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SHOCKWAVE EFFECTS IN THE TECHNOLOGY OF MEAT RAW MATERIAL PROCESSING

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Abstract
Meat tenderness is recognized as the most important quality characteristic determining consumer acceptability of fresh meat and meat products. Therefore, the development of effective methods for meat tenderization is a topical direction. The review considers the main aspects of the development of shockwave (SW) technology as an alternative method for meat tenderization. The paper analyzes the means of shockwave formation as well as possible mechanisms responsible for meat tenderization caused by shockwave treatment and related to the energy dissipation and mechanical load on the boundary zones of a biological material under processing. The results of the investigations of a shockwave effect on meat tenderness, microbial inactivation, structure and assimilability of muscle protein and other functional and technological properties of a product are presented. The majority of researchers who studied a SW effect on meat tenderization showed different degrees of the improvement in the Warner-Bratzler shear force and increase in sensory scores of meat tenderness. This review shows the main problems linked with commercialization of the meat treatment process using SW based on electrical discharges under water. This method of SW generation is considered safest but infeasible today due to occurrence of restrictions such as damage of packaging materials after treatment, a need to ensure effective SW propagation in a commercial unit and determine optimal treatment parameters in the process of shockwave tenderization. Furthermore, potential possibilities of using shockwave technologies in the food industry are discussed. In particular, shockwave treatment upon extraction is an effective method for extracting juice/ oil/ bioactive components from various plant materials, which can be used as the pretreatment or independent process.

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Introduction

An increase in consumer demand for high quality and minimally processed meat products has led to an extension of investigations and adaptation of several new technologies for the meat industry.

Over the last two decades, the use of high pressure in food systems especially ultra high pressure (>100 MPa) has attracted a significant attention of the scientific community and, as a consequence, their commercial application became a reality [1,2,3,4]. The reason is that the use of high pressure in food systems opens possibilities that cannot be achieved by conventional processing methods and, consequently, has a high potential in the development of new food technologies and optimization of the existing ones. Among these technologies are meat processing with the hydrodynamic shockwave and high pressure processing, which allow improving tenderness of meat raw materials depending on conditions during application of the technology [5].

High pressure can be used in two different forms of process organization: static (i. e., product treatment in a vessel) and dynamic (i. e., product treatment in a fluid flow).

The third method of pressure impact on foods is hydrodynamic pressure processing or shockwave treatment, which represents an instantaneous development of pressure waves up to 1 GPa in fractions of milliseconds. The pressure front can be generated both by detonating explosives and electrical discharge under water. In both cases, a result is the generation of a pressure wave or shockwave. The wave is characterized by the achieved intensity and speed of its propagation in time (that is, a pressure level and build-up time). A shockwave propagates through a liquid medium at a speed that exceeds the speed of sound. As meat is composed of 75% of water, a wave passes through a meat sample and ruptures muscle proteins. This gives what can be called "the rupture effect" and as a consequence favors meat tenderization [6]. Meat tenderness is an important quality parameter, which facilitates the total perception and acceptability of a product for consumers and can influence its cost [2,6,7].

Retrospective of the development of shockwave technologies and equipment for meat tenderization

The shockwave technology appeared for the first time as an alternative method for meat tenderization at the beginning of the 1970s. In 1970, Godfrey [8] patented a method and an apparatus for tenderizing foods, including meat, with the use of the explosive charge, which generated a shockwave, and called it hydrodynamic pressure processing (HDP). Then, Long [9,10] changed the technology to

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overcome its shortcomings and called it the Hydrodyne® process. The Hydrodyne® process was extensively studied by prof. M. Solomon el al. from the Food Technology and Safety Laboratory (Beltsville, MD, USA) [11], who demonstrated significant improvements in meat tenderness. However, the shockwave generation by explosives has certain drawbacks and problems related to the development of the equipment and potential product contamination with explosive residues as well as problems with regard to the safety of operators [6].

