CHAPTER 2

REVIEW OF LITERATURE

This chapter deals with the review of literature of tropical fruits, physical properties of fruits and vegetables, electrical conductivity, ohmic heating of foods and functional properties of fruit powder.

2.1 TROPICAL FRUITS

Tropical fruit juices have recently become important due to the overall increase in “natural fruit” juice consumption as an alternative to the traditional caffeine containing beverages [46].

2.1.1 Guava Fruit

Guava (Psidium guajava L.) is a tropical fruit native of America, which has been spread to different countries, due to its wide acceptance [1]. Guava is a member of the large Myrtaceae or Myrtle family [2]. Guava can be grown under different soil and climatic conditions. It bears fruit twice in a year but the best quality fruit is obtained in winter [47].

It is claimed to be the fourth most important fruit in terms of area and production after mango, banana and citrus. India is the major world producer of guava [2]. It has been in cultivation in India since early 17th century and gradually became a crop of commercial importance. Guava is quite hardy, prolific bearer and highly re-numerative even without much care. It is widely grown throughout India viz., Uttar Pradesh, Bihar, Madhya Pradesh, Maharashtra, Andhra Pradesh, Tamil Nadu, West Bengal, Assam, Orissa, Karnataka, Kerala, Rajasthan and many more states. Main Varieties grown in India are Allahabad Safeda, Lucknow 49, Chittidar,
Nagpur Seedless, Bangalore, Dharwar, Akra Mridula, ArkaAmulya, Harijha, Hafshi, Allahabad Surkha, CISHG1, CISHG2, CISHG3 (National Horticultural Board, 2010) [2, 48].

2.1.1.1 Nutritional Content of Guava Fruit

Guava is a good source of ascorbic acid, pectin, sugars, and certain minerals. Its skin and flesh colours vary from variety to variety depending on the amount and type of pigments. The fruit softens very rapidly during ripening. In early stages of development the firmness of guava is due to the presence of pectic substances. The softening is the result of degradative changes in the pectic substances due to the activity of pectic enzymes [49]. To those fruit lovers who familiarized with its penetrating aroma, guava is considered as one of the most detectable and fascinating fruits [49].

Guava is often marketed as "super-fruits" which has a considerable nutritional importance in terms of vitamins A and C with seeds that are rich in omega-3, omega-6 poly-unsaturated fatty acids and especially dietary fiber, riboflavin, as well as proteins, and mineral salts. Guava is rich in vitamin C (200-300 mg/100g), three to six times higher than the content in orange. It has the second richest vitamin C content among all fruits after acerola, which has the highest vitamin C content [3]. The high content of vitamin C (ascorbic acid) in guava makes it a powerhouse in combating free radicals and oxidation that are key enemies that cause many degenerative diseases. The anti-oxidant virtue in guava is believed to help reduce the risk of cancers of the stomach, esophagus, larynx, oral cavity and pancreas. The vitamin C in guava makes absorption of vitamin E much more effective in reducing the oxidation of the LDL cholesterol and increasing the (good) HDL cholesterol. The fibers in guavas promote digestion and ease bowel movements. The high content of vitamin A in guava plays an important role in maintaining the quality and health of eye-sight, skin, teeth, bones and the mucus membranes [2].
Dietary fibre in guava is largely composed of complex carbohydrates that are beneficial to digestion, because they contribute to maintain the colonic microflora and to remove waste and toxins. A major component of soluble fibre is pectin, which is an anionic polysaccharide mainly composed of partially esterified D-galacturonic acid monomers linked by α-(1-4) bonds. To this regard, red guava exhibits high pectin content (1.04-1.74 g/100 g of fresh weight) in comparison with other fruits. Guava pectin has a high methoxy index that imparts viscous properties to guava purees or juices [1]. Guava plays an important role in reducing nutritive disorders due to deficiency of vitamin C in human health. Adrees et al [50] and Archana and Siddiqui, [51], found that acetic acid ranged from 55.40 to 122.13 μmol/kg, total sugars from 7.93 to 8.90 %, reducing sugars 5.04 to 5.49 %. Singh and Dhaliwal, [52] reported that TSS ranged from 9.18 to 11.14 %, acidity 0.28 to 0.35 % and ascorbic acid from 122.50 to 206.00 mg per 100g. Bal and Dhaliwal, [47] observed that TSS varied from 9.60 to 11.00 %, acidity 0.26 to 0.38 % and vitamin C 167 to 210 mg per 100 g. Aulakh, [53] found that TSS ranged from 10.0 to 13.5 %, acidity 0.26 to 0.39 %, vitamin C 210 to 266 mg/ 100 g and total sugars 4.16 to 5.12 % in winter season guava fruit.

2.1.1.2 Guava Processing

Guava is one of the easiest fruits to process, showing good characteristics for the industry, mainly due to high contents of vitamins C and A. Guava does not show problems of a physical or biochemical nature in relation to texture, shape or pulp browning during the processing [54]. Guava can be consumed fresh or can be processed into juice, nectar, pulp, jam, jelly, slices in syrup, fruit bar or dehydrated products, as well as being used as an additive to other fruit juices or pulps [4]. The utilization of guava for preparation of beverages and intermediates moisture products has not been explored much. Guava pulp can be used as base for the preparation of these products [2].
2.1.2 Sapota Fruit

Sapota, *Manilkara achras* (Mill.) Fosberg (Syn: *Achras zapota* L.), is one of the most important tropical fruits belonging to the family sapotaceae [5]. It is a delicious fruit also known as chiku, dilly, sapota plum, sapodilla or prickly pear [6]. Sapodilla (*Achras zapota*) is a native of tropical America having originated in Mexico or Central America. It is widespread throughout the tropical regions of the world, including Central and South America, the West Indies, India, Florida in the United States, Sri Lanka, Indonesia and Malaysia [55]. India is the largest producer of sapota followed by Mexico, Guatemala and Venezuela. The most common cultivars grown are Kalipatti, Chaatri, Dhola Diwani, Long, Bhuri / Bhuripatti, Jingar, Venjet, Pala, Kirtha bharthi, Dwarapudi, Jonnavalasa Round, Cricket Ball, oval, Bangalore and Calcutta Round [56].

Sapota is cultivated mainly for its edible fruit, although it is also the source of chicle, the principle ingredient in chewing gum. The chicle is extracted from the trunk of the tree as a white latex exudate. The fruit is a fleshy berry, generally globose, conical or oval with one or more seeds. The fruit generally weighs about 75–200 g, ranging from 5 to 9 cm in diameter. The fruit has a thin rusty brown scurfy skin and a yellowish brown or red pulp with a pleasant, mild aroma and an excellent taste [7]. The flesh is often gritty; however superior strains will have a fine smooth texture with a slightly fragrant and sweet flavor. Mature fruits are used in jams and provide a source of raw material for the manufacture of industrial glucose, pectin and natural fruit jellies. Ripe sapota is eaten as a dessert fruit and also is canned [56].

In India, sapota ranks fifth both in production and consumption next to mango, banana, citrus and grapes. In India, especially in the southern states, it is a commercial fruit crop. The fruits of this tree take 10-10.5 months from anthesis to maturity [57]. It is cultivated mainly in the coastal regions of India from where it is distributed throughout the country. Sapota is a climacteric fruit and its rapid postharvest ripening and senescence followed by spoilage is due to high rate of
ethylene liberation [58]. The Kallipatti cultivar represents a major proportion of export of sapota from India [58].

2.1.2.1 Nutritional Content of Sapota Fruit

Sapota fruit is a good source of sugar which ranges between 12 and 14%. A 100 g of edible portion of fruit contains moisture (73.7 g), carbohydrates (21.49 g), protein (0.7 g), fat (1.1 g), calcium (28 mg), phosphorus (27 mg), iron (2 mg) and ascorbic acid (6 mg) as reported by Pawar et al [59]. TSS, % acidity and ascorbic acid content of the fresh fruits ranged between 12 to 18 °Brix, 0.31 to 0.35 % and 0.5 to 0.78 mg/100mg of pulp, respectively as reported by Ganjyal et al [56]. Sapota fruit is also rich source of protein, ascorbic acid, phenols, carotenoids and minerals like Fe, Cu, Zn, Ca and K [8]. It is also rich in bio-iron required for the formation of haemoglobin [5].

2.1.2.2 Sapota Processing

Although sapodilla are typically consumed fresh, considerable interest has developed in expanding the usage of sapodilla in other forms such as jelly, jam, candy, dehydrated slices, squash and also clarified juice [55]. Products like sweet chutney, sapota milk shake, nectar, blended sapota drinks, pickle, preserve and candy can also be prepared with good sensory quality [60]. Even wine can be prepared from sapota fruit [59, 61].

2.1.3 Papaya Fruit

Papaya (Carica papaya L.) belongs to the family Caricaceae, one of the most important fruits cultivated throughout the tropical and subtropical regions of the world including India [9, 10, 62]. It is native of tropical America and introduced from Philippines through Malaysia to India during 16th Century. It is cultivated in the world in an area of 3.83 lakh ha with a production of 8.05 million tones. In India, it is cultivated in 73,000 ha with a production of 23.17 lakh tones [9]. Papaya fruits are harvested during several months of the year. Papaya is one of the largest in size of the tropical fruits; it has a pulpy flesh yellow or orange colored with shades of
yellow and red, depending on the fruit variety. The fruit can be easily converted into a thick puree and preserved by common methods and later employed to manufacture papaya nectars. Papaya is nutritive and presents good organoleptic characteristics [63].

One distinguishing feature of papaya is the unusually high pH of the flesh, ranging from 5.5 to almost 6.0 when at the eating ripe stage. The weight of the papaya fruit ranges from 300 g to several kg and colour from light yellow to deep red-orange. The flesh is a good source of carotenoids, including beta-carotene with red flesh associated with more lycopene. The thin skin and soft flesh requires careful handling with peeling best accomplished by hand to prevent off flavour pick up from the skin, complete removal of skin and seeds are necessary to avoid off-flavour [64].

2.1.3.1 Nutritional Content of Papaya

Papaya is regarded as an excellent source of vitamin A and C (ascorbic acid) [65]; a good source of carotene, riboflavin and a fair source of iron, calcium, thiamin, niacin, pantothenic acid, vitamin B-6 and vitamin K, carotenoid content (13.80 mg/100 g dry pulp) of papaya is low compared to mango (50 to 260 mg/100 g dry pulp), carrot and tomato. The major carotenoid is cryptoxanthin. Carotenoids are responsible for the flesh colour of papaya fruit mesocarp [9].

Papaya is of explicit quality with great nutritional, medicinal, organoleptic, economic and traditional importance. Papaya fruits contain components that can increase the total antioxidant power in blood and reduce the lipid peroxidation level. These components include α-tocopherol, ascorbic acid, beta carotene, flavonoids, vitamin B₁, and niacin [10]. Papaya fruits are rich in enzymes called papain and chymopapain that break down the proteins from the food, a person eats, into amino acids and therefore helps in digestion [66]. The anti-inflammatory properties and high antioxidant content of papaya is known to prevent cholesterol oxidation and can be used in preventative treatments against strokes, heart attacks, diabetic, heart disease and blood pressure [66, 67].
2.1.3.2  Papaya Processing

Papaya fruit is consumed at unripe and ripe stages. Unripe fruits are cooked and utilized as vegetables, processed products and as a source of papain [68]. Ripe papaya is consumed as a fresh fruit and is also used for processing. At unripe stage, the fruit is consumed as a cooked vegetable where papaya is widely grown. It is available in plenty during a particular season but all have not been utilized to desired extent. Besides available traditional food products, it could be utilized in development of fast moving consumer goods like RTS beverage [62, 63]. Papaya can be made into jam, jelly, nectar, dried into slabs, canned in the form of slice and the fruit powder can be used for preparation of nectar, ice cream flavour and ready to eat fruited cereals [11].

