Science 4 Food

NEXT GENERATION FOOD PRESERVATION METHODS

for High Quality Foods in the Sustainable Society and Circular Economy Epoch

HIGH QUALITY FOODS

ADVANCED PRESERVATION TECHNOLOGIES

SUSTAINABILITY & CIRCULAR ECONOMY

SUSTAINABLE SOLUTIONS FOR A BETTER FUTURE

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SCIENCE FOR FOOD. SOLUTIONS FOR THE PLANET

NEXT GENERATION FOOD PRESERVATION METHODS

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ABSTRACT

The dominant food preservation methods used today were developed in the 19th and early 20th centuries and, since then, have played a significant role in ensuring unprecedented food abundance. However, in the 21st century, it has become evident that such processed foods pose significant, even pandemic, health risks and contribute to substantial food waste. In the era of the 5th Industrial Revolution, newly developed innovative food preservation methods offer solutions to these challenges by ensuring high-quality food with the benefits of fresh products, health-promoting properties, and extended shelf life. When adding natural reduction of losses and lower energy requirements during processing, a fair correlation with the Sustainable Civilization and the Circular Economy concept appears.

This report highlights two such methods that have already reached market validation: supercritical fluids (SCF) technology and high-pressure processing (HPP). In addition to their basic features and advantages, this report focuses on the underlying fundamental base. The latter is used as a reference for their possible next-generation developments: supercritical technology in the liquid phase. This is based on the specific properties of linseed oil and the *barocaloric effect*. It enables extended pasteurisation or even sterilisation.

Key Words: Industrial Revolution, Sustainability, Food Preservation, High-pressure Processing, Supercritical Fluids

INTRODUCTION

At the beginning of the 18th century, the economies of some European countries were evolving rapidly. Production, which had previously been dispersed and organised primarily through medieval guild structures, was increasingly taken over by large-scale manufactories that emerged spontaneously. The implementation of innovations accelerated this transformation, steadily increasing demand for raw materials and leading to the formation of modern industrial units. This, in turn, motivated ventures related to their acquisition and transportation. These ventures triggered social mobility by offering employment opportunities in the rapidly expanding new centres [1]. This process was further accelerated by the invention of the Newcomen steam engine in 1720, followed by the mass implementation of Watt's more efficient, 'modern' design. These unique innovations were widely implemented not only in the United Kingdom, but also exported to the continent [3]. In 1787, Samuel Homfray from Pennydarran, Wales, installed a water-removal pump in a zinc and silver mine in Tarnowskie Góry (then Tarnowitz in Prussia, now in Poland), based on Newcomen's idea, which Homfray had perfected. This was the first significant success of such an implementation on the continent, and the machine itself (still in operation) is now on display at the former mine museum [3].

Due to breakthrough advances in power source technologies, large-scale industrial plants emerged. They offered overwhelmingly affordable mass production. This was the beginning of the innovation-driven Industrial Revolution, which continues to this day [1,4].

The Industrial Revolution era is coupled with a uniquely rapid Super-Malthusian growth in the global population, which far exceeds the basic 'geometric' Malthusian pattern, with a constant growth rate (r) [5-8]:

$$P(t) = P_0 \exp(rt) \quad \Rightarrow \quad P(t) = P_0 \exp(r(t) \times t) \propto P_0 \exp\left(\frac{bt}{t-T_C}\right) \qquad (1)$$

where the left part is for the basic Malthus trend [5,6] obeying in years ~(1100 – 1700) [7,8] and the right-hand part is for the Super-Malthusian behaviour with the time-dependent rate factor, which trend can be approximated by the critical-constrained scaling relation with $T_C \approx 2226$ (year) [7].

This population boost fuelled accelerated urbanisation, ultimately resulting in today's megacities [9]. In the 19th century, feeding the ever-growing urban centres was a major challenge [2,8]. This was solved in a manner typical of the Industrial Revolution era: by developing innovative concepts. This involved introducing new agricultural practices and increasingly complex logistics.

Particularly significant was the development of innovative food preservation methods that enabled stockpiling and supported ever-extending logistics chains. Of course, several food preservation methods were developed over the millennia, each a significant innovation at the
time. They shaped the eating habits and foodstuffs of subsequent generations, many of which are still used today, enriching our modern-day cuisine [10,11].
However, in the 19th century, an even more pressing problem arose: how to extend the shelf life of existing products, including processed ones, while ensuring their safety, preserving the benefits of minimally processed products on a mass scale, and facilitating their mass industrial implementation. The first important question was identifying the main factor that could make food or drink unsafe. In the years 1857 - 1862, Louis Pasteur proved the importance of rapid and spontaneous bacterial contamination. Further, he proposed a simple method to prevent it: heating to $\sim 86°C$ for a few minutes, which was later named pasteurisation [12]. It is defined as a 5-log (10^5) reduction in the number of microorganisms. It was a major breakthrough innovation in the given field, solving a problem that had plagued humanity for millennia [10,11].

