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REVIEW ARTICLE

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Pulsed electric fields and meat processing: latest updates

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ABSTRACT

Pulsed electric fields (PEF) is a non-thermal technology that is still looking for implementation on a larger scale by the meat industry. Its sustainability dimension, which is much improved by lowering energy consumption and shortening treatment times compared to conventional technologies, may tip the scale for successfully shifting the PEF technology readiness level to industrial application. This review provides an overview of the latest knowledge, and in the last three years, on using PEF processing in meat to enhance its functionality, nutrition, texture, colour and sensory quality. PEF treatment could improve meat's protein digestibility and solubility while having no negative impact on its nutritional value. However, controversial indications regarding PEF's effect on meat cooking loss are reported. Colour changes of meat after PEF treatment are directly proportional to the extent of total specific energy inputs used in the processing, while the effect of PEF on meat sensory properties is yet to be discovered. Since the ability of PEF to achieve its desired goals is dependent on many different factors, including the type of meat, electric field strength, number and duration of electric pulses, and others, more studies are needed to fully understand specific conditions that can be dependably applied in the meat industry.

HIGHLIGHTS

- pulsed electric fields improve functional quality of meat
- pulsed electric fields do not negatively affect nutritional quality of meat
- pulsed electric fields sustainability research in meat industry is hugely missing

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Introduction

Electricity and food first met, in an industrial environment, almost a century ago when the ohmic heating was applied to milk in order improve its safety and shelf life. First notions that alternating current electric fields can disrupt biological cells, in the process called initially 'electro-plasmolysis', were published by the researcher on the Eastern side of the 'iron curtain' and were, at that time, virtually unheard of in the rest of the World (Sitzmann et al. 2022). Pulsed electric fields (PEF), as we call the technology today, was first applied 65 years ago for the extraction of sugar beet, and we are still addressing it as an emerging food technology. However, this term is not used to describe its novelty, but it refers more to the long-term efforts of both scientists and industry to the improvement and continual development of an already existing technology.

Two electrodes attached to source of high-voltage electric fields (5–50 kV/cm) and a food matrix located between them in the treatment chamber, exposed to a number (1–1000) of short pulses (μs-ms) at a certain frequency (Hz) is the simplest explanation of PEF setup. Depending on the distance between the electrodes, dimensions of the chamber, electric field strength and the treatment time, different amounts of specific energy inputs (kJ/kg) might be released.

Electro-poration and electro-permeabilization are most often used phrases to describe the PEF generated phenomenon(s) in biological cells. First one addresses the formation of aqueous pores in the lipid bilayer of the cytoplasmic membrane, and the other one increase in its permeability. These kinds of cell disruptions are the underlying mechanisms for the two major PEF applications in food/meat matrices: non-thermal microbial inactivation and mass transfer enhancement (Gómez

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et al. 2019). The capability of PEF to efficiently achieve the aforesaid objectives depends on different factors including the design of power supply (peak voltage, peak current, average power, pulse waveform, pulse width and pulse repetition rate), type of switching devices (transistors, semiconductors), and the design of the treatment chamber (electrode configuration, area, gap and the flow pattern) (Heinz and Toepfl 2022).

The use of PEF in liquid foods was a 'success story' from the beginning, and its application is expanding the number of substrates used in this regard, most recently including mixtures of a pineapple juice and coconut milk (Yildiz et al. 2023), red wine (Akdemir Evrendilek 2022; Delso et al. 2023), milk (Nabilah et al. 2022) and even human milk (Zhang J et al. 2023). Promising scientific results are leading to even more popular and wider application of PEF in liquid food industry (Li L et al. 2021). However, PEF and solid foods are a much more 'difficult' combination, mainly because microbial inactivation in them is relatively unrealistic. At least, low-intensity PEF treatment seems to be ineffective for the most species of microorganisms (Li Z et al. 2021). On the other hand, electroporation is an excellent pre-treatment of solid foods (including meat) before drying, cooking, and even freezing, *via* increased mass and energy transfer (Zhang C et al. 2023).