In view of the high pH, papaya puree is either frozen or acidified with citric acid or blended with acid juices prior to pasteurization. The flesh tolerates heat reasonably well during enzyme inactivation. Papaya is the source of papain, a proteolytic enzyme with many food uses. Papain is found in the peel latex, primarily in the immature fruit and industrially extracted, but absent from ripe fruit. Fruit from which latex is harvested are unsuitable for quality flesh or juice utilization. Another enzyme in papaya, pectinesterase, acts rapidly to demethylate pectin and form low methyoxide pectin gel with calcium. Hence, rapid heat inactivation, sweetening to 26 °Brix, or acidification to less than pH 3.6 is necessary to prevent gelation. Acidification followed by aseptic processing is an effective method for bulk handling the puree whose colour, bland flavour and high carotenoid content make papaya a popular blending stock for tropical drinks. Pectic enzyme treatment is necessary to thin the puree sufficiently to affect about a three-fold concentration to 24 to 36 °Brix [64].

2.2  PHYSICAL PROPERTIES OF FRUITS

Physical specification of agriculture products constitute the most important parameters needed in design of grading, transferring, processing and packing system.
2.2.1  Moisture Content

The solid content of food products are related to their food values. The greater the solid content (lower moisture content) of the fruits, the greater is its nutritional value. The moisture content of foods besides influencing engineering properties of fruits and vegetables is also of profound importance in determination of shelf-life of unprocessed and processed fruit and vegetables since it affects physico-chemical properties, microbiological spoilage and enzymatic change [69].

Furthermore, the high moisture and nutritional contents of the fruits and their juices make them suitable for spoilage organisms and agents to grow and multiply. Therefore, all the fruits and their juices are classified as highly perishable and cannot be preserved or stored at ambient conditions. In order to preserve these fruits and their juices, their moisture contents have to be reduced to the level that will make moisture unavailable for microbial growths. The ways, which these fruits can be preserved, include refrigerating or freezing. Acerola pulp have moisture content approximately 92 % [40], Thai seedless guava had moisture content of 92.9 % [46], Papaya have moisture more than 85.5 % [66], Sapota have moisture content ranging from 72-78 % (w.b) [56].

2.2.2  Dimensions of Fruits

Celik et al [70] studied the physical properties of pomegranate and reported that the fruit mass of cv. Eksinar varied from 154.4 to 289.5 g with average of 206.4 g. He also reported that fruit mass within the same pomegranate cultivar is very variable. On the other hand, average fruit length, width and fruit volume of cv. Eksinar were determined as 62.4 mm, 76.9 mm and 211.7 cm$^3$, respectively.

Arman et al [71] studied the physical properties of four verities of apple and reported that the mean fruit length, width, and thickness, for Ko variety were respectively 53.68, 51.72 and 49.33 mm, whereas the corresponding values for the At variety were 41.91, 40.19 and 31.94 mm, for the Pa variety was 40.26, 33.42 and 29.89 mm and for the Ka variety were 44.73, 43.50 and 38.94mm. The maximum, average and minimum apparent specific masses of apples were 0.7966, 0.7427 and
0.6836 gcm\(^{-3}\), respectively. Mass, volume and center of gravity, are the most important physical parameters of apple products used to sizing systems [72].

Keramat et al [73] studied the physical properties of date fruit and reported that the dimensions varied from 29.8 to 40.2 mm in length, 15.7 to 20.2 mm in width, and 15 to 19.7 mm in thickness, with average values of 35.68, 18.07, and 17.42 mm, respectively. The importance of dimensions is in determining the aperture size of machines, particularly in separation of materials as discussed by Mohsenin, [74]. These dimensions can be used in designing machine components and parameters. For example, they may be useful in estimating the number of fruits to be engaged at a time.

2.2.3 Geometric Mean Diameter and Surface Area of Fruits

The average value of the geometric mean diameter of pomegranate was calculated as 70.1 mm for cv. Eksinar. Mean surface area of cv. Eksinar fruit was 15496 mm\(^2\) [70]. The mean surface area of the apple varieties like Ko, At, Pa and Ka were 83.33, 44.89, 58.99 and 65.50 cm\(^2\) [71]. Geometric mean diameter of mango was reported as 63.2 cm\(^2\) [75]. Geometric mean diameter of cactus pear was reported as 59.68 mm\(^2\) [76]. Surface area of aonla fruit was reported as 37.25 cm\(^2\) [77]. The mean volume of the apple varieties like Ko, At, Pa and Ka were 84.59, 33.47, 47.61 and 46.27 cm\(^3\), respectively [71]. Size and shape determine the number of fruits that can be placed in containers with given size [71]. Volume and surface area could be beneficial in proper prediction drying rates and hence drying time in the dryer [71]. The surface area is a relevant tool in determining the shape of the seeds. This will actually be an indication of the way the seeds will behave on oscillating surfaces during processing. Size and shape determine the number of fruits that can be placed in containers with given size. Physical characteristics of agricultural products are the most important parameters to determine the proper standards of design of grading, conveying, processing and packaging systems [78].
2.2.4 Aspect Ratio and Sphericity of Fruits

Morphological properties such as roundness and sphericity are also used to characterize a food’s shape. Roundness is a measure of the sharpness of the corners of a solid. Sphericity indicates how the shape of an object deviates from a sphere. Sphericity is defined from the volume, surface area, or geometric dimensions of an object. Sphericity and shape factors are also needed in heat and mass transfer calculations [71]. The fruit shape was determined in terms of its sphericity, roundness and aspect ratio.

The aspect ratio of selected varieties of apple (Ko, At, Pa and Ka) was reported as 0.96, 0.96, 0.96 and 0.97, respectively [71]. Aspect ratio of mango was reported as 0.91 [75]. Sphericity of mango was reported as 0.95 [75]. The sphericity index percentage of Ko, At, Pa and Ka apple cultivars were respectively varied 0.96, 0.9, 0.95 and 0.95 %. Sphericity of apple was reported as 1.0028 [79]. Sphericity index of aonla was 1.08 [77] and cactus pear was 0.831 [76]. Packing coefficient of apple was reported as 0.5 [79]. Packing coefficient of orange was reported as 0.622 [19]. Shell ratio (%) of orange was reported as 25.40 [19].

2.2.5 Bulk Density, True Density and Porosity of Fruits

The true density, bulk density, porosity and packaging coefficient were 785.91, 503.70, 0.36 and 0.63 for Ko, 830.68, 364.90, 0.56 and 0.44 for At, 923.43, 417.31, 0.55 and 0.45 for Pa and 791.39, 304.05, 0.61 and 0.38 for Ka apple varieties, respectively. Bulk density, true density and porosity of apple were 0.3406 gcm$^{-3}$, 0.7966 gcm$^{-3}$ and 57.24, respectively for apple [79]. Bulk density, true density and porosity of orange were 527.80 kgm$^{-3}$, 865.55 kgm$^{-3}$ and 0.402 [19]. Bulk density, true density and porosity of cactus pear were 641.74 kgm$^{-3}$, 1224.34 kgm$^{-3}$ and 0.469, respectively [76].

The porosity of pomegranate ranged between 26.96 and 50.58 % and average porosity was 43.13 %. Fruit porosity may be useful in the separation and transportation of the fruits by hydrodynamic means [70]. The maximum, average and minimum porosity of apples were 57.24, 54.13 and 50.17 %, respectively [79].
Ikegwu and Ekwu [69] studied the density and relative density of some tropical fruits juices in Nigeria and reported that pawpaw fruit recorded the lowest density 88 kgm$^{-3}$, while guava fruit had the highest (1071 kgm$^{-3}$) density. The relative density of the fruit juices ranged from 1.032-1.065, with sour sop juice and water melon juice having the highest (1.065) and lowest (1.032) relative density, respectively. He also have reported that the relative density of the fruit juices had positive correlation with total solid of the juices examined, higher the percentage total solid, the higher the relative density.

The quality of a particular fruit can be determined by its density. The hollowness and soluble solid contents of intact fruits is related to their specific and solid densities. The variation in the density and relative density of the fruits and their juices might have been influenced by the structure of starch polymers which will result in low density. This imply that the lower the density, the higher the flotation of the fruit samples on top of water and as a result may not be of high quality and may in turn be rejected by consumers [69].

2.2.6 Coefficient of Friction of Fruit

Celik et al [70] studied the coefficient of friction of pomegranate and reported that the surface of materials had an effect on values of the static coefficient of friction. The highest coefficient of static friction was obtained on plywood, at 0.25, and followed by rubber, polyethylene and galvanized steel sheet, at 0.23, 0.22 and 0.21, respectively. Coefficient of static friction on plywood, galvanized iron steel, and glass surfaces of dates fruit were obtained as 0.27, 0.32 and 0.40, respectively. He also reported that the results of analysis showed that the surface of materials had a significant difference (P<0.01) on the static coefficient of friction. The static coefficient of friction on galvanized iron steel was higher than that on plywood and lower than that of glass surface. This is due to the frictional properties between the fruits and surface materials [73]. Coefficient of friction of apple was 29, 22 and 28 on glass, galvanized steel and plywood [79]. Coefficient of friction of orange was 0.27, 0.258, 0.247 against rubber, plywood, galvanized iron steel [19]. Coefficient of friction of Cactus pear was 9.243, 0.261 and 0.296 against galvanized
iron steel, plywood, and rubber [76]. These properties may be useful in the separation process and the transportation of the fruits [73].

2.2.7 Colour of Fruit

Color and discoloration of many foods are important quality attributes in marketing. Though they do not reflect nutrition or flavor, they are important as they relate to consumer preference based on appearance. Color measurement is a critical objective parameter that can be used as quality index measurements of raw and processed foods in quality control documentation, for determination of food quality and for analyses of quality changes as a result of food processing and storage [80].

Color is the stimulus that results from the detection of light after it has interacted with an object. The light may be reflected, transmitted, absorbed, or refracted by an illuminated object. If all the radiated energy is reflected back then the object is opaque and appears white and similarly if all the energy is absorbed then it appears black [81]. Therefore color arises from the presence of light in greater intensities at some wavelength than others and is mainly determined by the reflected light.

The color appearance can change depending on amount of light, the light source, the observer’s angle of view, size, and background differences [80]. The visual color results can be affected by all these factors and therefore instrumentation to measure color provides a subjective and consistent method of color quality.

2.2.7.1 CIE L*, a*, b*

Color representation by the L*, a*, b* notation was recommended by the CIE (Commission Internationale de Eclairage) in 1976. The calculation of L*, a*, b* for each color is based on CIE XYZ values. They are commonly used in food industry. L* is the degree of lightness of the color. This refers to the relation between reflected and absorbed light. L* values equals to zero for black and 100 for white. a* (red-green) is the degree of redness (0 to 60) or greenness (0 to -60) and b*(yellowblue) is the degree of yellowness (0 to 60) or blueness (0 to -60) [82].
Celik et al [70] analyzed the colour of pomegranate and reported that the
colour of Eksinar was determined as L* value 53.8, a* value 32.6 and b* value 28.7.
The colour of orange juice was reported L* as 64.67, a* as –32.24, b* as 68.17 [19].
The colour of anola juice was reported L* as 47.90, a* as -3.73, b* as 11.88 [77].

2.2.8 Rheological Properties of Fruit Pulp

Knowledge of the rheological properties of foods becomes necessary in a
series of applications such as: quality control, knowledge of the physical structure
and principally the control and sizing of industrial processes. The effect of
temperature and concentration on the density and viscosity of grape juice was
studied by Bayindirli [83].

