Oscillating Magnetic Field in Advanced Food Processing

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Introduction:

The focus of food engineers and food scientists in the last 20 years has been on finding alternative process and preservation technologies that are environment friendly, low in cost, and able to preserve the quality attributes of the food product. A number of novel non-thermal technologies such as high pressure and irradiation are currently under commercialization and offer many of these advantages to the consumer. These new technologies have been extensively researched worldwide from a microbiological point of view and study of composition factors and sensorial characteristics after processing has also been conducted. The main purpose of processing is the inactivation of pathogenic microorganisms and spores (depending on the treatment) to provide consumers with a microbiologically safe product. Scientists are exploring the use of pressure, light, different types of electromagnetic radiation, sound, and other physical hurdles to inactivate bacteria.

Food processing is a seasonal in nature in terms of demand of product and availability of raw materials. Food processing is the transformation of raw ingredients, by physical or chemical means into food or into other forms of food. Food processing combines raw food ingredients to produce marketable food products that can be easily prepared and served by the consumer. During the last two decades, a considerable change regarding research and developments in the food processing technology have occurred. These new advances infood preservation technologies fall under the umbrella of non-thermal food processing. Many of the methods investigated in this study are modifications of thermal food processing technologies. Non-thermal food processing methods are also known as minimal processing methods. These processing methods can preserve foods without substantial heating, while retaining their nutritional benefits and sensory characteristics. These processing methods also contribute by extending the shelf life of the product by inhibiting or killing microorganisms. Thus, they provide products that are fresher-tasting and more nutritious, without the application of heated chemicals. Innovative, non-thermal processes have attracted the attention of many food manufacturers, in search of new food processing methods. These food processing technologies played a vital role in environmental sustainability and universal food safety. The need of food processing is for -

- Removal of microbes, toxic materials from food

- To enable transportation
- To increase the shelf life
- For value addition
- To meet customer demand
- To improve the quality of food.

Non-thermal technologies represent a novel area of food processing and are currently being explored on a global scale research has grown rapidly in the last few years in particular. These new technologies for food processing are normally applied under non-thermal conditions. Although temperature could be used in combination with some of these novel technologies to enhance effectiveness, most of the research conducted is at room temperature, and due to extremely short processing times, food remains fresh.Non-thermal Food Processing Technologies are -

- High Pressure Processing (HPP)
- Ultrasound
- Pulsed Electric Field (PEF)
- Pulsed Light
- Plasma Sterilization
- Irradiation
- Oscillating Magnetic Field (OMF)

Oscillating Magnetic Field-

A magnetic field is a region in which a magnetic material is able to magnetize the surrounding particles.The induced magnetic field may be static or oscillating. The oscillating magnetic fields are produced by passing a fluctuating current by the electromagnets. High intensity magnetic fields are used in food processing. Oscillating magnetic fields (OMF) have been explored for their potential as microbial inactivation methods. An OMF is applied in the form of constant amplitude or decaying amplitude sinusoidal waves. The magnetic field may be homogeneous or heterogeneous. In a homogeneous magnetic field, the field intensity B is uniform in the area enclosed by the magnetic field coil, while in a heterogeneous field, B is non-uniform, with the intensities decreasing as distances from the center of the coil increases. OMF applied in the form of pulses reverses the charge for each pulse, and the intensity of each pulse decreases with time to about 10% of the initial intensity.

Mechanism of OMF

- A charged ion/particle (q) entering a magnetic field (B) at a certain relative speed (v) experiences a magnetic force (F), calculated as: $F = q(v \times B)$.
- When v and B are in parallel, F is zero. When v is normal to B, the ions move in a circular path.

- For other orientations between v and B, the ions move in a helical path.
- The frequency at which the ions revolve in the magnetic filed is known as ion's gyro frequency (n).
- This frequency is depends on the charge/mass ratio of the ion and the magnetic field intensity.