Heat induced food drying in an industrial setting brings quite large economic and environmental drawbacks because it demands vast amounts of energy. For this reason a number of innovative technologies, like microwave, irradiation, and ultrasound, have been employed to decrease the meat drying time and temperature but without a significant effect on the reduction on energy consumption (Mediani et al. 2022). An effective substitute to these innovative techniques could be the use of PEF for less energy demanding drying of meat samples (Ghosh et al. 2020). Since PEF is a non-thermal technology, it does not require additional cooling of the meat samples which leads to reduced water and energy consumption, as well. Therefore, substantial advantages in terms of energy and environmental aspects can be achieved for PEF technology compared to conventional processes. However, these kind of studies are lacking in general, and are performed more frequently on the PEF application for liquid foods, where actually lower environmental benefits might be expected (Aganovic and Smetana 2022). Possible explanation for this paradoxical situation might be found in the complexity of the meat matrix itself. Amount and allocation of fat and connective tissue in meat can differ considerably, depending on type and age of the animal, feed, meat cut, etc. Thus, these variables, alongside meat fibre orientation, can have explicit and considerable impact on the effectiveness of PEF treatment, as well as on the energy demand (Smetana et al. 2019), making it difficult for meat/PEF sustainability studies to be designed and successfully performed.

We have recently provided a detailed overview on the application of PEF in meat and fish processing industries (Gómez et al. 2019), although without the sustainability aspect, but it seems that most recent interest of both meat researchers and industry, on this topic, is bigger than ever. We have encountered novel scientific evidence provided by the recently formed research groups and institutions, that are shedding a new light on this subject. Most interestingly, some of the findings seem to be controversial and/or contradicting the previous conclusions and observations. Therefore, this review aims to provide the latest updates on the application of PEF in meat science and technology, its advantages, disadvantages and most recent (last three years) achievements and failures.

Method

Data collection and eligibility criteria

This systematic review manuscript followed the research steps cited in the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al. 2021). For this purpose, the authors followed a manual pre-selection and evaluation of papers published between 2020 and 2023, focussing primarily on the topics and abstracts of those articles. English was the exclusive language for paper selection and only research articles were considered to guarantee the information quality for this investigation. Other reviews, correspondence letters, dissertations, expert opinions, lectures, books, or chapters of books were excluded. Duplicate articles were only considered once. The study was considered relevant when: (i) it included information about PEF method; (ii) it had information about meat and/or meat products; (iii) evaluated changes in meat and/or meat products induced by PEF; (iv) evaluated the sustainability and energy efficiency of PEF in the meat processing; (v) the article was conducted as a unique research manuscript.

Information sources and search strategy

The literature selection was based on a manual validation using five different databases, i.e. Scopus, Science Direct, Web of Science, Wiley Online Library and PubMed. The exploring and screening for eligible articles was performed from December 2022, until February 2023. The combination of key words used for this investigation were: 'pulsed electric field' AND 'meat' AND 'products' AND/OR 'sustainability' AND/OR 'life cycle assessment' AND/OR 'energy efficiency'.

Results and discussion

Potential of hydrogen

Changes in the pH of meat, and after the PEF is applied, are connected to the alterations of meat conductivity and as a result of electroporation, particularly with usage of high electrical energy and high frequency (Kantono, Hamid, Ma, et al. 2021). However, chicken *m. pectoralis major* pH status was not significantly affected by the PEF treatment with the total energy input of 2.42 kJ/kg, most probably because the power extent used was not high enough to induce the outflow of cellular solutions due to the cell interruption. Regardless of the electric field strength (0.60–1.20 kV/cm) or the number of pulses (150–600) applied, pH of the PEF treated chicken meat samples remained comparable to the ones of the control (PEF non-treated) samples (Baldi et al. 2021). Similar was observed for the chicken breast meat in the investigation of Aşık-Canbaz et al. (2022) where the electric field strength of 7 kV/cm was not strong enough to cause changes in pH.

PEF-treated beef (0.52 kV/cm; 20 μs; 600 pulses) had a mean pH of 5.8 that was not significantly different from the pH of PEF non-treated beef (Bhat et al. 2020). Also, there were no general differences in pH of beef *m. semimembranosus* with or without PEF treatment (0.25–0.5 kV/cm, 20–100 Hz and 1000–5000 pulses) neither after 1 or 14 days of cold storage (Bolumar et al. 2022). Lamb meat cuts when PEF treated (88–109 kJ/kg, 90 Hz, 1–1.4 kV/cm, 964 pulses, 20 μs) exhibited no significant changes in pH values, compared to control samples (Kantono, Hamid, Ma, et al. 2021). Red deer loins had an average pH of around 5.7 before and after low (1.93 kJ/kg, 2.5 kV, 50 Hz, 20 μs) and high (70.2 kJ/kg, 10 kV, 50 Hz, 20 μs) intensity PEF treatments (Mungure et al. 2020).