Following this cognitive path, Charles Chamberland (1879) discovered thermal sterilization, involving heating to temperatures above 120°C–150°C, in an autoclave he designed [13]. At that time, the first chemical sterilization agents were also discovered [14]. Nowadays, they are present in most food products on supermarket shelves, ensuring a plentiful and varied selection. The first half of the 20th century saw the mass implementation of radiation techniques, as well as cooling and freezing methods [10,11]. The development and mass production of large-scale cold stores, as well as domestic refrigerators and freezers, were crucial for this [15].

The innovative food preservation technologies developed during the Industrial Revolution were crucial in providing food security for a rapidly growing human population, from 1 billion in 1800 to 2 billion in 1928, 4 billion in 1975, 5 billion 12 years later (1987), and in 2025: ~8.2 billion [7,8]. In 1950, New York became the first megacity with a population of over 10 million. By 2025, there will be 33 megacities, and it is expected that this number will reach 43 within the next five years [16].

The Industrial Revolution-related food preservation methods mentioned above are crucial not only for providing food for this 'Brave New World' [17] but also for minimizing famine and malnutrition, which have been a great cyclical problem plaguing humanity for millennia [11]. Unfortunately, famine still occurs locally in areas affected by political and organisational collapse, war, and climate change. The latter factor is becoming increasingly dominant due to the Global Warming catastrophe, which is explicitly linked to the booming development during the Industrial Revolution times. The next factor is Environmental Catastrophe, resulting from excessive and careless exploitation of natural resources, as well as large-scale waste production and pollution [18].

During the Industrial Revolution, the biblical notion of Human Dominion over nature and the world was caricatured as a massive implementation of the sequence 'take, make, use (for a short time), dispose (soon afterwards)' [19]. This led to the emergence of existential threats on a planetary scale. However, the true Dominus should respect and care for all the world, and it seems that people have finally realised this by attempting to implement a new model of Sustainable Civilisation and the Circular Economy.

Following the UN and EC related definition, ‘A sustainable civilization is a society that can persist indefinitely by meeting the needs of the present without compromising the ability of future generations to meet their own needs, balancing environmental, economic, and social priorities. It requires living within ecological limits, reforming harmful practices, and fostering a high quality of life for all by focusing on survival, prosperity, and mutual support for both humans and the environment’. The EU's planned 2026 Circular Economy Act aims to promote the efficient use of materials, increase the supply of high-quality recycled materials, and reduce many harmful environmental impacts. These concepts also involve considering people's needs, while showing consideration and respect for the environment and the planet [20].

When it comes to food, it is not only important to increase mass production, but also to improve utilisation and reduce losses. According to Eurostat, the European Union generated 58.2 million tonnes of food waste in 2023, a 0.7% increase on the previous year. Over half of this waste came from households, while 47% was generated along the food supply chain: 19% from food and drink production; 10% of primary output; 11% from restaurants and food service outlets; and 8% from retail and other distribution channels. On average, 130 kilograms of food were wasted per person in the EU in 2023. The amount of food wasted in the EU exceeds its total food imports [21]. The most apparent and perhaps most straightforward solution would be to improve food processing and preservation technologies, thereby extending the shelf life for later use and supporting the logistics chain. However, this approach has already been employed during the Industrial Revolution and led to the above problems and, worse still, long-unrecognised Health Catastrophes.

Chemical preservatives have been shown to cause a growing pandemic of gut diseases, various types of cancer, allergies, and obesity [22-26]. Pasteurization and thermal sterilization inherently reduce the quantity of vitamins and essential bioactive nutrients [10]. Irradiation preservation remains a niche due to insurmountable objections and adverse effects on certain products, such as flavour [10, 27]. The most crucial problem in refrigeration and freezing is the technology used to achieve low temperatures, which involves circulating fluids [28]. Failures and leaks are harmful to the environment, particularly in the context of global warming. This technology is also energy inefficient, making these devices among the world's largest consumers of electricity. The technologies that enabled the Industrial Revolution and relegated famines and shortages to the past are also proving to be a source of threats and problems.

During the Industrial Revolution era, one of the key ways to solve problems and overcome challenges was the development and implementation of technological innovations, often grounded in groundbreaking concepts. To address the ‘feeding challenge’ posed by the growing global population amid rapid urbanization, it also meant innovative food preservation and processing methods.

However, the enormous success of the methods described above also gave rise to catastrophic problems that have emerged in recent decades. Developing and implementing subsequent innovations remains the only way to overcome these challenges in the 5th Industrial Revolution.