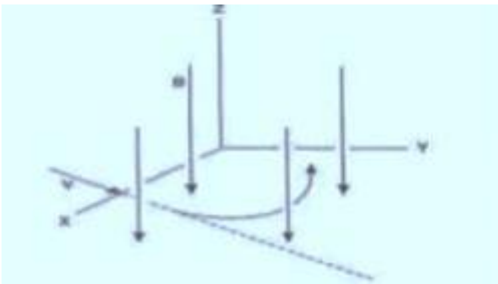

Fig. Charged particle in a magnetic field when v is normal to B

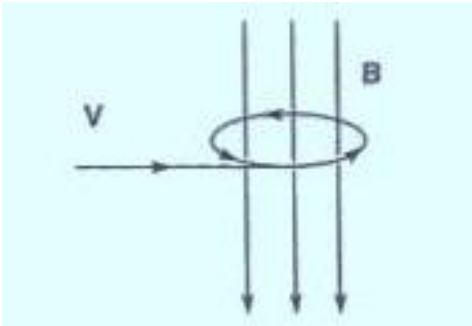

Fig. Charged particle moves in a circular path when v is parallel to B

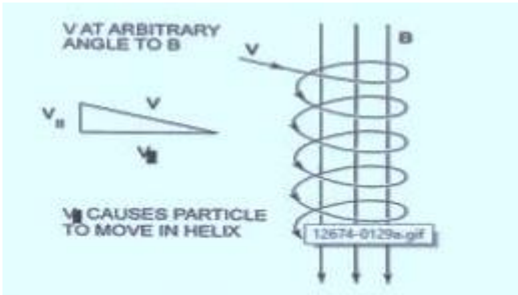

Fig. Charged particle moves in a helical path when v and B in other orientations

Generation of high intensity magnetic fields-

For high magnetic fields superconductor coils are used. The electric current passed through these coils, up to 40kA. High voltage DC power supply charges the capacitor. On closing the switch the oscillating current produced inside the capacitor. Thus an oscillating magnetic field induced to the food material kept with magnet coil. In order to inactivate micro-organisms, flux density of 5 to 20 T (Tesla) is required which corresponds to high intensity. OMF of this density can be generated by using (Gersdorf *et al*, 1983):

i) superconducting coils
ii) coils with produce DC fields
iii) coils energized by the discharge of energy stored in a capacitor