Drip, cooking and thaw loss

It is generally believed that PEF treatments with high intensity are causing an increase in drip loss of meat samples due to the irreversible damage forced upon cell membranes by electrical fields and/or myofibril fragmentation and protein denaturation (Gudmundsson and Hafsteinsson 2001). However, both drip and cooking loss (sous-vide cooking at 60 °C for 1, 3, 6, 12, and 24 h) of beef were not affected by the field strength (1.0, 1.5, and 2.0 kV/cm) of PEF but only by the sous-vide cooking time. Drip loss decreased and cooking loss increased significantly with a longer sous-vide time. However, after 12 h of sous-vide cooking no significant difference in cooking loss was observed between the control and the PEF-pre-treated samples ($p > .05$) (Jeong et al. 2020). Another investigation exposed beef meat to PEF (0.5–2.0 kV/cm, 50 μs, 125 pulses) and immersed it in brine with 8% (w/v) NaCl and 0.3% (w/v) $Na_5P_3O_{10}$ concentration, in order to reduce marination time (33% achieved) and improve diffusion of NaCl (69.0%) and water (51.8%). No significant effect of PEF on cooking loss (water bath at 76 °C to a core temperature of 70 °C) of the samples was observed (Zhang et al. 2022). The authors hypothesised that the water retention capacity of the beef meat was increased by the addition of NaCl and that a complex interaction between PEF and NaCl and their effect on meat cooking loss are yet to be better investigated and understood in the future.

In the research of Bolumar et al. (2022), after PEF treatment (0.25–0.5 kV/cm, 20–100 Hz and 1000–5000 pulses) and chilled storage for 14 days, drip loss of beef meat was slightly higher (0.6%) as compared to PEF non-treated samples, but these differences were not statistically significant (Bolumar et al. 2022). Similar was observed for cooking loss of the samples, as well. Again, no significant differences in weight loss of beef *m. transversus thoracis* were observed between the samples treated with high (84–111 kJ/kg), medium (57–71 kJ/kg) or low (28–35 kJ/kg) intensity PEF treatments (Karki, Oey, Bremer, Leong, et al. 2023). However, cooking loss (sous vide 60 °C for 12, 24, or 36 h) was significantly lower in samples with high intensity PEF pre-treatment as compared to non-treated samples. However, different study suggested that both low (30–35 kJ/kg) and high (90–100 kJ/kg) energy PEF treatments significantly decreased cooking losses (sous vide 60 °C for 24h) in beef short ribs but only for the samples with medium range of electrical conductivity (6–9 mS/cm) (Karki, Oey, Bremer, and Silcock 2023). The explanation provided was that PEF had a very little impact on meat intracellular water, that represents almost 97% of total water content in meat, and that it makes meat to form a sponge like microstructure that has an improved ability to retain water and limit both drip and cooking losses. The reason why, for the samples with lower (3–6 mS/cm) or higher (9–12 mS/cm) range of electrical conductivity, the effect of PEF treatment on cooking loss could not be observed by the authors was not provided (Karki, Oey, Bremer, and Silcock 2023).

In the study of Kantono, Hamid, Ma, et al. (2021) there were some ambiguities regarding the effect of PEF on cooking loss of chilled and frozen-thawed lamb meat cuts. Namely, the authors explained that 'PEF may have caused an alteration in the myofibrillar structure, which led to reduced water holding capacity of the muscle' but concluded that 'PEF treated rump and shank cuts had significantly lower cooking loss compared to non-PEF treated samples' (Kantono, Hamid, Ma, et al. 2021). Also, PEF treated chilled and frozen-thawed lamb knuckle cuts in their study had lower cooking loss in comparison to control samples, while for the chilled loin and shoulder cuts, and frozen-thawed rib cut quite the opposite was noticed. The explanation provided for the effect of the type of cut on the cooking loss, and in interaction with PEF treatment, was that distinctive kinds of muscles have individual physical/chemical attributes and muscle fibre contents, which can influence the water holding capacity of each muscle.

