Influence of various chilling methods on the sustainable beef production based on high voltage electrical stimulation

Joanna Katarzyna Banach1*, Ryszard Żywica1, Paulius Matusevičius2

1 Institute of Management and Quality, Faculty of Economics, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland, 2 Faculty of Animal Sciences, Veterinary Academy, Lithuanian University of Health Sciences, Kaunas, Lithuania

* katarzyna.banach@uwm.edu.pl

Abstract

Among the challenges of sustainable management of meat production, the key issue is to improve the energy efficiency of production processes, which will consequently affect the reduction of greenhouse gas emissions. Such effects are achieved by combining various chilling systems with electrical stimulation that determines the quality of meat at the slaughter stage. The novelties of the research undertaken included determining the impact of various variants of meat production (chilling method: slow, fast, accelerated + HVES/NES) on changes in the basic (industrial) quality indicators (pH and temperature) of beef produced from Polish Holstein-Friesian breed cattle, and then indicating the optimal variant for energy-efficient (sustainable) beef production. The HVES and the fast chilling method yielded positive economic (meat weight loss), technological (high quality, hot-boning), energetic (lower electricity consumption), and organizational effects (reduced chilling and storage surfaces and expenditures for staff wages) compared to the slow and accelerated methods. Reaching the desired final temperature with an increased amount of chilled meat enables obtaining a few-fold decrease in the specific energy consumption and a higher energy efficiency of the process. This allows recommending the above actions to be undertaken by entrepreneurs in the pursuit of sustainable meat production.

Introduction

One of the strategies of sustainable production in the agri-food sector, apart from striving to ensure high quality and safety of raw materials, envisages also effective management of energy and the environment throughout the food chain. Pursuant to this strategy, agricultural production is realized through changes in farm management, where energy is used with maximum efficiency (the so-called carbon footprint). Practical tools for the implementation of sustainable beef production at the rearing stage include measures aimed to improve: animal productivity (health and welfare), feed quality, soil fertility, and the efficiency of use of electricity and fertilizers [1]. Proposals for good cattle breeding practices in the Western European
Among the challenges of sustainable management of production as well as electricity and heat in meat plants, there is a need to, among others, improve production efficiency and reduce energy consumption, including mainly specific energy consumption of production processes, in order to reduce operating costs and mitigate side effects on the natural environment [3, 4]. This is especially important because the meat industry is characterized by a high demand for electricity, as chilling systems consume by far the most of this type of energy [5–7]. In addition, Polish plants with their profitability of meat sales reaching barely 1–2%, deem it necessary to take the above-mentioned measures [8]. However, the investment and modernization activities undertaken at the stage of cattle slaughter and beef carcass/half-carcass chilling need to be adapted to industrial needs, whereas ready-to-adopt technologies should be characterized based on production and energy efficiency indicators of devices/installations and eco-efficiency of plants [9–11].

Today, the development of meat chilling techniques is heading towards systems that do not use extremely low temperatures, and yet allow for low meat weight losses. To improve the energy consumption and economy of beef production, slow methods are replaced by fast and shock methods. In practice, however, too slow or too fast chilling of carcasses may result in their deteriorated quality. Therefore, great caution should be exercised when choosing the right chilling method [12, 13]. An adverse technological phenomenon that can occur during rapid meat chilling is the cold shortening. It happens when meat temperature drops below 10°C at a pH value above 6.2, i.e. when the muscles are before or during the rigor mortis state. To prevent this phenomenon, various physical methods are deployed to accelerate biochemical changes in meat in the slaughter / pre-chilling period. These include: tender stretching (hanging carcasses by the Achilles tendon / pelvic bone), electrostimulation, or delayed chilling—conditioning [14–17]. Electrical stimulation (ES) is considered an ideal non-invasive solution in this case. However, its implementation in practice depends on the specifics and capabilities of a meat processing plant, including its production efficiency, mechanization of production processes as well as the use of processing power and surfaces [18–20]. Methods used in practice include the low-voltage (ESNN, up to 100V) and the high-voltage one (HVES, from 100 to 3000V) electrical stimulation. The magnitude of their effects on biochemical processes in meat is determined by: animal type, process onset time, and choice of electrical current parameters (frequency, impulse shape, voltage type, etc.). Due to the possibility of exciting muscles through both the nervous system and muscle fiber conductivity, the HVES is considered the most effective method for meat quality improvement [21]. Considering the above, we have developed own concept of the sustainable beef production (Fig 1).

Research trends in the field of combining various red meat cooling systems with available techniques to improve its quality are still investigated [13, 22]. They are also in the focus of interest of entrepreneurs who are obliged to implement the concept of sustainable meat production [11, 23, 24]. The results of our previous investigations [25–28] indicating the beneficial effect of an own-construction device for HVES on the acceleration of post-slaughter changes and on the production of high-quality meat and products made of it (raw and steamed hams; salami-type sausage, beef pastrami) encouraged used to expand the scope of research interests with energy aspects of production. The novelty of the undertaken research lied in determining the quality of meat after HVES in combination with various chilling methods, and then indicating the optimal variant for energy-saving (sustainable) beef production. For this purpose, the aim of the first part of the study was to examine the influence of various variants of meat production (chilling method: slow, accelerated, fast, + ES/NES) on changes in industrial quality parameters (pH, temperature) of beef obtained from Polish Holstein-Friesian breed cattle, whereas that of the second part was to analyze energy consumption and weight loss of meat in...
the most advantageous production variant (fast chilling + ES), taking into account the varied amount of raw material chilled in the chamber.

**Material and methods**

The research material consisted of carcasses/half-carcasses of meat cattle (heifers, bulls—age around 18 months, cows—age around 10 years) of the Polish Holstein-Friesian Black and White breed. The hot carcass standard weight was approx. 240 kg (min. 178.9 ± 27.7 kg; max. 298.5 ± 41.5 kg). Stunning and post-stunning procedures were executed under industrial conditions following provisions of the Council Regulation (EC) No 1099/2009 of 24 September 2009 on the protection of animals at the time of killing. The study was carried out in a medium-sized meat processing plant with a capacity of the slaughter line reaching 100 carcasses per shift. The slaughter was controlled by the State Veterinary Inspector to keep required conditions concerning animal welfare and especially to minimize suffering. The slaughter was done by qualified persons using a pneumatic cattle gun.

**High-voltage electrical stimulation (HVES)**

Approx. 40 min, after stunning, carcasses were treated with a high-voltage electrical stimulation (HVES) device designed by Żywica, & Banach [29]. The left half-carcasses were subjected to ES using alternating electrical current with the following parameters: \( U = 330 \text{V}, f = 17\text{Hz}, \) rectangular shape of impulses, and pulse-duty factor 0.9 for 120 sec. The right half-carcasses served as the control non-electrostimulated sample (NES). Afterwards, the half-carcasses were washed with water having a temperature of ca. 10°C, weighed, and transferred to chilling chambers. This comparative system (ES/NES) was used to determine the changes in the pH values of meat of heifers, bulls, and cows since stunning. In the last stage of the study addressing the energy balance of the fast chilling method, ES was applied to whole carcasses.

