Review

Society & Science: High Pressures for Innovative Pro-Health Foods

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Abstract:
The report addresses quests related to innovative methods of food preservation in the context of the Industrial Revolutions epoch and the assisted population boost. Particular attention is paid to the High-Pressure Preservation/Processing (HPP) of foods that uniquely combine the pro-health expectations of 21st-century societies with the pro-environmental requirements of Sustainable Development. HPP technology also correlates with producers' and logistics' expectations due to the long period of fresh product quality preservation. Beneficial features of HPP technology and related physical foundations of high-pressure impact on foods are presented. HPP is related to "cold & high-pressure pasteurization" at near ambient temperature. This report also considers an innovative sterilization concept, linking colossal barocaloric effect (CBE) & HPP. It is related to compressing up to $\sim 600\mathrm{MPa}$ and high temperatures($90\ {}^{o}\mathrm{C} - 120\ {}^{o}\mathrm{C}$) controlled by the heat associated with CBE phenomenon. Further, the supplementary concept of 'cold sterilization' under medium-high pressures, related to $P \sim 200\mathrm{MPa}$ & $T \sim -20\ {}^{o}\mathrm{C}$, supported by the reversed CBE, is presented. Finally, socio-economic consequences of these unique technologies are discussed. They address 5th Industrial Revolution & Sustainable Development targets and expected new market niches.

Keywords: Industrial Revolutions; Food preservation; High-pressure processing (HPP); High-pressure sterilization; Physical origins; Socio-economic impacts

1. Population, Food & Malthusian Trap

In 1798, Thomas Malthus presented the model showing population growth (dynamics), exemplified by a scaling equation with the constant population growth rate coefficient r (Malthus, 1798; Galor, 2000; Weil and Wilde, 2010):

$$P(t) = P_0 \exp(rt) \;\Rightarrow\; \left[\frac{d\ln P(t)}{dt} = r \;\Rightarrow\; \frac{dP(t)}{dt} = rP\right] \;\Rightarrow\; \frac{dP(t)/P(p)}{dt} = G_P(P) = r\,, \qquad (1)$$

where $P(t)$ stands for population changes, P_0 is its value at the onset time $t = 0$, and $r = \text{const.}$ The left part is sunject to basic Malthus' scaling, including the coupled differential equation. The right part shows the new form associated with the population growth factor $G_P(P)$ - a quantity whose significance has been stressed recently (Sojecka and Drozd-Rzoska, 2024, Lehman et al., 2021).

Malthus explicitly declared inspiration by Isaac Newton's legacy, demonstrating the Scientific Method's extraordinary "cognitive power" (Malthus, 1798, Anstey, 2004; Gauch, 2012). He indicated that seemingly separate phenomena can be described via common scaling equations, supported by differential counterparts revealing their formal origins and discussed the significance of food resources, assuming the linear pattern of changes (Malthus, 1798):

$$F(t) = a + bt \quad , \qquad (2)$$

where $a, b = \text{const.}$ **Figure 1** presents the schematic interplay analysis of Eqs. (1) and (2). Malthus commented it as follows (Malthus, 1798): "The population increases in geometrical ratio and the subsistence rises only linearly, which finally leads to times of vice and misery", i.e., the Malthus Trap (Catastrophe) - indicated in the plot. Malthus advised population constraints or extra rise in subsistence (food) to escape the trap disaster. Unfortunately, the simplistic escape concept, namely robbery or conquest of other countries, has often been implemented (Reuveny, 2012).

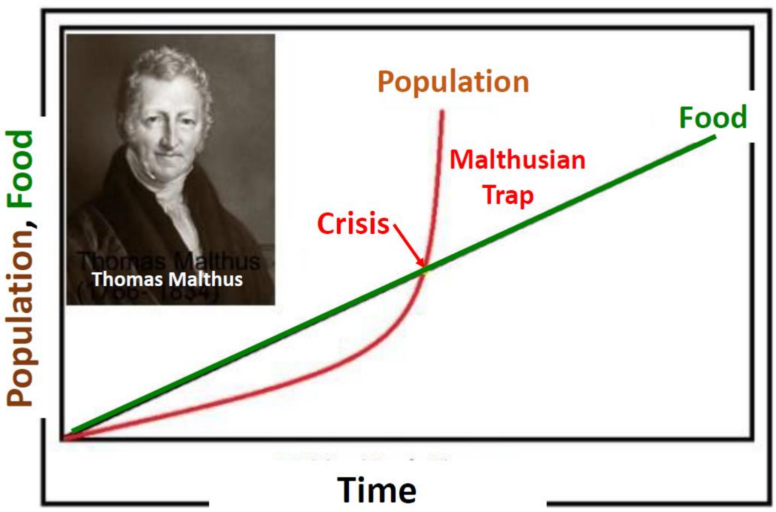

Figure 1. Malthusian human population and food "resources" changes, related to model scaling relation, Eqs. (1) and (2), and leading to the Malthusian Trap (Crisis, Catastrophe).

The experimental validation of conceptual model concepts is essential for the Scientific Method (Gauch, 2012). For Malthus, it could be observations of extraordinary changes in England, the World Leader in developing 1st Industrial Revolution, also named the Steam Age (Crump, 2007; Allen 2012). Numerous large industrial centers with huge demands for labor appeared. They were full of hopes for a new, better life, but also fierce economic relations and over-exploitation. Great wealth, hopes, and expectations accompanied dramatic poverty and decline. The general driving force of the Industrial Revolution was innovation: for the 1st Industrial Revolution, they explored coal, a new and effective energy source. Worth stressing are feedback interactions between technological innovations and the evolving political, economic, and social issues, yielding 'innovative & supporting' socio-economic surroundings.