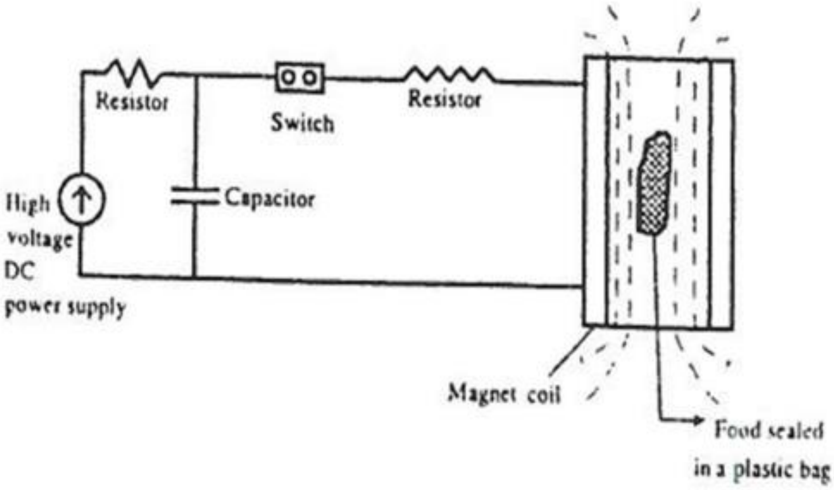

Fig. Electrical circuit generating oscillating magnetic field

When the core of paramagnetic or ferromagnetic material is placed inside the coil, magnetic fields are produced that having more intense. Magnets with superconducting coils will then need to be used to generate magnetic fields up to 20 T. In order to keep the superconductor filaments below the critical temperature (4.2K), liquid helium is used as a coolant for superconducting materials, whereas liquid nitrogen is used for higher temperatures. This combination generates high magnetic fields of more than 30 T. Thus the system uses the energy stored in a capacitor bank for later release by generating an oscillating electrical current that, in turn, generates an OMF. The frequency and intensity of the magnetic field are determined by the capacitance of the capacitor and the resistance and inductance of the coil. Superconducting magnets have several advantages over resistive electromagnets. The field is generally more stable, leading toless noisy measurements, they can be smaller, which allows more freedom when configuring the rest of the device, and consume much less power, since consumption is negligible in the steady state (Asner, 1999). Higher fields, however, can be obtained with cooled resistive and hybrid magnets, as the superconducting coils enter the normal,non-superconducting, state at high fields, resulting into Joule heating phenomena.

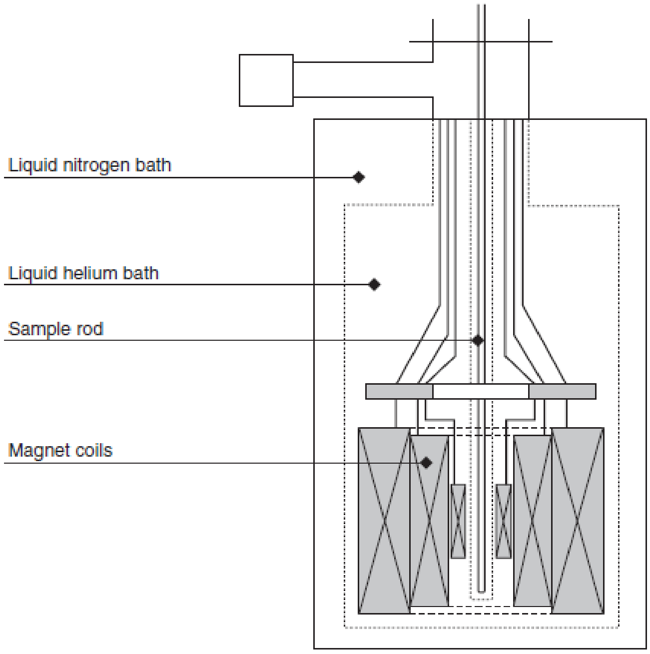

Fig. Schematic cross section of superconducting magnet

Mechanisms of Microbial Inactivation

OMFs have potential to inactivate food microorganisms. Different theories have attempted to explain the influence of magnetic fields on biological systems. Bacterial cell surfaces possess net negative electrostatic charges by virtue of ions developed on outer cell macromolecules which exposed to environment. Variations in the structure and chemical composition of these compounds have effect on bacterial surface charge. The force generated by a magnetic field in a food system may able to create an ion current from one location to another. OMF involves sealing food in a plastic bag and subjecting it to 1 to 100 pulses in an OMF with a frequency between 5 to 500 kHz at temperatures in the range of 0 to 50ºC for a total exposure time ranging from 25 to 100 ms. Frequencies higher than 500 kHz are less effective for microbial inactivation and tend to heat the food material. Inhibition or stimulation of the growth of microorganisms exposed to magnetic fields may be a result of the magnetic fields themselves or the induced electric fields.

Inactivation of micro-organisms due to magnetic field takes place by-

1) By loosening bonds between ions and proteins-

This stated that the oscillating magnetic field could loosen the bonds between ions and protein. Many proteins vital to cell metabolism contain ions. In the presence of steady magnetic field, the biological effects of OMF are more predominant at particular frequencies. Thus it stops the metabolic activities of cell of microbes.

2) By vibration in the calcium bound proteins-

This considers the effect of oscillating magnetic field on calcium bound proteins. Due to OMF effect calcium ions continually vibrate about an equilibrium position in the binding site. A steady magnetic field causes the plane of vibration to rotate or proceed in the direction of magnetic field. This adds a wounding magnetic field at a precise frequency to such an extent that it loses the bond between calcium and protein.