**Chilling methods**

The beef half-carcasses were chilled with the slow, accelerated, and fast two-phase methods (60 animals in each method—I stage), under the following conditions:
1. **Slow method (delayed chilling):** After leaving the slaughter line, the half-carcasses were transferred to a chilling chamber with air temp. of ca. +10°C, where they were kept for ca. 6h until the chamber had been filled up. Afterward, cooling aggregators were turned on and the half-carcasses were chilled with air having a temperature of ca. 2°C and humidity of ca. 90% for 24h.

2. **Accelerated method:** After transportation to the chilling chamber, the half-carcasses were chilled with air having a temperature of ca. 2°C and humidity of ca. 90% for 24h.

3. **Fast two-phase method:** After leaving the slaughter line, the carcasses ES were transferred to a fast chilling chamber with air temp. of ca. -8°C and humidity of 95%, where they were kept for 2.5h. Afterward, they were transferred to an equalizing (transitory) chamber to equalize temperatures of their outer and inner layers (for 0.5-3h depending on the number of half-carcasses), with the fans switched off. Next, they were dissected into quarter-carasses and transferred to a chilling tunnel with air temp. of 0–2°C and humidity of ca. 90% for ca. 16-18h.

   In all chilling chambers, the half-carcasses were moved in a continuous pendular motion with strong forced convection.

**Temperature measurements**

Meat temperature measurements were performed over the chilling time using a TES 1310 TYPE-K spike thermometer (accuracy of ±0.1°C), at three different localizations of non-stimulated (NES) half-carcasses: *semimembranosus* muscle, *longissimus dorsi* muscle, and around a shoulder blade, at a depth of ca. 7cm. The measurements were performed 1, 3.5, 8, and 24h after stunning, and their results are presented in Table 1 as mean values ± standard deviation.

The number of examined carcasses reached n = 60 in each chilling method. Due to the harsh industrial conditions (low temperatures and very high air humidity) and the need to obtain approval from plant management to enter the chilling chambers, the number of measuring points was reduced to the necessary minimum.

**pH measurements**

Measurements of pH of stimulated (ES, n = 15) and non-electrostimulated (NES, n = 15) beef chilled with the slow, accelerated, and fast methods were performed 2/3, 2, 6, and 24h after stunning with a pH-meter (CP-411, electrode OSH 12-01, Elmetron, Poland) in three different localizations in *m. longissimus thoracis et lumborum* between 7 and 8th rib. The decision to

| Experimental group | Chilling methods | Significance |
|-------------------|------------------|--------------|
|                   | SM (n = 60)      | AM (n = 60)  | FM (n = 60)  | SM-AM | AM-FM | FM-SM |
| Time after stunning [h] |
| 1                 | 38.8 ± 0.69a     | 38.6 ± 0.57a | 38.2 ± 1.04a | NS    | NS    | NS    |
| 3.5               | 35.7 ± 1.15b     | 25.7 ± 3.18b | 18.1 ± 1.57b | **    | **    | **    |
| 8                 | 25.3 ± 2.22b     | 11.9 ± 2.58c | 10.3 ± 1.68c | **    | NS    | **    |
| 24                | 4.8 ± 0.45d      | 3.8 ± 0.79d  | 1.4 ± 0.95d  | **    | **    | **    |

a-d—means in columns with different letters differ significantly at p<0.01;
NES-beef: non-electrostimulated beef.
**—significance level p<0.01;
NS—non-significant.

https://doi.org/10.1371/journal.pone.0240639.t001
choose *m. longissimus* as the representative muscle for pH measurements was driven by the results our previous research [30–32]. Before the measurements made for meat from a given experimental group (ES, NES), the electrode was washed with distiller water and the pH-meter was calibrated.

**Weight losses of meat (WLM)**
The effect of the fast chilling method on weight losses of stimulated meat (WLM) was determined based on the difference between the weight of carcasses (*n* = 390) before (*M*<sub>i</sub>) and after (*M*<sub>f</sub>) the chilling process (initial—*W*<sub>i</sub> and final—*W*<sub>f</sub> weight, respectively) and expressed in per cents (Eq 1).

\[
WLM = \frac{(M_i - M_f)}{M_i} \cdot 100\% \tag{1}
\]

**Energy balance, specific energy consumption, and energy efficiency**
The heat balance of the chilling chambers used in the fast chilling method was based on the amount of heat necessary to be removed from the fast chilling chamber (area of 84 m<sup>2</sup>) and the chilling tunnel (area of 57 m<sup>2</sup>) during one chilling cycle. The measurements were carried out in the spring season for 8 working days (D1-D8), with varying amounts of carcasses (*n* = 10 to *n* = 144) in the chamber.

The total heat (*Q*) collected from the chilling chamber (Eq 2) and its components were calculated using the following formulas (Eqs 3–6):

\[
Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_d [kJ] \tag{2}
\]

where:
- *Q*<sub>1</sub>—heat removed form products (half-carcasses);
- *Q*<sub>2</sub>—heat transferring to the environment; the so-called transfer heat;
- *Q*<sub>3</sub>—ventilation heat;
- *Q*<sub>4</sub>—engine work heat;
- *Q*<sub>d</sub>—additional losses, in small chambers.

\[
Q_1 = M \cdot c_w \cdot (t_p - t_k) [kJ] \tag{3}
\]

where:
- *M*—weight of chilled half-carcasses [kg]—before transfer to the chilling chamber,
- *c*<sub>w</sub>—specific heat capacity of half-carcasses [2.85 kJ/kg °C],
- *t*<sub>p</sub>—mean initial temperature of half-carcasses [°C],
- *t*<sub>k</sub>—mean final temperature of half-carcasses [°C].

\[
Q_2 = 3600 \cdot k \cdot F \cdot (t_z - t_w) \cdot \tau [kJ] \tag{4}
\]

where:
- *k*—heat transfer coefficient of a building partition [0.44 W/m<sup>2</sup> K],
- *F*—size of a building partition [m<sup>2</sup>],
- *t*<sub>z</sub>—mean outer temperature of chamber environment [°C],
- *t*<sub>w</sub>—mean inner temperature of the chamber [°C],
- *τ*—heat transfer time [h].

The size of a building partition was assumed to be the size of the outer walls and ceiling of the chamber.

\[
Q_3 = n \cdot V \cdot d \cdot (i_1 - i_2) [kJ] \tag{5}
\]

where:
- *n*—number of air exchanges in a chamber, for chilling chambers: *n* = 2 per day.
V — cubic capacity of a chamber [m³],
d — mean air density in a chamber [kg / m³],
i₁ — fresh air enthalpy [kJ / kg],
i₂ — enthalpy of air in a chamber [kJ / kg].

Engine work heat (Q₄) was assumed to be the electric energy consumed by engines installed in the chamber. It was calculated based on engine power and work time.

\[ Q₄ = 0.15 (Q₁ + Q₂ + Q₃ + Q₄) [kJ] \] (6)

The heat of lighting and the heat of men’s work did not occur in the applied chilling technology. Data regarding: casing losses (Q₂ — heat penetrating from the environment), total lighting, engine work, losses due to door opening, and fan work were derived from the ‘Operation and Maintenance Documentation’ available at the technical department of the audited plant.