At the beginning of 2000, a new concept of the development of the shockwave technology was devised, which enabled the electrical generation of a shockwave by the capacitor discharge system. Also, three additional patents were filed for continuous shockwave food processing with shockwave reflection and shockwave food processing with acoustic converging wave guide. As a result of the integration of these concepts, the commercial system called the TenderClass System (TCS) was developed by Hydrodyne Incorporated. In 2007, Long et al. [12] patented a system, in which a shockwave was transmitted to meat through the diaphragm.

In Russia, a method and device were patented for meat tenderization and destruction of microorganisms in it due to the fact that meat was subjected to an effect of plasma shockwaves or pulses generated by the capacitor discharge between two electrodes [13]. According to this patent, meat is exposed to a shockwave propagating through an incompressible fluid medium. With that, a meat raw material is placed adjacent to the first surface of the drum-shaped diaphragm, which has the acoustic resistance approximately the same as the acoustic impedance of the incompressible fluid medium. The incompressible fluid medium is adjoining to the second surface of the drum-shaped diaphragm, which separates meat from the incompressible fluid medium. When meat is subjected to an impact, its movement is restricted; the shockwave passes through the incompressible fluid medium, then through the drum-shaped diaphragm and after that enters the product. The shockwave generation chamber is used for containing an incompressible fluid, which has the first acoustic impedance. The invention allows improving meat tenderization while destroying microorganisms in meat.

Studies on meat tenderization using a plasma sparking device were carried out based on the patent of Cooper and Solomon [14]. In general, about 20 patents linked to this technology were registered in the whole world [6].

During 2008–2011, an experimental unit for shockwave generation for meat tenderization by electro-hydraulic underwater discharges was developed and realized in the German Institute of Food Technologies (DIL) within the framework of the German research project. A prototype with an average power of 2 kW and a peak power of 40kW with a vessel volume of 50 l was designed. The effective energy conversion from electrical energy to mechanical energy was achieved and its effectiveness in meat tenderization was demonstrated. The developed equipment was successfully used to reduce the time of ageing for beef cuts from 14 to 7 days. Currently, an industrial prototype for continuous shockwave treatment has been under development within the framework of the European-funded project Shockmeat. The aim of the project is to overcome shortcomings of the first prototype developed by DIL and ensure safety in the industrial conditions. Shockmeat is aimed towards continuous treatment of meat rather than a batch system [2,6].

The shockwave technology applied for meat tenderization is a relatively inexpensive and non-invasive method that does not exert a negative effect on the microbiological and chemical stability of a product. However, the commercial application is infeasible up to date as it is necessary to study and overcome such restrictions as a damage of a packaging material after shockwave treatment, ensure effective shockwave propagation in an industrial unit and determine parameters of treatment ensuring tenderization of a particular meat type, that is, to develop an effective process of product tenderization reducing treatment duration, energy consumption and expenditures for obtaining high quality meat products [6].

Methods for shockwave generation and mechanisms of its effect on meat under treatment

The shockwave technology or hydrodynamic pressure processing (HDP) is considered a potential method for tenderization due to instantaneous creation of high pressure [2,6,15].

The mechanism of the shockwave impact is related in this case with energy dissipation and mechanical load on the boundary zones of materials having different speeds of sound propagation and acoustic impedance. A wave is characterized by an achieved intensity and the speed of its propagation in time (that is, the level of pressure and built-up time). Packed meat is placed in the working container with water and is exposed to shockwaves. The created shockwave passes through a liquid with the high energy, extremely high speeds and passes through a product placed into the unit. A wave passing through a meat sample ruptures muscle proteins, which allows destruction of the muscle structure leading to an instantaneous tenderization effect and accelerated ageing of meat (duration of processing is reduced from 14 to 7 days). After cooking treated meat, a decrease in the shear force was observed. The total energy expenditure is only several kJ per kilogram of a product, which corresponds to a temperature increase by less than 1 °C [15].