This paper highlights two innovative food processing and preservation methods: high¬pressure processing/preservation (HPP) [29,30] and supercritical fluid processing (SCF) [31,32], which have already been market-validated on a global scale. It presents their main advantages for sustainable, circular-economy-based development, also recalling phenomenal physical foundations. The latter serves as a basis for indicating their possible next generation: economically attractive and offering new product and technology development opportunities.

1. Supercritical fluids technology advances

Supercritical fluid (SCF) technology offers unique opportunities to extract specific components or remove undesired agents from a foodstuff. One can recall the decaffeination of coffee beans, the recovery of aromas and flavours from herbs and spices, or the removal of contaminants [31,32].

Conceptually, the technology explores unique properties above the gas-liquid critical temperature and pressure. In the supercritical domain, properties are driven by multimolecular pretransition (critical) fluctuations, whose size (correlation length ξ) and lifetime (τ_{fl}) rise infinitely on approaching critical pressure (P_C) and temperature (T_C) [33]:

$$\xi(T) \propto |T - T_C|^{-\nu} \quad \text{for } P = const; \ \xi(P) \propto |P - P_C|^{-\nu} \quad \text{for } T = const \qquad (2)$$

$$\tau_{fl}(T) \propto |T - T_C|^{-z\nu} \quad \text{for } P = const; \ \tau_{fl}(P) \propto |P - P_C|^{-\nu} \quad \text{for } T = const \qquad (3)$$

where ν is for the correlation length critical exponent and z is the dynamic exponent; for the gas-liquid critical point $\nu \approx 0.63$ and $z = 3$.

In the supercritical domain the system time and space scale change from the nano-scale remote from the critical point to $\xi(T,P) \to \infty$ and $\tau_{fl}(T,P) \to \infty$ for $T \to T_C$ and $P \to P_C$. It yields singular changes of physical properties, that can be tuned by decades when shifting temperature or pressure with respect to (T_C,P_C) values. One can indicate the compressibility

$\chi_T = dV/dP \propto |T - T_C|^{-\gamma}$, and heat capacity $C \propto |T - T_C|^{-\alpha}$, where for the gas-liquid critical point the exponent $\gamma \approx 1.2$ and $\alpha \approx 0.12$ [33, 34]

For the supercritical fluids (SCF) technology, essential are Kirkwood (Eq. 4, [35]_ and Noyes-Withney (Eq. 6, [36]) relations [37]:

$$k, s \propto exp\left[\frac{K}{T}\left(\frac{1}{\varepsilon} - 1\right)\right] \quad \Rightarrow \quad k, s \propto \frac{K}{T}\left(\frac{1}{\varepsilon_C + a(T-T_C) + A(T-T_C)^{1-\alpha} + ..} - 1\right) \qquad (4)$$

$$\frac{dm}{dt} \propto D(C_S - C_B) \Rightarrow \quad \frac{dm}{dt} \propto CT(a_\sigma(T - T_C) + A_\sigma(T - T_C)^{1-\alpha}) \qquad (5)$$

where s is for the solubility, k denotes reaction rate, m is for the transferred mass, D means the diffusion rate, C_S and C_B are for surface and bulk concentrations, ε means dielectric constant; parameters $K, a_\sigma, A_\sigma = const$.

The left-hand part of the above relations is for the original formulations of the Kirkwood [35] and Noyes-Withney [36] equations, and the right-hand part is the formulation near the critical point derived by the authors in ref.[37]. It explored the dependence of the precritical anomaly of dielectric constant (ε):

$$\varepsilon(T), \sigma(T) \approx c + b(T - T_C) + A(T - T_C)^{1-\alpha} \qquad (6)$$

where c, a, A are constant parameters

Equations (4) and (5) are essential to SCF technology. showing the essential meaning of dielectric properties, of the reference system in which SCF processing takes place. For foods and pharmaceuticals, this is usually carbon dioxide (CO_2), as it does not affect their essential properties. Targeted properties related to extraction or a chemical reaction can be achieved by adding a small amount of a compound that interacts with the selected ingredient to a limited extent. It can be qualitatively tuned as one approaches these critical points. The reference parameters for CO_2 are highly favourable for applications, due to the low critical pressure and temperature, $P_C = 7.38MPa$ and $T_C = 304.13K$, which are close to room temperature [31, 32].

Figure 1 shows the new-generation apparatus for SCF-related R&D activities across an extended pressure and temperature range, along with high-level parameters tuning.

Despite numerous monographs on SCF technology applications, an important and yet overlooked aspect related to equations (4–6), warrants attention. They define the fundamental basis of the method and show its coupling to precritical changes of dielectric properties, particularly dielectric constant.

For the SCF standard applications associated with the gas-liquid critical point, in Equations (4-6) the critical exponent $\phi = 1 - \alpha \approx 0.88$. This value is close to '1', and then both temperature-dependent terms in Eq. (6) have a comparable impact in the supercritical domain.