Energy consumption of the production process, meaning the demand for heat energy necessary to accomplish a specified production process, was determined based on measurements of electric energy consumption by chilling devices (compressors, FChCh+ChT). Indicators of the total specific energy consumption (SEC₁ and SEC₂) and energy efficiency, i.e., reduction of energy consumption (EE₁, EE₂), per number or weight of slaughtered animals, were used to determine the effect of employing innovative solutions (fast chilling method + HVES). They were computed using the following formulas (Eqs 7–10):

\[ SEC₁ = \frac{Q}{Z₁} \quad [kJ/\text{number of carcasses}] \] (7)

\[ SEC₂ = \frac{Q}{Z₂} \quad [kJ/kg] \] (8)

\[ EE₁ = \frac{Z₁}{Q} \quad [\text{number of carcasses} / kJ] \] (9)

\[ EE₂ = \frac{Z₂}{Q} \quad [kg / kJ] \] (10)

where: 
Q₄ — total heat removed from chilling chambers — FChCh + ChT,
Z₁ — number of carcasses (number of slaughtered animals),
Z₂ — weight of slaughtered animals [kg].
SEC₁, SEC₂ — Specific Energy Consumption per number / weight (initial) of slaughtered animals [kJ/number of carcasses] / [kJ / kg],
EE₁, EE₂ — Energy Efficiency per number or weight of slaughtered animals.

Statistical analysis

The statistical analysis of the effects of chilling duration and method and of electrical stimulation on changes in meat temperature and pH was carried out using Statistica 13.1 software based on one-way analysis of variance (ANOVA, \( p < 0.01, p < 0.05 \)).

Results and discussion

Effect of the chilling method on changes in temperature of non-electrostimulated (NES) meat

Analyses carried out in the first part of the study were expected to allow understanding the mechanisms of the impact of various chilling methods on the basic meat quality attributes, expressed by changes in the temperature inside the meat and in meat pH, determining the rate of post-stunning changes, as well as quality and safety of beef during further storage or processing.
Results of meat temperature measurements demonstrated that the type of the chilling method (slow, accelerated, fast) had a significant effect on the rate of changes in muscle tissue temperature. Beef chilling with the slow method caused very slow but significant \( (p < 0.01) \) changes in its temperature. The storage of beef half-carcasses in a chilling chamber for 2.5h at the elevated temperature (ca. +10°C/6h) contributed to meat temperature decrease by barely ca. 3°C, i.e. to ca. 36°C. In turn, after 8h and 24h of slow chilling, meat temperature dropped to ca. 25 and 5°C, respectively. Compared to the slow chilling method, slightly higher rate and significant \( (p < 0.01) \) changes in meat temperature were demonstrated during accelerated chilling. As soon as after 2.5h of chilling, meat temperature decreased by ca. 13°C and reached ca. 26°C. After 8h and 25h after stunning, it reached ca. 12°C and 4°C, respectively (Table 1). The above results corroborate literature data indicating that achieving this rate of changes in meat temperature in the first hours of post-stunning slow and accelerated chilling can pose the risk of microbiological contamination caused by the rapid proliferation of microorganisms on the surface of half-carcasses [21]. In contrast, the rate of changes in meat temperature was consistent with the ‘10/10 rule of thumb’, indicating that meat chilling to a temp. not lower than 10°C within 10 h post-slaughter, at pH below 6.2, allows avoiding the ‘cold shortening’ phenomenon. The effect of counteracting this adverse phenomenon can be intensified by delayed/slow chilling, which involves keeping the half-carcasses outside the chilling room for some time [33] or under either elevated temperatures, i.e., 10–16°C / 3-12h [34–36] or lower temperatures, i.e., 5–6°C / 24h [37].

The chilling of beef half-carcasses with the fast two-phase method had a strong effect on meat temperature decrease compared to the slow and accelerated methods. Keeping the half-carcasses in the chilling chamber for 2.5h caused its temperature to drop from ca. 38°C to ca. 18°C. During further meat keeping in a chilling tunnel, its temperature dropped to ca. 10°C after 8h and to 1.4°C after 24h. The final temperature of meat chilled with the fast two-phase method was lower than of the meat chilled with the slow (ca. 5°C) and accelerated (ca. 4°C) methods. The statistical analysis of the effects of chilling methods on changes in meat temperature also demonstrated significant \( (p < 0.01) \) differences between mean meat temperatures recorded after 3.5 and 24h of chilling with SM, AM, and FM as well as between mean meat temperatures measured after 8h of chilling with SM/AM and FM/SM (Table 1).

**Effect of chilling method and electrostimulated on changes in meat pH**

The subsequent part of the study aimed to determine the effect of different meat production variants (chilling method slow, fast, accelerated + ES/NES) on changes in the industrial indicators (pH and temperature) of beef quality [32, 38]. This complex approach was expected to allow identifying the optimal variant of meat production, ensure its high quality, and reduce its harmful effect on environment.

Results of pH measurements of the *longissimus dorsi* muscle of ES and NES heifers, cows, and bulls chilled with the slow method showed that ES significantly \( (p < 0.001) \) accelerated the post-stunning transformations during 24-h chilling. The highest and significant differences in pH values were obtained after 2 and 6 h of chilling when meat temperature was very high (ca. 37–30°C). The pH\(_{2h}\) value of ES heifer, cow, and bull meat ranged from 5.98 to 6.10 and was lower by ca. 0.9 units compared to the pH\(_{2h}\) value of control samples. After 6h post-stunning, the pH value of ES meat was still significantly lower (by 0.7–0.8 units, \( p < 0.001 \)) compared to the pH values of meat of non-stimulated heifers, bulls, and cows that reached 6.42, 6.54, and 6.63, respectively. The final pH values (pH\(_{24h}\)) of both ES and NES meat were similar and reached before 5.7; however, the pH\(_{24h}\) values of ES and NES meat of heifers and cows differed significantly at \( p < 0.05 \) (Table 2). The analysis of meat temperature recorded after ca. 3.5h of
changes in the pH of NES meat over the chilling period had similar values (did not differ significantly) as in the slow method. Therefore, these changes were not presented in Table 3. Higher and more differentiated pH values of meat of the stimulated bulls proved that bulls are more susceptible to the pre-slaughter stress than heifers and cows [21]. Negligible differences in the rate of pH changes between ES and control meat indicate that the AM chilling method is more rational and efficient than the SM, from the practical point of view.

The use of lower temperatures during the fast chilling of ES meat (-8°C/2.5h, 1–2°C/ca. 16–18h) than in the accelerated and slow methods contributed to the slower post-stunning chilling (Table 1) and pH value of ES meat measured 2h post-stunning allows concluding that the use of HVES enables the hot-boning of meat as soon as 2h after stunning without the fear of its cold shortening during consecutive ripening. Moreover, electrostimulation allows eliminating the phase of meat retention in the chilling chamber (2.5h/ ca.10˚C) and increasing production surface [39, 40].