When it comes to poultry and contrary to what is generally believed, Baldi et al. (2021) have reported the reduction of drip loss by 13% to even 28.5% in chicken meat samples after PEF was applied and during the four days of cold storage. They also observed that an increase in number of pulses was much more favourable in this regard, in comparison to the surge in electric field strength. The authors hypothesised that this phenomenon might be explained by entrapment of water molecules into the hydrophilic pores of the membrane lipid bilayer generated by PEF, that might reseal in milliseconds after the end of the treatment or the effect of 'moisture re-compartmentalization'. The other explanation might be the PEF induced proteins' conformational changes which lead to enhanced interaction with water molecules and subsequently reduced drip loss (Baldi et al. 2021). Individually or jointly, these two mechanisms might best explain why lower intensity PEF treatments might be responsible for the increased water holding capacity of meat. In a different investigation of Wang J et al. (2022), synergistic effect of PEF (electric field intensity of 1 kV/cm) and immersion of chicken breast meats in $CaCl_2$ solution (0.4 mol/L) resulted in a significantly improved water holding capacity (16.61%) and decreased cooking loss (28.93%) of the samples. The reason why such an effect was accomplished have been provided by the nuclear magnetic resonance spectroscopy and magnetic resonance imaging analysis. These images revealed higher extent of immobilised water into the enlarged spaces between the myofibrils due to their swelling. PEF induced 'conformational changes of myofibrillar proteins and accelerated the degradation of low-molecular weight proteins', as well. However, when higher intensity PEF was applied (2 kV/cm) to chicken breast meat, its water holding capacity has decreased by 2.17% compared to 1 kV/cm treatment (Wang J et al. 2022). Also, PEF assisted (1–3 kV/cm, 2000 µs, 50 Hz) thawing of Pekin duck breasts meat was faster (50%) and with decreased thawing loss (28%) and protein loss (19%) compared to samples thawed in refrigerator (Lung et al. 2022). Still, at 4 kV/cm thawing loss was significantly higher compared to control samples because electric field strength became strong enough to induce protein denaturation resulting in increased water and soluble protein loss along with deterioration of meat nutritional value (Toepfl et al. 2014; Qian et al. 2019).

Thawing and cooking (water bath at 80 °C/internal temperature 75 °C) losses of red deer m. *longissimus et lumborum* were higher for wet (21 d at 4 °C, vacuum packed) then for dry (21 d at 4 °C, relative humidity 80%, air velocity 1.5 m/s) aged samples. However, neither high (70.2 kJ/kg, 10 kV, 50 Hz, 20 µs) nor low (1.93 kJ/kg, 2.5 kV, 50 Hz, 20 µs) pulsed fields had an effect on both of those types of losses (Mungure et al. 2020). Finally, emulsion composite gels made with myofibrillar proteins extracted from fresh pork loins (*m. longissimus lumborum*), exhibited vast increase in water holding capacity (37.9%) after being exposed to PEF ($2.5-5.0$ kV/cm, 500 Hz, 6 µs). However, when PEF exceeded intensity of 7.5 kV/cm a deterioration in gel water holding capacity was noticed and explained by the possible protein aggregation. The authors also concluded that PEF energy inputs (0.76 × 103–5.32 × 103 kJ/kg) used in their study were not capable of modifying the primary structure of myofibrillar proteins but were sufficient to exert conformational changes. (Wang Q et al. 2022).

Functionality and nutrition

PEF can provoke the partial unfolding of meat proteins, which leads to better gastrointestinal digestion due to their increased vulnerability to hydrolysis done by the enzymes, and even more so if they are already denatured because structural protein changes have a strong influence on protease activity (Kaur et al. 2014; Simonetti et al. 2016; Liu et al. 2018).