Ikegwu and Ekwu [69] studied the viscosity of some tropical fruits juices
in Nigeria and reported that viscosity values for the juices tested ranged from 728.0-
1236.0 CPs. He also reported that sour sop juice had the highest (1236.0 CPs)
apparent viscosity value followed by Guava juice (1212.2 CPs), while water melon
juice has the least apparent viscosity value (728 CPs). The viscosity of the samples
decreased with increase in moisture content. The observed increase in viscosity
could be attributed to solubility and the quantity of total solids in the sour sop juice.

2.2.9 Specific Heat

Specific heat is defined as the quantity of heat gained or lost by a unit
mass of fruits and their juices to accomplish unit change in temperature [84]. The
amount of heat Q that must be added to a unit mass M (kg of mass or specific weight
kg/m^3) to raise the temperature from T_2 to T_1 can be calculated using the following
equation [84]:

\[ Q = MC_p(T_2 - T_1) \] (2.1)

Magerramov [84] studied the specific heat of apple, cherry, and raspberry
juices. He reported that the heat capacity of apple, cherry and raspberry juice
increased with increase in temperature and decreased with increase in dry matter
concentrations. Heat capacity of apple juice was 3.752 and 2.761 at 14.3 % and 51.6 % of dry matter concentration. Heat capacity of cherry juice was 3.820 and 2.760 at 11.3 % and 48.4 % of dry matter concentration. Heat capacity of raspberry juice was 3.842 and 2.853 at 13.1 % and 51.6 % of dry matter concentration.

Zainal et al [85] studied the effect of temperature on the physical properties of pink guava juice at two different concentrations and reported that the specific heat increased with increasing temperature and decreased with decreasing total soluble solids. Similar results were also reported for tamarind juice concentrates and clarified apple juice [86].

Giovana et al [87] studied the physical properties of acerola and blueberry pulps and reported that specific heat of water is the highest. Thus, the higher the product moisture content, the greater its specific heat. Minim et al [88] investigated the effect of temperature and water content on the physical properties of milk and results showed that the heat capacity increased linearly with the increase of both temperature and water content. Similar results were also reported for mango pulp [13], clarified apple juice [86] and orange juice [89].

Specific heat, $C_p$, of foods is drastically influenced by water content. For example, specific heat has been found to vary exponentially with water content in fruit pulps at above ambient temperatures. Furthermore, nonaqueous components show lower $C_p$. The specific heats of oils and fats are usually about one-half the specific heat of water, while the specific heat of dry materials in grains and powders is approximately one-third to one-fourth that of water. As a result of solute water interactions, the $C_p$ of each individual component in a food differs from the $C_p$ of a pure component, and usually changes with the concentration of soluble solids [86].

### 2.2.10 Differential Scanning Calorimetry (DSC)

In DSC, the measuring principle is to compare the rate of heat flow to the sample and to an inert material, which are heated at the same rate of temperature [90]. Changes in the sample those are associated with absorption or evolution of heat cause a change in the differential heat flow which is then recorded as a peak. The
area under the peak is directly proportional to the enthalpy change and its direction indicates whether the thermal event is endothermic or exothermic [91].

A thermogravimetric measuring unit consists mainly of a sensitive weighing balance that is placed within an oven. During a temperature–time program in the oven, the weight of the sample is measured and recorded over time. The oven atmosphere is nitrogen. At high temperatures, volatile substances are driven off, and a decrease in sample mass is observed and measured. DSC plot is sometimes called a thermogram. In thermodynamic systems analysis, heat taken up by a system (gain) is considered positive, while heat given up (loss) is considered negative. Likewise with heat flow, in which heat flowing into a system is positive (endothermic), and heat flowing out is negative (exothermic).

In Differential Scanning Calorimetry (DSC) experiment, there are two pans isolated from the ambient environment in a chamber. The fruit powder sample was kept in one pan and the other one is a reference pan [92]. Both pans have heaters underneath them that are used to raise the temperature. Each pan also has a sensor that indicates what the temperatures of the pans are at any given moment. Using computer controlled sensors and logic, the heaters are set to heat the pans at a constant rate ($\Delta T/\Delta t$), that is the rate of temperature change is the same, 20°C per minute. The computer keeps track of the starting temperature, heating rate, and heat flow, and records the difference in heat flow between the reference pan and the sample pan, which is the heat flow for the sample, and plots it against temperature [93, 94].

Igor et al [93] studied the thermal stability of okra fibres by thermogravimetric analysis and reported that TG curve of okra fibres shows three weight loss steps, whilst their decomposition occurs in two main stages. Osorio and Carriazo, [1] studied thermal stability of guava (Psidium guajava K) powders obtained by two dehydration methods hot air drying and freeze drying and Thermal analysis curves showed some differences between hot air dried and freeze dried powder.
2.2.11 **Dielectrical Properties**

Dielectric properties are also important in the selection of proper packaging materials and cooking utensils, and in the design of microwave and radio frequency heating equipment, because they describe how the material interacts with electromagnetic radiation. Studies of heating uniformity and temperature elevation rate involve dielectric properties [95].

Li et al [96] measured moisture content of cookies using dielectric spectroscopy. Nelson et al [97] measured the dielectric constant and loss factor with an open-ended coaxial line probe and an impedance analyzer on external surfaces and internal tissue of four cultivars of miniature watermelons provided new permittivity data over a range of maturities at frequencies from 10 MHz to 1.8 GHz at 24°C. They reported both the dielectric constant and loss factor of internal tissues decreased monotonically with increasing frequency showing the dominance of ionic conduction at lower frequencies and dipolar losses at the higher frequencies. Mizukami et al [98] measured moisture content of tea leaves using electrical impedance and capacitance method.

### 2.2.11.1 Dielectric Constant

To perform dielectric study, the pellets were prepared and the surface was smoothened by velvet cloth. In order to prepare the pellets sample the fruits powder was taken in a 10 mm die and the same was pressed into pellets in a hydraulic press at a pressure of 3 tonne. The surface of pellet was maintained as smooth as for a good electrode contact. Platinum paint was used as the electrode and it was pasted on both sides of the test sample (pellet disc). The test sample was placed in copper conducting sample holder and the electrode connections were taken from the surfaces of the test sample and connected to the analyzer. The whole setup was placed inside a tubular furnace in which the temperature was gradually increased by a periodical adjustment of dimmer stat. The dielectric measurements were carried out using a two-probe LCR meter of ANDO AG–4311B type analyzer up to 150°C for various frequency ranges [99].
From the LCR meter, the resistance (R) and the capacitance (C) value were measured. The value of resistivity of the fruit sample can be calculated as

\[ \rho = \frac{RA}{L} \]  \hspace{1cm} (2.2)

\( \rho \) = Resistivity, \((\Omega^{-1} \text{cm}^{-1})\)

R = Resistance of the sample, \((\Omega)\)

A = Area of the sample, \((\text{m}^2)\)

L = Thickness of the sample, \((\text{m})\).

Electrical conductivity can be calculate using the following equation,

\[ \sigma = \frac{1}{\rho} \]  \hspace{1cm} (2.3)

Where, \( \sigma \) – is the electrical conductivity, \((\text{Sm}^{-1})\).

2.2.12 X-ray Diffraction (XRD) Analysis

The XRD is used to measure the average spacings between layers or rows of atoms and determine the orientation of a single crystal or grain and to analyze the crystal structure of an unknown material. Another important application of XRD is to measure the size, shape and internal stress of small crystalline regions.

The fruit powder was kept in a sample holder and the X-rays of known wavelength were allowed to incident on the powder sample and the corresponding reflections were recorded for different 2θ value. The intensity of the diffracted beam was measured in an ionization chamber attached with instruments. Copper (Cu) X-ray tubes are most commonly used for X-ray diffraction. The wavelength of the strongest Cu radiation (Kα) is approximately 1.54 angstroms (Å) is used in this study. The results were presented in a graphical way by means of the intensity of diffracted beam in Y-axis and the 20 value in X-axis.
The particle size of the fruits powder was measured using XRD. The Scherrer equation in X-ray diffraction and crystallography, is a formula that relates the size of sub-micrometre particles, or crystallites, in a solid to the broadening of a peak in a diffraction pattern. It was named after Paul Scherrer [100].

XRD powder analysis has been used to study starch granule crystalline properties. Starch can be classified into A, B and C forms. A form starch is mainly present in cereal starches, such as maize starch and wheat starch. The XRD patterns of these starches give the stronger diffraction peaks at around 15, 17, 18 and 23°. The B form starch is usually available in tuber starch such as potato and this type of starch gives the strongest diffraction peak at 17° 2θ. There were also few small peaks at around 2θ values of 20, 22 and 24°. The C pattern starch is a mixture of both A and B types, such as smooth seeded pea starch and various bean starches [101].

Theivasanthi and Alagar [101] studied the XRD of Jackfruit Seed and reported diffraction peaks at around 15°, 17°, 23°, 31° and 38°. Deraman and Zakaria, [102] have used XRD to study fiber of oil palm empty fruit bunch and rubberwood for medium-density fiberboard. Kategunya and Sanguansri [103] analyzed the jack fruit seed starch using XRD and reported that the XRD was used to reveal the presence and characteristics of crystalline structures of starch granules. The XRD pattern of jackfruit seed starch exhibit the typical A type with appearance of peaks of 2Θ at 15°, 17°, 17.9° and 23°. Osorio and Carriazo [1] studied the XRD of guava powders obtained by hot-air drying or lyophilisation methods and reported that XRD analysis of dehydrated solids showed a similar semi-crystalline profile in both cases, with the characteristic peaks of pectin. The main interplanar spacings (separation of planes, d) for guava pectin were d = 4,0 Å, d = 5,3 Å and d = 8,8 Å.

2.2.13 X-Ray Fluorescence Spectrometry Analysis

Yoshiki [104] used X-Ray Fluorescence Spectrometry, to determine tin in canned foods and reported that to determine tin levels in canned foods, they developed a relatively simple and reliable XRF methods in which the sample is only
homogenized, freeze dried, diluted with cellulose powder, and formed into a pellet for X-ray measurements. The analytical results for several canned foods indicated that both syrup and fruit in plain cans contained tin at higher concentrations than those in cans that were entirely coated with resin. Sangita et al [105] have used XRF for quantitative estimation of macro, micro nutrients and trace elements from Aglaia lawii (white).

2.2.14 Fourier Transform Infrared Spectroscopy Analysis

Loredana et al [106] used FTIR for quantitative determination of carbohydrates, such as glucose, fructose and sucrose, in 28 processed commercial fruit juices and 5 genuine juices obtained from squeezed fruits. Loredana et al [107] determined the total antioxidant capacity (TAC) of 23 fruit juice samples using the TEAC assay, and also, it was predicted by FTIR, the plot of measured and predicted values showing a good correlation ($R=0.97$). Thus, FTIR spectroscopy is a promissory technique for rapid screening of TAC of fruit juices. Loredana and Carmen [108], used FTIR for quantification of carbohydrates in fruit juices.