The analysis of pH values of meat chilled with the accelerated method (AM) demonstrated the rate of changes in pH of NES meat over the chilling period had similar values (did not differ significantly) as in the slow method. Therefore, these changes were not presented in Table 2. In turn, the pH values of ES meat of heifers, cows, and bulls were insignificantly higher than in the slow chilling method (SM). The pH values measured in ES meat 2, 6, and 24h post-stunning fitted within the following ranges: pH

| Experimental group | Heifers | Cows | Bulls |
|--------------------|---------|------|-------|
|                    | ES (n = 15) | NES (n = 15) | Significance | ES (n = 15) | NES (n = 15) | Significance | ES (n = 15) | NES (n = 15) | Significance |
| Time after stunning [h] | | | |
| 2/3 | 6.95 ± 0.10a | 7.02 ± 0.09a | NS | 6.98 ± 0.11a | 7.00 ± 0.06a | NS | 6.86 ± 0.11a | 6.91 ± 0.08a | NS |
| 2 | 5.98 ± 0.05b | 6.61 ± 0.05b | *** | 6.10 ± 0.08b | 6.87 ± 0.04b | *** | 6.03 ± 0.09b | 6.66 ± 0.02b | *** |
| 6 | 5.75 ± 0.04c | 6.42 ± 0.03c | *** | 5.79 ± 0.07c | 6.63 ± 0.02c | *** | 5.82 ± 0.10c | 6.54 ± 0.05c | *** |
| 24 | 5.64 ± 0.05d | 5.73 ± 0.06d | * | 5.69 ± 0.03d | 5.75 ± 0.05d | * | 5.70 ± 0.12d | 5.78 ± 0.03d | NS |

— means in the columns with different superscripts are significantly different, P<0.01.
***—significance level P < 0.001;
**—significance level P < 0.01;
*—significance level P < 0.05;
NS—non-significant.

https://doi.org/10.1371/journal.pone.0240639.t003

Table 2. Changes in the pH value (± SD) of the longissimus dorsi muscle of non-electrostimulated (NES) and electrostimulated (ES) heifers, cows, and bulls chilled with the slow method.

| Experimental group | Heifers | Cows | Bulls |
|--------------------|---------|------|-------|
|                    | ES (n = 15) | NES (n = 15) | Significance | ES (n = 15) | NES (n = 15) | Significance | ES (n = 15) | NES (n = 15) | Significance |
| Time after stunning [h] | | | |
| 2/3 | 7.00 ± 0.07a | 6.98 ± 0.07a | | 6.89 ± 0.10a | | | 6.89 ± 0.10a | | |
| 2 | 6.01 ± 0.04b | 6.06 ± 0.05b | | 6.03 ± 0.13b | | | 6.03 ± 0.13b | | |
| 6 | 5.73 ± 0.05c | 5.78 ± 0.09c | | 5.87 ± 0.13c | | | 5.87 ± 0.13c | | |
| 24 | 5.60 ± 0.05d | 5.65 ± 0.04d | | 5.73 ± 0.17c | | | 5.73 ± 0.17c | | |

— means in the columns with different superscripts are significantly different, P<0.01.
NS—non-significant
*—significance level P < 0.05)
changes in pH of NES meat over the chilling period had similar values (did not differ significantly) as in the slow method.

https://doi.org/10.1371/journal.pone.0240639.t003

Table 3. Changes in the pH value (± SD) of the longissimus dorsi muscle of electrostimulated (ES) heifers (H), cows (C), and bulls (B) chilled with the accelerated method.

| Experimental group | Heifers ES (n = 15) | Cows ES (n = 15) | Bulls ES (n = 15) | Significance |
|--------------------|---------------------|-----------------|------------------|--------------|
| Time after stunning [h] | | | | H-C C-B B-H |
| 2/3 | 7.00 ± 0.07a | 6.98 ± 0.07a | 6.89 ± 0.10a | NS NS NS |
| 2 | 6.01 ± 0.04b | 6.06 ± 0.05b | 6.03 ± 0.13b | NS NS NS |
| 6 | 5.73 ± 0.05c | 5.78 ± 0.09c | 5.87 ± 0.13c | NS NS NS |
| 24 | 5.60 ± 0.05d | 5.65 ± 0.04d | 5.73 ± 0.17c | NS NS NS |

— means in the columns with different superscripts are significantly different, P<0.01.
NS—non-significant
*—significance level P < 0.05}
biochemical changes of meat and, consequently, to pH values higher by ca. 0.3 units at particular measuring points. While the temperature of stimulated meat chilled with the fast method reached 18 and 10˚C after 2 and 8h since stunning, its pH$_{2h}$ was at ca. 6.2 and 6.3, and its pH$_{6h}$ was at 5.95 (Table 4). This means that the coupling of HVES treatment performed with the own-construction device and the fast chilling method allows achieving a very rapid temperature drop before the onset of rigor mortis and producing high-quality meat without the fear of its cold shortening [41–44]. In the case of NES meat, at pH$_{2h}$ = 6.7–6.8 and pH$_{6h}$ = 6.5–6.6, the biochemical processes are still in progress, and meat is still before the rigor mortis state; therefore, its rapid chilling without ES is not recommendable [45].

Given the results presented above, it has been concluded that the coupled use of HEVS performed using an own-construction device and a fast chilling method is justified considering both the economic and meat quality class established based on pH [32].

**Energy consumption of the meat chilling with the fast method**

The rational management of electrical energy in the production process entails not only accomplishing economic effectiveness (increasing savings) but also reducing the energy consumption of technological processes and facilities, which determine the magnitude of effects of technical and man activities on the natural environment [23, 46]. The chilling systems are the largest electricity consumers in the meat industry—they account for 50–93% of the total electric energy consumed in a typical slaughterhouse [5, 47]. Therefore, as part of internal cost control / production savings and preparation for the energy audit [48], entrepreneurs (with individual production specifics) should keep records of the total consumption of energy carriers. In addition, determination of the electric energy consumption of production processes allows entrepreneurs to compare their production expenditures with those of the competition. The extent of implementing the sustainable energy policy in the meat (food) industry is most of expressed by the specific energy consumption–SEC [49–51].

Results of measurements and calculations of the heat balance of the fast chilling chamber (FChCh) and the chilling tunnel (ChT) demonstrated that the heat of penetration, lighting heat, and engine work heat in these rooms had constant values (FChCh = 33.94 kJ/h, ChT = 23.26 kJ/h). The total amount of heat necessary to be removed from the chambers depended on the duration of their work and the amount of raw material being chilled (half-carcasses, quarter-carcasses). In turn, the weight and type of chilled raw material, as well as the final temperature of chilled meat (0–2˚C) determined the amount of heat that had to be
removed from it \[52, 53\]. Apart from the mentioned factors, the total amount of heat depended on additional heat losses associated with door opening (10–15%) and heat emitted by ventilation fans (20%)—Table 5.

