Pulsed Electric Field: A Modern Innovation in Food Processing

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Abstract

Pulsed Electric Field (PEF) is an emerging non-thermal food processing technology that uses short bursts of high voltage electricity to permeabilize cell membranes. This technique enhances the extraction of bioactive compounds, improves juice yield and inactivates microorganisms while preserving the nutritional, sensory and phytochemical qualities of foods. Because it requires less heat and shorter processing time than conventional methods, PEF is considered an energy-efficient, environmentally friendly and high-quality alternative for food and bioprocessing applications.

Introduction

Bioactive compounds are extra-nutritional constituents that are found in small quantities in foods providing health benefits beyond the basic nutritional value of the product. There are various bioactive compounds present in the fruits like vitamins A, C and E, minerals such as Ca, K, Mg, phenolics like gallic acid and ellagic acid, flavonoids like quercetin and kaempferol, colouring compounds like anthocyanins and carotenoids, tannins like catechins and theaflavins etc.

All these bioactive compounds are associated with various health benefits like anti-cancerous, anti-oxidant, anti-bacterial and anti-diarrhoeal properties. They also have wound healing properties and able to reduce cholesterol in human body. Hence in order to acquire all these health benefits, the bioactive compounds have to be extracted very carefully without any degradation. The major degradation causing factors are: thermal treatment, oxidation, hydrolysis, varying pH, enzymes and light. Among these the degradation is majorly caused due to the thermal treatment (50-60%) during the extraction process.

Hence in order to avoid this, one has to opt for non-thermal extraction technology which is a novel and emerging technology to extract the bioactive compounds without any heat damage. The important benefits of non-thermal extraction technology include, it provides sustainable food production, it is an environmentally friendly technique, generates less waste, improves food safety and food quality and also prevents nutrients loss. Among many one of the major non thermal extraction technology is the pulsed electric field technology which efficiently extracts the bioactive compounds without any loss.

Need for the extraction of the bioactive compounds arises mainly due to:

1. Isolate the targeted compounds from the complex samples
2. Characterize and separate the compounds with different polarities
3. Increase the selectivity of analytical methods
4. Convert the bioactive compounds into a more suitable form for easy detection and separation.

The bioactive compounds present in the fruits are mainly extracted by two methods namely-

Conventional/traditional method of extraction

A. Hydro distillation: Hydro distillation is a traditional method for extracting essential oils and bioactive compounds from plants. It involves boiling plant material in water or steam to separate the essential oils from the plant's oil glands.
B. Steam distillation: Steam distillation is a separation technique that uses steam to extract volatile organic compounds from a mixture.
C. Solvent extraction: It is a technique that separates compounds based on their relative solubilities in two different immiscible liquids.
D. Cold press method: It is a mechanical process, that uses pressure to extract bioactive compounds from plant materials.
E. Enfleurage: The extraction of essential oils and perfumes from flowers by using odourless fats.
F. Maceration: Soaking a raw material in a solvent to extract its components.
G. Soxhlet extraction: It is a continuous extraction method where a solvent is repeatedly cycled through solid sample and extract bioactive compound.

Non-conventional/modern method of extraction

A. Pulsed electric field: By using short, high-voltage electric pulse to extract bioactive compound.
B. Ultrasonication: It is the process of using high-frequency sound waves to extract bioactive compound.
C. Microwave assisted extraction: It is a process of using microwave energy to heat solvents in contact with a sample in order to partition analytes from the sample matrix into the solvent.
D. Supercritical fluid extraction: It is a process that uses a supercritical fluid like CO_2 to separate one component from another.
E. High hydrostatic pressure: Using water as a pressure transmitting medium to extract bioactive compound.
F. Cold plasma: Type of plasma that operates at relatively low temperature.
G. Enzyme assisted extraction: It is a novel strategy to disrupt the cell membrane structures to release bioactive compounds.

Table 1: Difference between conventional and non-conventional methods of extraction

Conventional method	Non-conventional method
Low efficiency of extraction	High efficiency of extraction
Low quality of extracted compounds	High quality of extracted compounds
High extraction time	Low extraction time
High energy consumption	Low energy consumption
More use of solvent	Less use of solvent
More CO_2 emission	Less CO_2 emission

As the non-conventional extraction methods are more efficient, they are used in various industries like:

- Dairy industry for fermentation and emulsification of milk products.
- Fruits and vegetables industry for reducing drying time, pesticide reduction and enzyme inactivation.
- Meat industry for tenderization, curing and enhancing colour of meat products.
- Egg industry for gelation, colour enhancement and microbial inactivation.
- Fish industry for thawing, reducing cooking time and to decrease allergenicity.

Pulsed electric field (PEF)

It is a low-energy technology that can extract food bio active compounds at lower temperatures and less time. It involves applying short high-voltage pulses lasting µs to ms with electric field intensity ranging from 10-80 kV cm^{-1} to food placed between two electrodes. It modifies the membrane permeability and thus increases the extraction yield. It is also called high electric field pulses.