Igor et al [93] reported the FTIR analysis of okra fibre, A broad absorption band in the region 3600–3100 cm$^{-1}$ corresponds to the characteristic OAH stretching vibration and hydrogen bond of the hydroxyl groups. The broad peak is centred at 3300 cm$^{-1}$. The peaks at 2925 and 2854 cm$^{-1}$ are the characteristic band for the C-H stretching vibration from CH and CH$_2$ in cellulose and hemicellulose components; whilst the absorbance at 1743 cm$^{-1}$ belongs to the carbonyl C-O stretching vibration of linkage of carboxylic acid in lignin or ester group in hemicelluloses. The little shoulder at 1627 cm$^{-1}$ may be due to the presence of water in the fibres. A little peak at 1517 cm$^{-1}$ is attributed to C-C stretching of aromatic ring of the lignin. The absorbance at 1430 cm$^{-1}$ is associated to the CH$_2$ symmetric bending present in cellulose. The absorbance peaks at 1384 cm$^{-1}$ and 1243 cm$^{-1}$ correspond to the C-O stretching vibration of the acetyl group in lignin and hemicellulose component, respectively.
Osorio and Carriazo [1] studied the FTIR of guava powder and reported a broad and intense band at 3400 cm$^{-1}$ is assigned to –OH stretching vibrations; an intense band at 2930 cm$^{-1}$ corresponds to C-H stretching of -CH$_2$- groups; bands that appear at 1743 and 1630 cm$^{-1}$ can be assigned to C=O stretching vibration of methyl esterified carboxylic group and vibrations of the carboxylate (-COO–) group, respectively. On the other hand, a vibration observed at 1250 cm$^{-1}$ indicates the presence of C-O bond, which is common in several organic compounds, and the intense signal at 1064 cm$^{-1}$ can be attributed to stretching vibrations of C-O-C bonds in ethers or related compounds. This band is characteristic of carbohydrates, which show high absorbance between 1200 and 950 cm$^{-1}$ wave numbers values.

2.3 OHMIC HEATING

Conventional heating processes essentially consist of heat-transfer mechanisms of conduction, convection and radiation. The internal resistance by conduction results in very heterogonous treatment and the notable loss of product quality. To overcome these problems, alternative technologies utilizing electrical energy directly in the food processing have attracted interest in the food industry in recent decades [37].

2.3.1 Preamble of Ohmic Heating

Ohmic heating (also called Joule heating, electro-pure process, electrical resistance heating, direct electrical resistance heating, electroheating or electroconductive heating) is defined as a process where electric currents are passed through foods to heat them. Heat is internally generated due to electrical resistance [109].

Ohmic heating is a thermal process in which heat is internally generated by the passage of alternating electrical current (AC) through a body such as a food system that serves as an electrical resistance [24]. Most foods contain ionic species such as salts and acids, hence, electric current can be made to pass through the food and generate heat inside it [25]. Ohmic heating is an in-situ electrical heating
technology that applies electric current through electrodes into a food product, which impedes current and causes it to give off heat. There are several advantages associated with Ohmic heating [110]. It provides very fast heating rates and the heating occurs throughout the entire food product through which the electrical current passes, heating occurs volumetrically and the product does not undergo large temperature variations or come in contact with surfaces hotter than the fluid itself [22]. Also because the voltage being applied can be easily and rapidly changed, the product temperature can be very accurately controlled and no residual heating occurs when the current is shut off. Thus, fouling of the system or scorching of the product is minimized and resistive heating systems have the potential for operating for longer time than indirect heat exchangers in which fouling and build up of a bio-film requires frequent cleaning to be performed.

Ohmic heating, direct resistance heating or the electro-pure process was used in the early 20th century where electric pasteurization of milk and other food materials was achieved by pumping the fluid between parallel plates with a voltage difference between them [39, 44]. Ohmic heating occurs when alternating electrical current (I) is passed through a conductive material of resistance (R), with the resultant energy generation causing temperature rise. The amount of heat generated is directly related to the current induced by the electrical field strength, and the electrical conductivity. The rate of ohmic heating is directly proportional to the square of the electrical field strength and the electrical conductivity [27, 44]. Palaniappan and Sastry [25] reported that the electrical conductivity is a linear function of temperature [111].

The applicability of ohmic heating is dependent on the electrical conductivity of the product. The electrical conductivity of foods affects with temperature, applied voltage, concentration of the electrolytes, food particle size and type of pretreatment [27, 28]. Most food preparations contain a moderate percentage of free water with dissolved ionic salts and therefore conduct sufficiently well for the ohmic effect to be applied [29].
It also enables, under certain circumstances, large particulates and carrier fluids to heat at comparable rates, thus making it possible to use High Temperature Short Time (HTST) and Ultra High Temperature (UHT) techniques on solids or suspended materials [112], increasing the final product quality and adding value to products [31, 113-115]. This very desirable scenario is hardly achieved using conventional heating [28]. Thereby the aseptic processing of fluids containing particulates and fluids of high viscosity are considered the most promising applications of ohmic heating in the food industry [116, 117].

Ohmic heating is currently being used for the processing of whole fruits in Japan and the United Kingdom [118], for production of syruped fruit-salad and fruit juices [29].

Ohmic heating technology has gained interest recently because the products are of a superior quality than those processed by conventional technologies [30, 31, 113]. Moreover, the ohmic heater assembly can be incorporated into a complete product sterilization or cooking process. Among the advantages claimed for this technology are uniformity of heating and improvements in quality with minimal structural, nutritional or organoleptic changes [30, 31]. The potential applications are very wide and include e.g. blanching, evaporation, dehydration, fermentation, pasteurization and sterilization [119].

2.3.2 Electricity

All substances are comprised of atoms, which are in turn comprised of electrons (negatively charged), neutrons (neutral charge), and protons (positively charged). A substance is known as a conductor if the electrons move freely from one atom to another. An insulator is a substance in which the electrons are bound tightly together and do not move freely. This flow of electrons throughout a substance is known as electricity.

Electricity is comprised of electrical current, voltage and resistance. Electrical current is measured in amperes, where 1 ampere is the flow of ~6x10^18 electrons per second through a substance. Voltage is the electron pressure, or a
measure of the ability to move an electrical charge through a resistance (opposition to flow of electricity). Voltage can be calculated by multiplying the current and the resistance. This principle is known as Ohm’s Law, first published by physicist Georg Ohm in 1827.

\[ V = I \times R \]  
(2.4)

Where, voltage (V), current (I), and resistance (R) [120].

As shown in Figure 2.1, the concept of ohmic heating is quite simple. The passage of electric current through an electrically conductive food material obeys Ohm’s law (V = IR); and heat generation due to the electrical resistance of the food, is given by:

\[ F_{\text{heat}} = I^2 R \]  
(2.5)

The design of ohmic heaters is governed by the electrical conductivity of the food. Since most food materials contain a considerable amount of free water with dissolved ionic species, the conductivity is high enough for a heating effect to occur.

Figure 2.1 The concept of ohmic heating

2.3.3 Electric Field

In order to generate heat in an ohmic heating system an electric field must be applied to the food. The electric field (voltage distribution) is a function of the electrode and system geometry, electrical conductivity and also of the applied voltage [109]. The electric field is determined by the solution of Laplace’s equation:
\[ \nabla (\sigma \nabla V) = 0 \] (2.6)

Where \( \sigma \) is the electrical conductivity and \( \nabla V \) is the voltage gradient. This equation has been obtained combining Ohm’s law with the continuity equation for electric current [121], and differs from the usual form of Laplace’s equation:

\[ \nabla^2 V = 0 \] (2.7)

Because, \( \sigma \) is a function of both position and temperature, as mentioned before.

In order to solve Equation (2.5), boundary conditions specific for each case must be established. The solution has been obtained by De Alwis and Fryer [109] for a static ohmic heater containing a single particle, using as boundary conditions: a) a uniform voltage on the electrodes or b) no current flux across the boundary elsewhere. For a more general case of many different particles flowing in a fluid composed of several liquid phases (e.g. vegetable soup, where different vegetable solid pieces are dip in a fluid broth with at least an aqueous and a lipid phase), the mathematical solution for Equation 2.5 is, to author’s knowledge, still unknown. In these cases, the prediction of the electric field has been based on semiempirical models [22].

2.3.4 Heating Mechanism of Ohmic Heating

In ohmic heating, an electrical current is applied to the food. Owing to the food’s resistance to the applied alternating current, heat is generated within it. The mechanism behind this is that charged molecules in the food such as ions move and collide with their surrounding molecules, which then release energy in the form of heat [122].

Since the heating happens within the food and is not dependent on any hot surfaces, the heating pattern in ohmic heating is much more uniform than in conventional heating technologies [123]. Ohmic heating is therefore suitable for the processing of viscous or multiphase foods which may otherwise be difficult to heat.
2.3.5 Principle of Ohmic Heating

The principle of ohmic heating is based on Ohm’s law [123]. It is the process by which the passage of an electric current through a conductor, in case of food, heat is generated within it due to its electrical resistance. The simplest models of an ohmic heater are two plates between which the food flows or are contained, as illustrated in Figure 2.2 [122].

![Figure 2.2 The principle of ohmic heating](image)

The technology has gained interest during the past few decades since experiments repeatedly show that it results in processed products with a superior quality to those processed by conventional technologies [115]. The reduced processing times in ohmic heating cause minimal structural, organoleptic and nutritional changes and can be related to the rapid internal heating of the food that is not dependant on any hot surfaces. Studies also suggest that ohmic heating may provide additional non-thermal lethal effects on microorganisms, such as electroporation, which enables the use of an even shorter thermal treatment without interfering with product safety [122].

2.3.6 Basic Ohmic Heater Configurations

The fundamental requirements for ohmic heating equipment for food processing are a pair of electrodes, a container for the food to be processed and an alternating power supply.

The ohmic heater can be integrated into a batch or continuous process. The most typical configuration for the ohmic heater is that of a horizontal cylinder...
with one electrode placed in each extremity for a batch process (Figure 2.3a). For a continuous process the design of the ohmic heater can be more variable, depending on the manufacturer. It can range from a simple tube with pairs of opposing electrodes mounted on the tube walls opposite to each other (Figure 2.3b), to coaxial tubes acting as electrodes with the food flowing between (Figure 2.3c), or a vertical tube with the electrodes embodied at regular intervals (Figure 2.3d). As the electric field is perpendicular to the food flow for the equipment represented in Figure 2.3b and 2.3c, these configurations are often called cross-field. If the electric field is parallel to the food flow (Figure 2.3d) the configuration obtained is termed in-field. Ideally, it is possible to consider that in the cross-field configuration the electric field strength is constant. For the in-field configuration, $\sigma$ will increase and therefore the field strength experienced by the product will increase as it approaches the outlet. The product will heat during its path through the heater. To minimize this effect, when multiple electrodes are used in series (Figure 2.3d) they are spaced to account for the increase of $\sigma$ of food with temperature. Therefore, as the product approaches the outlet of the heater a lower value of the electric field strength is needed and this is accomplished by increasing the spacing between each pair of electrodes [124].

![Figure 2.3 Basic configurations for ohmic heaters: a) batch; b-d continuous; c) cross field configurations; d) In-field configuration.](image-url)
The choice of the best configuration will obviously depend on the food being processed and the objectives of the process (e.g. cooking, pasteurization, sterilization). Batch processes are typically used to cook e.g. meat products [125], while continuous processes are more appropriate for viscous fluids or fluids with particulates.

2.3.7 Ohmic Heating System Design

There are endless possibilities for the design of an ohmic heating system, but there are several key elements that will be present in each one. A power supply (generator) is needed to produce the electricity. Electrodes connected to the power supply must be in physical contact with the substance in order to pass the electric current through. The electrode gap (distance between the electrodes in the system) can fluctuate depending on the size of the system, but by changing this distance, the electric field strength, expressed in volts per centimeter \([V\text{cm}^{-1}]\), can be varied. For a moving system, such as a conveyor or tube, the electrodes can be placed at various positions along the length of the product flow path for an in-line field (Figure 2.3 c), or placed perpendicular to the flow path for a cross field (Figure 2.3 d). In an in-line field system, the material upstream experiences higher field strength than the material downstream due to the drop in voltage throughout the system. In a cross-field system, the electric field strength is constant throughout [126].