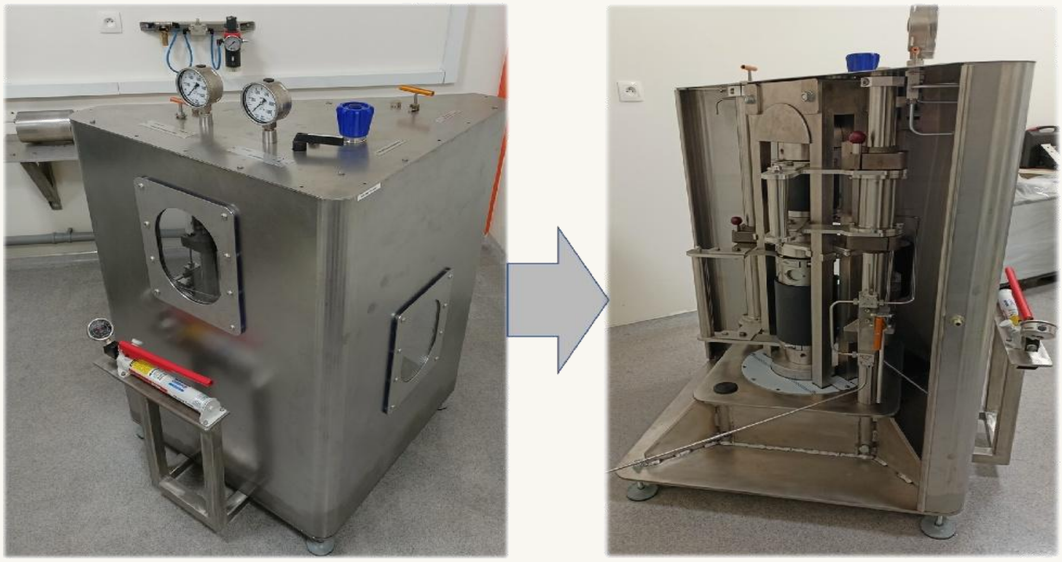


Figure 1 Set-up for supercritical (SCF) studies available in X-PressMatter Lab IHPP PAS (Poland) [38]. Parameters: pressures up to 150 MPa, temperatures from $-20\ ^{o}C$ to $200\ ^{o}C$, working volume $V = 0.5L$. Two sides view is shown, including the insight into the interior of the apparatus

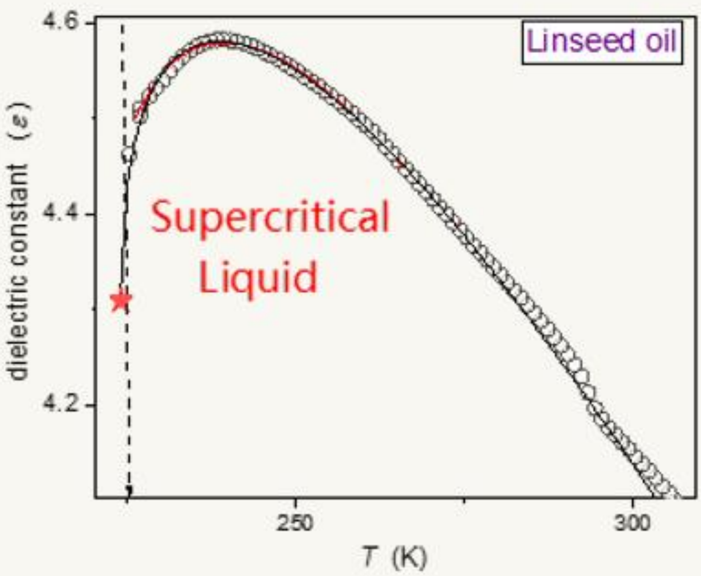


Figure 2 Dielectric constant changes in liquid linseed oil, showing critical changes of dielectric constant portrayed by Equation (6), with the critical exponent $\alpha = \mathbf{1/2}$ **.** The star indicates the critical point, and the vertical arrow shows the liquid – solid phase transition. The plot also presents the dried flax, ready to be used as seeds source, from which oil can be obtained by pressing, and fibers for fabric manufacturing. Based on the data given in the ref.[**40**]**.**

Consequently, the explicit critical contribution $\propto (T - T_C)^{1-\alpha\approx 0.88}$ is weak, and emerges only very close to the critical point. For the experimental evidence, see ref. [39]. It limits tuning possibilities for required properties in SCF technology implementations. It is also notable that the use of high-pressure equipment that uses large volumes of gas can be risky if not operated by qualified staff in specially designed facilities. The next issue is the potential risk of CO2 release to the atmosphere.