3) By breakdown of covalent bonds in the DNA-

The energy gets coupled into magnetically active parts of large molecules like DNAs. Within 5-50 T range, the amount of energy per oscillation coupled to 1 dipole of DNA is nearly 10.2-10.3 eV. These several oscillations may weaken the structure. Due to activation of OMF around the product results in breakdown of covalent bonds in the DNA molecules and inhibition of growth of micro-organisms.

Critical Process Factors

The critical process factors influencing the effectiveness of magnetic field treatments on microbial populations are mainly magnetic field characteristics, electrical resistivity, microbial type, microbial growth stage, treatment time and treatment temperature.

1) Magnetic Field-

Exposure to a magnetic field may stimulate or inhibit the growth and reproduction of microorganisms. A single pulse of intensity of 5 to 50 T and frequency of 5 to 500 kHz generally reduces the number of microorganisms by at least 2-log cycles (Hoffman 1985). High intensity magnetic fields can affect membrane fluidity and other properties of cells (Frankel and Liburdy,1995). Inconsistent results of other inactivation studies, however, make it impossible to clearly state the microbial inactivation efficiency of magnetic field or to make any predictions about its effects on microbial populations. In the specific case of OMF, an electrical current will be induced in the exposed product.

2) Electrical Resistivity-

The electrical resistivity is a measure of how strongly a material opposes the movement of electrically charged particles.For microorganisms to be inactivated by OMF, foods need to have a high electrical resistivity (greater than10 to 25 ohms-cm). The applied magnetic field intensity depends on the electrical resistivity and thicknessof the food being magnetized, with larger magnetic fields intensities used with products with large resistivity and thickness.

3) Microbial Growth Stage-

Tsuchiya and others (1996), working with homogeneous (7 T) and inhomogeneous (5.2 to 6.1 T and 3.2 to 6.7 T) magnetic fields, found a growth stage dependent response of *Escherichia coli* bacterial cultures. The ratio of cells under magnetic field to cells under geomagnetic field was less than 1 during the first 6 h of treatment and greater than 1 after 24 h. These authors also found that cell survival was greater under inhomogeneous compared with homogeneous fields. Based on the assumption that magnetic fields could act as a stress factor, cells collected after 30 min of incubation under magnetic field treatment (lag or early lag phase) or in the stationary phase after long-term magnetic field treatment were heated to 54ºC. No differences were observed between the treated and control samples. Little else is known about theeffect of microbial growth stage on susceptibility to magnetic fields.

4) Temperature-

Little is known about the dependence of micro-organism inactivation upon temperature. Berk *et al* (1997) evaluated the effect of 71 and 106 mT magnetic fields on three potentially pathogenic amoebae. They found that the number of amoebae in the three species was significantly reduced after a 72-hour exposure to magnetic fields at temperature 20ºC or above. Final counts of magnetic-field-exposed amoebae ranged from 9 to 72% lower than counts in unexposed samples.

Case Study-

The oscillating magnetic fields are produced by passing a fluctuating current by the electromagnets. The field strengths are high when compared with the earth magnetic field, which would approximately be 5 to 100 T. Frequencies ranging between 5-500 kHz are applied for around 25µs to a few milliseconds. This helps in the inactivation of vegetative cells. However, if the frequencies are higher than 500 kHz, the food gets heated and the inactivation process is not effective. In recent studies, it has been observed there are not much of effects on the spores or enzymes. In addition, it can lead to the growth of vegetative cells. For instance, when an oscillating magnetic field strength of 12 T was applied to milk at a frequency of 6000 Hz, cells were reduced from 25,000 to 970 ml^{-1} (Fellows, 2009).

Effects of oscillating magnetic fields on crab sticks were analyzed in a study conducted by Otero, Pérez-Mateos, Rodríguez, and Sanz (2017). The crab sticks were frozen both with and without oscillating magnetic field application. The entire process was observed for approximately 12 months. During this process, various quality attributes were assessed. The results indicated the oscillating magnetic field had no effect on the crab sticks. The drip loss, water-holding capacity, toughness and whiteness remained the same. Additionally, the quality of the frozen samples also remained the same. It is important to note during this experiment; the strength of the oscillating magnetic field was lower than 2mT. This is only two orders of magnitude more than earth's natural magnetic field. The frequency range was between 6 to 59 Hz. It should be noted, if the frequencies and magnetic strengths of this study were varied, the results could have changed.