The hydrodynamic shockwave for meat tenderization can be generated either by detonating explosives or by creating electrical discharges under water [2,6,16]. For example, Solomon et al. [11] showed that detonating explosives under water can tenderize meat.

Shockwaves impact meat both directly and after reflection from the floor and walls of the working chamber creating a tenderizing effect. High-pressure shockwaves created by a small amount of explosives significantly increase tenderness of beef, pork, mutton and poultry meat [17,18,19].

The meta-analysis that compares studies on an effect of a shockwave impact on different meat types and muscles shows that explosive shockwaves can reduce the peak shear force after meat treatment by 17.7 N and the electrical shockwave by 7.5 N, respectively [5].

However, safety problems related to the use of explosives significantly limit commercial applicability of this method.

An alternative to shockwave generation by explosives is generation of shockwaves by electrical discharges under water. This method allows avoiding problems linked with the use of explosives, increasing automation of the process, ensuring its continuity, reducing the treatment duration and facilitating modulation of the shockwave intensity by supplying different electrical intensities and/or number of pulses per treatment [6].

Propagation and impact of a shockwave through food depends on the acoustic impedance, which is directly proportional to the product density [20]. The pressure of the wave front can vary from 30 to 100 MPa depending on the distance from the energy source [2], and a shockwave impact can cause a damage of cell walls and destruction of connective tissue depending on a food matrix [21] and wave intensity. Upon an impact on a food product, a shockwave divides into the wave of propagation and the wave of reflection due to changes in the density. Foods differ significantly by the density and matrices, which ensures variable resistance to shockwaves and, consequently, the mechanism of wave action for particular products [20] and a possibility of using the method can be individual.

Initially, it was shown that potentially safer method of the underwater electrical discharge (electrohydrodynamic shockwave) had an ability to tenderize poultry meat [22].

The high effective compact sparkers favor emergence of the electrohydrodynamic shockwaves for meat tenderization [23,24].

A sparker is an electrically driven acoustic source that creates high pressure shockwaves similar to explosives. A sparker operates by pulsing high voltage across an electrode gap, which leads to a plasma discharge that creates a pressure pulse or shockwave. The discharge leaves behind a high-pressure vapor cavity (bubble), which expands and then collapses creating an additional pressure peak. The process is repeated until the bubble energy is fully dissipated. The spark sources also provide an opportunity of electronic pressure control, which is potentially useful for tenderizing different meat cuts and types.

Claus [25] as well as Sagili and Claus et al. [26] showed earlier an improvement in product tenderness when beef and pork cuts were treated using a focused type sparker.

Bowker et al. [23] studied interrelation between working parameters of a sparker and the meat tenderization process with its use. The sparker source system used in this research consisted of the annular head with a pair of concentric cylindrical electrodes separated by an annular insulator. The sparker head was placed into water in a 19 L cylindrical plastic container. Vacuum packed meat samples were put on the bottom of the container on a flat steel plate (with a thickness of 1.3 cm) at a distance of either 3.75 or 7.5 cm from the sparker head located above the beef samples. Both the medial and lateral portions of each steak were treated with the sparker applying either 40 or 80 pulses at each position [23].

The tenderizing effects of beef loin treatment with high-pressure shockwaves from a sparker were assessed by the Warner-Bratzler shear force (WBSF) measured on days 0 and 7. The results of the research show that the distance between the sparker head and a muscle sample and, therefore, the shockwave peak pressure play a crucial part in determination of the tenderization degree. When the sparker head was set at a distance of 7.5 cm above the samples, an improvement in tenderness was on average only 5–10% on day 0 with a maximum improvement of 24%. At this sparker setting, a reduction in overall WBSF by more than 10% compared to the control was observed in 44% of treated steaks on day 0. When the sparker head was placed at a distance of 3.75 cm above the samples, the peak pressure increased from 6.6 to 12.3 MPa. At this distance, the average increase in tenderness was 20–25% on day 0, while the maximum increase in tenderness was 37%. Moreover, at a distance of 3.75 cm, a decrease in WBSF by more than 10% was recorded in all treated steaks; whereby, 70% of the treated samples showed a reduction in WBSF by at least 20% [23]. The WBSF value reduced both in the treated and control samples from day 0 to 7.