Results of measurements and calculations demonstrated that the total heat needed to be removed from chilling chambers increased along with the increasing number of carcasses intended for chilling (10–114 animals). However, ca. 11-fold increase in the number of chilled carcasses caused over 4-fold increase (391.54–1717.23 kJ) in the fast chilling chamber (FChCh), and a 2-fold increase (660.52–1331.37 J) in the chilling tunnel (ChT) in the amount of heat that had to be removed from these rooms (Table 5). This indicates that the heat load of the chilling chamber (production of the amount of chill and electrical energy consumption) increases along with the increasing load of products placed in it within a day, with the increasing specific heat of the chilled product, and with the increasing difference of temperatures [47]. Keeping the temperature lower than the ambient temperature in cold rooms requires also discharging heat energy from them, which entails higher losses (longer work of compressors) that will generate greater costs of energy consumption. The amount of heat that needs to be

| Table 5. Energy balance, Specific Energy Consumption (SEC), and Energy Efficiency (EE) for the fast chilling process, and changes in weight losses of electrostimulated meat during 8 days (D1–D8). |
|---------------------------|-----------------|---------|---------|---------|---------|---------|---------|---------|---------|
| No | Specification | Unit | D1 (n = 10) | D2 (n = 21) | D3 (n = 26) | D4 (n = 42) | D5 (n = 50) | D6 (n = 59) | D7 (n = 68) | D8 (n = 114) |
| --- | --------------- | ----- | ---------- | ---------- | ----------- | ----------- | ----------- | ----------- | ----------- | ----------- |
| 1 | Casing losses (Q₂+Q₄) | FChCh | kJ/h | 33.94 | | | | | |
| 2 | | ChT | | 23.26 | | | | | |
| 2 | Work time | FChCh | h | 3.5 | 4.5 | 5.0 | 6.5 | 8.0 | 7.5 | 7.5 | 8.5 |
| 3 | | ChT | | 18.0 | 18.0 | 17.5 | 16.0 | 14.5 | 15.0 | 15.0 | 14.0 |
| 4 | Total housing losses (1×2) | FChCh | kJ | 118.79 | 152.73 | 169.70 | 220.61 | 271.52 | 254.55 | 254.55 | 288.49 |
| 5 | | ChT | | 418.68 | 418.68 | 407.05 | 372.16 | 337.27 | 348.90 | 348.90 | 325.64 |
| 6 | Heat removed from half-carcass (Q₃) | FChCh | kJ | 178.90 | 325.72 | 347.66 | 600.64 | 609.11 | 616.41 | 622.73 | 1009.70 |
| 7 | | ChT | | 61.90 | 147.56 | 158.27 | 264.99 | 291.23 | 322.63 | 386.56 | 631.84 |
| 8 | Heat removed (3+4) | FChCh | kJ | 297.69 | 478.45 | 517.36 | 821.25 | 880.63 | 870.96 | 877.28 | 1298.19 |
| 9 | | ChT | | 480.58 | 566.24 | 565.32 | 637.09 | 628.50 | 671.53 | 735.46 | 957.48 |
| 10 | Open-door losses (Q₆) | FChCh | % | 10 | | | | | |
| 11 | | ChT | | 15 | | | | | |
| 12 | Ventilation heat losses (Q₇) | FChCh | % | | | | | | |
| 13 | | ChT | | 20 | | | | | |
| 14 | Total heat removed from: | FChCh | kJ | 391.54 | 632.99 | 684.57 | 1084.05 | 1174.82 | 1145.25 | 1158.00 | 1717.23 |
| 15 | | ChT | | 660.52 | 775.42 | 797.18 | 879.14 | 898.48 | 966.57 | 1014.83 | 1331.37 |
| 16 | Heat removed per carcass Total heat removed (5+6+7) | FChCh | kJ/ carcass | 39.15 | 30.14 | 26.33 | 25.81 | 23.50 | 19.41 | 17.03 | 15.06 |
| 17 | | ChT | | 60.05 | 36.40 | 30.67 | 20.93 | 17.97 | 16.38 | 14.92 | 11.68 |
| 18 | Electric energy consumed by compressors | FChCh | kJ | 460.77 | 683.99 | 740.52 | 1009.89 | 1062.53 | 1089.14 | 1160.62 | 1746.20 |
| 19 | | ChT | | | | | | | |
| 20 | SEC₁ | kJ/ carcass | 46.08 | 32.57 | 28.48 | 24.05 | 21.25 | 18.46 | 17.07 | 15.32 |
| 21 | SEC₂ | kJ/kg | 0.154 | 0.123 | 0.112 | 0.098 | 0.108 | 0.103 | 0.096 | 0.056 |
| 22 | EE₁ | carcass/kJ | 46.08 | 32.57 | 28.48 | 24.05 | 21.25 | 18.46 | 17.07 | 15.32 |
| 23 | EE₂ | kg/kJ | 0.154 | 0.123 | 0.112 | 0.098 | 0.108 | 0.103 | 0.096 | 0.056 |
| 24 | Initial weight (W₁) | kg | 2985 | 5569 | 6616 | 10331 | 9866 | 10553 | 12072 | 31437 |
| 25 | Final weight (W₂) | kg | 2842 | 5369 | 6411 | 9969 | 9639 | 10300 | 11746 | 30620 |
| 26 | Weight losses of meat (WLM) | % | 4.8 | 3.1 | 3.1 | 3.5 | 2.3 | 2.4 | 2.7 | 2.6 |
| 27 | Average weight loss of meat (n = 390) | % | | | | | | | 2.8 |

Q₂—heat transferring to the environment; the so-called transfer heat; Q₄—engine work heat; FChCh—fast chilling chamber; ChT—chilling tunnel.

https://doi.org/10.1371/journal.pone.0240639.t005
removed from chilling chambers is also strongly affected by the ambient temperature related to the season of the year. According to Neryng et al. [54], greater by ca. 32% electric energy consumption per chilled product unit is recorded in the spring than in the winter. The higher temperature around the chilling chamber contributes to, e.g., slower cooling of half-carcasses after slaughter, the higher temperature in the chamber before the chilling process, and a higher value of the transfer heat.

