG).*

The electrical measurement has a great potential application in assessing the freshness of apple fruits during the storage as indicated by author in literature [33]. The developed special electrode for their study used to measure the electrical resistance changes of apple fruits stored for 24 days at 22±2°C and in this case there is no physical damage to the apple fruits. The results of their study showed that measuring the nondestructive electrical features of fruit samples at high frequencies (e.g. 1 kHz) is an appropriate way to indicate the postharvest quality of apple fruits during the storage period. It is quite possible to use a non-destructive approach through measurement of fruit electrical resistance and analysis of its apparent and shape to determine the freshness of apple fruits.

The skin of fruits on plant rose gradually but dropped suddenly in their electrical conductivity during the pre-climacteric phase and this phenomenon in turn has an application in quantitative methods of assessing fruit development between harvests and ripening [36]. The writer further states that, the damage on banana skin can also quantitatively assessed by measuring conductivity of their skin. That is because, the conductivity of damage banana skin severely reduced as compared with health banana fruits.

One report from SRM University, the knowledge of electrical properties is useful in selection of packaging materials and cooking utensils, and in the design of microwave and radio frequency heating equipment because they describe how a material interact with electromagnetic radiation [3].

The electrical conductivity is important parameters to determine the applicability of ohmic heating technology for specific products [16]. The electrical conductivity of fresh fruit juices was related with higher accuracy to measured temperature and total soluble solids [9]. The writers further explain that the electrical conductivity is affected more with change in total soluble solid than with unit change in temperature. These empirical relations could be easily employed to predict electrical conductivity of juices, which in turn will have bearing in the performance of ohmic heating processes. Observing the expected variation will be the main utility of such relationships. However, validation of these fitted relationships with wider data sets remains, and should be taken up further.

The concept of electrical conductivity has also found applications in ripenning testing of some fruits and vegetables. Forinstance, to determine banana ripening, measurement of electrical properties of the fruit is good non destructive method. Most of the methods used for detection of ripeness stages of fruits and fruit vegetables are destructive and are wastage when appied. Fore example, impuct force and penetrometer apply some types of force on fruit and destroy the whole or at least part of the fruits. The other methods of measuring chemical composition and parameters correlated with ripness such as TSS, pH, titratable acidy, ethylene content in ripeness determination need destroying the fruit and applying complex analytical methods like, gas liquid chromatography (ethylene), titration (acidity). More recently, other non dstructive methods of determining fruit ripeness like nuclear magnetic resonance (NMR) and Protone magnetic resonance (PMR) have been emerged to measure soluble solid content. But, again these methods have some problems with them that they need expensive equipment and fruit color and ripeness are not always correlated. An attractive methods to measure fruit and vegetables maturity levels uses parallel plate capacitor wich rely on electrical properties [36]. The principle behind is, during ripening there are extensive change in cell wall, cell membrane and chemical makeup of the cell contents. All these changes would affect the capacitance of the tissues. If permeability of cell membranes around cytoplasm were affected in such a way as to eliminate ionic polarization in the region of the membrane, large change in capacitance would occur [36].

5. Summary and Discussion

Electrical conductivity in a food or agricultural product is the measure of the ability of a given food matrix to conduct electric current and hence, is the ability of the food and agricultural products to conduct an electric current. Electrical conductivity of food is the measure of how well the electric current flows through the food of cross sectional area A, length L and resistance R. The interest in electrical conductivity which was started recently is the response to newly emerging food processing technology, ohmic heating and pulsed electric field. In ohmic heating there is flowing electric current which will later generate heating energy due to the resistance of the food matrix to the flowing electric current. Hence, ohmic heating is called electric resistance heating or joule heating. In pulsed electric field processing there is application of high intensity electric field for only short time length, two to ten micro second and this high electric pulse will inactivated the microbial cells via membrane rapture and assure the food is good in its quality and safety. The measurement of electrical conductivity can be through dielectric analysis or electrical intendance spectroscopy measurement.