Preliminary experiments showed that the tenderizing effect was reduced after a certain number of spark pulses. It was found during the experiment that the number of sparker pulses necessary for achieving the tenderizing effect significantly depends on the height of sparker head setting relative to the product under treatment, which, possibly, is linked with a decrease in the shockwave pressure upon an increase in the distance. When the sparker head was set closer to the sample surface, the higher degree of tenderization was achieved with the lower number of sparker pulses (5–10 pulses in three places compared to 40–80 pulses in two places). The use of the lower number of pulses is beneficial with regard to maintenance of muscle tissue and packaging integrity.

The results of this research show that high-pressure shockwaves generated by a sparker are an effective technology for post-slaughter processing to tenderize beef.

Effects of shockwave treatment on meat

Effect of shockwaves on microbial inactivation in meat

There are few studies on an effect of shockwaves on microbial inactivation in meat; however, their results are quite contradictory [2].

For example, it was reported that explosive shockwave treatment allows reduction by up to a 4.5 log10 CFU in ground beef stored aerobically (5 °C) for 14 days, while the results of other studies showed no effect on coliforms and aerobic plate counts in pork loins treated with explosive shockwaves [7].

McDonnell et al. [7] assessed an effect of electrical shockwave treatment on the microbial load during long-term storage in the experiments on beef samples: striploin (longissimus lumborum) and brisket, point end deckle off (pectoralis profundus). Treatment in the unit (Shockwave, DIL German Institute of Food Technologies, Quakenbrueck, Germany) included placing the vacuum packed sample directly in the impact area under the emitting head (a source of a shockwave) located 13 cm from the sample. The treatment regime was as follows: 25 kV with the treatment intensity of 8 pulses with duration of 1 s in the stationary mode with a water temperature of 22 °C throughout the process. The total process time from sample loading to unloading was about 5 min. After treatment, the sample temperature increased from 3.7 ± 0.4 to 5.5 ± 1.0 °C.

The control and experimental (shockwave-treated) samples had six storage points (0, 4, 8, 12, 16 and 20 weeks).

Total viable counts (TVC) were similar in the shockwave treated and untreated control samples; whereby, the mean counts in all sample/treatment combinations at all time points were regarded as microbiologically acceptable when a cut-off of 7 log10 CFU/cm^2 was applied. The similar trends for lactic acid bacteria (LAB) and TVC in the storage experiments suggest that the microbial population consisted mainly of LAB, which corresponds to the previous results observed in striploin (longissimus lumborum) stored under similar conditions [7].

Effect of shockwaves on an increase in meat tenderness and changes in the functional-technological properties

Shockwaves largely exert the mechanical action on a processed product facilitating tenderization of muscle and connective tissues. The majority of scientists studying an effect of shockwaves on meat tenderization showed different degrees of improvement in Warner-Bratzler shear force and scores of sensory tenderness [2,5,6,28].

Solomon [19] showed that high-pressure shockwaves increased beef tenderness as effective as meat ageing with instantaneous improvement in tenderness by 37–57%. When meat is processed using shockwaves, muscle proteins are destructed [6]. The high-intensity shockwave changes the structure of meat collagen breaking peptide bonds and causing disruption in the myofibril structure [29].

A possibility to use shockwaves in the meat processing technology was studied in the North Caucasus Federal University. The experiments were carried out in chilled pork in a medium of modeled brine contained salt, sugar and nitrite. The treatment conditions were as follows: discharge of 1.81 kJ at treatment intensity 300 pulses [30].