A device for measuring temperature in the system, such as an electrically isolated thermocouple, would be inserted at certain key positions. A data logger connected to the system would record essential information such as temperature, voltage, current and time. Additional equipment may include a pH probe, a spectrophotometer for measuring optical density, a refractometer for measuring °Brix (soluble solids), and sampling ports (in a closed system).

Ohmic heating has internal energy generation within its system. In theory, there is no upper limit to the temperature that can be produced. However, several other factors will influence the temperature achieved by the system: 1) the electrical conductivities of the food substance, 2) the design of the system, 3) the
time that the substance is subjected to the heating, 4) the thermophysical properties of the food, 5) the electric field strength and constancy, 6) the temperature dependence of electrical conductivities, and 7) the extent of the interstitial motion in the food [127].

2.3.8 Ohmic Heating of Particulate Foods

In an ohmic heating process for particulate foods, the most desirable situation is that in which the electrical conductivities of fluid and solid particles are equal, thus close matching of electrical conductivities between phases would be highly desirable [128]. Wang and Sastry [128] showed that it is possible to increase the electrolytic content within foodstuffs, and raise electrical conductivity by salt infusion. This effect may be accomplished via the relatively slow soaking or marination process or the more rapid blanching process in salt solution. However, it is also necessary that the composition and other properties of the food are not greatly affected. By adjusting the electrical properties of different solid components it may become possible to heat solids at similar rate or even faster than the sauce [128].

2.3.9 Applications of Ohmic Heating in Food Processing

The ohmic heating technology provides new, high-added-value, shelf-stable products with a quality unachievable by the traditional processing technologies. The process can be used in a) the thermal processing of high-acid food products such as tomato-based sauces, b) pasteurization of whole liquid egg, c) fish pastes, d) on meat products processing as an alternative cooking to the traditional smokehouse [113].

2.3.9.1 Meat Products

The first experiments using ohmic heating in meat products were made in Finland in the 1970’s, but operational difficulties led to the abortion of the project. Later on, in the 1990’s a project for cooking liver pate and hams was carried out in France by the Meat Institute Development Association (ADIV) and Electricite de France (EDF). One ohmic heating application is thawing process, when the
traditional thawing methods cannot provide high quality products. Wang et al [129] applied the technology to frozen meat samples, in a liquid-contact thawing method. The results demonstrated a uniform and quicker thawing process. Also, meat properties such as color and pH were not changed significantly and the final products achieved a good thawing quality. These results demonstrate the potential uses of ohmic heating in contact thawing, especially for meat products [125].

Brine-cured meat products were found to be admirably suited to ohmic heating having extremely reduced cooking times (e.g. a ham weighing one kilogram was cooked in less than two minutes). However, these flash cooking times did not reduce the bacterial load to levels that guaranteed product safety. Pasteurization had to be taken into consideration and a time temperature profile was established. However, under these conditions, no noticeable changes were reported in the products’ taste, texture or shelf-life.

Combined ohmic and conventional cooking of hamburger patties has recently been patented as a new method of cooking [126]. The method is based on passing electric current through the meat patties causing internal heat generation. It has been found to reduce cooking time up to half the time usually required in conventional cooking. It was also concluded that ohmic heating has no effect on the quality of the ohmically-cooked hamburger [10].

2.3.9.2 Fruit and Vegetable Products

Strawberry fruit jam is extremely important for the Portuguese fruit jam industry because they account for most of its sales (around 90 %). The search for alternative processing technologies leading to higher quality products is one of the main goals and the economic viability of this technology depends on the possibility of applying it to most of the products processed by this industry [30]. In the study by Castro et al [23] several strawberry based products were tested by ohmic heating. The obtained results showed that, for most of the products, high heating rates could be achieved, despite the significant differences of σ between the products tested. Also, the increase of the applied electric field could increase the heating rate.
The suitability of ohmic heating for strawberry products having different solids concentrations, or Brix values, was also tested [30]. σ was shown to decrease with the increase of solids content in a mixture of particles with a bi-modal particle size distribution, but the decrease was more significant for the bigger particles tested. The results also suggest that for higher solids content (> 20 % w/w) and sugar contents over 40.0 °Brix, σ is too low to use in the conventional ohmic heaters and a new design is required.

Wang and Sastry, [130] studied the effects of an ohmic pre-treatment and found no significant changes in the moisture content of the final products. This technology might be an alternative to conventional blanching treatments.

Eliot et al [131] studied the influence of precooking by ohmic heating on the firmness of cauliflower. The experimental data showed that ohmic heating combined with low-temperature precooking in saline solutions offers a viable solution to HTST sterilization of cauliflower florets. A similar study was also performed with potato cubes [131, 132] and concluded that an ohmic pre-treatment prevented loss of firmness when compared to a conventional pre-treatment (50 % in some cases).

2.3.9.3 Seafood Products

Most of the scientific literature concerning seafood products deals with surimi. Surimi is stabilized myofibrillar proteins from fish muscle, which is used in several Japanese food products. The textural properties of the products treated by ohmic heating were found to be superior to those heated in a 90°C water bath. Also, an increase in shear stress and shear strain of surimi gels was found when ohmic technology was applied [133] and, in addition, a superior gel quality was achieved. Higher heating rates are not beneficial to surimi manufacture [134]. Instead, slow heating rates produce stronger gels. Ohmic processing of surimi is very effective in obtaining a wide range of linear heating rates which plays an important role in the study of surimi gelation. It is expected that with the continuous research and
development of new electrode materials and of equipment with innovative design, several other food applications using ohmic heating will soon be possible.

2.3.9.4 Other Applications

A large number of actual and potential applications exist for ohmic heating, including blanching, evaporation, dehydration, fermentation, extraction, thawing, solidification sterilization, pasteurization and heating of foods to serving temperature, including in the military field or long-duration space missions [123]. Today, the technology is successfully being used for the processing of whole fruits, berries, fruit juices, liquid egg and soups in Japan, the United Kingdom and Northern America [135].

2.3.10 Advantages of Ohmic Heating

In general, ohmic heating systems are advantageous due to an optimization of investment (increased efficiency), instant shutdown of the system, and reduced maintenance costs because of the lack of moving parts.

Major advantages of ohmic heating are [113]:

- Continuous production without heat-transfer surfaces;
- Rapid and uniform treatment of liquid and solid phases with minimal heat damages and nutrient losses (e.g. unlike microwave heating, which has a finite penetration depth into solid materials);
- Ideal process for shear-sensitive products because of low flow velocity;
- Optimization of capital investment and product safety as a result of high solids loading;
- Reduced fouling when compared to conventional heating;
- Better and simpler process control with reduced maintenance costs;
• Environmentally friendly system.

Ohmic heating is also favored for higher energy conversion efficiency, because up to 90% of the electrical energy is converted into heat and lower in capital cost due to reduced moving parts. Ohmic heater cleaning requirements are comparatively less than those of traditional heat. Fouling of the system or scorching of the product is minimized and ohmic heating systems have the potential for operating for longer time than indirect heat exchangers in which fouling and build up of a bio-film requires frequent cleaning to be performed. Its advantages compared to conventional heating include maintaining the colour and nutritional value of food, short processing time and higher yield [23, 29, 35 and 137].

2.3.11 Advantages of Ohmic Heating over Conventional Heating

Ohmic heating is defined as purely volume and direct resistance heating, in opposition to heating by conduction from the hot surface of a heat exchanger. The heat transfer coefficient between the hot wall and the fluid is irrelevant, as there is no hot wall at all, which constitutes a major advantage for food applications. The degradation of thermo-sensitive compounds through overheating (change in taste, undesirable reactions, burning) as well as heat exchanger fouling are theoretically strongly reduced [38].

Ohmic heating has numerous advantages over conventional heating methods. Ohmic heating heats the entire mass of the food material volumetrically because of its inherent electrical resistance [26]. The differences between the principles of these heating procedures decide the heating effects. The way that how conventional heating methods work make them struggle to achieve the necessary high rates of heat transfer into the material in order to heat sufficiently without causing product degradation. Therefore, the most important advantage of ohmic heating is the rapid and uniform heating. With ohmic heating, the resulting product is heated rapidly (increase 50°C in less than 0.1 second) and without temperature gradients.
Another particular advantage over conventional heating are problems such as fouling, “burn-on” where thermal degradation occurs as a result of high temperature gradients. During conventional heating methods, significant product quality damage may occur due to slow conduction and convection heat transfer.

Furthermore, the time takes to increase the temperature at the coldest point which is generally the center of the largest particle, may over-process the remaining particles and the surrounding liquid. But during ohmic heating, the voltage being applied can be easily and rapidly changed, the product temperature can be very accurately controlled and no residual heating occurs when the current is shut off. And hot surfaces for heat transfer are eliminated, resulting in optimized time and temperature control profiles with less overcooking, thus fouling and “burn-on” of such surfaces are greatly reduced, offering less maintenance and better product flavor [113].

Additionally, it is possible to process large particulate foods (upto 1 inch) with ohmic heating that has a larger heat penetration depth compared to other heating techniques [136], like microwave and radio frequency heating.

2.3.12 Disadvantages to Ohmic Systems

Some of the disadvantages accounting for ohmic heating are the higher initial operational costs and the lack of information or validation procedures for this technology [138].

A disadvantage related to the type of food that can be processed lies in the presence of fat globules. A food that has fat globules can be troublesome to effectively heat ohmically, as it is non-conductive due to lack of water and salt [138]. If these globules are present in a highly electrical conductive region where currents can bypass them, they may heat slower due to lack of electrical conductivity. Any pathogenic bacteria that may be present in these globules may receive less heat treatment than the rest of the substance [139].
Another slight disadvantage relates to the electrical conductivity of a substance. As the temperature of a system rises, the electrical conductivity also increases due to the faster movement of electrons. Thus, this creates the possibility of ‘runaway’ heating [127]. An ohmic heating system that has not been cleaned thoroughly enough may result in electrical arcing due to protein deposits on the electrodes. But, by utilizing the knowledge of the aforementioned issues in designing an ohmic heating system, these disadvantages may be more easily controlled.

2.4 ELECTRICAL CONDUCTIVITY OF FOODS

The electrical conductivity of foods is of relatively recent interest to researchers. Little literature exists on this topic, since electrical conductivity was not critical in food applications prior to the late 1980s. Electrical conductivity is a critical parameter for both the ohmic heating and pulsed electrical field processes.

Electrical conductivity is the measure of how well a substance transmits electric charge, expressed in Siemens per meter (Sm\(^{-1}\)). Electrical conductivity is a ratio of the substance density to electric field strength and is affected by the chemical composition of a substance. In ohmic heating terminology, the conductivity is a measure of the mineral or ionic content. For food substances, the most common ionic ingredient is salt (NaCl). The higher the amount of dissolved salts in a substance, the higher the conductivity. Seawater has a conductivity measurement of ~5 Sm\(^{-1}\), whereas regular drinking water has a conductivity measurement of ~0.0005 to 0.05 Sm\(^{-1}\) [38]. One method of measuring electrical conductivity is to use a TDS (Total Dissolved Solids) meter. TDS are the total amount of mobile charged ions in a substance (mg/L or ppm), calculated by measuring the number cations (positively charged) and anions (negatively charged) ions in the substance. Electrical conductivity is ~100 times the total number of cations and anions present. To be able to process food by ohmic heating, its electrical conductivity should be in the range 0.01 and 10 Sm\(^{-1}\) at 25°C [38]. Ohmic heating can be used for heating food that is an electrically conducting moist material. For example, milk, which contains water and ionic salts, is capable of
conducting electricity, but it also has a resistance which generates heat when an electric current is passed through it. Therefore, the rate of heating is directly proportional to the square of the electric field strength and the electrical conductivity. The electric field strength is controlled by adjusting the electrode gap or the applied voltage. However, the heating rate depends largely on the physical characteristics of the food itself, especially on the electrical conductivity [39].