Figure 2 presents the results of studies, showing a new phenomenal opportunity that avoids all the problems mentioned above. It shows long-range, and very strong, associated with the critical exponent $\phi = 1 - \alpha = 1/2$ in Equations (4-6), pretransitional changes of dielectric constant in linseed oil. It is associated with the liquid–solid transition and reached only by temperature shift, under atmospheric pressure.

It can be considered the reference proposal for the next-generation SCF technology, which is independent of the liquid-gas transition. Linseed oil can be considered a cheap, widely available, and ecological SCF technology reference carrier. After processing, it can be easily reused, enabling closed-loop operation with no environmental impact. The other practical consequences of unusual ‘critical properties of linseed oil are discussed in ref. [40].

2. High¬Pressure Processing (HPP) technology advances

Research on the effects of high pressure on food products began with Bert Hite in 1899, for milk and beef. He observed effects similar to thermal pasteurization when compressing to $P = 670MPa$ for $\sim 1\,hour$ [41]. Percy W. Bridgemann, Nobel Prize winner in 1946 ‘for the invention of an apparatus to produce extremely high pressures, and for the discoveries he made therewith in the field of high pressure physics’ [42], began his research in the high-pressure topic by observing the effect of pressure ($P = 590MPa$ for 1 hour) on egg albumin, yielding the post-compressing coagulation [43].

The first commercial products based on high-pressure preservation/processing (HPP) appeared only in 1990, in Japan. These were HPP-formed strawberry, apple, and kiwi jams, as well as grapefruit juice [44]. The terms 'preservation' and 'processing' are used here because compression led to 'cold' pasteurisation at approximately room temperature, resulting in products with an appealing 'velvety' flavour and texture. The appearance of these products was associated with the fact that only in the late 20th century did high-pressure systems with industrial-sized chambers — meaning at least several dozen litres — become available at an affordable price, and offering reliable operation for thousands of compression and decompression cycles [29, 45-48].

Another significant factor was the emergence of consumer sentiment towards premium products, with specific functional and health-promoting qualities. Over the following decades, interest in

food HPP spread worldwide, and it now represents a significant market niche for premium, pro-health food products [45-48], and even pet food [49].
Figure 3 shows photos of two HPP processors: (i) a lab-scale. With the pressure chamber volume of 1.5 litres and (ii) a pilot-scale pressure chamber volume of 50 litres. It is worth noting that only a part of the high-pressure chamber can be filled with the processed product — typically less than 60% [29, 30}.

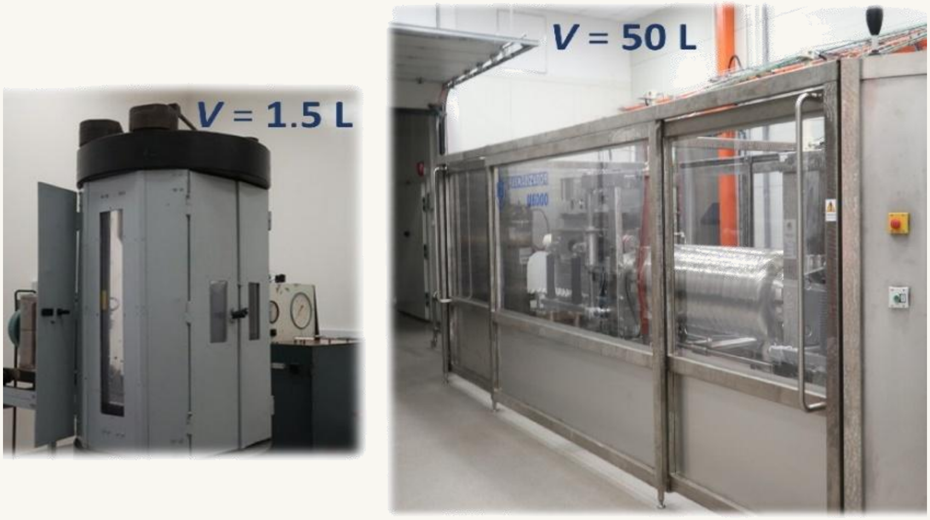


Figure 3: Processor for high-pressure preservation/processing (HPP) with pressure chambers of different volumes, as indicated in the figure. Facilities in X-PressMatter Lab IHPP PAS [38]. They are lab-scale (left) and pilot-scale (right) facilities, with the volumes of the pressure chambers shown in the plot. The operation up to $P = 600 MPa$.