James, Reitz and James (2014) conducted a study to investigate how garlic bulbs would react when subjected to oscillating magnetic fields, as compared to freezing them under normal conditions. The results of this study showed substantial cooling in the garlic bulbs, during some of the freezing trials. However, freezing stage the oscillating magnetic fields had a significant effect on the garlic bulbs over the normal freezing method. Also, the researchers concluded super-cooling was more effective with garlic bulbs if they were frozen at an initial ambient 21 ± 1ºC rather than 4 ± 5ºC.

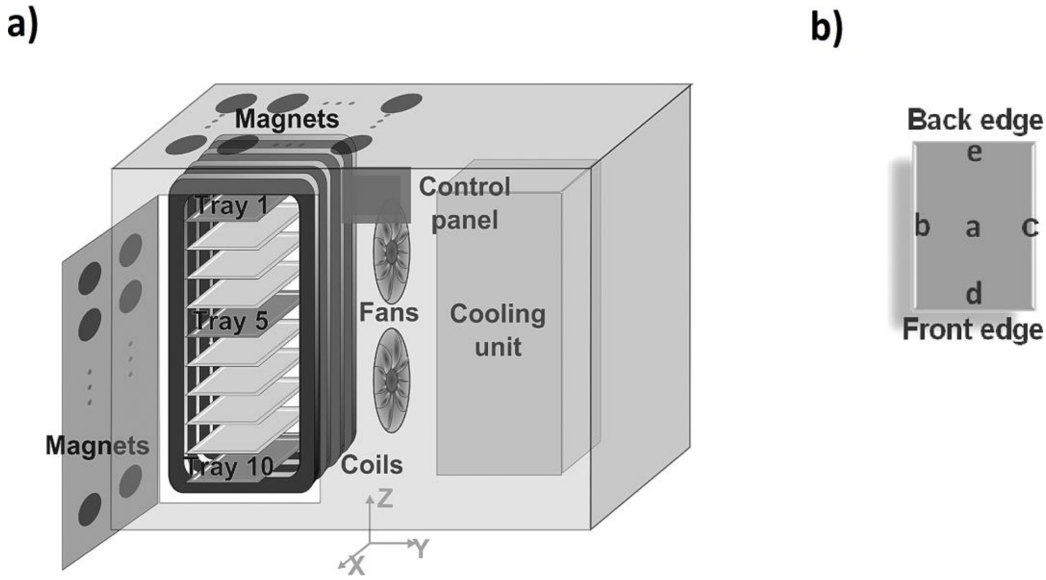

Fig. Schematic drawing of the CAS freezer

a) Main components,

b) Points at magnetic field measurements were performed in freezing trays 1, 5 and 10 T.

Kang *et al* (2021) conducted a study to examine the effect of oscillating magnetic fields (OMFs) at different intensities (up to 100 mT) on the extended water supercooling. The exterior super cooling chamber with specialized air circulation was invented for validation of the influence of OMF without any heat involvement. The pendulum experiment demonstrated that water tended to move in a direction opposite to the applied OMF due to diamagnetic repulsion, and the magnitude of the displacement increased proportionally with increases in the OMF intensities. Supercooling probability results indicated that OMF intensities of 50 mT inhibited ice nucleation in supercooled water when stored at the temperature of -11ºC, whereas OMF intensities exceeding 100 mT induced freezing. In this respect, the OMF at the field strength of 50 mT was applied for the supercooling preservation of fresh-cut mango slices, which were preserved in a supercooled state at −5ºC for up to 7 days. The quality assessment, such as weight loss and firmness, indicated that the supercooling preservation potentially extended the shelf-life of fresh-cut mangoes while maintaining their original quality.