Electrical conductivity is the reciprocal of resistance through a unit cross-sectional area $A$ over a unit distance $L$, or the reciprocal of resistivity.

$$\sigma = \frac{L}{AR} \quad (2.8)$$

or

$$\sigma = \frac{I}{V} \frac{L}{A} \quad (2.9)$$

Where, $A$ is the area of cross section of the sample $(\text{m}^2)$, $I$ is the current through the sample $(\text{A})$, $L$ is the electrode gap or length of sample $(\text{m})$, $R$ is the resistance of the sample $(\Omega)$, $V$ is the voltage across the sample $(\text{V})$, and $\sigma$ is the specific electrical conductivity $(\text{Sm}^{-1})$ [29].

2.4.1 Heat Generation during Ohmic Heating

In order to generate heat in an ohmic heating system an electric field must be applied to the food.

The electric field (voltage distribution) is a function of the electrode and system geometry, electrical conductivity and also of the applied voltage [109]. The electric field is determined by the solution of Laplace’s equation:

$$\nabla(\sigma, \nabla V) = 0 \quad (2.10)$$

Where $\sigma$ is the electrical conductivity and $\nabla V$ is the voltage gradient. This equation has been obtained combining Ohm’s law with the continuity equation for electric current [121] and differs from the usual form of Laplace’s equation:
\[ \nabla^2 \psi = 0 \]  

(2.11)

\( \sigma \) is a function of both position and temperature.

The dependence of position is because foods are not necessarily homogeneous materials; the limiting scenarios being foods containing particles (e.g. vegetables soup) and that of a reasonably homogeneous liquid (e.g. orange juice). The relation of \( \sigma \) with temperature is usually well described by a straight line of the type \[25\]

\[ \sigma_T = \sigma_{\text{ref}} \left[ 1 + m (T - T_{\text{ref}}) \right] \]  

(2.12)

Where \( \sigma_T \) is the electrical conductivity at temperature \( T \), \( \sigma_{\text{ref}} \) is the electrical conductivity at a reference temperature, \( T_{\text{ref}} \), and \( m \) is the temperature coefficient.

The important parameter in ohmic heating of a liquid food product is its electrical conductivity behavior. It depends on temperature, applied voltage gradient, frequency, and concentration of electrolytes \[140\].

Icier and Ilicali \[140\] conducted ohmic heating studies on tylose and minced beef and reported, that the temperature values of the samples inside the test tube during heating were close to each other. The maximum temperature difference measured at different locations during heating was 2°C. The salt components, acids, and moisture are highly effective in increasing electrical conductivity, while fats, lipids, and alcohols decrease it.

2.4.2 Electrical Conductivity of Particulate Foods

In a non homogeneous material, such as soups containing slices of solid foods, the electrical conductivity of the particles and its relation to the fluid conductivity is pointed as a critical parameter to the understanding of the particles’ heating rate under ohmic heating \[44\]. Proper electric conductance management is essential to successfully apply ohmic heating \[23, 110, 117 and 136\]. The heating rate of particles in a fluid depends on: (i) the relative conductivities of the system’s
phases and (ii) the relative volume of those phases [141]. Low conductivity solid particles, comparatively to the fluid conductivity, tend to lag behind the fluid at low concentrations related to the volume of the fluid. However, in conditions where the concentration of the particles is high, those same low conductivity particles may heat faster than the surrounding fluid. So, the phenomenon of particle-lagging or particle-leading depends on the significance of particle resistance to the overall circuit resistance [22]. This phenomenon occurs because, with the increase of the particles’ concentration, the electric current path through the fluid becomes more tortuous, forcing a greater percentage of the current to flow through the particles. This can result in higher energy generation rates within the particles and consequently in a greater relative particle heating rate [22, 141]. This fact indicates that it may be possible to adjust the heating pattern of solid fluid systems by adjusting the overall influence of particle’s resistance in the system through setting the particles concentration in the fluid.

The electric conductivity of some systems may also be altered to achieve the ideal ohmic heating situation, when the conductivity of the particles is equal to the surrounding fluid [128]. However, as pointed by Halden et al [142] it is unlikely that the exact same heating rate can be achieved throughout the process, even though the thermal difference, in practical terms, may be too small to be significant.

There are also critical $\sigma$ values below 0.01 Sm$^{-1}$ and above 10 Sm$^{-1}$ where ohmic heating is not applicable. This is because very large voltages or very large amperage values would be needed to generate the amount of heat required raising temperature substantially by the Joule effect, in case of very low or very large $\sigma$ values, respectively [143, 144]. Darvishi et al [37] postulated that ohmic heating is most satisfactory for products having values in a range of 0.01–10 Sm$^{-1}$, with optimum efficacy in the range 0.1–5 Sm$^{-1}$.

2.4.3 Effect of Temperature on Electrical Conductivity

Icier and Ilicali [145] conducted ohmic heating studies on tylose and minced beef and reported that as the temperature increased the electrical
conductivity of the minced beef samples increased up to a critical temperature of 45–50°C and then the rate decreased. However, for the tylose samples, the electrical conductivity values increased as the temperature increased up to 60°C. For the minced beef samples, it is thought that electrical conductivity may be decreased as a result of chemical reactions induced by the effect of increase in temperature and the electrical current. In particular, the denaturation of the proteins may cause changes in the ionic movements and decrease the electrical conductivity. As the temperature increased electrical conductivity values increased. The results are similar to those reported by Icier and Ilicali [29] and Icier et al [137]. Increase in the electrical conductivity values with temperature has been explained by reduced drag for the movement of ions. It has been reported that when water is boiling, gas bubbles are formed. This phenomenon appears due to localized high current densities of various oxidation/reduction reactions (e.g. H₂ or O₂ gas) [140]. Increase in the electrical conductivity during heating of biological tissue occurs due to increase in the ionic mobility because of structural changes in the tissue like cell wall protoplast breakdown, expulsion of non conductive gas bubbles, softening, and lowering in aqueous phase viscosity [37].

Palaniappan and Sastry [44] observed that electrical conductivities decreased with temperature rise after bubbling started and the heating was stopped when bubbling started. It has been discussed that due to formation of electrolytic hydrogen bubble, fruit juices are acidic [37].

Icier and Ilicali [29] found a linear relationship between temperature and electrical conductivity of orange juice. Castro et al [30] reported that electrical conductivity of strawberry-based products increased with temperature following linear or quadratic relations depending on product type tested.

Castro et al [30] measured the electrical conductivity of fresh strawberries at different field strengths from 25 to 70 Vcm⁻¹, and found that the electrical conductivity increased almost linearly with the field strength. At 25 Vcm⁻¹ they reported conductivity to be approximately 0.05 Sm⁻¹ at 25°C and 0.55 Sm⁻¹ at 100°C. Sarang et al [146] reported the conductivity at 25°C of pear as 0.084 Sm⁻¹,
red apple as 0.075 Sm\(^{-1}\) and of golden apple as 0.067 Sm\(^{-1}\). He also reported that the conductivity of strawberry increased from 0.186 Sm\(^{-1}\) at 25°C to about 0.982 Sm\(^{-1}\) at 100°C. Typical values ranging from 0.5 to 1.6 Sm\(^{-1}\) over temperatures of 20–80°C have been reported for low viscosity liquids such as orange, tomato and carrot juices by Palaniappan and Sastry, [25]. Electrical conductivity of lemon juice was reported as 0.4–1.0 Sm\(^{-1}\) at 30–55 Vcm\(^{-1}\) and 20–74°C [37], 0.38–0.78 Sm\(^{-1}\) for grape juice at 20–40 Vcm\(^{-1}\) and 20–80°C [137], 0.15–1.15 for orange juice at 20-60 Vcm\(^{-1}\) and 30–60°C, 0.51–0.91 Sm\(^{-1}\) for peach puree and 0.61-1.2 Sm\(^{-1}\) for apricot puree at 20–70 Vcm\(^{-1}\) and 20–60°C [140].

### 2.4.4 Effect of Voltage Gradient on Electrical Conductivity

Icier and Ilicali [145] investigated the ohmic heating of, minced beef samples having two different fat contents were heated using voltage gradients in the range of 10-50 Vcm\(^{-1}\). The effect of voltage gradient on the ohmic heating times were found to be statistically significant (P<0.05). As the voltage gradient increased the heating times to reach the prescribed temperature decreased.

Hong et al [147] investigated the changes in the heating profiles of apple juice by ohmic heating. They found that heating rate increased proportionally to the number of electrode pairs and was highly dependent on applied voltage.

As the voltage gradients applied increased, the ampere passing through the system reached higher values suddenly at lower temperatures. This caused violent evaporation of water in the samples and thus heating processes were stopped in these samples. These juices could not be heated up to 80°C [38, 140 and 141]. Darvishi et al [37] reported that as the voltage gradient increased the heating time of the lemon juice required to reach the prescribed temperature decreased. Other researchers who have found a linear increase in electrical conductivity with increase in temperature include Castro et al [23] and Zareifard et al [32], Legrand et al [38], Icier and Ilicali [145] and Sarang et al [146].
2.4.5 Effect of Solute Concentration on Electrical Conductivity

Icier and Ilicali [145] studied the effect of salt concentration of the ohmic heating rate of tylose sample, and reported that, as the salt content increased the times required to ohmically heat to the prescribed temperature decreased especially at low-voltage gradients.

The conductivity of white egg was high compared to yolk and liquid whole egg. Higher electrical conductivity of white egg may be attributed to the high water and low fat content and hence higher ionic mobility in comparison to the low water and high fat content of yolk and liquid whole egg [37].

Icier and Ilicali [148] conducted ohmic heating of apple and sourcherry concentrates having 20-60 % applying five different voltage gradients (20-60 Vcm⁻¹). He observed that electrical conductivities of apple and sourcherry juices were significantly affected by temperature and concentration (P<0.05). He also reported that sourcherry juice concentrates heated faster than the apple juice concentrates for all voltage gradients applied and at all concentrations. The sourcherry juice had higher electrical conductivity values than the apple juice for the same temperature at all concentrations and for all voltage gradients applied. This was attributed to the higher acid content of the sourcherry juice having similar insoluble solid content with the apple juice.

For the same voltage gradients, the electrical conductivity values measured at the same temperature decreased as the concentration increased. Palaniappan and Sastry [44] reported that the electrical conductivities of juices increased linearly by decreasing insoluble solid contents, whereas a nonlinear relationship was obtained in this study. Castro et al [23] suggested that electrical conductivity decreases with increase in solids and sugar content of strawberry-based products. They mentioned that for formulations of products having solid content over 20 % w/w and over 40 °Brix, a different design of ohmic heater may be necessary because of the low values of electrical conductivity [148].
Cristina et al [149] reported that the electrical conductivity was dependent on the concentration (°Brix) and the temperature (20-80°C) for lemon juice. The electrical conductivity increases with increasing concentration up to approximately 30 °Brix, when it starts to decrease. The decrease in electrical conductivity may be due to the increase in viscosity of the juices with concentration which decreases the mobility of the ions.

The reason for the differences between the effects of solids contents by various researchers may be explained by the nature of the solutes in the samples used. Some components may influence the electrical conductivity of the sample, depending on their electrolytic characteristics. In fruit juices, the main solute component is the sugar having nonelectrolytic behavior [148]. Icier and Ilicali [148] reported that as the sugar content increased electrical conductivities of the liquid solutions decreased. However, the acidity of the juices enhanced their electrical conductivities. Sugar content and the nature of the other components may cause different electrical conductivities between the juice samples compared.