The fluid medium, in which the high-voltage discharge occurs, is a transformer of energy released in the channel. The pulsed release of electrical energy in the latter leads to an increase in pressure in the system under treatment due to low compressibility of the fluid. High pressure forms and spreads intensive excitations in the environment. It is necessary to note that from the hydrodynamic point of view, an electrical discharge in fluid can be regarded as a process of non-stationary expansion of an impenetrable cavity. Due to high pressure near the discharge channel, the formation of the excitation is significantly influenced by non-linear effects that can lead to an increase in the steepness of the compression wave and to the shockwave generation.

The effect of shockwaves on pork samples was assessed by their histological analysis.

The histological investigation of the muscle cross-sections showed that the highest fiber diameter was observed in the experimental pork samples achieving 65–70 μm compared to 35–40 μm in the control sample.

In general, muscle fibers had the polygonal shape with restricted roundness. Part of muscle fibers of the experimental sample with a diameter of more than 60 μm had the round or oval shape and more uniform color. In the experimental samples, arrangement of individual fibers in the primary bundle was quite loose with well pronounced light spaces between muscle fibers. In these samples, a space between muscle fibers in bundles was notably lower than in the control groups.

An effect of shockwaves on muscle tissue was manifested in muscle fiber swelling, weakening of cross-striation, an increase in the development of transverse microfractures or slot-shaped spaces in muscle fibers as well as destruction of myosin and actin myofilaments. The observed changes in muscle tissue correspond to higher sensory indices — tenderness and juiciness of the finished product [25].

Schilling [31] demonstrated a 42% increase in tenderness upon treatment with the explosive generated shockwave. The similar result was obtained in the experiments on chicken broiler breasts exposed to hydrodynamic shockwaves generated in a cylindrical processor with the 40-gram explosive 25 min after deboning (77 min after slaughter) or after 24-hour storage (4 °C), respectively [17].

Analysis of an effect of the electric shockwave process on tenderness of chicken breasts (80 samples, 45 min. after slaughter) and turkey breasts (21 samples, 72 hours after slaughter) revealed a decrease in the Warner-Bratzler shear force by 22% and 12%, respectively, compared to the control after treatment. Cooking losses in turkey breasts were higher than in chicken breasts [20]. Meek et al. [18] also found an increase in tenderness by 19.1–28.1% in chicken breasts with early deboning. The electrical shockwave process can provide processors with a possibility of early deboning and obtaining tender chicken breasts as well as turkey fillets with increased tenderness [17].

To study an effect of hydrodynamic shockwave treatment on beef tenderization and ageing, samples of beef muscles *M. longissimus thoracis* and *M. semitendinosus* were vacuum packed in polyamide/polyethylene packages and subjected to shockwave treatment in a prototype unit produced by the German Institute of Food Technologies (DIL, Quakenbrück, Germany). Muscles were processed using electrical discharges under water in the following mode: 35 kV (corresponding to 11025 J per pulse) and a distance of about 20 cm from the meat sample to the shockwave spark at the frequency of 1 pulse every 3 cm. Subsequently to shockwave treatment, the muscle samples were cut into three pieces with a length of 10 cm and vacuum-packed before aging during up to 21 days at 4 °C. Texture, color, drip losses, cooking losses and the muscle structure (by scanning electron microscopy (SEM)) were analyzed in all meat muscle samples [32].

Shockwave treatment of *M. longissimus thoracis* led to a significant decrease in the Warner-Brazler peak force values at all storage points compared to the control (untreated) samples: 12.4% at day 1, 8.2% at day 11 and 5.8% at day 21, respectively. The results of the scanning electron microscopy revealed some differences between muscles treated with shockwaves and control samples on the 1st day of storage showing slightly larger intermuscular fiber space, which, possibly, led to increased tenderness [29,32]. Shockwave treatment did not significantly influence cooking losses and changes in color parameters (L*, a*, b*) in beef muscles during storage. In general, beef muscle color depended on storage duration. The value of lightness (L*) increased in the samples with storage time and redness (a*) slightly decreased both in *M. longissimus thoracis* and *M. semitendinosus*.

