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Ohmic Heating Technology and Its Application in Meaty Food: A Review

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Authors' contributions

This work was carried out in collaboration among all the authors. Authors RR, NCS, AS, UCL, PKO and TKB conceptualized the study. Authors RR, NCS, AS, UCL designed the study and wrote the protocol. Author RR wrote the first draft of the manuscript and revised by authors NCS, UCL and PKO. All authors read and approved the final manuscript.

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ABSTRACT

The purpose of the current review paper is to investigate and analyze about the effects of ohmic heating (OH) different application in the field of fish, meat and its product and compare it with other conventional thermal methods of food processing such as thawing, heating, cooking etc. Food quality, food safety, convenience, freshness, healthy food, natural flavor and taste with extended

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shelf-life are the main criteria for the demand made by today's consumers. Ohmic heating is a substitute of conventional heating method of food commodities. It has shorter heating times, avoid hot surfaces and help to minimize temperature gradients. Product parameters such as electrical, thermo-physical and rheological properties of the food and process parameters such as the current frequency, electrode material and the geometry of ohmic chamber affect the process. as a result various application of OH are found such as heating, evaporation, dehydration, extraction, waste water treatment, thawing, cooking of different type fish and meat and its product such as meat ball, hamburger patties surmi, beef, turkey etc.

Keywords: Ohmic heating; electrical conductivity; fish and meat.

1. INTRODUCTION

Food is a basic element that living animals eat to get the proper nutrition essential for their life and growth. There is a need to process food to prevent, reduce and eliminate infestation microbial growth or toxin production as microorganisms lead to food deterioration like degradation of substance, quality loss viz appearance change, off-odors & color deterioration and health problem can be avoided. Food production processes inactivate microorganism hence provide good product quality and safety management [1,2].

Present scenario of supermarkets get changed as compare to past there is more requirement of ready to eat product in market. Apart from fruit and vegetable there is also a huge demand of fish and meat ready to product such as soup, biscuit, fish and meat ball, cutlet, nuggets, sausages, pickle etc. and its hygienic marketing for earning higher economic returns and its availability throughout the year. Through value addition cost can be enhanced and it also adds over few per cent more profit. India is lagging in fish and meat processing sectors as compare to other country. Conventional heating and cooking has many disadvantages viz low rate of heat penetration to the centre (pasteurization) which causes long cooking time and outer layer of muscle absorb more heat which deteriorate the quality of the product. It also causes high heat loss (conduction and convection) due to heat-transfer mechanisms of conduction, convection and radiation. The internal resistance causes heterogonous heating thus creating significant loss of product quality [1,3,4, and 5]. Hence alternative technologies are introduced to overcome these disadvantages. The utilization of electrical energy directly in the food has grabbed the attention in the food industries.

2. PROCESSING TECHNIQUE AND PRINCIPLE of OHMIC HEATING

2.1 What is Ohmic Heating?

Ohmic heating is a novel thermal food processing operation in which electric currents are passed through conductive foods with the prime purpose of heating them and as food also has some resistive properties so heat is generated because of resistance [6]. Joule heating, electrical resistance heating, direct electrical resistance heating, electro-heating, and electro-conductive heating are some another name of OH. Joule heating is a practice by which the passage of an electric current through a conductor releases heat. Its basic principle shows in Fig. 1. The amount of heat released is proportional to the square of the current as shown in equation 4 [7].

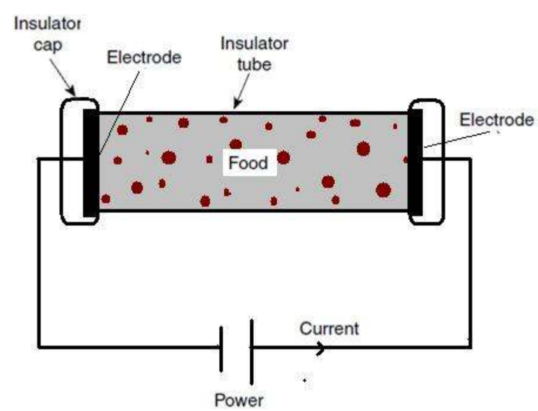

Fig. 1. Ohmic heater principle

2.2 How Ohmic is Different than Conventional Heating

In conventional method heating are applied at the coldest point of a system, which is generally the center of the largest particle. In conventional heating, the time it takes to increase the temperature at this cold point may over process the remaining particles and the surrounding liquid. This over-heating causes the destruction of nutrients and flavor. Ohmic heating processes the particles and neighboring particles at the same time and inhibit overcooking and reduces fouling problems and thermal damage to a product due to absence of hot surface [8].