There are numbers of factors to influence electrical conductivity of foods and agricultural products. Among these factors temperature, field strength, total solid content, nature of product itself and the like are well known to influence the conductivity in the food materials. As it has been stated in the literatures, the increase in temperature increases the electrical conductivity. The increase in electrical conductivity of a given product with increase in temperature is due to the increase in mobility of the tissue constituents as a result of higher temperature. When mobility of food matrix increases, then the capacity of materials conduct electric current also increase.

In the whole fruits and vegetables, the firmness of the products is also affecting the electrical conductivity. As fruit is ripening, it is known phenomenon that the firmness of fruit is decreasing and hence, fruit membranes is losing its integrity. Since membrane integrity is declining, electrical conductivity of the fruit is expected to be increasing. For instance measure the electrical conductivity of avocado fruits during ripening and come up with inverse relationship between fruits firmness and electrical conductivity. That means, as firmness of fruit is declining, the electrical conductivity is increasing. The total soluble solid content of fruits and vegetables is also affecting their electrical conductivity. Different authors have reported the decrease of electrical conductivity with increase in soluble solid content. They suggest the presence of fats, sugar, oils and other solid contents are contributing to the decrease of electrical conductivity. The storage duration (days) is also another possible factor to influence electrical conductivity. The literatures reviewed above indicated that electrical conductivity is increasing until the fruits over ripe or undergo the senescence process. Decrease in membrane integrity may also contribute here as elaborated in different literatures. However, different authors also reported drop in electrical conductivity after ten days of storage which they correlated with total softening and loss of membrane. Increase in field strength is also known to increase the electrical conductivity of fruits and vegetables. The nature of the product themselves are also affecting their electrical conductivity. Conductance along the stem is higher than the electric conductance across the stem in bamboo shoots and sugarcane, while the reverse is true in lettuce stem and mustard stem.

Electrical conductivity of foods is gaining application in different food processing and non destructive quality inspection. Currently different authors are reporting possible application of electrical conductivity in different food processing and quality evaluation. For example, it has application in pulsed electric fields, ohmic heating, induction heating, radio frequency, electronic nose, and microwave heating. Electrical conductivity is also applicable in measurement of different properties of agricultural products like frost sensitivity, chilling and freezing tolerance. Electrical conductivity has also application in non destructive quality inspection, ripening evaluation and defect analysis. With the great acknowledgement of the research work done until today, much work is expected for full utilization of electrical conductivity in much of its possible application area.

6. Conclusion

Electrical conductivity of food is the properties of food itself. It is gaining attention from food processing due to the new emerging food processing technology; ohmic heating and pulsed electric field processing. When electricity is applied to a given food product be it liquid, semi-liquid or solid, heat is produced due to the resistance of the food matrix. It is this heat that used in food processing by ohmic heating also known as electric resistance heating or joule heating. In ohmic heating of food there is transformation of energy in which applied electrical energy is converted into thermal energy within the given food materials. The rate of heating in this heating type is very high; it will take few seconds to few minutes to heat the food products. Pulsed electric field is emerging food processing technology in which high intensity electric field is applied for short duration of time. It is the flush type of heating; hence, little effect on natural characteristics of foods. Thus, this processing can cause rapture of microbial cells and ensure quality and safety of the given food products. The knowledge of electrical conductivity of food under ohmic and pulsed electric field heating is important in food quality inspection, process design and improving processing technology. The measurement methods of electrical conductivity can be by electrical impendence spectroscopy or dielectric analysis. Electrical conductivity of foods and agricultural products are dependent on numbers of factors like product type and nature of product, temperature, applied voltage gradient, frequency, particle size; concentration and concentration of electrolyte.

7. Prospect

As it is tried to be raised in different articles and books repeatedly, relative to the other food processing and quality evaluation techniques, the application of electrical conductivity in both food processing technology and fruits and vegetable quality inspection are young technology. This is an indication that this field of science is in need of efforts with respect to scientific research in order to be utilized in as much area as possible. Measurement methods of EC should be studied further to come up with non destructive and non invasive types of quality, ripening and defect evaluation. The possible application of electrical conductivity in different food processing technology should be studied further so that mild type of heat treatment which does not affect the natural quality of foods to large extent will be used in the future. When we take the issue of this electrical conductivity to the developing countries like Ethiopia, it is untouched area of science which needs an in depth study to characterize our different food product.

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