In systematization of studies using meta-analysis of publications, no effects of shockwave on changes in meat color characteristics were found [28].

Schilling et al. [33] determined protein functionality of bovine *Biceps femoris* (BF) muscle proteins after treatment with the hydrodynamic shockwave generated by the explosive method, which created hydrodynamic shockwaves with pressure fronts of 83, 104 and 124 MPa. The explosives were nitromethane and ammonium nitrate in amounts of 105, 200 and 305 g. In general, hydrodynamic shockwaves reduced the shear stress values in beef streaks by 20%; whereby, no differences in solubility of myofibrillar and sarcoplasmic proteins were found between the control and experimental beef samples. The results of gel-electrophoresis showed that proteolysis (protein breakdown) of myosin or actin was not visually observed on the myofibrillar gels, while proteolysis of myoglobin was not visually observed on the sarcoplasmic gels as a result of hydrodynamic shockwave treatment compared to the control. Myoglobin denaturation and, consequently, color changes in shockwave treated beef did not occur [33]. Cheftel J. C. and Culioli J. (1997) [34] reported that pressure from 200 to 350 MPa for 2–5 min after achieving the targeted pressure was required for meat color changes due to myoglobin denaturation.

Frankfurters made from the experimental shockwave treated beef samples and control beef samples did not have differences in cooking losses and color characteristics [33].

Shockwave treatment as a method for increasing tenderness of beef muscles up to 15% compared to the control (untreated) muscles showed a high potential that minimally influenced meat quality characteristics.

Taking into account that shockwave (SW) processing changes the muscle structure [35], it was suggested that these changes have a probable effect on the biological availability of food enzymes for their substrates, which can influence the nutritional value of meat products. To this end, an effect of shockwave processing on the molecular structure of beef muscle protein was studied using a FT-IR microspectroscopy [36].

Steaks were obtained from Simmental beef briskets (21–22 month old) 11 days after slaughter and exposed to hydrodynamic shockwaves (intensity = 11 kJ/pulse, one pulse per step, continuous system) with the following sous-vide cooking at 60 °C for 12 hours. After that, gastric digestion process was simulated for 1 hour at pH 3 and 37 °C in the presence of pepsin.

The infra-red spectra of both myofibers (MF) and connective tissue (CT) obtained using a FT-IR microspectroscope (Thermo Scientific, Nicolet iN10) were analyzed to study changes in the structure. It was found that shockwave (SW) treatment changes the native α-helix structure of connective tissue protein [37]. After sous-vide processing, the intensity of 1655 cm^{-1} band of the myofibers from the SW treated beef samples was significantly lower than that from the control untreated meat sample, which indicates more profound protein denaturation in the treated sample during thermal processing. After an hour of *in vitro* gastric digestion, the intensity of 1655 cm^{-1} band in the center of the cooked meat sample treated with SW was significantly higher than that in the control cooked meat sample suggesting that the acidic gastric condition exerted the higher and faster effect on the untreated control sample, which led to a higher degree of α-helix denaturation of the myofibers in the latter. Therefore, hydrodynamic shockwave treatment changes the protein secondary structure, which can influence functional and nutritional quality of meat and meat products [36].

Shockwave treatment causes changes in the muscle structure such as fragmentation of myofibrils along Z-discs and destruction of collagen fibrils. However, a shockwave effect on the molecular structure of muscle protein is unknown [38].

To optimize the technology of meat tenderization with shockwaves with its following commercialization, the spatial modeling of hydrodynamic shockwave distribution was carried out. Quantitative assessment of distribution and penetration of hydrodynamic shockwaves was performed using laminated pressure sensitive paper (Fujifilm low pressure 2.5–10 MPa, Bestech, Australia). After shockwave treatment (15–30 kV) by electrical discharge under water in a specialized SW unit (DIL, Quakenbrück, Germany), the pixel intensity on the paper was analyzed using an Epson Perfection V370 Photo Scanner.