2.3 How Heat Is Generated

Since electrical energy can directly be converted into thermal heat without any loss of heat this principle is use to generate an internal energy in the material which causes the heating of material. The rate of heat generation is directly proportional to the square of electric field strength and electrical conductivity of material [9]. These are generated because of the motion and collision of ion in food. This collision causes the transfer of momentum which increases the KE hence generating heat in it. Transfer of momentum is the amount of momentum the one particle transfer to another. The presence of electrodes contacting the food, frequency, and waveform (also unrestricted, although typically sinusoidal) made it different from other electrical heating methods. Generally 50-60 Hz alternating current is used for ohmic heating [10].

2.4 Working of Ohmic Heating

Foods with water and ionic salts have conductive property but due to their resistive behavior it generates heat when an electric current is passed through them, as resistive material oppose the current and movement of ion. The food behaves as an electrical resistor. The electrical resistance of a food is the most important factor in determining how rapidly it will heat. Therefore in product formulation, process control and quality assurance conductivity measurement is important all foods that are heated electrically.

Ohmic heating depend on the Ohm's Law which deals with the relationship between voltage and current in an ideal conductor

$$V = IR \quad (1)$$

The measured resistance is converted to conductivity using:

$$R = \frac{1}{\sigma} x \, L/A = \rho L/A \quad (2)$$

So by putting R value in eq^n 1 $V = I\,(1/\sigma)\,L/A$

$$\sigma = \frac{I}{A} / \frac{V}{l} \quad (3)$$

Where $\sigma = 1/\rho$

$$H = E^2\,\sigma \quad (4)$$

$$E = V/\ l \quad (5)$$

$$H = I^2RT \quad (6)$$

Where

ρ = resistivity of product
σ =product conductivity in (S/ m)
R Resistance in ohms (Ω), present in the conductor
V = potential difference between two points which include a resistance R
I = current flowing through the resistance which flow in conductor
L = Length of the cell in m and
A = Area of the cell (m^2)
I/A = current density
L/A Cell constant
E =electric field strength
V/ L = Voltage gradient ie. ratio voltage applied to distance between two electrode
t is the amount of time that this happens for.
H is the amount of heat

2.5 Factors affecting Ohmic Heating Process

In any process food (material) and machine (system) both parameters affect the process. Electrical conductivity of a food product is a vital factor which affects the ohmic heating while temperature, voltage gradient, frequency, and concentration of electrolytes influence the electrical conductivity [11,12 and 13]. Machine parameters such as rate of heat generation, electrical field strength, residence time and the method by which the food flows through the system affect OH [14,15]. In machine variables voltage or voltage gradient, electrode distance and area of electrode while in material or product variables composition, physical and electrical properties of food influence the effectiveness of ohmic heating. Food, which have ample amount of water and ionic salts, is the most appropriate for ohmic heating [9]. Heating follows Ohm's law in which the current flowing between product and electrode are determined by conductivity or resistivity of food. Machine and material as an independent variables which affect ohmic heating process are tabulated in Table 1.

2.5.1 Food properties affecting ohmic heating

2.5.1.1 Electrical properties

2.5.1.1.1 The electrical conductivity (σ)

It is a measurement of how well and easy the movement of an electric charge. It is the ratio of the current density to the electric field strength and unit is Siemens per meter (S/m), which can be calculated from the equation (3). It is a mainly depend on food chemistry and structure and temperature. Food components such as ionic components (salt), acid amount and type of electrolyte, pH, protein and moisture content affect electrical conductivity positively while fat, lipids and alcohol affect it negatively [16,17] hence by altering these EC can be changed. For purely liquid foods, the electrical conductivity increases linearly with temperature due to increased ionic mobility but overall falls as the concentration of liquid in it increases [18]. In solid foods, the situation is more complicated as the electrical conductivity rises linearly with temperature, especially at low voltage gradients and may be different in different directions within the solid. Hence high temperature can be attained by increasing the current or voltage and using longer distance between electrodes Ionic mobility can also be altered by changing the structure in tissue like cell wall break down, softening and reducing the phase viscosity [19].