Figure 2 shows global population changes during Industrial Revolutions times, based on the authors' data obtained by collecting data from different sources and their numerical filtering. It yielded the "analytic set" of global population data, for which the derivative analysis was possible (Sojecka and Drozd-Rzoska, 2024 and 2025). The nonlinear pattern of changes in **Figure 2**, which uses the semi-log scale, is in explicit disagreement with Malthus model predictions, for which the linear behavior is obligatory (Eq. (1).

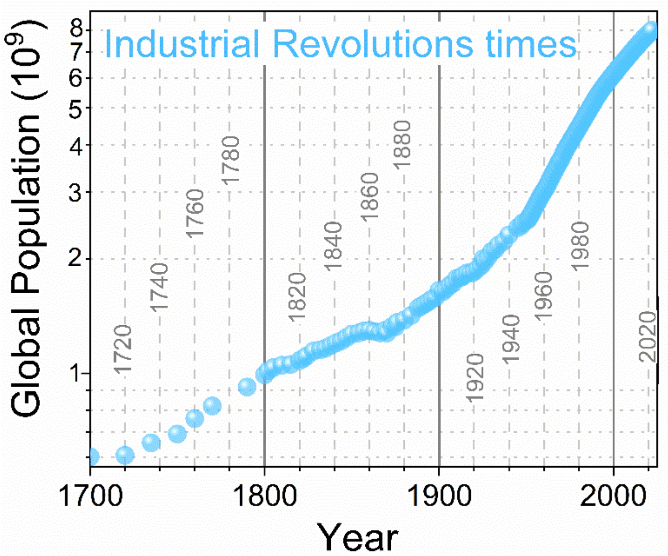

Figure 2. Global population growth during the Industrial Revolutions, based on the authors' data (Sojecka and Rzoska, 2024).

2. Super-Malthus Population Growth and Food Resources

For portraying non-Malthus changes in global population growth, the following extension of Eq. (1) was suggested (Sojecka and Drozd-Rzoska, 2024):

$$P(t) = P_0 \exp(rt) \Rightarrow P(t) = P_0 \exp(r(t)t) = P_0 \exp\left(\frac{t}{\tau(t)}\right) \quad . \tag{3}$$

In this dependence, for which the name Super-Malthus (S-M) equation was proposed (Sojecka and Drozd-Rzoska, 2024), the time-dependent rate coefficient $r(t)$ has been introduced. Equally important is the introduction of the relaxation time $\tau(T) = 1/r(t)$, the parameter commonly used in the physics of complex systems. It offers a reader-friendly interpretation, i.e., the estimation of the time required for the population to change by 50% from the value of $P(t)$ at a given moment in time: $t_{50\%} = \tau(t)\ln 2$.

Unfortunately, the non-defined functional form of $\tau(t)$ evolution can suggest a seemingly impossible portrayal of $P(t)$ data directly via Eq. (3). Nevertheless, one can focus on the relaxation time itself, using Eq. (3) for calculating $\tau(t)$ changes: $\tau(t) = t[\ln(P_0/P(t))]$. (Sojecka and Drozd-Rzoska, 2024). Such behavior, associated with data presented above, is shown in **Figure 3**. The plot reveals two characteristic time domains. In the huge time interval, ranging between years ~1100 and ~1700, the relaxation time changes are described by the horizontal line, i.e., $\tau(t) = \tau =$ const, which also means $r =$ const. Consequently, in this period, the basic Malthus model (Eq. (1): left part) yields the dominant description for the global population evolution, with a disturbance correlating with the Black Death pandemic times. Starting from year ~1700, which can be associated with the Industrial Revolutions times onset, the dominant trend changes: $\tau(t) = a - bt$ (Sojecka and Drozd-Rzoska, 2024).

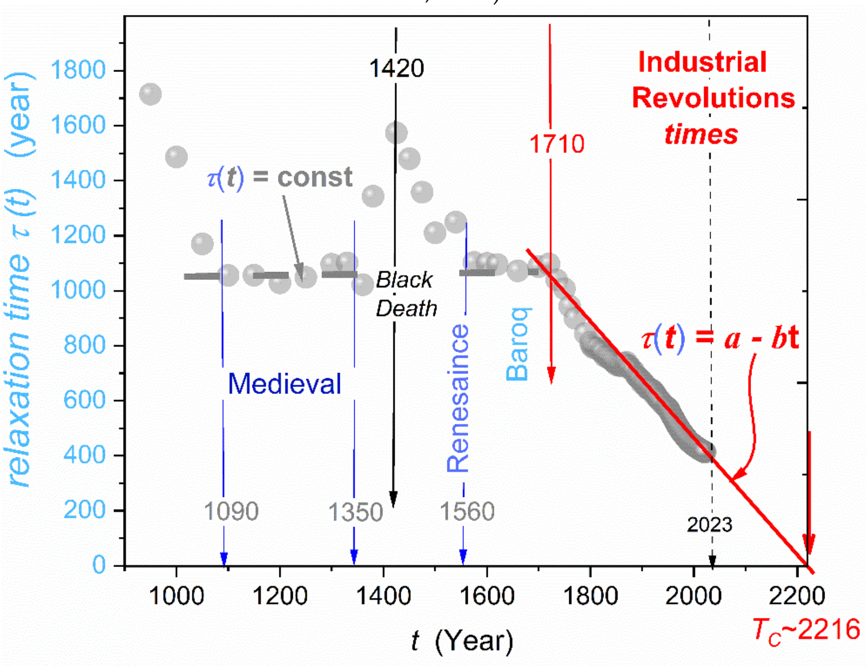

Figure 3. The evolution of the relaxation in the last millennium, related to the general Super-Malthus Eq. (3). Subsequent epochs and relevant events (Black Death) are indicated.