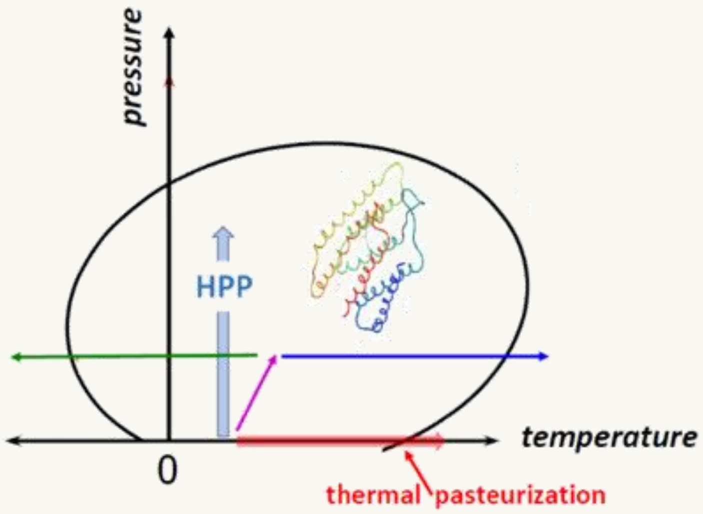
As described above, standard thermal pasteurisation involves protein denaturation when a temperature threshold is exceeded, typically near 86°C. Crossing this temperature triggers protein denaturation, which is lethal to selected parasitic microorganisms. However, it also affects the entire product. The latter causes changes in flavour, taste after thermal pasteurisation, something everyone experiences when buying milk from the shops. However, it also reduces the product's nutritional values and bioactivities [30].

Compressing related HPP 'cold pasteurization' can be achieved at near room temperature. It is primarily associated with the disruption of cell membranes and the destruction of intracellular organelles. Consequently, only the selective destruction of undesirable/harmful microorganisms occurs. After decompressing, the observable impact on significant processed food properties can be minimal. Thus, HPP technology enables selective pasteurisation, and processed food retains the qualities of fresh produce.

However, this requires matching the HPP compression conditions to a given product, as too high a pressure can reduce the number of undesirable microorganisms while also damaging the product's texture [50], for example

Figure 4 shows the conceptual basis of the HPP technology, schematically depicting the denaturation curve on the pressure-temperature (P-T) plane [29, 51, 52]. The red ‘wide’ arrow shows the path of standard thermal pasteurisation, and the blue ‘wide’ arrow is for 'cold' HPP pasteurisation. For the latter, the process can terminate before crossing the denaturation curve.

Figure 4: Denaturation curve in the pressure–temperature plane, showing the paths leading to pasteurisation and sterilisation.



The horizontal 'broad' red arrow indicates the standard pasteurisation process, which first terminates at the thermal pasteurisation temperature of -86°C. The vertical, broad, light-blue arrow indicates the standard HPP treatment. A schematic presentation of protein structures in their native and denatured forms is also shown. The plot also shows the process paths for the next-generation barocaloric effect-supported technology. The horizontal green arrow indicates the use of barocaloric elements with materials characterised by$dT_m/dP > 0$., where T_m is the melting temperature. The horizontal blue arrow shows the use of barocaloric elements with materials characterised by $dT_m/dP < 0$ [4, 30].

The aforementioned characteristics of post-HPP foods naturally reduce losses during transportation and storage. Implementing HPP in the processing stage produces no pollutants and requires 3–5 times less energy than standard thermal pasteurisation. This is because significant energy consumption occurs only during the short compression period to the required pressure. To pasteurize food and reduce the number of microorganisms to the required level, a pressure of 400-600 MPa is required for 5-15 minutes. HPP possesses the characteristics of a technology that perfectly meets the expectations of the 'Sustainability & Circular Economy'. It produces high¬quality, often health-promoting food with minimal environmental impact and significant energy savings.

However, there are also problems. Large-volume HPP processors with a chamber volume of at least 100 litres are expensive and require qualified technical staff for current maintenance. The obligatory service after the standard 100,000 compression and decompression cycles can be very expensive. Consequently, products incorporating HPP technology, by definition premium-class, are more expensive than their standard counterparts.

This demonstrates that reaching the goals of 'Sustainability & the Circular Economy' requires not only the development and implementation of appropriate technologies, but also a society that is able to accept such products. This primarily means that policymakers must ensure that people's incomes are high enough to enable them to select health-promoting premium products.

Although HPP technology enables the pasteurisation of food products, the pressure-assisted sterilisation remains a challenge. This cannot be achieved solely by increasing processing pressure. Even approaching the pressure limit of HPP technology, $P \sim 600 MPa$, can be destructive for some products. On the other hand, an effective impact on spores and viruses requires an even higher pressures: $P > 1 GPa$ [53, 54]. Such HPP processors are more expensive and riskier to operate.

A possible solution is to combine temperature and pressure, now known as high-pressure and high-temperature (HPHT) processing [55, 56]. The only commercially available concept involves preheating of the product to around 90 °C, i.e., above the thermal pasteurisation threshold, placing it in a thermally insulated container and then shifting to the standard HPP processor, where it is subjected to a standard cycle up to $P = 600 MPa$ [56]. This methodology negates some of the advantages of the standard HPP technology, such as reduced energy consumption. Furthermore, the product is exposed to high temperatures for a prolonged period throughout the entire long HPP cycle, including compressing and decompressing periods.