2.5.1.1.2 Electric field strength

It can be calculated by equation (5) and its unit is V/cm may be varied by changing either the applied voltage or gap between the electrodes. The electrode gap (distance between the electrodes in the system) can be adjusted according to the size of the ohmic heater.

2.5.2 Rheological properties

Higher viscosity fluids have faster ohmic heating than lower viscosity fluids. Ohmic heating follows power law between their apparent viscosity and shear rates. Example ice cream mixes exhibit non Newtonian behavior. Apparent viscosity of ice cream mixes decreases as the temperature increases [20].

2.5.3 Physical properties

Density, size and shape of particle pieces. Electrical conductivity decreases as particle size and concentration increases [13].

2.5.4 Thermal properties

Thermal properties of food such as specific heat and thermal conductivity also affect the ohmic heating as electrical energy is going to be converted into thermal energy and provide heat to food. Specific heat capacity is the amount of energy needed to increase the temperature of a substance by a certain interval. It determines temperature distribution in a substance that is to be heated ohmically. High heat transfer and heating rate can be obtained for the lower heat capacity of product. Thermal conductivity also gets changes as temperature changes.

2.5.4.1 Heating power supplied to ohmic heater

The energy (heat, P) supplied to the ohmic heater are calculated by using the current (I) and voltage (ΔV) during heating time [11].

Work done on resistor = Energy given to system

$$W = VI\Delta t$$

$$W/\Delta t = P = VI \quad (7)$$

$$W = P = VI\Delta t \quad (8)$$

Where

W= Work done
P =Energy supplied to the ohmic heater

Table 1. Variables affect ohmic heating process

Food variables (Material)	Ohmic heater variables (Machine)
Electrical properties (electrical conductivity, electric field strength)	Voltage or voltage gradient
Rheological properties(viscosity)	Distance between electrode
Physical properties (size and shape)	Area of electrode
Thermal properties (rate of heat generation)	Current

2.5.4.2 Rate of heat generation

Electrical energy is converted into thermal energy and a sensible heat is generated which causes rise in the temperature of the sample rise from T_i to T_f. Energy required to heat the product can be calculated from the following equation (9).

$$Q = m\, C_p\, (T_f - T_i) \quad (9)$$

Electrical resistance of the food produces the energy which causes a change in thermal energy of the product between inflow and outflow [21].

$$P = VI = m\, C_p\, (T_f - T_i) + m\,\lambda + Q_{loss} \quad (10)$$

Heat dissipated through product = thermal heat generated in the product

Where

- m = Mass of the product
- C_p = Specific heat
- T_i = Initial temperature of product
- T_f = Final temperature of product

2.5.5 Ohmic heater system variables affecting ohmic heating

2.5.5.1 Voltage gradient

The amount of heat generated is directly related to the current induced by the Voltage gradient in the field. It has increasing effect on electrical conductivity [17].Voltage application causes fluid motion through the capillary porous membrane of biological tissue. Applied voltage also affects the electric field strength.

2.5.5.2 Electrode area and distance between electrodes

They affect electrical conductivity, temperature profile and heating rate during the ohmic heating process.

2.5.5.3 Electrode material

1-mm-thick platinised titanium electrode found to be the most appropriate electrode material for the ohmic heating [22] as it is resistant to electrolysis, provide a suitable heating rate.

2.6 How Ohmic Heating Affect Microbial Inactivation

Ohmic heating inactivate the microbes and its basic principle is thermal in nature. Ohmic heating may cause mild electroporation of cell membrane under applied electric field. Low frequency (50 - 60 Hz), allows cell walls to build up charges and form pores [7]. Electroporation is a formation of pores in cell membranes due to the presence of an electric field which enhance the permeability of the membrane. Material diffusion throughout the membrane is achieved by electro-osmosis [23,24]. It is assumed that the electric breakdown or electroporation mechanism is dominant for the non-thermal effects of OH [25].