Systematization of the experimental data revealed the front of pressure alterations upon shockwave treatment, whereby the green, red and yellow zones on the laminated paper indicated pressures of < 2.5 MPa, 2.5 to 10 MPa and > 10 MPa, respectively. The results demonstrated the even pressure distribution from top (5.32 MPa) to bottom (4.70 MPa) in the treatment chamber with an insignificant increase in pressure towards the shockwave source. The predicted and measured values were comparable, which enabled creating a model that could simulate pressure at various distances from the shockwave source [39].

Therefore, the use of shockwave treatment for meat tenderization is promising. However, up to date, the majority of studies on a shockwave impact on foods, including meat, are at the stage of laboratory experiments and verification, and require further research aimed to an increase in the effectiveness, development of rules and safe methods of using before large-scale commercialization as well as evaluation of consumer acceptability.

One of other possible methods for application of the shockwave technology is processing oysters. Raw oysters are placed into water and exposed to shockwaves. The adductor muscle is relaxed and an oyster is opened. Nowadays, samples of such equipment for treating individual batches have been already applied in practice and it is planned to develop a continuously operating unit [15].

Using shockwaves in the technology of plant raw material processing

Over the last decade, studies on using shockwaves for softening fruit and vegetables were carried out to increase the effectiveness of extracting juice/oil from them. The researchers found that treatment of plant materials with shockwaves enables obtaining extraction products with higher quality than those produced with the use of thermally processed fruit due to the minimum comparative effect on nutritional and sensory properties [40]. It was suggested that an increase in the extraction effectiveness upon shockwave treatment is conditioned by increased damage of plant cells before extraction [41]. Underwater shockwaves passing through the plant tissue collide with plant cells and exert high pressure on the cell wall. This creates cracks on the cell wall destructing the cell structure, softening and even liquefying the plant tissue. Therefore, the cell content of plants, including juice, oil and bioactive compounds, penetrates easier through the cell wall destroyed by a shockwave compared to intact cells [42]. Kuraya et al. [42] reported that upon shockwave pretreatment of yuzu, the juice yield increased up to 170% compared to the conventional squeezing methods (yuzu is Japanese citrus fruit with the characteristic pleasant aroma and antioxidant capacity, which is usually consumed as juice).

Yasuda et al. [41] found that carrot subjected to shockwave pretreatment showed a significant increase in juice yield to 44.5% compared to 0.79% in the control raw carrot and 34.4% in the preliminary heat-treated sample. In addition, a significant increase in the carotenoid content was observed in the experimental carrot juice compared to the control (147.6 vs. 103.7 GAE μg/mL). Moreover, the energy input was about 40–50 kJ/kg for the SW treatment compared to heat treatment at 90 °C (which will require, as a minimum, 300 kJ/kg) leading, therefore, to the higher rate of extraction. This shows that energy consumption was significantly lower for SW compared to the methods of heat treatment [41].

It was also established that shockwave treatment increased the rate of extraction compared to various conventional methods including Soxhlet extraction, liquid-liquid extraction, microwave-assisted extraction, and ultrasonic extraction (USE). Molina G. A. et al. [43] reported that the use of shockwaves increased the rate of polyphenol extraction compared to conventional extraction methods with or without solvents. In particular, phenolic compounds and flavonoids from heartwood were extracted over 5 min using shockwave extraction (EP-SW), while the conventional Soxhlet extraction method required 96 hours. In addition, SW extraction did not require the use of organic solvents and led to extraction of significantly higher levels of reducing sugars and lower levels of phenolic acids than Soxhlet extraction. The results of the studies also showed that the time necessary for extraction in the shockwave treatment method was less than that in conventional methods (12.5 min for SW at 0.5 Hz; 20 min for ultrasonic-assisted extraction at 40 kHz; 96 h for Soxhlet extraction) [43].