Timeline of PEF

1920: The 'Electropure' process introduced electricity for milk pasteurization.

1950: The use of high-voltage pulses for microbial inactivation was explored.

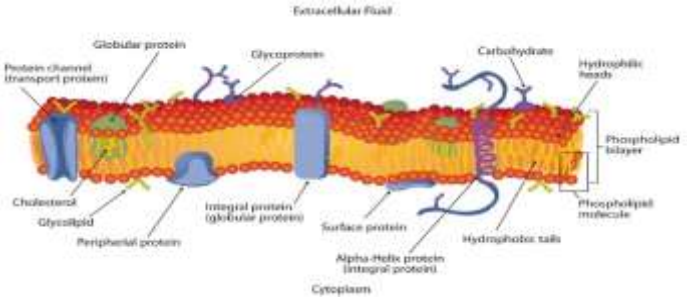
1967: Sale and Hamilton investigated the lethal, non-thermal effect of pulsed electric fields on microbes.

1980: Krupp in Germany applied early patents for PEF to inactivate microorganisms in milk and fruit juices with electric fields up to 30 kV cm^{-1}.

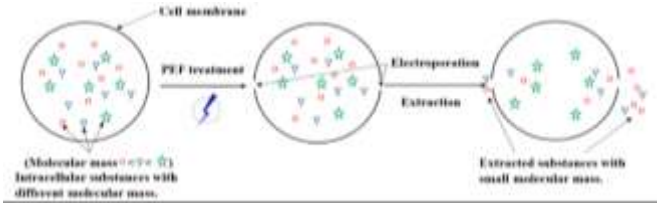
1987: Dunn and Pearlman studied electric fields effects on fruit juice quality.

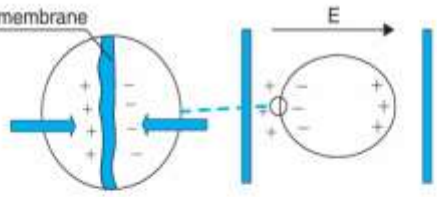
Principle of PEF

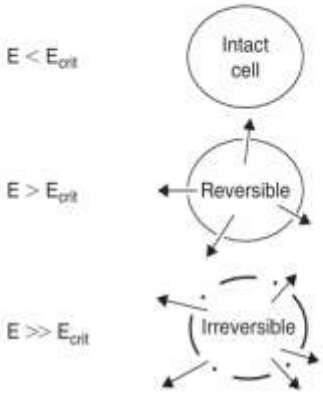
Works on the principle of Electroporation



When a cell is exposed to PEF, it undergoes a process is known as electroporation. The cell membrane consisting of a lipid bilayer, is made up of lipid molecules with hydrophilic head and hydrophobic tails which exhibit dipolar properties. When an electric field is applied, it exerts a torque on these dipoles causing the hydrophilic heads align towards the electric field and hydrophobic tails align away from it. The realignment disrupts the structural integrity of lipid bilayer leading to the formation of temporary or permanent pores in the membrane. These pores allow the passage of ions and molecules.





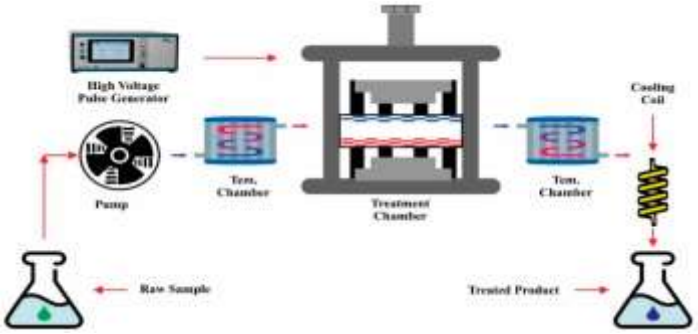


- ❖ If electric field is weak, due to reversible permeabilization the cells repair their membrane through resealing the electropores immediately after PEF treatment.
- ❖ If electric field is strong leads to irreversible breakdown of cell membrane.

Effects of PEF on cell structure

- Insertion of proteins into the cell membrane

- Insertion of small molecules into the intracellular environment
- Insertion of large molecules into the intracellular environment
- Cell fusion
- Cell destruction



PEF working system

Fig.1: A representation of pulsed electric field process

1. PEF system consists of a treatment chamber containing 2 parallel electrodes held in place by an insulating substance thus forming a food material enclosure.
2. High voltage pulse generator which converts alternate current (AC) to direct current (DC) with the help of a device called capacitor.
3. A cooling system/coil for temperature rise balance during treatment.
4. An injection port for inserting raw sample.
5. A pumping device for circulating food across the chamber.
6. Lastly, a treated product collection chamber.

There are 2 types of working system namely:

1. Static/batch system
2. Continuous system

Static system

Here the food treated with little solvent is directly placed between 2 electrodes and connected to a PEF generator which generates high voltage pulses thus the food gets treated.