Mean *in vitro* gastrointestinal protein digestion of venison meat after PEF treatment (10 kV, 20 Hz, 20 μs) of 93.0% was observed, and was significantly higher ($p < .05$) as compared to control samples (91.8%) (Bhat et al. 2021). Same investigation also observed an increase in protein solubility in both *in vitro* gastric and intestinal digestion. The authors stipulated that the trends observed in their experiment might be explained by the improved penetration of the enzymes into the meat matrix because of electroporation. Similarly, beef brisket (*m. pectoralis*) exhibited an improved (29%) *in vitro* oral–gastro–small intestinal protein digestibility after being exposed to a combined effect of PEF (99 ± 5 kJ/kg, 0.7 kV/cm, 20 μs and 50 Hz) and sous vide cooking (60 °C for 24 h) (Chian et al. 2021). Increased proteolysis of myosin heavy chains and C-protein was also observed. The authors have explained that micro- and ultrastructure of the PEF treated + sous vide cooked and control (only cooked sous vide) samples was not significantly different before the *in vitro* digestion, but only after the end of it. They also suggested that an increased infiltration of digestive juices in the PEF treated samples was noticed, as a consequence of electroporation in muscle cells, because more swollen sarcomeres were observed. Their conclusion was that PEF led to an improved *in vitro* protein digestibility of the meat that was only enhanced by the effect of sous vide cooking (Chian et al. 2021). Likewise, mild PEF treatment (<2.5 kV/cm) preserved functional properties of chicken muscles since no negative effects were observed on protein solubility or denaturation processes, regardless of neither the electric field strength nor the number of pulses applied. Total protein denaturation enthalpy procedure revealed that this low energy pulsed fields have not been able to induce these processes in chicken meat, avoiding negative effects on its functional properties (Baldi et al. 2021).

Gastrointestinal digestion of cooked venison released the same quantities of different minerals (Fe, K, P, Ca, Na, Mg, Cr and Ni) in the liquid digesta regardless of the absence or presence of the PEF treatment, beforehand (Bhat et al. 2021). No significant ($p > .05$) effect of PEF processing (0.52 kV/cm, 10 kV, 20 Hz, 20 μs) was noted on the minerals of beef jerky, as well (Bhat et al. 2020).

Texture

Electroporation of sarcomeres during PEF processing might progress activity of calpain-2 enzyme, because the disruption of sarcoplasmic reticulum progresses to an early release of calcium ions, which leads to the proteolysis of muscle proteins (both desmin and troponin-T) and therefore improve the texture of meat (Ji and Takahashi 2006; Bhat et al. 2019).

In the investigation of Bhat et al. (2020), PEF processed (0.52 kV/cm, 10 kV, 20 Hz, 20 μs) beef meat samples with 1.2% NaCl had significantly lower values (up to 22%) for shear force (N), toughness (N/mm s) and firmness (N/mm) in comparison to PEF non-treated samples with 2% NaCl. Likewise, Bolumar et al. (2022) confirmed that 5–10% shear force reduction might be achieved in beef *m. semimembranosus* after 14 days of cold storage and after applying relatively low electrical field strengths (0.5 kV/cm) of PEF (50 ms or 5000 pulses) (Bolumar et al. 2022). It was previously established that increased electrical conductivity of meat is an indicator of the degree of tissue disintegration and changes in membrane permeability (Byrne et al. 2000). The higher was the electrical field strength (1.0, 1.5, and 2.0 kV/cm) of the PEF treatment, applied to beef *m. semitendinosus* muscle, the bigger was its electrical conductivity, suggesting a greater degree of tissue breakdown. This led to a significant decrease in cutting force (35%), hardness, and chewiness of the meat and proportionally to the strength of the electrical field (Jeong et al. 2020). Increased tenderness of the beef *m. semitendinosus* samples induced by PEF was retained even after the subsequent sous vide cooking (60 °C for 1, 3, 6, 12, and 24 h) because this gentle culinary method does not provoke muscle contraction, in general.

Myofibrillar fragmentation index and collagen solubilisation percentage of beef short ribs was proportional to the increase of PEF treatment intensity (28–111 kJ/kg) leading to an increase in tenderisation of the treated samples (Karki, Oey, Bremer, Leong, et al. 2023). The interaction between PEF pre-treatment and sous vide cooking (60 °C for 12h) on improved cohesiveness, springiness, gumminess, chewiness, and resilience values was also significant.