In general, the use of shockwave treatment in extraction is an effective method to extract juice/oil/bioactive components from different plant materials. This method can be used as a pretreatment or independent process.

The main problems in commercialization of the shockwave use

An effect of shockwave treatment on packaging materials

Commonly used food packaging materials are prone to damages caused by high-intensity shockwaves generated during processing. Bolumar and Toepfl [2] reported that meat swelling caused by shockwave treatment led to disruption of plastic packages. They came to a conclusion that today there are no packaging materials that are completely resistant to SW and it is important to develop not only such a material but also a technology for their use. At present, the most promising packaging material is probably polypropylene due to the fact that its acoustic resistance is similar to acoustic resistance of water, which reduces shockwave absorption [44].

To eliminate the problem with package damage during shockwave treatment, the researchers studied treatment of food products without packaging, when a product was in the direct contact with water during the process. Claus et al. (2001) [17] applied shockwave treatment of chicken breasts packed with water to simulate meat treatment in water. The results showed an increase in cooking losses in chicken breasts submerged in water, which can be caused by increased water absorption.

Furthermore, it is necessary to note that in shockwave treatment, water used in reservoirs is a potential source of product contamination, and it is necessary to develop corresponding mandatory requirements to label a product treated in this way.

Consumer acceptance of the shockwave treatment technology

To introduce new technologies, it is necessary to overcome natural resistance to changes. A consumer perception of the use of different beef processing technologies including shockwaves as a method for food quality improvement was analyzed within the framework of the European project ProSafeBeef. Researchers came to a conclusion that consumers regard as undesirable multiple impacts on meat that move a product away from its initial state. Beef processing technologies were mainly considered valuable options for consumers' convenience. In general, consumers supported the development of technologies that could provide more wholesome and quality food; if such technologies were "not invasive", the chances of their acceptance by target audience increased. The final conclusion showed a serious skepticism about excessive interventions into food technologies and a strong desire to make food and beef processing as "simple and natural" as possible [6].

It was noted that the fact of using low-grade beef as a raw material for shockwave treatment could cause doubts about product quality among the participants of the study and, therefore, this could have a negative effect on the results. Moreover, the participants said that such processing technology would be suitable only for consumers with limited budgets ("it might be okay for others, but not for me") and several respondents linked it with a probable carcinogenic risk.

Focusing their attention on the shockwave technology, the researchers noted that consumers had doubts about the effects of this technology and consequently their perception was different. On the one hand, the tenderizing effects and non-invasive character of the technology were regarded as quite positive. On the other hand, the absolute lack of knowledge about the technology exerted a significant negative effect on its acceptance by consumers due to unknown risks that it may pose. However, the lack of knowledge can be eliminated by proper consumer education and communication campaigns [6].

Conclusion

Studies on the use of shockwave treatment of foods began in the 1990s. However, their development has not led to large scale commercialization and remains to be at the experimental and pilot stages.

Recently, a great success has been achieved in the understanding of the fundamental mechanisms underlying the SW treatment. The use of shockwaves is a non-thermal and non-invasive technology and a promising method for accelerated meat ageing and its tenderization, as well as for increasing the yield and nutritional value of juice/oils extracted from plants.

The main problems in the industrial introduction of the underwater shockwave technology include an absence of the corresponding packaging materials resistant to the destructive effect of shockwaves, necessary capital investments, absence of the normative-legal base regarding the use of shockwave technologies and assessments of consumer opinion. Up to now, the majority of the studies on the shockwave effect on foods are at the stage of laboratory investigations.

The development of the innovative technologies extends the technological tools in the food industry due to introduction of new processing methods into the circle of the verified convenient technologies.

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The author declare no conflict of interest.