The substitution of $\tau(t) = a - bt$ into Eq.(3) yields:

$$P(t) = P_0 \exp\left(\frac{t}{a-bt}\right) = P_0 \exp\left(\frac{t/b}{a/b-t}\right) = P_0 \exp\left(\frac{ct}{T_C-t}\right), \quad (4)$$

where $c = 1/b =$ const and $T_C = a/b \approx 2216$ years.

This new global population growth pattern, introduced in (Sojecka, Drozd-Rzoska, 2024) correlates with dynamics of constrained and frustrated systems considered in Complex Systems Physics. Regarding constraints, one can indicate global-scale spatial limitations and the environment's ecological carrying capacity. Frustrations include numerous political and economic disturbances, which can rapidly grow up to a global scale.

3. Innovative Food Preservation Methods in Industrial Revolutions times

During the Industrial Revolutions times, global and local populations have grown dramatically, following the Super-Arrhenius pattern discussed above. In 1700, there were ~610 million people on Earth, after millennia since the Anthropocene onset (10 000 BCE). By 1800 it was ~1 billion, and by 1900: 1.6 billion (Sojecka and Drozd-Rzoska, 2024).

These rapid changes were accompanied by the emergence of populous and increasingly numerous industrial centers, for which providing a sufficient amount of health-safe food was a critical challenge. Generally, human populations have struggled with the problem of pro-health food safety since the beginning of its history, which has led to the creation of many "preservation techniques" and products that enrich our cuisine to this day. However, a new generation of preservation methods has become necessary for the growing global population and industrial centers. They should not change basic features noted by consumers, like the view and taste, and be suitable for highly processed "industrial food", massively "fabricated".

The scientific basis and target for these methods could be defined due to the breakthrough research of Louis Pasteur's (1863). He linked the fast loss of food properties to spontaneously rising contamination by dangerous microorganisms – bacteria (Hunter, 2014). Pasteur found a general remedy: heating the product to a temperature of $84-86\ ^0\mathrm{C}$, for several minutes. This process is known as the thermal pasteurization. For decades, it has been one of the essential preservation methods: the basic examples can be milk or juice in stores. Currently, this process is defined by 5-decade reduction in the number of microorganisms to the level of 10^{-5} in comparison to the native state. Using the commonly used jargon: it is 5-log reduction (Rahman, 2007; Sun, 2005).

For many food types, essential is the very long microbiological safety guaranteeing negligible microbiological contamination, and simply applicable for solid and liquid products. For this purpose, many chemical preservatives or their complexes have been worked out. For decades, it has remained one of the leading food and beverage preservation methods (Rahman, 2007). Today, chemical preservatives are present on store shelves as a dominant part of products.

In the 20th century, there was also a mass implementation of preservation techniques based on products cooling to a temperature of $6-8\ ^0\mathrm{C}$ or freezing at temperatures reaching $-30\ ^0\mathrm{C}$. A significant novelty was the appearance of large refrigerated facilities for mass cooling/freezing, often associated with a unique oxygen-free atmosphere (Rahman, 2007). A significant breakthrough was the development of home refrigerators and coolers, mandatory equipment of every home nowadays. This was possible after implementing the physical concept of circulating, suitably selected liquid, in which adiabatic decompression yields a strong decrease in temperature. Significant was finding a liquid where it is associated with the exceptional colossal entropy change $\sim 400\ \mathrm{JK^{-1}kg^{-1}}$, which is the process metric. They are hydrofluorocarbons, especially their most famous representative with the trade symbol HF134a (Sojecka et al., 2024).

Another modern and widely used preservation method is the impact of ionizing radiation. It is the basic method for very dry products, such as spices (Rahman, 2007).

In the 21st century, however, significant side effects of the above-mentioned food preservation technologies have appeared:

- Numerous food preservation chemical agents are the cause of the obesity epidemic, allergies, and even some types of cancer diseases. They are also linked to fatal, intestinal gut complications (Anand and Sati, 2013; Reardon, 2015)
- Thermal pasteurization, and much more sterilization can deprive food and beverages. From 60% to 80% of their nutritional and bioactive values are lost, and these numbers increase during storage (Sojecka et al., 2024).
- Freezing, due to the appearance of ice crystals, can partially destroy the product's texture (Bald, 2012).
- Freezing/cooling equipment like air conditioning and most of the heat pumps use the above-mentioned thermodynamic cycle with circulating and rapidly compressed/decompressed 'fluid agents'. However, hydrofluorocarbons (inluding their 'soft, eco-friendly' counterparts) are hundreds of times or more harmful to Global Warming than CO_2 which dominates discussions in mass media (Sojecka et al., 2024).

The innovative food preservation methods implemented since the 19th century have greatly impacted the current state of food abundance on store shelves and the elimination of many disease threats. They have also supported efficient logistics in numerous populated urban centers.

However, in the 21st century, the cumulated 'side effects' of these methods have appeared, creating new, global-scale threats. The fundamental way to solve such challenges in Industrial Revolutions times was/is the next Grand Innovation, avoiding the above-mentioned problems and responding to consumers' expectations and producers' logistical requirements.

It turns out that a method with such unique features exists. It can be the High Pressure Processing / Preservation (HPP) (Sojecka et al., 2024).