Karki, Oey, Bremer, and Silcock (2023) concluded that PEF pre-treatment could be used to tenderise tough beef *m. transversus thoracis* (short ribs) during the sous vide cooking (60 °C for 24h) when high energy PEF (90–100 kJ/kg, 10 kV, 20 μs, 50 Hz, 5200 pulses) was applied. It has significantly lowered the TPA hardness of short ribs with electrical conductivity of 6–9 mS/cm, which is an effect that that was observed in samples with lower (3–6 mS/cm) or higher (9–12 mS/cm) electrical conductivity but only after additional 12h of sous vide cooking. Springiness and cohesiveness remained unaffected by neither the PEF treatment nor the duration of sous vide cooking. Similarly, beef (m. *longissimus lumborum*) marinated (30–180 min in brine with 8% (w/v) NaCl and 0.3% (w/v) $Na_5P_3O_{10}$) and PEF treated (0.78–12.50 kJ/kg, 50 μs, 125 pulses) samples exhibited lower shear force, hardness and chewiness values compared to untreated samples, but with no significant difference ($p > .05$) in springiness (Zhang et al. 2022). With a treatment of 2.0 kV/cm and 12.50 kJ/kg, reduction of 22.90% in shear force values was achieved. Overall, PEF-supported marination had the ability to enhance the tenderness and texture of beef meat.

Wet aged (21 d at 4 °C, vacuum packed) red deer *m. longissimus et lumborum* samples also had significantly lower shear forces (9%), when they have received PEF pre-treatment (70.2 kJ/kg, 10 kV, 50 Hz, 20 μs) before ageing, as compared to the PEF non-treated samples. Transmission electron microscopy revealed the reason for improved tenderisation, showing disruptions in the myofibrillar protein structure as induced by high intensity PEF (Mungure et al. 2020). Otherwise, hardness and shear force values of fresh female Pekin duck breasts was completely comparable to the ones measured from the same type of (frozen) meat samples but after the PEF treatment (1–4 kV/cm, 2000 μs, 50 Hz) was applied to thaw them (Lung et al. 2022).

Colour

Colour variations in meat, after the PEF treatment with higher total specific energy inputs, rich with myoglobin are usually explained with its alterations caused by the rise of sample temperature during the course of action. High-intensity PEF (84–111 kJ/kg) of beef *m. transversus thoracis* induced significant changes in its lightness (L*), redness (a*), hue angle (H) and chroma values (C), while yellowness (b*) remained unaffected. After 24h of sous vide cooking of the samples, the effect of PEF on colour was considerably reduced, and no significant difference in redness, hue angle, and chroma could be detected between high intensity PEF treated short ribs and control samples (Karki, Oey, Bremer, Leong, et al. 2023). The authors postulated that very low oxygen permeability of vacuum bags used led to a lower oxidation and denaturation of myoglobin produce pinkish coloured sous vide cooked meat, as perceived by their sensory assessors. Interestingly enough, similar group of investigators (Karki, Oey, Bremer, and Silcock 2023) considered the same kind of samples (beef *m. transversus thoracis*) but now taking into account their different electrical conductivity divided into three distinct groups (3–6 mS/cm, 6–9 mS/cm and 9–12 mS/cm). This time, their conclusion was that PEF treated (input voltage of 10 kV, pulse width of 20 μs, pulse frequency of 50 Hz, specific energy 30 - 100 kJ/kg and pulse number 1600 – 5200) short ribs of differing conductivities were not significantly different in CIE Lab values (Karki, Oey, Bremer, and Silcock 2023). On the other hand, when low intensity treatments (<5 kJ/kg) were performed on chicken meat with poor content of myoglobin, within the study of Baldi et al. (2021), PEF with pulse width of 20 μs have not altered redness significantly regardless of the number pulses or electric field strength. However, controversial were the conclusions that a lower electric field strength (0.6–1.2 kV/cm) and number of pulses from 150 up to 300 were linked to an increase in the meat lightness, while additional rise in pulse numbers (450–600) led to a decrease in both lightness and yellowness of samples. Baldi et al. (2021) stipulated that such a phenomenon might be explained by the water redistribution caused by the PEF treatment, with low total specific energy, leading to a shift in the refractive properties of the chicken muscle tissue. Similar was observed for the chicken breast meat in the investigation of Aşık-Canbaz et al. (2022) where the electric field strength of 7 kV/cm was not strong enough to cause changes in lightness, yellowness or chroma values of the samples.