Recently, drawing on their experience in pressure research in soft matter systems and HPP technology, the authors of this report proposed a qualitatively new concept utilising the barocaloric effect [4, 30]. The barocaloric phenomenon has attracted significant interest in recent years due to its potential to revolutionise the operation of refrigerators, cold stores, air conditioners, and thermal storage systems, making them energy–efficient and environment-neutral [57-61].

The impact of the reference melting/freezing phenomenon is experienced by many people living near large bodies of water, such as the sea or lakes. During freezing in early winter and then melting in early spring, the climate differs from that in more distant, ‘continental’ regions. It is due to the emission or absorption of large amounts of thermal energy from the environment during freezing (solidification) and melting (liquidation).

Freezing and melting are discontinuous phase transitions, and the emission and absorption of heat to and from the environment described above are fundamental features related to changes in the system's internal energy.

Conceptually, the phenomenon is illustrated by the Clausius–Clapeyron equation [62, 63], formulated in the 19th century, which in the given case can be presented as follows:

$$\frac{dT_m}{dP} = T_m \frac{\Delta v}{L} \quad (7)$$

where dT_m/dP describes the slope of $T_m(P)$, showing whether compressing rise ($dT_m/dP > 0$) or decrease ($dT_m/dP < 0$) of the discontinuous phase transition temperature; Δv is for the molar volume changes between adjacent phases at T_m, and L is the phase transition 'hidden heat', reflecting the which can be released into the environment or taken from it during a phase transition.

The barocaloric effect exploits the melting transition-related caloric effect described by the above equation when a system is compressed and decompressed under adiabatic conditions, i.e., when thermally isolated from the environment. This effect is particularly pronounced in so¬called 'Soft Matter' systems, which was discovered in 2019 [57, 58].

Recently, the authors of this report proposed using this phenomenon for next-generation HPP processing, enabling enhanced pasteurization and sterilization at low (sub-zero) temperatures, i.e., promising conditions that remain a technological challenge [4, 30].

In this concept, the barocalic material was placed in a metal tube with high thermal conductivity (such as copper), and terminated with a pressure-transferring element, such as a bellows, that reduces the tube's length and volume when compressed. The scheme of such an element is shown in ref. [30].

These elements are then placed between food products in a standard HPP processor chamber. The latter approach involves supplementing the chamber with a thin-walled tube adjacent to its walls to thermally insulate it from the surrounding environment and ensure adiabatic conditions. The standard HPP cycle then begins, involving compression to the planned pressure and maintaining it for a predetermined time, followed by decompression. Importantly, no thermal pre-treatment of the processed food is required.

Figure 4 also illustrates the operating paths for the next-generation, barocaloric-effect-supported HPP. First, compression increases the temperature in the thermally insulated interior of the pressure chamber by raising the internal energy of all components. The sloping purple arrow shows this process. Once the pressure corresponding to the discontinuous phase transition (P_m, T_m) is reached, a phase transition to the next phase occurs.

For the 'barocaloric materials', where $dT_m/dP > 0$, significant thermal energy is released into the environment, increasing its temperature and that of any food products placed there. This is indicated by the blue horizontal arrow in Figure 4. For 'soft barocaloric materials', where pressure lowers the temperature of the discontinuous phase transition (i.e., for systems characterised by $dT_m/dP < 0$), a significant temperature reduction is possible. This leads to cold pasteurisation or sterilisation (indicated by the horizontal, light-blue arrow in Figure 4).

During decompression, these processes occur in reverse, and the food products are removed from the processor at the same 'comfortable' temperature at which they were placed. The important advantages of the next generation barocaloric effect-driven HPP can be concluded as follows: (i) a standard HPP processor can be used; (ii) the process is controlled solely by pressure changes; (iii) high-temperature operation is limited and strictly defined by a given reference processing pressure; and (iv) the required electrical energy is preferably the same as in the standard HPP process.

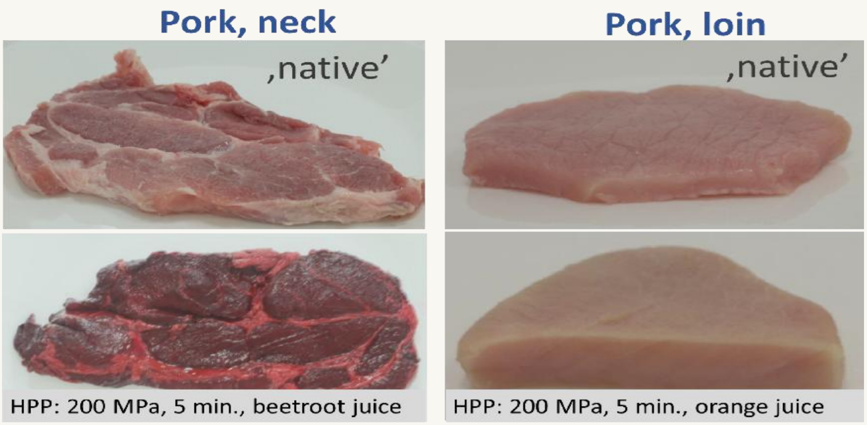


Figure 5 Pork neck and pork loin after low/moderate pressure treatments in a beetroot juice and orange juice, under the conditions given in the figure.