In addition to this, Icier and Ilicali [148] reported that the decrease in the concentration of the apple and sour-cherry juices from 60 % to 20 % enhanced the ohmic heating rate of the juices. Icier and Ilicali [140] reported similarly that electrical conductivity depended on the viscosity of the heated solution during ohmic heating.

Icier and Ilicali [29] reported that the increase in the electrical conductivity values with temperature has been explained by reduced drag for the movement of ions. It was observed that electrical conductivities decreased with temperature rise after bubbling started. The decrease in electrical conductivity may be caused by increased concentration of solids (due to evaporation of water) causing a drag in the ionic movement. The highest value of the electrical conductivity of pomegranate juice was $1.037 \text{ Sm}^{-1}$ during boiling at the highest voltage gradient of $55 \text{ Vcm}^{-1}$. 
Palaniappan and Sastry [44] found that the drag for ionic movement increased when the solid content increased, which might be a reason for the decreasing trend in electrical conductivity with increasing solid content. Icier [150] conducted ohmic heating experiment on reconstituted whey solutions, (in the range of 8–24 % w/v solute concentrations) were heated from 20°C to prescribed temperatures (30, 40, 50, 60, 70 or 80°C) ohmically by applying voltage gradients of 20, 30 or 40 Vcm⁻¹, and conventionally at water bath. He reported that although the effect of voltage gradient was statistically important on ohmic heating times from 20 to 80°C, the solute concentration was not effective (P<0.01). As the voltage gradient increased ohmic heating time decreased sharply, due to the increase of heat generation inside food per unit time with the voltage gradient. On the other hand, ohmic heating was longer at lower solute concentrations. It could be explained by decreasing amount of free ions/charge carriers, which decrease the electrical conductivity, at lower concentrations. In that, the fast heating occurred in solutions having higher electrical conductivity. The application of ohmic heating at high voltage gradients and at higher solute concentrations could be advantageous to obtain faster heating at the industrial processing of whey solutions [150].

Increase in the electrical conductivity during heating of the biological tissue occurs due to increase in the ionic mobility because of structural changes in the tissue like cell wall protopectin breakdown, expulsion of non conductive gas bubbles, softening, and lowering in aqueous phase viscosity. Higher electrical conductivity of strawberry and peach may be attributed to the softer tissues and hence higher ionic mobility in comparison to the harder tissues of apples, pineapple and pear. Also, presence of large amount of air might result in lower electrical conductivity of apple tissues [151].

Palaniappan and Sastry [44] have studied the ohmic heating behaviour of orange juices having re-suspended insoluble solids in the range of 0–16.7 % solids. They reported that the electrical conductivity of juices increased linearly by decreasing the insoluble solid content. They have also suggested that the drag for ionic movement increased when the solids content increased, which might be a reason for the decreasing trend in electrical conductivity with increasing solid
The soluble solid mass fractions of the orange juice concentrates were 0.20-0.60 in this study and the same decreasing trend in the electrical conductivity values with increasing concentration was determined [29].

Assawarachan [152] conducted ohmic heating experiment with red grape juice having concentrations of 10.5, 12.5 and 14.5 °Brix by applying three different voltage gradients (10, 12 and 15 Vcm$^{-1}$) in the temperature range of 25-80°C and reported that electrical conductivity increased as concentration and temperature increased. The increase of concentration of red grape juice was highly significant on increasing the electrical conductivity. Because the concentration increased solid particle in red grape juice, and it accelerated more electric current passed through red grape juice than low concentrated juice. The concentration of soluble solid in red grape juice explained the change in electrical conductivity. Addition of external compounds, like sugar and citric acid, resulted in a decrease in the conductivity values, while evaporative concentration provided an increase in conductivity.

Assiry et al [111] conducted experiment on electrical conductivity of seawater during ohmic heating, and reported that pure water is not a good conductor of electricity and it has a conductivity of 0.055 μScm$^{-1}$. Because the electrical current is transported by the ions in solution, the conductivity increases as water dissolved ionic species increase. Electrical conductivity of oceans and seawater was reported to be 53 (mScm$^{-1}$). It can be noticed that as the temperature approached 95°C, there was a slight drop in the electrical conductivity especially at high concentration and high electrical field strength. This drop could be the result of localized boiling and generation of vapor bubbles that reduced the electrical conductivity of the solution.

The concentration has more effect on the electrical conductivity than the temperature especially at high concentrations. The electrical conductivity increased as the temperature and the solute concentration increased, at all voltage gradients. The temperature dependency of electrical conductivities of whey solutions having solute concentrations of 8-24 % was linear [150].
2.4.6 Statistical Model of Electrical Conductivity during Ohmic Heating

Icier and Ilicali [145] conducted ohmic heating studies on tylose and minced beef and proposed a linear temperature dependent electrical conductivity equations as shown in Equation 2.13

Electrical conductivity, $\sigma = BT + C$ \hspace{1cm} (2.13)

Linear relationships having high regression coefficients were found for the temperature range of 30–60°C. Since the experimental electrical conductivity results for the minced beef samples showed a non-linear trend with increasing temperature, a non-linear equation shown in Equation 2.14

Electrical conductivity, $\sigma = BT^N + C$ \hspace{1cm} (2.14)

Darvishi et al [37] conducted ohmic heating in whole egg, white egg and yolk and reported that electrical conductivity increased almost linearly with temperature. High coefficients of determination ($R^2 > 0.98$) indicate the suitability of the linear model for conductivity variation with temperature for all the samples tested.

Darvishi et al [153] reported that as expected, the linear model gives the highest value of $R^2$ thus, the linear model may be assumed to represent the electrical conductivity of pomegranate juice during ohmic heating. The linear model has also been suggested by others to describe the ohmic heating of orange juice by Icier and Ilicali [29]; seawater by Assiry et al [111]; apricot and peach purees by Icier and Ilicali [145]; red apple, golden apple, peach, pear, pineapple and strawberry by Sarang et al [146]; and lemon juice by Darvishi et al [154].

Icier and Ilicali [29] reported that the orange juice concentrates having 0.20–0.60 mass fraction soluble solids, ohmically heated by using five different voltage gradients (20–60 Vcm$^{-1}$), showed linear relationship between temperature and the electrical conductivity for each concentration and voltage gradient applied. Castro et al [30] reported that electrical conductivity of strawberry-based viscous
products increased with temperature following linear or quadratic relations, depending on product type tested. Icier and Ilicali [29] recommended to use linear regression equation than non-linear regression equation for the orange juice tested at 0.20–0.60 mass fraction soluble solids, using five different voltage gradients (20–60 V cm\(^{-1}\)), as the regression coefficient was higher with linear regression.

2.5 ASCORBIC ACID DEGRADATION DURING OHMIC HEATING

Ascorbic acid is very important for human nutrition, since it is an essential substance that prevents diseases like scurvy, and it plays the role of biological antioxidant. As humans have no capability to synthesize this component, it should then be supplied by the diet [45].

Vitamin C is the least stable of all vitamins and is easily destroyed during processing and storage. The rate of destruction is increased by the action of metals, especially copper and iron, and enzymes. Availability of oxygen, prolonged heating in the presence of oxygen and exposure to light are all harmful factors to vitamin C content of foods [155, 156]. When oxygen is present, the contribution of the anaerobic degradation to the total vitamin C loss is small or not noticeable, compared to the aerobic degradation which has a much higher degradation rate [157].

The application of heat treatment is the most common method for stabilizing foods, because of its capacity to destroy microorganisms and inactivate enzymes. However, since heat can impair as well many organoleptic properties and reduce the contents or bioavailability of some nutrients, there is a growing interest in searching for new technologies able to reduce the intensity of the heat treatments needed for food preservation [158].

Ascorbic acid (AA), also known as vitamin C, has been the subject of numerous investigations in many scientific disciplines, including food science, medicine, and biochemistry. In recent years, AA has gained a renewed interest as a nutraceutical since it possesses antioxidant properties providing potential health benefits. AA is considered to be one of the most heat sensitive nutrients in foods,
and its degradation has been reported to vary with pH, oxygen, enzymes, metal catalysts, initial concentration, and light. This inherent instability of AA is a major concern in thermal food processing. Although a number of studies have examined AA degradation under conventional heat treatments, a little information is available related to ohmic heating [158].

Assiry [45] studied degradation kinetics of AA under ohmic heating conditions with stainless steel electrodes, and compared it with conventional heating. The results indicate that, at pH 3.5, although kinetics of AA degradation can be described adequately by a first order model for both conventional and ohmic heating, a number of electrochemical as well as secondary chemical reactions appear to have some effects on the kinetic parameters. Assiry et al [27] noted the influence of reactions at electrode/solution interfaces on degradation of AA in buffer medium during 60 Hz ohmic heating with stainless steel electrodes.

Giovana et al [40] studied vitamin C degradation in acerola pulp during ohmic and conventional heat treatment, and the results revealed that when experiments conducted with higher voltages (34 Vcm$^{-1}$), presented higher degradation percentage of 10%. When experiments conducted at lowest voltage 21 Vcm$^{-1}$, showed the lowest degradation percentage of 3%. Independent of the solids content of the pulp, lower values of degradation percentage were obtained using lower voltages. A greater degradation of ascorbic acid in acerola pulp is observed using high voltages because electrolysis and metal corrosion increase when high electric fields are applied, producing compounds that catalyze the degradation pathways of ascorbic acid in the presence of oxygen.

Vikram et al [35] studied the kinetics of ascorbic acid degradation during ohmic heating of orange juice by applying an electric field strength of 42 Vcm$^{-1}$; after 3 min of heating at 90°C, degradation percentage was approximately 35%. Lima et al [159] used ohmic heating to heat orange juice for 30 min at 90°C with an electric field of 18.2 Vcm$^{-1}$, and degradation percentage was approximately 21%. Clearly, the literature values for ascorbic acid degradation in food products are quite varied. This behavior may be due to vitamin C degradation mechanisms that differ
depending on the nature of the food system or reaction medium. Degradation can occur through aerobic and/or anaerobic pathways, depending on a number of factors such as pH, acidity, metal ions, light, humidity, water activity and temperature, presence of amino acids, carbohydrates, lipids and enzymes, among others [155].

Lima et al [159] verified that the presence of an electric field had no significant effect on the ascorbic acid degradation in orange juice. Although there was electrolysis and metal corrosion when stainless steel electrodes were used, these phenomena did not affect the final concentration of ascorbic acid.

2.5.1 Ohmic Heating versus Conventional Heating-Ascorbic Acid Degradation

Ohmic heating experiments carried out at low voltages (<140 V) exhibited AA degradation similar to the conventional heating (0 V). Castro et al [23] determined the ascorbic acid degradation kinetics in strawberry pulp under ohmic and conventional heating. The ascorbic acid degradation kinetics for temperatures ranging from 60 to 97°C was not affected by low values of electric field (<20 Vcm⁻¹). Studies performed by Lima et al [28] also demonstrated that the nature of the heating, either ohmic or conventional, did not significantly affect the degradation of AA in orange juice. He also reported that, high voltages promoted greater AA degradation during the ohmic heating when compared to the conventional heating. This behavior can be explained by the increase of electrochemical reactions during high voltage gradient operations which release ions into the liquid that catalyze the oxidation of ascorbic acid.