Once more, PEF-treated beef that has experienced the temperature increase of only 4 °C, exhibited no changes in lightness, redness, yellowness, chroma and hue angle, compared to PEF non-treated beef (Bhat et al. 2020). The same was observed in beef *m. semimembranosus* even after two weeks of cold storage and when PEF treatment (0.25–0.5 kV/cm, 20–100 Hz and 1000–5000 pulses) was applied to the meat samples (Bolumar et al. 2022). Instead, PEF treatments of different intensities (1.0, 1.5, 2.0 kV/cm) on beef marinated (30–180 min in brine with 8% (w/v) NaCl and 0.3% (w/v) $Na_5P_3O_{10}$) meat increased lightness, decreased redness, chroma and hue angle, while values for yellowness remained unaffected. Lower intensity treatment (0.5 kV/cm) had no significant effect on any of the colour parameters, as compared to PEF non-treated samples (Zhang et al. 2022). However, the total colour difference values (ΔE) in all PEF pre-treated samples and different intensities were above 1 unit, which is the limit value of the visible difference (Altmann et al. 2022), indicating that PEF pre-treatment would trigger perceivable sensory difference of beef colour. In the experiments of Jeong et al. (2020), PEF non-treated beef *m. semitendinosus* muscles had a higher total myoglobin content and redness values as compared to PEF treated (2.0 kV/cm, 20 µs, 200 pulses) samples. However, after subsequent sous vide cooking at 60 °C and for more than 12h, no significant colour differences between the control and the PEF-pretreated samples were observed (Jeong et al. 2020).

Apart from beef, lower lightness, redness and yellowness values were also observed in PEF treated (specific energy 88–109 kJ/kg, frequency 90 Hz, electric field strength 1–1.4 kV/cm, number of pulses 964, pulse width 20 µs) chilled and frozen-thawed lamb meat cuts. The authors reported that an increase in temperature of about 10 °C was noted and postulated that this was not the reason (higher oxidation in myoglobin to metmyoglobin) for the perceived changes in colour, because they appeared only in chilled and frozen-thawed samples. Instead, they suggested that the decrease in lightness may be due to enhanced sensitivity of meat to lipid oxidation (Kantono, Hamid, Ma, et al. 2021). As reported by Lung et al. (2022), lightness of fresh L* (lightness), a* (redness), b* (yellowness), C (chroma) and H (hue angle) breasts was like the one of PEF thawed (1–3 kV/cm, 2000 µs, 50 Hz) samples, and only after the highest extent of electrical field power (4 kV/cm) was applied it has significantly decreased. Similar was observed for yellowness while the difference was that it has increased when maximum power was applied. Finally, even the lowest amount of power was enough to induce significant increase of redness in PEF treated duck meat samples.

Sensory quality

The release of iron with storage, which is an active lipid oxidation catalyst, from sources such as haemoglobin, myoglobin and ferritin, catalyses lipid oxidation. However, no impact of PEF treatment was observed on the lipid oxidation of beef during storage (Bhat et al. 2020). No impact of PEF treatment or salt reduction was observed on the protein oxidation of the products, as well. However, in chilled lamb meat cuts and after the PEF (specific energy 88–109 kJ/kg, frequency 90 Hz, electric field strength 1–1.4 kV/cm, number of pulses 964, pulse width 20 µs) was applied, the level of lipid oxidation significantly increased. More so, PEF treated frozen lamb knuckle and rib cuts, and after seven days of cold storage, demonstrated higher contents of malondialdehyde exceeding the limits of thresholds for rancidity or off-flavour development in meat (Kantono, Hamid, Ma, et al. 2021).

Both high and low-value lamb meat cuts when PEF treated (88–109 kJ/kg, 90 Hz, 1–1.4 kV/cm, 964 pulses, 20 µs) exhibited significant changes in the composition of volatile compounds which led to the alterations in sensory profiles as compared to control samples. PEF treatments resulted in dominant meaty and oxidised flavour sensations, in general. The later were observed in PEF treated frozen–thawed rib cut and after the seven days of cold storage, while temporally dominant meaty and juicy flavour sensations were noted in PEF treated chilled samples and were associated with the presence of certain fatty acids. Finally, chilled and frozen lamb meat cuts had browned and livery sensory characteristics after PEF was employed (Kantono, Hamid, Chadha, et al. 2021). In opposition, overall sensory acceptability (observed by 65 panellists) in the work of Bhat et al. (2020), between the PEF treated and non-treated beef topsides of premium quality was not significantly different.