3. OHMIC HEATING APPLICATION IN MEATY FOOD

Ohmic heating is getting popular as an alternative method of the indirect heating of food processing [26,17] such as heating of liquid foods such as soups, stews, and fruits in syrup, heat sensitive liquids processing, Juices treated to inactivate proteins (such as pineapple or papaya), blanching, thawing, starch gelatinization, sterilization, peeling of fruits and vegetables (eliminating the need for lye-a harmful corrosive chemical), dehydration, extraction, fermentation and processing of protein-rich foods which tend to denature and coagulate when thermally processed. Except this now days application of ohmic heating is also becoming popular for meaty food such as meat product and fish products etc. Applications related to fish and meat is discussed as below:

3.1 Fish

Fish is good sources of animal protein with low fat which is in high-quality. Beside this it contains omega-3 fatty acids, vitamins such as D and B_2 (riboflavin) and calcium and phosphorus and other minerals, such as iron, zinc, iodine, magnesium, and potassium which is essential for maintaining a good health, brain, and heart. It has high moisture content and low acid content which make it an extremely perishable after catch if not utilized within one day under normal condition, get spoiled as it is a good medium for the growth of microorganisms after death. Microbial action, chemical action, enzymatic action and physiological deterioration degrade the fish quality (example proteins, carbohydrates, fat and color) after death without any preservative or processing measures within 12-20 hours at tropical temperature.

3.1.1 Fish heating

OH of fish inactivates endogenous enzymes and stop microbial growth [27]. Optimization of process variables for ohmic heating (OH) of fish steaks was done by response surface methodology. Ohmic heating maintain good product quality.

Ohmic cooking of shrimps (Pandalus Borelias) was done at a core temperature of 72℃ in a brine solution using a small batch ohmic heater. A comparative analyses of the temperature development between different sizes of shrimps and thickness over varying salt concentrations (10 kg m^{-3} to 20 kg m^{-3}) and electric field strengths (1150 V m^{-1} to 1725 V m^{-1}) with the heating time as the response was done; 2) a 2 level factorial experiment for screening the impact of processing conditions using electric field strengths of 1250 V m^{-1} and 1580 V m^{-1} and salt concentrations of 13.75 kg m^{-3} and 25.75 kg m^{-3} and the heating time until the set temperature of the shrimps, weight loss, press juice and texture profile were measured as a response. It was possible to fit main effects model relating process settings and the heating time, weight loss and press juice measurements. It was found that no significant changes were seen in the texture measurements of the shrimps and that the shrimp achieved a comparable quality compared to the conventional heating processes hence ohmic heating is good method for shrimp [28].

Ohmic heating of Alaska pollock surimi mixed with native and pregelled potato starch at different concentrations (0%, 3%, and 9%) was done to find out the electrical conductivity at different moisture contents (75% and 81%). Surimi-starch paste was tested up to 80°C at frequencies from 55 Hz to 20 KHz and at alternating currents of 4.3 and 15.5 V/cm voltage gradients. Electrical conductivity increased when moisture content, frequency and voltage increased, but decreased when starch concentration increased. Electrical conductivity was correlated linearly with temperature ((R^2) approximately 0.99). At high concentration of starch when temperature changes after 55℃ the electrical conductivity behavior changed. Starch gelatinization also affects the electrical conductivity. Whiteness and texture properties decreased with an increase of starch concentration and a decrease of moisture content [29].

3.1.2 Fish waste water treatment

Protein removal can be done from fish mince (threadfin bream) using ohmic heating in order to improve water quality under different electric field strengths (EFS, 20, 25, and 30 V/cm) until reaching the desired temperature (50, 60, and 70℃), and further held at that temperature for a certain time (0, 15, and 30 minutes). Among all the different level of temperature 70℃ resulted in a better protein removal when compared to 50 and 60℃. Reduction of protein, COD, BOD, TS, and TDS to 42%, 25%, 23%, 44%, and 61%, respectively obtained after ohmic treatment. The electrical conductivity has a linear relationship with temperature and the temperature confirmed a parabolic relationship with heating time. EFS and holding time have no significant effect on protein removal [30].

3.1.3 Ohmic thawing of frozen surimi or fish product

A frozen saline surimi cube can be thawed using ohmic heating. A homogeneous temperature distribution in the frozen surimi was obtained at different concentration of electrode solution and at a certain level of applied voltage of V and frequency of Hz. The thawing rate increased linearly with the increasing concentration of electrode solution. The changes in thawing rate and temperature distribution with the concentration of electrode solution could be explained by an equivalent electric circuit. As compare to conventional thawing the ohmic thawing had a higher thawing rate and resulted in stronger gels [31].