4. High Pressure Processing (HPP) of foods

High Pressure Processing (HPP), also called cold or pressure pasteurization in canonical version, is related to compressing in the range of $p = (300\mathrm{MPa} - 600\mathrm{MPa})$ for several minutes. Comparing cold 'pressure pasteurization' with the classic/standard thermal pasteurization, the Super-Arrhenius (SA) and Super-Barus (SB) relations describing temperature and pressure-related dynamics in complex systems, like foods, are worth mentioning (Drozd-Rzoska et al., 2008; Drozd-Rzoska et al., 2023):

$$k\langle r^2\rangle d \propto \exp\left(-\frac{E_a(T)}{RT}\right) \qquad \text{(SA: } p = \text{const)} \tag{5}$$

$$k\langle r^2\rangle d \propto exp(cP) = \exp\left(-\frac{PV_a(T)}{RT}\right) \qquad \text{(SB: } T = \text{const)} \tag{6}$$

where k stands for chemical reaction rate, also related to bondings, d is the diffusion rate, $\langle r^2\rangle$ describes the average fluctuations of molecules around the equilibrium position, R denotes the gas constant, $c = \text{const}$; $E_a(T)$ is the apparent (temperature dependent) activation energy and $V_a(p)$ is the apparent (pressure-dependent) activation volume.

For $E_a(T) = E_a = \text{const}$ one obtains the simple Arrhenius equation when substituting to Eq. (5). Heating increases $k\langle r^2\rangle d$ values, and the effect can be further increased for the SA ($E_a(T) \neq 0$) dynamics. For proteins, with their multi-level complex structures, these factors lead to their permanent intrastructural changes when passing the denaturation border. **Figure 4** shows the schematic view of this process. Bonds breaking, mainly in secondary and tertiary intra-structural protein parts, is related to rising thermal fluctuations impacting $k\langle r^2\rangle$ matched with the activation energy changes.. This leads to irreversible changes associated with denaturation. For food products, it means eliminating the dominant part of the living microbiological contaminations and permanent changes in properties. An example would be the specific taste of milk purchased in stores.

The standard HPP technology is related to isothermal pressure changes, the consequences of which are illustrated by Eq. (6). Essential is the impact of compressing on the free volume. For foods, it is related to intermolecular volumes and between different macromolecular and multimolecular assemblies with varying degrees of complexity. The activation volume in Eq. (6) is the effective metric of these compressing impacts on all these 'free volume components'. The mentioned sub-elements are also characterized by strongly different local compressibilities, i.e., sensitivity to compression, expressed by the change in the local volumes they occupy or the distances between individual components. For food, the basic ingredient is water, the compression of which to $p \sim 600\text{MPa}$ leads to an 18% decrease in density, which further means that the average inter-element distances decrease to ~93% from the reference state. It can be much larger locally for macromolecules and multi-molecular assemblies. Consequently, strong gradients of local shear forces induced by local compressibility gradients must appear inside a food product. They can be extreme for such very complex Soft Matter systems as living microorganisms.

Local shear forces associated with compressing must lead to breaking bonds between local sub-elements of food and even more for extremely complex microorganisms. As the pressure increases, the rising impacts microorganisms appear, starting from the largest multi-molecular structures, such as cellular walls or intracellular structures. Their irreversible damage is the significant cause of parasitic microorganisms' destruction in HPP technology. The above shows that an optimally designed HPP implementation can almost exclusively affect undesirable microorganisms, preserving fresh food product features when decompressing. Further and stronger compression must lead to denaturation, an irreversible process. The undesirable destructions of products in the pressure range used for HPP technology have little or no effect on viruses, which relatively less complex structure can explain in comparison to bacteria, yeast,…

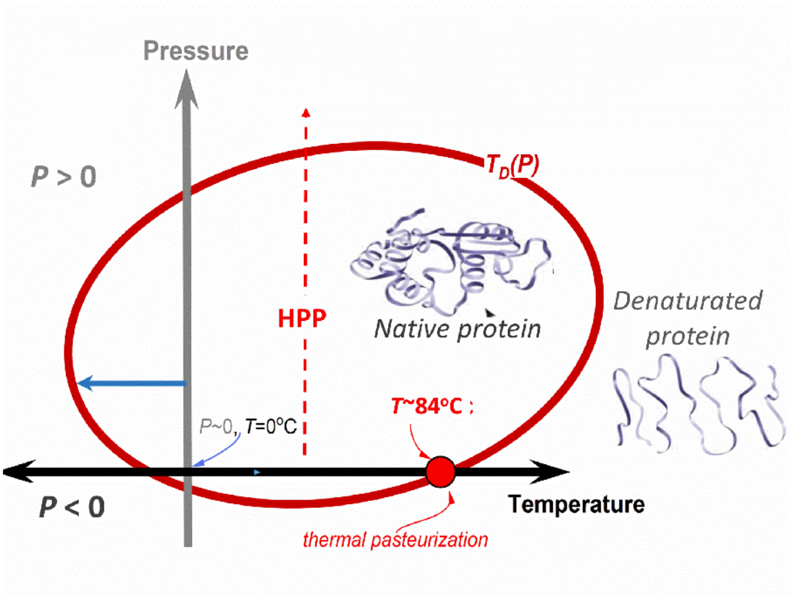

Figure 4 The scheme of the denaturation curve $T_D p$, in pressure – temperature (p-T) plane. The thermal pasteurization temperature (under atmospheric pressure), the standard HPP path (vertical, dashed red arrow), and the possibility of the 'mild' pressure-assisted pasteurization or sterilization (horizontal blue arrow) are indicated. Note positive and negative (isotropic stretching) pressure domains. The plot schematically shows native and denatured proteins related to domains separated by the elliptic denaturation $T_D(p)$ curve.