The results of analyses of the energy consumption of production per carcasses are in contrast to those of the total amount of heat calculated (Table 5, item 9). With an almost 9-fold increase in the number of carcasses, it was necessary to remove approx. 3 times less heat units from the fast chilling chamber (39.15–15.06 kJ/carcass) and more than 5 times less heat units from the chilling tunnel (60.05–11.68 kJ/carcass). This was due to the large proportion of heat associated with the housing losses (light transmission, motor operation, door opening) in the total amount of heat, that needed to be removed from the chambers. This, in turn, was related to the time of chambers’ work. With an increase in the number of cattle/weight of carcasses, the values of the specific electricity consumption (SEC) and energy efficiency of the process (EE) calculated for the rapid chilling of stimulated meat (ES) decreased 3 times (SEC1 = 46.08–15.32 kJ/carcass, SEC2 = 0.154–0.056 kJ/kg) and increased (EE1 = 0.022–0.065 carcass/kJ, EE2 = 6.478–18.003 kg / kJ), respectively. These results indicate that with the maximum loading of the chilling chambers, the combination of innovative solutions (fast chilling + ES) is energetically and economically viable. Nunes, Silva, & Andrade [47] have demonstrated a higher Specific Energy Consumption by the meat industry in Portugal, i.e. 1208 kWh/Mg. In turn, Żywica, Banach, & Gornowicz [55] achieved Specific Energy Consumption of compressors at SEC = 19 MJ/Mg when chilling 10,320 Mg of meat with the fast two-phase method, and almost 2-fold lower SEC (SEC = 10.27 MJ/Mg) when chilling the meat with the shock method. By reducing the amount of chilled meat (6,182 Mg), they reduced electric energy consumption to 15 and 4.03 MJ/Mg, respectively. Data presented in Table 5 indicate that with the comparable weight of chilled meat, i.e. 10,553 kg and 6,616 kg, the SEC values obtained in the present study were substantially lower and reached 0.103 and 0.112 kJ/kg. This indicates that the optimal variant of beef production established in the present research is far more energy efficient than other production variants presented in literature.

Considering that one chilling cycle in a fast chilling chamber lasts 2.5h, its prolongation by 1h with carcass number of 10, by 2–3.5h with carcass numbers of 22 and 26, and by 6.5h with carcass number of 114 was due to the stable time of cooling the chambers before they were filled with half-carcasses (regardless of the amount of chilled material) and the stable chilling time of one half-carcass in the chamber. Besides, the temperature decrease by ca. 20˚C in the fast chilling chamber and by ca. 18˚C in the tunnel (14 to 18h, Table 1) influenced the total unitary amount of heat that had to be removed from both types of chambers (FChCh and ChT). During chilling, the total heat capacity per carcass was 99.20 kJ with 10 carcasses, and ca. 4-fold lower (26.74 kJ) with 114 carcasses (Table 5).

An indispensable side effect of the meat chilling process are its weight losses. They generate economic losses, the magnitude of which depends on the chilling method type. According to Brown et al. [56], the cost incurred by small UK plants due to meat weight losses was higher than the cost of electricity. Therefore, quick chilling methods are recommended [13] to reduce meat weight losses and achieve the best efficiency of the chilling process (shortening the time, ensuring meat safety and quality).

Results of determinations of weight losses of meat (WLM) caused by water evaporation from meat surface during its chilling with the fast two-phase method demonstrate large differences between particular days of measurements assuming various numbers of animal carcasses to be chilled (Table 1). The highest WLM (4.8%) was obtained during chilling 10 beef carcasses,
presumably due to the highest volume of water evaporated from half-carcasses in the fast chilling chamber. On days 2, 3, and 4 of measurements, when the number of chilled carcasses was 21–42, the WLM ranged from 3.1 to 3.5%. The results of measurements allow concluding that smaller WLM were recorded (2.3–2.6%) with carcasses having a higher meat content, more densely packed, and touching one another in the chamber than with the lower number of chilled carcasses (Table 5). According to Klettner [57], the weight loss of meat caused by its chilling with the fast one-phase method was at 1.6% and was higher by ca. 0.3% from the WLM recorded during the shock chilling process (from –3 to –5˚C/2h, 0˚C/16–22h). However, the carcasses intended for chilling should not be moist because of the possibility of meat surface freezing during chilling with this method. As reported by Żywica, Banach, & Gornowicz [55], WLM obtained using the shock and fast chilling methods reached 2.2 and 3.6%, respectively.

Summing up, the analysis of energy consumption of the examined meat production variant–coupled use of HVES and fast chilling method, showed that it enabled achieving a lower value of the specific energy consumption and WLM of 2.8% at highly diversified amounts of meat chilled in the chambers, compared to the values reported by other authors. It may thus be concluded that this production variant contributes to the efficient energy consumption in the production process and sustainable company management through, among others, reducing the carbon footprint of beef and energy costs.

Conclusions

1. The use of HVES and the fast chilling method at the slaughter line enables producing high-quality meat, reducing expenditures related to electric energy consumption, and increasing work effectiveness of cooling appliances compared to the slow and accelerated chilling methods. The coupling of these techniques is recommended for both investment and modernization undertakings in pursuit of sustainable meat production.

2. The intensive chilling of beef to ca. 20˚C within 2.5h and the break in the chilling process until temperature equalization between its outer and inner layers allow the producers for getting the optimal rate of pH changes, rational quality management and changes in production organization, mainly through increasing chilling speed and reducing storage surface and expenditures for staff wages.

3. The heat balance of fast chilling chambers (FChCh+ChT) demonstrated that achieving the desired final temperature resulted in several times lower value of the specific energy consumption at the lowest amount of chilled meat, and in higher energy efficiency of the process at the highest amount of chilled meat.

4. Evaluation of the industrial quality indicators of beef and energy consumption of its production process in the variant with the coupled use of own-construction device for HVES at the slaughter stage and meat chilling with the fast method demonstrated that it allowed accomplishing the principles of sustainable beef production. In addition, it was found to indirectly contribute to mitigating the adverse effects of the meat production plant on the natural environment and to improving its image.

Supporting information

S1 Dataset. (XLS)
Author Contributions

Conceptualization: Joanna Katarzyna Banach, Ryszard Żywica.
Data curation: Joanna Katarzyna Banach, Paulius Matusevičius.
Formal analysis: Joanna Katarzyna Banach.
Funding acquisition: Joanna Katarzyna Banach.
Investigation: Joanna Katarzyna Banach, Paulius Matusevičius.
Methodology: Joanna Katarzyna Banach, Ryszard Żywica.
Project administration: Joanna Katarzyna Banach.
Supervision: Joanna Katarzyna Banach, Paulius Matusevičius.
Validation: Joanna Katarzyna Banach, Ryszard Żywica.
Writing – original draft: Joanna Katarzyna Banach, Ryszard Żywica, Paulius Matusevičius.
Writing – review & editing: Joanna Katarzyna Banach, Ryszard Żywica, Paulius Matusevičius.