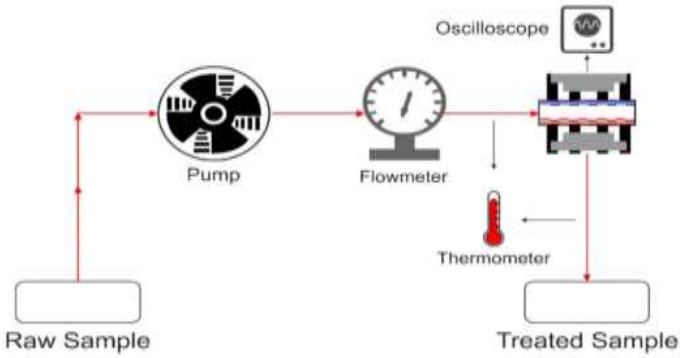


Fig. 2. (a). PEF batch extraction system

Continuous system

This system is mainly used in industrial system to provide more capacity. Here the food solvent mixture is pumped into the treatment chamber by a peristatic pump at a constant fluid velocity which is connected to a PEF generator that generates high voltage pulses and thus the food gets treated.

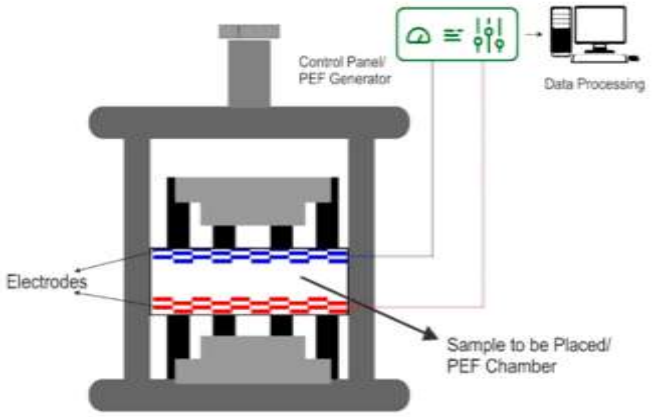


Fig. 2. (b). PEF continuous extraction system

Factors influencing the PEF process

1. Electric field intensity (EFI): It is reported in kV/cm, it depends on the voltage conveyed and as the distance between the electrodes.
2. Frequency: It is reported in Hz and it is the number of pulses/second.
3. Specific energy: It is reported in kJ/kg. It depends on the food conductivity, geometry and the resistance of the chamber and as well as the pulse width.
4. Treatment time: It is reported in μs, it is a function of the number of pulses applied and the pulse width.

Advantages of PEF

1. PEF can effectively permeabilize cell membranes without significantly increasing temperature.
2. PEF is a low energy cost technology.
3. PEF can enhance extraction efficiency and reduce extraction time.
4. PEF has no evidence of toxicity.
5. PEF can preserve colors, flavours and nutrients.
6. It is a waste free process thus is a environmentally friendly technique.

Applications of PEF

1. Microbial reduction
2. Enzyme inactivation
3. Extension of shelf life
4. Enhances drying process
5. Meat tenderization
6. Preservation of nutrients
7. Juice extraction

Prominent companies manufacture PEF systems

- Elea GmbH, Germany
- CoolWave Processing, Netherland
- Diversified Technologies, United States
- Pulsemaster, Netherlands
- Energy Pulse Systems, Portugal

Commercially available PEF treatment products

- ✓ **Genesis Juice Corporation**: It is introduced the first FDA approved, PEF processed juice to the US market in 2005. The shelf-life of these juices was 4 weeks at storage temperatures of 4°C.
- ✓ **Hoogesteger:** It is Europe's leading supplier of fresh, cold pressed juices. Since 2012 the company has installed PEF systems in its production facilities. PEF pasteurization has increased product shelf life from 6-7 days up to 21 days.

Challenges

- ➢ Improved impulse generation systems are required to deliver sufficient electrical field strength, power and repetition rates while maintaining affordability.
- ➢ PEF-treated foods must comply with regulatory standards to ensure safety and quality comparable to conventionally processed foods.
- ➢ Electrochemical reactions at stainless steel electrodes must be mitigated to avoid toxicity from released particles and heavy metals.

Future prospects

- ❖ Future advancements in PEF technology could lower its high initial costs, making it more affordable for commercial use.
- ❖ Improvements in selectivity could lead to higher purity and quality of extracted compounds.
- ❖ As it doesn't affect enzymes efforts should focus on expanding its applications.
- ❖ Merging PEF extraction with nanotechnology or biotechnology could greatly enhance its extraction efficiency.

Conclusion

Pulsed Electric Field (PEF) assisted extraction offers superior efficiency in recovering bioactive compounds from fruits while significantly reducing processing time and minimizing energy consumption. This technique helps preserve the phytochemical, nutritional and sensory properties of the extracted compounds, ensuring high-quality outcomes. By maintaining these beneficial attributes, PEF supports the development of healthier products and holds strong potential for applications across both the food and pharmaceutical industries.

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