In conclusion, denaturation is the dominant mechanism responsible for standard thermal pasteurization under atmospheric pressure. For HPP, the pressure dependence of the denaturation curve, with the elliptic curve in the pressure-temperature plane, is essential. Such form is the consequence of the extended Clausius – Clapeyron (C-C) equation, with the pressure-dependent changes of the volume ($\Delta V(p)$) and enthalpy ($\Delta H(p)$), (Sojecka et al., 2024):

$$\frac{dT_D}{dP} = T_D(\text{ref.})\frac{\Delta V(P)}{\Delta H(P)} \quad , \qquad (7)$$

where $T_D(\text{ref.})$ is the reference onset temperature; ΔV and ΔH are for the volume and enthalpy change when passing a discontinuous phase transition – or, in the given case, the denaturation curve. Originally C-C equation was related to the melting (liquid – crystal) discontinuous transition and for pressures in the immediate neighboring of the atmospheric pressure, where $\Delta V = \text{const}$ and $\Delta H = \text{const}$. However, it can be linked to two borders of two states with significantly different ordering. This is also the case with denaturation curves, which separate states with essentially different conformational arrangements of proteins.

Bert Holmes Hite carried out the first studies on high pressures' impact on foods at the end of the 19th century, focusing on microbiological contaminations in milk subjected to pressures up to $p = 670$ MPa for 10 minutes and showed a $5 - 6$ log reduction in total counts (Hite, 1899). He also tested beef meat treated with pressure $p = 530$MPa for an hour. After three weeks of storage, only insignificant microbial growth was noted. In 1912, Percy W. Bridgeman reported egg albumin coagulation after compressing at $p = 590$ MPa for 1hour (Brifgemenn, 1912). Bridgeman was honored with the Nobel Prize for extensive high-pressure studies in 1946 (Bridgeman, 1946).

These early works indicated basic features of HPP technology on foods, namely the reduction of parasitic microorganisms and the denaturation of proteins. However, it was not until 1989 that the first HPP-treated food products appeared in Japan (Sojecka et al., 2024). For decades, the barrier was the construction of large-volume pressure processors with chamber volumes of $V \sim 50$L, 100L, and more. For the last decade of the 20th century, market demands for new-generation, health-promoting food preservation methods also became notable. The HPP-treated food products market is worth at least USD 8.2 billion and is expected to grow by ~120% in the next decade globally (Sojecka et al., 2024).

Unique benefits of HPP technology (Sojecka et al., 2024):

- fresh product quality: nutritional properties, taste, flavor, texture, …
- shelf-life extension from 2–3 days to even up to 180 days!
- high microbiological safety
- taste, flavor, and appearance of a fresh product
- vitamin composition of the fresh product
- maintained bioactive properties
- limited or even no chemical preservatives
- activation/deactivation of selected enzymes
- salt-free products
- sugar-reduction possibilities
- application to fluid, soft, and solid food
- application to packed food: secondary contamination risk avoided
- environment-friendly technology, namely: (**i**) $\sim 4x$ less electric energy required than for the thermal pasteurization; (**ii**) practical lack of waste
- reduction of the of expired products number: disposal costs environmental "costs" reduction
- "clean label" and innovative technology
- creation of new products and a new market niche
- products, including ready-to-eat meals, for customers/patients with special health needs
- immediate exposure of the entire volume of the product to high-pressure

The standard thermal pasteurization is related to the general principle applicable to each product, i.e., exposure to temperatures of $\sim 84-86\ ^{o}\mathrm{C}$ for at least several minutes. HPP technology requires an individual implementation protocol for each product. This applies to (Sojecka et al., 2024):

(i) Pressure pulse duration and its value (usually $300-600\ \mathrm{MPa}$)
(ii) Time profile of the pulse edges
(iii) Processing temperature (standard range: $10\ -50\ ^{o}\mathrm{C}$)
(iv) In advanced applications: the number of HP pulses and their arrangement

The Photo in **Fig. 5** shows the HPP processor, with $V=1\mathrm{L}$ pressure chamber volume, supported by a programmed control system for preliminary preparation of the implementation protocol for a food product. The subsequent test requires the pilot-scale facility, such as the one shown in **Fig. 6**, with the pressure chamber volume $V=50\mathrm{L}$, compressing up to $P=600\mathrm{MPa}$, with remote control of the cycle. It is the central part of the pilot line, composed of vehicle ramps, large-scale coolers at the entrance and exit, and the HPP processor in between. Additionally, the pilot line is assisted with the product preparation room. The facilities shown in **Figures 5** and **6** are parts of the X-PressMatter laboratory located in the Innovation Park of the Institute of High Pressure Physics of the Polish Academy of Sciences in Celestynów near Warsaw (Poland). X-Press Matter Lab is included in 'RoadMap' of Significant Research Infrastructure (Poland).

5. HPP – innovative frontiers

Standard HPP implementation is related to the 'cold pasteurization' for foods, pharmaceuticals, or cosmetics. It shows beneficial 'mild method' features, linking high microbiological safety with fresh (native) product quality. In some cases, even strengthening pro-health features is possible (Sojecka et al., 2024). Implementation of standard HPP technology means a qualitative reduction in the number of parasitic microorganisms to the reference level of the thermal pasteurization but without numerous adverse side effects of the latter.
The obvious path for developing HPP technology seems to be pressure-driven sterilization. This technology is widely used for thermal sterilization under atmospheric pressure for many products on store shelves, such as milk in cartons and numerous juices in their "healthy" versions.