References

1. Asem-Hiabie S., Battagliese T., Stackhouse-Lawson K.R., & Alan Rotz C. (2018). A life cycle assessment of the environmental impacts of a beef system in the USA. International Journal of Life Cycle Assessment, 24, 441–455. https://doi.org/10.1007/s11367-018-1464-6
2. O’Brien D., Herron J., Andurand J., Caré S., Martínez P., Migliorati L., et al. (2020). Life beef carbon: a common framework for quantifying grass and corn based beef farms’ carbon footprints. Animal 14(4): 834–845. https://doi.org/10.1017/S1751731119002519 PMID: 31666147
3. Giaccone E. & Mancò S (2012). Energy efficiency measurement in industrial processes. Energy, 38: 331–345. https://doi.org/10.1016/j.energy.2011.11.054
4. Wang L. (2014). Energy efficiency technologies for sustainable food processing. Energy Efficiency 7 (5): 791–810. https://doi.org/10.1007/s12053-014-9256-8
5. Feliciano M., Rodrigues F., Gonçalves A., Santos J. M. R. C. A., & Leite V. (2014). Assessment of Energy Use and Energy Efficiency in Two Portuguese Slaughterhouses. World Academy of Science, Engineering and Technology International Journal of Environmental and Ecological Engineering 8(4), 253–257. https://doi.org/10.5281/zenodo.1091846
6. Ferrarez A.H., Oliveira D., Lacerda A.F., Costa J.M., & Aparisi F.S. (2016). Supplying the energy demand in the chicken meat processing poultry with biogas. Ingeniería e Investigación, 36(1), 118–121. http://dx.doi.org/10.15446/ingen. investig.v36n1.52576.
7. Wojdalski, J., Kupczyk, A., Niżnikowski, R., Krajewski, K. & Dróżdż, B. Energy efficiency and environmental aspects of work in the agri-food industry. Selected Issues. (Efektywność energetyczna i środowiskoaspektyparzystympolnoprowozowego.WybraneZadania.)Proc.XXXVIIScientificandTechnicalConference“Energyandenvironmentalproblems”.Poland,JanówPodlaski. 2–6.09.2018r.
8. Pathare P.B., Roskilly A.P., & Jagtap S. (2019). Energy Efficiency in Meat Processing. In: Novel Technologies and Systems for Food Preservation. IGI Global.
9. Tanaka K. (2011). Review of policies and measures for energy efficiency in industry sector. Energy Policy, 39(10), 6532–6550. https://doi.org/10.1016/j.enpol.2011.07.058
10. Alcázar-Ortega M., Álvarez-Bel C., Escrivá-Escrivá G., & Domíjan A. (2012). Evaluation and assessment of demand response potential applied to the meat industry. Applied Energy, 92, 84–91. https://doi.org/10.1016/j.apenergy.2011.10.040
11. Song W., Wang G.-Z., & Ma X. (2020). Environmental innovation practices and green product innovation performance: A perspective from organizational climate. Sustainable Development, 28, 224–234 https://doi.org/10.1002/sd.1990
12. Braden K.W. (2013). Converting muscle to meat: the physiology of rigor. In: KERTH C.R. (Ed.). The scienceof meat quality. Iowa: J. Wiley & Sons, 79–97. https://doi.org/10.1002/9781118530726.ch5
13. Zhang Y., Mao Y., Li K., Luo X., & Hopkins D.L. (2019). Effect of Carcass Chilling on the Palatability Traits and Safety of Fresh Red Meat. Comprehensive Reviews in Food Science and Food Safety. 18 (6), 1676–1704. https://doi.org/10.1111/1541-4337.12497 PMID: 3336955

14. Banach J.K., & Żywica R. (2010). The effect of electrical stimulation and freezing on electrical conductivity of beef trimmed at various times after slaughter. Journal of Food Engineering. 100, 119–124. https://doi.org/10.1016/j.jfoodeng.2010.03.035

15. Kim Y. H. B., Stuart A., Nygaard G., & Rosenvold K. (2012). High pre rigor temperature limits the ageing potential of beef that is not completely overcome by electrical stimulation and muscle restraining. Meat Science, 91, 62–68 https://doi.org/10.1016/j.meatsci.2011.12.007 PMID: 22226363

16. Beffin T.E., Smith M.A., Bush R.D., Collins D., & Hopkins D.L. (2018). The Effect of Combining Tender-stretching and Electrical Stimulation on Alpaca (Vicugna Pacos) Meat Tenderness and Eating Quality. Meat Science, 145, 127–136. https://doi.org/10.1016/j.meatsci.2018.06.002 PMID: 29957529

17. Mikołajczak B., Iwańska E., Spychaj A., Danyluka B., Montowska M., Grześ B., et al. (2019). An analysis of the influence of various tenderising treatments on the tenderness of meat from Polish Holstein-Friesian bulls and the course of changes in collagen. Meat Science, 158, 107906. https://doi.org/10.1016/j.meatsci.2019.107906 PMID: 31398624

18. Savell, J. W. (2012). Beef carcass chilling: Current understanding, future challenges. http://www.beefresearch.org/CMDocs/BeefResearch/BeefCarcassChilling%20White%20Paper_final.pdf

19. Wojdalski, J., Dróżdż, B., & Lipiński, P. (2010). Energy consumption efficiency in a small meat processing plant. Współczesne zagadnienia rozwoju sektora energetycznego i rolniczego. SGGW, 110–121.

20. Wojdalski, J., & Niżnikowski, R. (2019). Energy, water and the environment in dairy production (Energia, woda i środowisko w produkcji mleczarskiej – zarys problematyki). Animal Production Review, no. 6/201 (in Polish). http://ph.ptz.icm.edu.pl/wp-content/uploads/2019/11/8-Wojdalski.pdf

21. Żywica, R. (2010). Electrical phenomena in the production and commodity assessment of meat quality (Zjawiska elektryczne w produkcji i towaroznawczej ocenie jakości mięsa) (Ed.), Poland: University of Warmia and Mazury in Olsztyn (in Polish).

22. Bakker C., Underwood K., Grubbs J.K. & Blair A. (2021). Low-voltage electrical stimulation of beef carcasses slows carcass chilling rate and improves steak color. Foods 10, 1065. https://doi.org/10.3390/foods10051065 PMID: 34065955

23. Pagan, R., Renouf, M., & Prasad P. (2002). Eco-efficiency manual for meat processing. Meat and Livestock Australia Ltd.

24. Ramirez C.A., Patel M., & Blok K. (2006). How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. Energy, 31, 2047–2063. https://doi.org/10.1016/j.energy.2005.08.007

25. Banach J.K., Żywica R. & Tkacz K. (2012). Usability of own-construction device for high-voltage electrical stimulation of beef carcasses in production of pastrami type hams. Polish Journal of Commodity Science, 2(31): 87–94.

26. Banach, J.K. & Żywica, R. Influence of high-voltage electrical stimulation on tenderness of raw beef hams. Proc. 15th Symposium of IGWT “Global Safety of Commodity and Environment. Quality of Life”- Up-to-date materials and technologies (part VII). 12–17.09.2006., Kyiv, Ukraine, s. 1207–1211.

27. Kłębukowska L., Żywica R., & Sienkiewicz J. (2001). Effect of electrical stimulation on the microbiological quality of beef. Proc. 47th International Congress of Meat Science and Technology, 26–31 August, Kraków, Poland, s. 36–37.

28. Kornacki K., Żywica R., Kłębukowska L. & Budny J. (1998). Effect of electrical stimulation, starter culture and gluten-δ-lactone on microbiological quality of fermented salami-type sausage. Natural Science, 1: 215–227.

29. Żywica, R., & Banach, J.K. (2014). Device for electrical stimulation of beef carcasses (Urządzenie do elektrostymulacji tusz wołowych). Patent PL no. 216791 (in Polish).

30. Żywica R. (1999). The influence of high voltage electrical stimulation on post-slaughter changes in selected physical and chemical parameters of beef. Dissertations and Monographs, 12, 1–7, UWM, Olsztyn (in Polish).