HPP technology enables achieving the microbiological safety of food products in a standard HPP processor at relatively low reference pressures, using an approach that differs slightly from the commonly used concepts nowadays. Figure 5 shows photos of pork neck and pork loin pieces in their 'native' form, as well as after being compressed in beetroot and orange juice for 5 minutes at 200 MPa. While this low/moderate pressure generally does not ensure microbiological safety through compression alone, it can be achieved by performing the process in an appropriate juice environment. For example, pork loin retains its positive properties even after a month of storage in a standard refrigerator following such processing, which can be attributed to the juice permeating the entire meat volume and altering the pH. This effect is particularly noticeable in pork necks after HPP processing, as shown in Figure 5.

It is worth emphasising that there is no 'brightening' of the product surface, which results from surface denaturation and is an undesirable effect that occurs during standard HPP treatment at pressures greater than 400 MPa. The authors also found the flavor of the pork loin cutlets, 'filled' with orange juice throughout the volume, to be uniquely tasty after such processing.

5. CONCLUSIONS

In 5th Industrial Revolution times, civilizational development grounded in a Sustainable Society & Circular Economy concepts is a necessity [64, 65]. This is driven by the need to minimise the ongoing catastrophic impacts of Global Warming, Environmental Pollution, and Pandemic Health threats. The latter is significantly associated with the food preservation methods developed and implemented on a large scale in the early stages of the Industrial Revolution. These methods have been highly successful in providing a rich, extensive assortment of products on store shelves, and essential minimising local famine catastrophes worldwide.

Today, high-quality, health-promoting food is a necessity and an expectation for numerous consumer groups – citizens. However, it requires the implementation of innovative food preservation and processing methods. that do not have adverse health effects, coupled with the nowadays dominant technologies.

This report discusses two such methods: supercritical fluids (SCFs) and high-pressure preservation/processing (HPP) technologies. Their unique features, including pro-health benefits and high-quality products, align with the expectations of Sustainable Development & the Circular Economy. It also involves minimizing food losses in the logistics chain and reducing energy demands during processing. In the report, particular attention was paid to the fundamental, physical basis of these methods, which was further used as a reference for the development of next-generation versions of these innovative methods. Notably, the authors have conducted preliminary lab/pilot validation tests for the presented concepts.

It is particularly important to emphasise that the proposed next-generation SCF and HPP technology developments offer several advantages over the standard methods currently in use. These include the specific characteristics achievable in the processed product and the functional simplification of the technology. This applies to both environmental safety and the implementation process. These concepts are also inherently energy-efficient.

The next-generation SCF and HPP concepts shown above greatly simplify the processing stage, to the extent that they could enable small-scale facilities to be built for use by local mini-enterprises. For instance, an HPP processor with a chamber volume of 50 litres costs around $1,000,000$ \$ A processor with a $V\sim 10L$ chamber can cost less than a quarter of that price, while providing at least 100,000 compression/decompression cycles. Upgrading such a device to the barocaloric effect HPP standard maintains favourable energy and environmental characteristics while enabling deep pasteurisation and sterilisation of the product without altering its unique properties.

This opens the possibility of distributing exquisite, unique food products and dishes online without losing any of their functional characteristics, from health benefits to taste. For a local manufacturer, a chamber volume of 10 litres may be sufficient. Another option is for restaurants and bars to offer high-quality dishes while minimising product losses, such as expired products. This also enables chefs to embrace 'new creativity'.

This could create new job opportunities, including creative roles, and open previously unexplored avenues for developing new product ranges using the technologies described here. In this development model within the framework of 'Energy & Environment Protection – Innovation – Locality', the benefits of developing artificial intelligence and AI-supported humanoid robots are currently being highlighted. Massive job losses are already being observed [66]. However, implementing new-generation food preservation methods and having local enterprises utilize them to offer excellent local products on a semi-global scale could create numerous new jobs, also supporting local organic agriculture. In such a model, even AI-supported humanoid robots could be a factor supporting, rather than reducing, human employment opportunities.

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Solution 4 Planet

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"New food technologies should preserve not only food, but also health, resources, and the future."

Author's own statement