Vikram et al [35] compared the ascorbic acid degradation kinetics of orange juice by conventional heating, microwave heating and ohmic heating. He observed that the ohmic heating method facilitated higher nutrient retention at all temperatures, compared to other methods, followed by infrared and conventional heating. The degradation was highest in microwave, which may be attributed to uncontrolled temperatures generated during processing, which exceeded 100°C reaching 125°C and due to the heat labile nature of vitamin C.
Castro et al [23] studied the ascorbic acid degradation kinetics of strawberry products, and reported that the obtained kinetic parameters were identical for the two types of heating processes (conventional and ohmic heating) leading to the conclusion that the presence of an electric field does not affect the ascorbic acid degradation. Lima et al [159] took similar conclusions for orange juice systems.

Assiry et al [27] studied the Degradation kinetics of ascorbic acid during ohmic heating with stainless steel electrodes. The degradation rate under ohmic heating was not significantly different from that under conventional heating, except at high power (150 W) high NaCl content (1 %) and low temperature (40°C) conditions. Under these conditions the ohmic heating degradation rate was significantly greater than for conventional heating.

2.6 MECHANISM OF MICROBIAL INACTIVATION BY OHMIC HEATING

2.6.1 Need for microbial inactivation

Inactivation of microorganisms is important in many industrial applications and novel low-energy or energy-efficient methods of inactivation continue to attract interest [22, 144]. Concerning product safety and quality management, microbial inactivation is a key parameter to be addressed in food production processes. The presence of undesired or high numbers of certain microorganisms may cause product deterioration (e.g. substance degradation), quality loss (e.g. appearance changes, off-odors, off-taste, color deterioration, etc) and/or health problems (e.g. diseases and/or illnesses). Inadequate cooking, for example, is thought to be the major cause of Salmonella spp. outbreaks [160, 161].

2.6.2 Electroporation Effect of Ohmic Heating

Additionally to the heating promotion, research data strongly suggests that the applied electric field under ohmic heating causes electroporation of cell membranes. The cell electroporation is defined as the formation of pores in cell membranes due to the presence of an electric field and as consequence, the
permeability of the membrane is enhanced and material diffusion throughout the membrane is achieved by electro-osmosis [41, 159]. It is assumed that the electric breakdown or electroporation mechanism is dominant for the non-thermal effects of ohmic heating [42, 43].

Yoon et al [162] observed that under ohmic heating the electric field appeared to have both direct and indirect effect on the cell wall, and intracellular materials were exuded to the culture medium. The exudates seemed to be composed of amino acids, protein, nucleic acids, coenzymes, and related material. It is stated that, below 50°C, similar concentrations of exuded material were detected in the yeast supernatant, under conventional or ohmic heating [162].

However, at temperatures above 50°C, the concentration of exuded materials from the ohmic heated groups were higher than those from conventional groups (P<0.01) and that the rate of protein exuded per unit temperature increase was found to be significantly higher (P<0.01) with ohmic heating than with conventional heating. The authors hypothesized that the higher exudation rate was not only dependent on the destruction rate of the yeast cells but also on the type of heating method. The influence of the electrical field within ohmic heating might have increased the rate of electroporation, thereby leading to excess exudation and cell death. It was also observed that the amount of exuded protein increased significantly as the electric field increased from 10 to 20 Vcm⁻¹. Spectroscopic analysis has shown that for ohmic heatng at 20 Vcm⁻¹ the absorbance at 260 nm typically attributed to nucleic acids was 2-fold (P < 0.01) and the total protein content was 3-fold higher (P < 0.01) when compared with that at 15 Vcm⁻¹ [162].

All living cells, whether a prokaryote or eukaryote, contain cell membranes. These membranes are comprised of lipids (fatty molecules) and proteins. Prokaryotes have an additional layer outside the membrane known as the cell wall. At low frequencies (50-60 Hz) and high field strengths (>100 Vcm⁻¹) most commonly associated with ohmic heating, the naturally porous cell walls (Figure 2.5) can allow the cell membrane to build up charges, forming disruptive
pores (Figure 2.6). Electroporation occurs because the cell membrane has a specific dielectric strength, which can be exceeded by the electric field [119].

The dielectric strength of a cell membrane is related to the amount of lipids (acting as an insulator) present in the membrane itself. The pores formed can vary in size depending on the strength of the electric field, and can reseal after a short period of time. Excessive exposure causes cell death due to the leakage of intracellular components through the pores. Therefore, electroporation is highly damaging to a cell and would enhance the lethal effects of thermal abuse already present from the ohmic heating.

Pereira et al [163] have reported lower D and z values for the inactivation of *E. coli* and *B. licheniformis* when submitted to ohmic heating. In this research, comparing conventional against ohmic heating, the thermal history of the samples analyzed was adjusted to match. The D values observed for *E. coli* at 65°C were 3.5 and 0.86 min for conventional and ohmic process, respectively. The z values were also reported as 23.1 and 8.4°C respectively. The observed results indicate that the electric current may have affected the microbial death rate [163].
In the study, performed by Cho et al [119] on the *B.subtilis* and *Bacillus atrophaeus* inactivation kinetics by conventional moist heating and ohmic heating, it is possible to observe that the application of an electric field leads to lower thermal inactivation time, for the same temperature of treatment.

However, Palaniappan and Sastry, [116] found no difference between the effects of ohmic and conventional heat treatment on the death kinetics of yeast (*Zygosaccharomyces bailii*), under identical heating histories. In some cases, however, a mild electrical pretreatment decreased the subsequent inactivation requirements, for *E. coli*. The authors observed only slightly lower D values for the inactivation of *Zygosaccharomyces bailii* and *E. coli* when ohmic heating was applied at temperatures lower than 56°C. Although these D values were lower when compared to conventional heating, a t-test comparison at 95 % confidence level showed no significant statistical difference between treatments.

Milk viable aerobes and *S. thermophilus* inactivation have been accessed by Sun et al [164]. According to the authors the observed results demonstrated that ohmic heating causes higher microbial death than the conventional heating process. In this study, the final microbial count and the calculated D values for ohmic heating were significantly lower than those acquired from conventional heating, under the same temperature history conditions.

Yoon et al [162] have investigated the effect of ohmic heating on the structure and permeability of cell membrane of yeast cells (*Saccharomyces cerevisiae*). Under similar time-temperature history, for both conventional and ohmic heating, the authors have observed that little differences between processes could be observed under 50°C but the difference of yeast cell destruction rate under ohmic heating became much pronounced at 70-80°C.

Yildiz and Baysal [165] studied the effects of alternative current heating treatment on *Aspergillus niger*, pectin methylesterase and pectin content in tomato. These authors concluded that the critical treatment time for *A. niger* decreased as the electric field strength increased.
2.7 ELECTROCHEMICAL REACTIONS DURING OHMIC HEATING

Palaniappan and Sastry [25]; Assiry et al [27]; Assiry [45]; Uemura et al [166]; and Reznick [167] observed apparent electrolysis of the heating medium and electrode corrosion during ohmic heating. Some of these authors reported that those electrochemical effects diminish with increasing frequency. A broad discussion of fundamental electrochemistry related to ohmic heating has been given by Amatore et al [168]; and the use of high alternating frequencies was suggested to inhibit adverse electrochemical effects. Tzedakis et al [169] has recently examined the electrochemical behavior of platinum and platinized-titanium electrodes for ohmic sterilization of some commercial food products. Their results indicate that, at the frequency of 50 Hz, only platinized-titanium would be capable of suppressing the electrochemical behavior.

2.7.1 Effect of Electrochemical Reactions on the Ohmic Heating Process

In ohmic heating, the electrical energy provided to the heating cell is ideally used only for heat generation; and electrochemical reactions at electrode/solution interfaces are considered undesirable. Electrodes in ohmic heating can be regarded as a junction between a solid-state conductor (i.e. current feeder) and a liquid-state conductor (i.e. heating medium). They play a vital role by conveying the current uniformly into the heating medium. Various materials, so far, have been used as electrodes in different ohmic heating studies and applications, Aluminum, Carbon (graphite), Platinum, Platinized-titanium, Rhodium plated stainless steel, Stainless steel, Titanium [170].

At low-frequency (50–60 Hz) alternating currents, corrosion of electrodes and apparent (partial) electrolysis of the heating medium were noticed with most of those electrodes. With some electrodes, a particular electrochemical reaction may occur slowly or not at all; but with another type of electrode, the same reaction may be faster under the same set of conditions. Such information about electrodes under ohmic heating conditions is, therefore, important to avoid or inhibit
the electrochemical reactions by choosing appropriate electrode materials [170]. In stainless steel electrodes, there was possibility of electrochemical reactions occurred at the electrode/solution interfaces as mentioned in Assiry et al [27] and Icier [150].

Food materials are inherently a complex mixture of several different chemical compounds. During ohmic heating, various electrochemical reactions can potentially occur. In addition, some of the products of those electrochemical reactions may initiate a number of secondary chemical reactions [170].

2.7.2 Electrode Corrosion

In ohmic heating, electrodes are necessary to convey the current to the food material to be heated. During heating, electrode corrosion occurs mainly via electro-dissolution induced by the low-frequency AC. For metallic electrodes (M), a generalized anodic half reaction for the electrode corrosion can be written as follows.

\[
M_{\text{(solid)}} \rightleftharpoons M^{n+}_{\text{(aqueous)}} + n \text{e}, \quad (\text{where } n = 1, 2, 3...)
\]  

(2.16)

The metal ions (M \(^{n+}\)) migrated into the heating medium are basically contaminants, and may have some toxic potential. However, on the other hand, the electrode corrosion might represent an opportunity to introduce essential minerals into the processed foods. Since food systems are generally rich in ligands, the migrated transition metal ions can form various coordination complexes. Those metal complexes typically have characteristic colors; and therefore, they may involve alteration of color of the processed foods. It is also known that, some transition metal ions have catalytic effects for certain food reactions, such as lipid oxidation. Therefore, the electrode corrosion may have an impact on flavor quality of the processed food products [170].
2.7.3 Titanium Electrodes

Titanium is considered to have high corrosion resistance and biocompatibility characteristics [158]. It is generally the material-of-choice for chloride environments. Although the SEM micrograph indicates poor double layer capacitance, the corrosion rates of titanium electrodes at all the pH values were significantly lower (P≤0.05) than those of the stainless steel and graphite electrodes. The possible reason could be the oxide layer that covers active titanium metal, protecting it against corrosion. Since titanium exhibits high affinity towards oxygen [171], the protective oxide layer could be formed by reacting with atmospheric oxygen even before using the metal as electrodes, and also during the ohmic heating treatments. Tzedakis et al [169] discussed the possibility of forming rutile (TiO$_2$) due to electrochemical processes during ohmic heating, partially passivating the titanium electrodes.

Titanium forms various oxides having different colors, such as TiO$_2$ – anatase (yellowish), TiO$_2$ – rutile (white), TiO$_{1.9}$ - oxygen deficit (bluish), and Ti$_3$O$_5$ (violet) [171]. At all the pH values, author observed formations of adherent surface films with a yellowish-brown color with some blue and violet coloration, which therefore, imply the electrochemical generation of oxygen during ohmic heating. However, there was no detectable pH change of the heating medium at any pH.

2.7.4 Stainless Steel Electrodes

Stainless steel is an iron-chromium alloy containing at least 11 % chromium. The grade designated by 316 belongs to austenitic family of stainless steels, and contains chromium (17 %), nickel (10 %), and molybdenum (2 %) as major alloying elements [172]. In the food industry, stainless steels are in widespread use as food contact surfaces. The stainless steel electrodes exhibited pronounced corrosion rates, hydrogen generation, and also pH changes of the heating media at all the pH values. In addition to the chemical reactivity of stainless
steel, the lack of double layer capacitance, would be responsible for the pronounced electrochemical behavior. The observed adherent surface films formed on the stainless steel electrodes during ohmic heating, were transparent, with a light golden color and some brown rust. The films, however, did not uniformly cover the electrode surfaces, and showed several cracks [173].