31. Żywica R. & Banach J.K. (2007). Analysis of changes in electric current intensity during high voltage electrical stimulation in the aspect of prediction the pH value of beef. Journal of Food Engineering, 81, 560–565. https://doi.org/10.1016/j.jfoodeng.2006.11.030

32. Banach J.K., Modzelewska-Kapitula M., Wichman K., Tkacz K., & Żywica R. (2018). Effects of electrical stimulation applied in combination with shock chilling method on selected quality attributes of beef from young bulls, heifers and cows carcasses. Journal of Food Processing and Preservation 42, 1–7 https://doi.org/10.1111/jfpp.13571
33. Smulders F. J. M., Toldra F., Flores J., & Prieto M. (1992). New technologies for meat and meat products, 186–188. Utrecht, The Netherlands: Audet Tijdschriften.
34. White A., O’Sullivan A., Troy D. J., & O’Neill E. E. (2006). Effects of electrical stimulation, chilling temperature and hot-boning on the tenderness of bovine muscles. Meat Science, 73(2), 196–203. https://doi.org/10.1016/j.meatsci.2005.11.020 PMID: 22062289
35. Prado C.S., & Felício P.E. de. (2010). Effects of chilling rate and spray-chilling on weight loss and tenderness in beef strip loin steaks. Meat Science, 86, 430–435. https://doi.org/10.1016/j.meatsci.2010.05.029 PMID: 20647150
36. Pflanzer S.B., Gomes C.L., & de Felício P.E. (2019). Delayed carcass chilling improves tenderness of the beef gluteus medius muscle. Pesquisa Agropecuária Brasileira, 54, e00099, https://doi.org/10.1590/S1678-3921.pab2019.v54.e00099
37. Janz J., Aalhus J. L., Roberson W. M., Mer D., Larsen I. L., & Landry S. (2004). The effects of modified carcass chilling on beef carcass grade and quality of several muscles. Canadian Journal of Animal Science, 84(3), 377–384. https://doi.org/10.4141/A03-067
38. Contreras-Castillo C.J., Lomiwes D., Wu G., Frost D., & Farouk M.M. (2016). The effect of electrical stimulation on post mortem myofibrillar protein degradation and small heat shock protein kinetics in bull beef. Meat Science, 113, 65–72. https://doi.org/10.1016/j.meatsci.2015.11.012 PMID: 26624792
39. Pisula A., & Tyburcy A. (1996). Hot processing of meat. Meat Science 43, S125–S134. https://doi.org/10.1016/0309-1740(96)00060-5 PMID: 22060646
40. Simmons N.J., Daly C.C., Mudford C.R., Richards I., Jarvis G., & Pleiter H. (2006). Integrated technologies to enhance meat quality—an Australasian perspective. Meat Science 74, 172–179. https://doi.org/10.1016/j.meatsci.2006.05.007 PMID: 22062726
41. Li K.; Zhang Y.; Mao Y.; Cornforth D.; Dong P.; Wang R.; et al. (2012). Effect of very fast chilling and aging time on ultra-structure and meat quality characteristics of Chinese Yellow cattle M. Longissimus lumborum. Meat Science, 92, 795–804, https://doi.org/10.1016/j.meatsci.2012.07.003 PMID: 22857853
42. Pinto Neto M., Beraquet N. J., & Cardoso S. (2013). Effects of chilling methods and hot-boning on quality parameters of M. longissimus lumborum from Bos indicus Nelore steer. Meat Science, 93(2), 201–206. https://doi.org/10.1016/j.meatsci.2012.08.024 PMID: 23021627
43. Devine C. E., Hopkins D. L., Hwang I. H., Ferguson D. M., & Richards I. (2014). Electrical stimulation. In Dikeman M. & Devine C. (Eds.), Encyclopedia of meat science (Vol. 1, 486–496). Oxford, UK: Elsevier.
44. Sikes A. L., Jacob R., D’Arcy B., & Warner R. (2017). Very fast chilling modifies the structure of muscle fibres in hot-boned beef loin. Food Research International, 93, 75–86. https://doi.org/10.1016/j.foodres.2016.12.027 PMID: 28290282
45. Strydom P.E., Frylinck L., & Smith M.F. (2005). Should electrical stimulation be applied when cold shortening is not a risk? Meat Science, 70, 733–742. https://doi.org/10.1016/j.meatsci.2005.03.010 PMID: 22063900
46. Pelletier N. (2008). Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agricultural Systems, 98, 67–73. https://doi.org/10.1016/j.agsy.2008.03.007
47. Nunes, J., Silva, P.D., Andrade, L.P. (2011). Energetic efficiency evaluation in refrigeration systems of meat industries. Proceedings of the 23th International Congress of Refrigeration (ICR 2011, Prague, Czech Republic, 21–26.08.2011).
48. Munguia N., Velazquez L., Bustamante T.P., Perez R., Winter J., Will M., et al. (2016). Energy Audit in the Meat Processing Industry-A Case Study in Hermosillo, Sonora Mexico. Journal of Environmental Protection, 7, 14–26.
49. Tasmania, H.C. (2009). Red Meat Processing Industry- Energy Efficiency Manual, in: Australia, M.L. (Ed.), North Sydney.
50. Wojdalski J., Dróźdż B., & Powęźka A. (2009). Effectiveness of energy and water consumption in a poultry processing plant. TEKA Kom. Mot. Energ. Roln.–OL PAN. 9, 395–402. https://citeeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1058.7506&rep=rep1&type=pdf
51. Wojdalski J., Dróźdż B., Grzechowicz J., Magryś A., & Ekielski A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food Bioprocess Technology, 6, 2621–2629. https://doi.org/10.1007/s11947-012-0924-4
52. Fontana, A.J., Varith, J., Ikediala, J., Reyes, J., & Wacker, B. (1999). Thermal properties of selected foods using a dual needle heat pulse sensor. Paper No. 9996063. (American Society of Agricultural Engineers: Toronto, Canada).
53. Kaliszanz M., Hauser R., Kaliszanz R., Wiczling P., Buczynski J., & Penkowski M. (2005). Verification of the exponential model of body temperature decrease after death in pigs. Experimental Physiology 90, 727–738. https://doi.org/10.1113/expphysiol.2005.030551 PMID: 15944204

54. Neryng, A., Wojdalski, J., Budny, J., & Krasowski E. (1990). Energia i woda w przemyśle rolno-spożywczym. WNT Warszawa. 227–245. (in Polish: Energy and water in the agro-food industry).

55. Żywica R., Banach J.K. & Gornowicz M. (2008). Selected energetic and economic aspects of modelling the quality of beef in the electrical stimulation and chilling process. Polish Journal of Commodity Science, 3(16): 69–78.

56. Brown T., Richardson R. I., Wilkin C. A., & Evans J.A. (2009). Vascular perfusion chilling of red meat carcasses–A feasibility study. Meat Science, 83, 666–671. https://doi.org/10.1016/j.meatsci.2009.07.017 PMID: 20416641

57. Klettner P.G. (1996). Kühlen und Gefrieren von Schlachttierkörpern. Fleischwirtschaft, 7 (76), 679–687.