3.2 Meat

Red meats are a tremendous source of high protein, vitamin B12, niacin, vitamin B6, iron, zinc and phosphorus, source of long-chain omega-3 polyunsaturated fats, riboflavin, pantothenic acid, selenium and possibly also vitamin D. It is mostly low in fat and sodium and sources of a range of endogenous antioxidants and other bioactive substances including taurine, carnitine, carnosine, ubiquinone, glutathione [32].

3.2.1 Meat heating

Ohmic cooking of minced beef–fat blends having different fat level (2%, 9% and 15%) and full meat-fat samples were done at different voltage gradients (20, 30 and 40 V/cm). Temperature and the composition of the blends affect electrical conductivity. Initial fat content has significant effect on electrical conductivity while voltage gradient did not have any effect on the electrical conductivity changes during cooking treatment ($p > 0.05$). The electrical conductivity of the samples increased with increasing temperature up to the critical initial cooking temperature (60–70℃) depending on the fat level, and then decreased (cooking region) due to structural changes and the increase in the bound water during cooking. The nonlinear mathematical model including the effects of initial fat level and the temperature on the electrical conductivity changes had good agreement (r = 0.952; SEM = 0.009) with the experimental data. During the ohmic cooking, as the initial fat content increased the change in the fat content during cooking increased. The moisture removal was not different for the different voltage gradients applied [33].

Cylindrical cores of beef semitendinosus (500 g) were cooked in a combined ohmic/convection heating system to low (72℃, LTLT) and high (95℃, HTST) target end-point temperatures. A control was also cooked to an end-point temperature of 72℃ at the coldest point. Microbial challenge studies on a model meat matrix confirmed product safety. Hunter L-values showed that ohmically heated meat had significantly ($p < 0.05$) lighter surface-colours (63.05 (LTLT) and 62.26 (HTST)) relative to the control (56.85). No significant texture differences ($p \geq 0.05$) were suggested by Warner-Bratzler peak load values (34.09, 36.37 vs. 35.19 N). Cook loss was significantly ($p < 0.05$) lower for LTLT samples (29.3%) compared to the other meats (36.3 and 33.8%). Sensory studies largely confirmed these observations. Cook values were lower for LTLT (3.05) while HTST and the control were more comparable (6.09 and 7.71, respectively). These results demonstrate considerable potential for this application of ohmic heating for whole meats [34].

<u>3.2.2 Meat thawing</u>

Frozen storage preserve meat for a long time. Meat thawing and thawing process may affect the qualifications of quality as much as preservation due to physical and chemical activities. Longer thawing time, weight loss due to the high amount of leakage, nutritional loss with the leaked fluids and unwanted microbial activity during thawing are the some drawback of the conventional thawing. In context to this ohmic heating system provide good thaw quality product with fastest thawing and the least weight loss [35].

Ohmic thawing of the frozen beef at different voltage gradients 10, 20 and 30 V/cm, also shows a good result as compare to conventional thawing 25℃, 95% RH. Different sample sizes of beef cuts (2.5 cm × 2.5 cm × 5 cm, 2.5 cm × 5 cm × 5 cm, 3. 5 cm × 5 cm × 5 cm) was reached to the center temperature +10℃ from −18℃. Significant differences were found between thawing methods in terms of the temperature homogeneity, the thawing time and the thawing loss ($P < 0.05$). The thawing time decreased with increase in voltage gradients, while the thawing loss remained unchanged. There was a decrease in the EUR (47–70%) with the increase in the sample size and the voltage gradient applied during ohmic thawing [36].

<u>3.2.3 Meat product (other example of meat ohmic heating with experimental result)</u>

3.2.3.1 Hamburger patties

Combined ohmic and plate cooking can improve cooking time of hamburger patties over conventional plate cooking process. Meat emulsion batters cooked very rapidly using ohmic heating. Overall average proximate was determined for leg lean, shoulder lean, belly fat and back fat. Within each of the meats there are no significant differences ($P < 0.05$) between the compositions of the individual batches. The protein, fat and ash values for pork leg and shoulder were significantly different ($P < 0.01$) but no significant difference ($P < 0.05$) was found in the moisture and salt contents. Lean belly had significantly lower moisture and higher fat and ash contents than the other lean components and was intermediate in protein content ($P < 0.05$). Back fat had significantly lower ($P < 0.05$) moisture, protein fat and ash contents than belly fat [37].