Figure 5. HPP lab scale processor with $V = 1\text{L}$ pressure chamber, for basic research and preliminary establishing of implementation protocols for "HPP foods". X-PressMatter Lab, IHPP PAS (X-PressMatter, 2025).

Figure 6. HPP pilot processor with $V = 50L$ pressure chamber for the industrial-scale test, finalization of implementation protocol, and market experiments. X-Press Matter Lab, IHPP PAS (X-PressMatter, 2024).

A typical thermal sterilization process is arranged in two versions (i) wet pasteurization at a temperature of $121 - 125\ ^{o}\text{C}$ for $\sim$15 minutes in the presence of saturated vapor, and (ii) short-tome (~ 1 second) treatment with a temperature above $150\ ^{o}\text{C}$ (Teixeira, 2014).
Notwithstanding, after such sterilization, the destruction of some nutritional properties and bioactivity of processed products must be even more deteriorated than after the thermal pasteurization carried out at $T \sim 86\ ^{o}\text{C}$. It is suggested that increasing compression up to even ~1.4GPa in HPP technology can also destroy spores and viruses, thus leading to pressure sterilization. However, it also means the essential rise of HPP processor costs, limiting its durability and increasing the costs of service inspections. Extreme pressures can be destructive to essential food properties. In such context, the maximum pressure $P = 600\text{MPa}$ of standard HPP industrial processors available today seems to be a favorable compromise (Koutchma, et al.; 2005).
When considering the impact of pressure, the simultaneous link of compressing at $p = 600\ \text{MPa}$ matched with heating in the range $90\ ^{o}\text{C} - 120\ ^{o}\text{C}$ is considered the High Pressure High Temperature (HPHT, HPT) sterilization technology. There are no essential problems in creating such conditions for the lab-scale, where simply the pressure chamber can be heated. For industrial-scale or even pilot-scale HPP processors, this is not possible. Probably the only commercial solution to this challenge is related to the thermo-isolated

container in which the product is pre-heated to ~90 ^{0}C. The adiabatic compressing up to $p = 600\text{MPa}$ can further increase the temperature up to $\sim 120\ ^{0}\text{C}$. In this way, HPT technological sterilization is achieved (Hyperbaric, 2024).

The mentioned solution is undoubtedly effective for high pressure & high temperature sterilization (HPT, HPHT), but it has obvious limitations. First, it requires a significant amount of energy comparable to the amount necessary for thermal sterilization. Second, the process requires a relatively large number of operations, and third, the volume available for the product inside the HPP chamber is reduced.

Very recently, the concept that significantly reduces the above problems was proposed (Sojecka et al., 2024). Its essence is the application of the barocaloric effect, originally considered an innovative physical concept for the new generation of refrigerators and air-conditioners (Lloveras, et al.; 2019). During compressing, a strongly discontinuous phase transition from a disordered to an ordered phase is passed, releasing a significant amount of heat associated with the change in internal order (H_a in C-C Eq. (7)).

For the implementation proposed in (Sojecka et al., 2024), elements containing neopentyl glycol (NPG), the basic material exhibiting the so-called Colossal Barocaloric Effect (CBE) (Lloveras, et al.; 2019) is placed within the pressure chamber together with the processed product. A thermo-isolated layer, such as Teflon, covers the pressure chamber's walls. It converts the standard HPP processor to the facility to the adiabatic pressure chamber. The process design causes that heat from CBE elements is released only at pressures close to the planned stationary value, for instance, $p = 600\text{MPa}$. Additionally, the temperature is increased due to standard internal energy changes during compressing. Consequently, the "designed" temperature range $90\ ^{0}\text{C} - 120\ ^{0}\text{C}$ can be reached, and it appears only for the well-defined time of the maximal, stationary compressing. For the decompression stage, the temperature inside the pressure chamber immediately drops (Sojecka et al., 2024), and post-process product removed from the processor is again at ambient temperature, which facilitates handling.

Notable, that such an innovative CBE-supported concept of HPT technology requires an energy supply similar to the standard HPP applications, i.e., ~4x or lesser than for the "classic" thermal pasteurization under atmospheric pressure.

Notwithstanding, the general problem of HPT / HPHT technology remains - it is no longer a "mild & gentle" treatment of food processing, which is the essential prevalence of basic HPP "cold pasteurization". The crossover of the high temperature thermal pasteurization limit ($84 - 86\ ^{0}\text{C}$) must always lead to a reduction of the essential values of food products, even when pressure-assisted. Nevertheless, HPT/HPHT process creates unique possibilities for the deactivation and activation of enzymes, which may be important for people with unique health problems and food limitations. For the CBE-supported HPP version, such processing can be controlled precisely, also offering new opportunities for pharmaceutical industry applications.

Figure 4 shows the denaturation curve for the p-T plane. The horizontal arrow (in blue) indicates the other possibility of CBE-supported & adiabatic HPP-based innovative sterilization/paseurization concept. For still limited cases of materials, the so-called inverse-CBE has been found (Zhang, et al; 2023). For such a system, compressing causes thermal energy absorption from the environment, i.e., a drop in surrounding temperature under adiabatic conditions. For decompressing, heat emission from the CBE element to the environment occurs.