Sustainability

One of the triggers in implementing PEF in meat sector, is understanding pros and cons of this technology, and constraints in transferring from research to industry (Gómez et al. 2019). Obviously, its sustainability dimension may tip the scale for successful shifting the technology readiness level (TRL) to industrial application. Sustainability impact may be evaluated using a mixture of different tools such as mass-energy balance modelling of the lab-scale equipment (Rezek Jambrak et al. 2018), return of investment calculations depending on TRL (Djekic and Tomasević 2022), life-cycle assessment (LCA) 'gate-to-gate' studies (ISO 2006) or life cycle sustainability assessment combining LCA, life cycle costing and social LCA (Ren 2020). In parallel, food safety and food security studies contribute to sustainability of PEF (Arshad et al. 2021). In spite of application of PEF in food industry, its environmental dimension is still scarce, mostly covering processing plant-origin food such as juices or vegetables (Aganovic and Smetana 2022).

PEF processing improves its sustainability dimension by lowering energy consumption and shortening treatment time (Djekic and Tomasević 2022). As a consequence, this energy-saving technique decreases the indirect energy usage and reduces greenhouse gas emissions (Arshad et al. 2021). Combating climate change in food supply chains is considered as priority of utmost importance (Djekic et al. 2021). Ghosh et al. (2020) showed that combination of PEF and conventional drying extend shelf life of meat sample with confirmed low energy-consumption. Another potential was revealed by Smetana et al. (2019) proposing PEF-assisted cooking as it has quality and sustainable benefits.

Besides the use in meat processing, PEF can also be used for decreasing environmental impact of meat production. Main impacts are consumption of natural resources, disposal of waste, discharge of waste water and emission of greenhouse gasses (Djekic and Tomasevic 2016). Extraction of bioactive compounds (from various types of waste and by-products) can be achieved by using different extraction technologies. PEF consumes lower energy when compared to other thermal and non-thermal technologies (Velusamy et al. 2023). This can be an advantage in the meat sector bearing in mind that almost 25% of produced meat in the European Union is wasted in different stages of the meat supply chain (Karwowska et al. 2021). In parallel, knowing the negative effects of meat waste and difficulties in waste conversion to useful products, Ghosh et al. (2019) validated that PEF joint with mechanical pressing is a promising green technology for functional extraction of various bioactive compounds and useful chemicals. Similar group of researchers also reported that PEF can contribute to the significant energy savings ($933.18 \pm 22\,\mathrm{J\ g^{-1}}$) when it comes to meat drying technology (Ghosh et al. 2020). We also know that PEF assisted meat marination times can be shortened by 33% by an improvement of NaCl (69.0%) and water (51.8%) diffusion (Zhang et al. 2022). PEF supported thawing of duck breasts meat can be 50% faster as compared to conventional methods (Lung et al. 2022).

It is important to analyse the triumvirate of three main elements when analysing sustainable potentials of PEF in the meat sector: TRL of PEF technology, its environmental indicators and its benefits to all stakeholders. The technology is high on the TRL scale in other food sectors, as it has already been commercialised for fruit juice and potato. However, TRL of PEF in the meat sector is at level 6–7, through development of various prototypes verified at lab scale but still not fully employed throughout the industry. Environmental indicators/footprints per functional unit (FU) of 1 kg of processed meat should cover two main indicators: global warming potential [kg CO_2e/FU] and energy consumption [MJ/FU] (Djekic and Tomasevic 2018). For example, these indicators for different types of foods, other than meat, were systematically outlined in the work of López-Gámez et al. (2023). Unfortunately, this kind of research regarding PEF and meat technology is almost non existing.

Finally, benefits for all stakeholders should be also financial (as one of sustainability pillars), widening the perspective of production of safe products (Rezek Jambrak et al. 2018).

Conclusions

It seems that PEF has limited to no effect on pH regardless of the type of meat or the energy of the treatment applied. Controversial indications are reported regarding its effect on meat cooking loss, that seems to be meat type and processing conditions related but still with no clear explanations about the nature and extent of this dependence. We can be almost certain that it improves the functional properties of meat and especially protein digestibility and solubility while having no negative impact on its nutritional value. Colour changes of meat after PEF treatment are directly proportional to the extent of total specific energy inputs used in the processing, while the effect of PEF on meat sensory properties is yet to be desired. Finally, important research and its results, on all three pillars of PEF sustainability in meat industry, are hugely missing and further investigations are necessary if we are to have some quantifiable conclusions on this matter.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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