3.2.3.2 Bologna meat sausages other example of meat ohmic heating with experimental result

A bologna emulsion (lean and fatty pork meat, sodium chloride, sodium erythorbate, and sodium nitrite) was cooked in 1-kg portions, either in a smokehouse of 180-min cycle at a core temperature of to 70℃ or by ohmic heating (64 to 103 V; 3.9℃/min to 10.3℃/min; to 70℃ to 80℃). The finished products were compared for color, texture, pH, drip, Eh, and rancidity. Heating rates, final temperatures, and holding time of 20 min had little influence on the quality of ohmic sausages. Ohmic sausages quality was similar to smokehouse products except for texture, which was significantly softer ($P > 0.05$) in ohmic products but could be hardened by use of binders [38].

3.2.3.3 Meat ball other example of meat ohmic heating

The mixtures of pork meat ball and water were cooked using static ohmic heater. Ohmic heating was done at heating rate of 4.9℃/min and at 24.5℃/min. Ohmically heated meat balls attributes were compared with conventionally-heated samples. Models were developed for estimating the sample temperatures during ohmic heating and also investigated the effects of ohmic heating on the meat ball qualities. Sukprasert's model was the most precise while the finite difference model was accurate with empirical terms [39].

Effectiveness of ohmic treatment on some quality attributes of semi-cooked meatballs was studied. Meatball samples were semi-cooked by 15.26 V/cm voltage gradient and 0 s holding time at 75℃. Although ohmic cooking significantly reduced the numbers of total mesophilic aerobic bacteria, mould-yeast, *Staphylococcus aureus* and completely eliminated *Salmonella* spp. from meatball samples ($p < 0.05$), it was not found efficient to inactivate all *Listeria monocytogenes* cells. Ohmic semi-cooking process was resulted at higher cooking yields, which were supported by high fat and moisture retention values in meatball samples. Metal levels (iron, chromium, nickel and manganese) of ohmically semi-cooked meatball samples were found below the upper level of dietary exposure levels. Ohmic cooking procedure was found to be safe in terms of PAH formation and mutagenic activity. Sensory evaluation showed that the overall acceptance of the semi-cooked meatball samples were good. These results demonstrate considerable potential for the application of ohmic process for semi-cooking of meatballs [40].

3.2.3.4 Ohmic reheating chicken noodle soup and black beans

A pulsed ohmic heating system and flexible package for food reheating and sterilization were developed to minimize Equivalent System Mass during long-duration space missions. A package made of flexible pouch materials was powered through a pair of metal foil electrodes extending out. Preliminary tests of the package within an ohmic heating enclosure show that International Space Shuttle menu items such as chicken noodle soup and black beans could be heated using pulsed ohmic heating technology. The electrical conductivities of selected samples ranged between 0.01 and 0.03 S/cm. A 2-D thermalelectric model was developed using commercial CFD software Fluent to optimize the design and layout of electrodes to ensure uniform heating of the material. A package configuration with V-shaped electrodes with dimensionless width of 0.147 was validated to be most appropriate for uniform heating while minimizing the cold zone to 2% of total area. The effect of field overshoot near the electrode edge is expected to be crucial to determine the uniformity of heating [41].

In a flexible package such as chicken noodle soup and black beans could be reheated to serving temperatures using pulsed ohmic heating. Depending upon the electrode configuration, thermal behavior of food samples were observed with diversity that were numerically modeled. The predictive accuracy was typically lower at each end of the package (maximum prediction error of 14℃), wherein the electric field strength is weakened. This might be because of localized non uniformity between the two phases, i.e., liquid and particulate [41].

4. CONCLUSION

Ohmic heating is an emerging novel technology; which has a ample number of industrial function such as blanching, evaporation, dehydration, fermentation, extraction, sterilization, pasteurization and heating of foods and all these application are also used and investigated for fish and meat processing industry. Its basic principle is based on Joule heating in which the passage of an electric current through a conductor releases or dissipates heat. The electrical conductivity of food materials controls ohmic heating system which provides superior product quality, less cooking time and uniform heating. It can be concluded that ohmic heating offer good result as compare to all conventional method of heating, product development such as hamburger patties, meat ball, meat sausages etc products, microbial inactivation and cooking. It is also observed that OH not only used for meaty food processing but it can also be used for effluent and waste water treatment of food processing industry. Different fish and meat product and value added product can be formed through ohmic heating. Beside all these advantages more research is required to maintain the uniform heat generation rate, especially for semi solid, and high moisture content food [34].

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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