The eutectic minimum for water (the main component of food), causes that it remains liquid under pressure $p \sim 200\text{MPa}$ down to $T \sim -21\ ^{0}\text{C}$. It means that, for instance, at process onset temperature $T \sim 10\ ^{0}\text{C}$, one can carry out compression up to the "mild value" $= 200\text{MPa}$ withint "HP-adiabatic" process. Reaching this pressure can trigger the absorption of heat energy by the "inverse-barocaloric" elements. It can yield a rapid temperature decrease to $\sim -20\ ^{0}\text{C}$. If necessary, one can now consider further compressing up to $p \sim 300$ MPa or more.

Notable, water inside the chamber and food products does not crystallize, thanks to the mentioned eutectic minimum. Therefore, there are no destructive effects of ice crystallites inside the product.

For the descibed process, $T_D(p)$ denaturation curve is passed, as indicated in **Fig.4** by the horizontal blue arrow. This t indicates the possibility of low-temperature "mild" pressure-

assisted HPP sterilizations – supported by the inverse colossal barocaloric effect (ICBE). Such innovative processing is related to a strictly defined exposure time and reduced temperature.
The described low-temperature "HPP-adiabatic" processing supported by the inverse CBE can offer a qualitatively new opportunity also for activating and deactivating some enzymes, which currently pose great challenges for the entire population, significantly related to chemical preservatives in food over-using.

6. Conclusions: Innovative H & Socio-Economic Impacts

There are disputes about the beginning of the Industrial Revolutions. It is considered between 1700 and 1750, with a significant number of researchers indicating the latter date. The analysis of global population changes (**Fig. 3**, Sojecka and Drozd-Rzoska, 2024) definitely points to the year ~1700, the time of the first industrial applications of coal-fired steam engines/machines. This was also the beginning of the unique Enlightenment cultural period and the pan-European dissemination of the Scientific Method as a new cognitive method, happily supported by reformed political and social systems. In such unique circumstances, a growing avalanche of innovations appeared spontaneously: and were precursors to the Steam Age. Interestingly, their creators often were sons of blacksmiths, whose forges were scattered local "centers of advanced technology" in previous eras. Another important factor is exposed - the unprecedented social and economic advancement opportunities - driven by outstanding skills in science and technology only.
At the beginning of the 18th century, the innovations-driven civilization was referred to as the Industrial Revolutions epoch. In this New World, so different from previous epochs, the main factors creating progress and development were technological and scientific innovations, spontaneously and widely implemented, supported by feedback interactions with the socio-economic and political environment.
The current era of the 5th Industrial Revolution (IR) is defined as "harmonious human–machine collaborations, with a specific focus on the well-being of the multiple stakeholders" (Martin, 2023). This is a general and ambiguous definition compared to the earlier IR epochs, which referred to leading "emerging" technological aspects. The 5th Industrial Revolution is sometimes linked to artificial intelligence (AI). But isn't AI (nowadays) a continuation and consequence of the main challenge of the previous IR phase?
All the above is well visible in definitions of earlier Industrial Revolution (IR) stages (Allen, 2017):
1st IR: Steam Age
2nd IR: Electricity Age
3rd IR: Electronic Technologies & Computers Age
4th IR: Datafication and Internet Age
5th IR: New Generation of Energy Sources & Innovative Materials Age
For the the authors, this definition of the 5th IR can be better suited to support the Sustainable Society Development.
Food is the most important energy resource, directly and daily necessary for every human. Currently, losses in produced food at the processing and logistics stages can be estimated (at least) by ~30% (Marimuthu. et al., 2024). One can even expect to double this value at the final consumer use stage. An important source of losses is the quality of delivered products and their still limited durability, often extended at the cost of introducing agents unfavorable to health, as discussed above.
The HPP for food technologies described in this work can be considered the innovative material engineering, leading to better use of Earth's most important energy resource - food. It creates products with qualitatively new features that benefit humans/consumers health, and the environment due to the qualitative reduction of losses and disposals.
Mass implementation of innovative methods for food processing and preservation, where HPP holds a special and already market-proven position, can qualitatively increase the amount of available food without all the problematic environmental issues related to its production.

In the Industrial Revolutions epochs, leading innovations yielded huge market niches associated with new jobs. The authors' would like to point out this aspect for this chapter, complementing the discussion in the recent report (Sojecka and Drozd-Rzoska, 2024).
Each country has many excellent local products, which in all their richness of taste - but also nutritional - are available only at the local level due to natural time constraints. In Poland, dozens, if not hundreds, of products and dishes can be enjoyed when visiting the country's central, coastal, eastern, or mountainous parts. Thanks to HPP technology and its advanced innovative developments, these excellent products and dishes may be available in every corner of Poland and even Europe.
Another possibility is for restaurants - to use high-pressure HPP technologies directly in their kitchens, which opens up new and previously unexplored creative options for chefs. Many of the essential kitchen products could be delivered in small packages, previously subjected to HPP technology, without preservatives and with the benefits of a fresh product. It could qualitatively change the style of work and reduce losses.
The above examples indicate possible emerging market niches and "innovative" jobs that can arise within the pro-health and environmentally sustainable economy supported by "HPP food engineerig" innovations.