Table- Effect of magnetic fields on microorganisms

Microorganism	**Type of Magnetic Field**	**Field Strength (T)**	**Frequency of Pulse (Hz)**	**Effect**	**Reference**
E. coli	OMF	0.15	0.05	Inactivation of cells atconcentration of 100 cells/mL.	Moore, 1979
Streptococcus themophilus in milk	OMF	12.0	6,000 (1 pulse)	Cell population reduced from 25,000 cells/mL to 970.	Hofmann, 1985
Saccharomyces in yogurt	OMF	40.0	416,000 (10 pulses)	Cell population reduced from 3,500 cells/mL to 25.	Hofmann, 1985
Saccharomyces in orange juice	OMF	40.0	416,000 (1 pulse) Cell	Population reduced from 25,000 cells/mL to 6.	Hofmann, 1985
Mold spores	OMF	7.5	8,500 (1 pulse)	Population reduced from 3000 spores/mL to 1.	Hofmann, 1985

Magnetic Fields Applications in Food Preservation

OMFs can be applied to stabilize and preserve either solid or liquid foods. Preservation of solid foods with OMF involves sealing the food in a plastic bag, whereas for liquid foods, the product is pumped through a pipe in continuous flow. OMF treatments consist of subjecting the product to 1 to 100 pulses with frequencies between 5 and 500 kHz at temperatures ranging from 0 to 50ºC for a total exposure time of 25 to 100 ms (milliseconds). Frequencies higherthan 500 kHz are less effective for microbial inactivationand tend to heat the food material (Barbosa-Canovas *et al*., 1998b). Magnetic field treatments are carried out at atmospheric pressure and moderate temperatures; the product is slightly heated to temperatures ranging from 2 to 5ºC. According to Hofmann (1985), exposure to magnetic fields above 2 T will cause inhibition of growth and reproduction of microorganisms. Field intensities of 5–50 T and frequencies of 5–500 kHz were applied to liquid media, reducing the number of microorganisms by at least 2 log cycles. Further, OMF technology may be used to improve the quality or increase the shelf life of food products in combination with traditional processing techniques, for example low pasteurization treatments. No special preparative steps need to be followed before treating food products with OMF. Frequencies higher than 500 KHz are less effective for microbial inactivation because the temperature of food products will increase due to Joule heating processes. Magnetic field treatment is considered safe because the intensity of the field only persists within a very short distance from the coil and drops drastically upon moving away from the treatment zone.

Research Needs

Each non-thermal technology has specific applications in terms of the types of foods processed. OMF technology is potentially useful for processing both liquid and solid foods. However, the main limitation of most non-thermal technologies, OMF included, is the inadequate inactivation of resistant microbial forms such as spores. Taking a more combined methods approach is necessary to study the possible synergies between treatments. There is a significant lack of information on the ability of OMF treatment to inactivate pathogenic micro-organisms and surrogates. A main area that needs to be elucidated is the confirmation that magnetic field treatment is an effective process for inactivation of microbes. Once established, significant data gaps will still need to be closed before this technology can be safely and practically applied to food preservation. Some of the more significant research needs are as:

- to establish the influence of magnetic fields on the inactivation of microorganisms;
- to elucidate the kinetics of microbial inactivation by magnetic fields;
- to identify key resistant pathogens;
- to determine the mechanisms involved in microbial inactivation by magnetic fields;
- to identify critical process factors and effects of microbial inactivation;
- to validate the process and evaluate indicator organisms and appropriate surrogates; and
- to identify process deviations and ways to address them.

Concluding remarks:

- OMF has been found effective in reduced energy requirements for adequate processing.
- It has potential for treatment of foods inside a flexible film package to avoid post-harvest/process contamination.
- The effects of magnetic fields on the quality of food and the mechanism of inactivation of microorganisms required to be studied in detail.
- Additional research is necessary to correlate the inactivation of microorganisms in food and OMF techniques.

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