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References

1. Allen RC. The Industrial Revolution: A Very Short Introduction; OUP Oxford: Oxford, UK, 2017.
2. Anand SP, Sati N. Artificial preservatives and their harmful effects: Looking toward nature for safer alternatives. Int J Pharm Sci Res. 2013; 7:2496–2501. Available at: https://ijpsr.com/bft-article/artificial-preservatives-and-their-harmful-effects-looking-toward-nature-for- safer-alternatives/: Access on:10.02.2025.
3. Anstey PR. The methodological origins of Newton's queries. Stud History Philos Sci Part A. 2004; 35:247–269. DOI: 10.1016/j.shpsa.2003.11.001
4. Bald B. Food Freezing: Today and Tomorrow. Springer, Berlin, Germany, 2012.
5. Bridgeman PW. The coagulation of albumen by pressure. J Biol Chem. 1912; 19:511–512. DOI: 10.1016/s0021-9258(18)88287-4
6. Bridgeman PW. General Survey of Certain Results in the Field of High-Pressure Physics. Nobel Prize in Physics Lecture. 1946. Available at: https://www.nobelprize.org/uploads/2018/06/bridgman-lecture.pdf. Accessed on 20 June 2024.
7. Crump T. A Brief History of the Age of Steam. The Power that Drove Industrial Revolution. Robinson, London, UK, 2007.
8. Drozd-Rzoska A, Rzoska SJ, Ziolo J, Anomalous temperature behavior of nonlinear dielectric effect in supercooled nitrobenzene. Phys Rev E. 2008; 77:041501. DOI: 10.1103/PhysRevE.77.041501
9. Drozd-Rzoska A, Rzoska SJ, Starzonek S. New scaling paradigm for dynamics in glass-forming systems. Progress in Materials Science. 2023; 134:101074. DOI: 10.1016/j.pmatsci.2023.101074
10. Galor O. Population, technology, and growth: From malthusian stagnation to the demographic transition and beyond. Am. Econom. Rev. 2000; 90: 816–828. Available at: http://www.nber.org/papers/w6811. Accesson: 10/02/2025.
11. Gauch HG. Scientific Method in Brief; Cambridge. University Press: Cambridge, UK, 2012.
12. Hite BH. The effect of pressure in the preservation of milk. West Va Agric Exp Stn Bull. 1899:58. DOI: 10.1038/scientificamerican09091899-19820supp
13. Hyperbaric Company: HPP blog. High Pressure Thermal Processing (HPTP). 2014. Available at: https://www.hiperbaric.com/en/high-pressure-thermal-processing-hptp/. Accessed on 10 June 2024.
14. Hunter, N. Louis Pasteur; Raintree Publishers: Oxford, UK, 2014.

15. Koutchma T, Guo B, Patazca E, Parisi B. High pressure-high temperature sterilization: From kinetic analysis to process verification. J Food Proc Eng. 2005; 28:610–629. DOI:10.1111/j.1745-4530.2005.00043.x
16. Lehman C, Loberg S, Wilson M, Girham E. Ecology of the Anthropocene signals hope for consciously managing the planetary ecosystem. Proceedings of the National Academy of Sciences USA (PNAS). 2021; 118: e2024150118. DOI: 10.1073/pnas.2024150118
17. Lloveras P, Aznar A, Barrio M, Negrier P, Popescu C, Planes A, Mañosa L, Stern-Taulats E, Avramenko A, Mathur ND, Moya X. Colossal barocaloric effects near room temperature in plastic crystals of neopentylglycol. Nat Commun. 2019; 10:1803. DOI:10.1038/s41467-019-09730-9
18. Malthus T. An Essay on the Principle of Population (first published in 1798); in Winch D. Oxford Univ Press, Oxford, UK, 1987.
19. Marimuthu S, Saikumar A, Badwaik LS. Food losses and wastage within food supply chain: a critical review of its generation, impact, and conversion techniques. Waste Dispos Sustain Energy. 2024; 6:661–676. DOI: 10.1007/s42768-024-00200-7
20. Martin A. Industry 5.0. Introductory Guide to the 5th Industrial Revolution. Milano, Italy, 2023.
21. Rahman MS. Handbook of Food Preservation. CRC Press: Boca Raton, FL, USA. 2007.
22. Reardon S. Food preservatives linked to obesity and gut disease. Nature. 2015:1476-4687. DOI: 10.1038/nature.2015.16984
23. Reuveny R. Tacking Stock of Malthus. Modelling the collapse of historical civilization. Ann. Rev. Resource Econom. 2012; 4:303-329. DOI:10.1146/annurev-resource-110811-114537
24. Sojecka AA, Drozd-Rzoska A. Global Population: From Super-Malthus Behavior to Doomsday Criticality. Sci Rep. 2024; 14:9853. DOI: 10.1038/s41598-024-60589-3
25. Sojecka AA, Drozd-Rzoska A. Verhulst equation and the universal pattern for global population growth. axXiv. 2024; arXiv:2406.13016, https://doi.org/10.48550/arXiv.2406.13016
26. Sojecka AA, Drozd-Rzoska A, Rzoska SJ. Food preservation in the Industrial Revolution Epoch: Innovative High Pressure Processing (HPP, HPT) for the 21st-Century Sustainable Society. Foods. 2024; 13:3028. DOI: 10.3390/foods13193028
27. Sun DW. Thermal Food Processing: New Technologies and Quality Issues. CRC Press, Boca Raton, FL, USA. 2005.
28. Teixeira AA. Thermal food preservation techniques (pasteurization, sterilization, canning and blanching. In Conventional and Advanced Food Processing Technologies, Bhattacharya S (Ed.). Wiley: New York, NY, USA, 2014. DOI:10.1002/9781118406281.ch6
29. Weil DN, Wilde J. How relevant is Malthus for economic development today? Am Econ Rev. 2010; 100:378–382.
DOI: 10.1257/aer.99.2.255
30. X-PressMatter available at: https://young4softmatter.pl/. Accessed on 10.2.2025.
31. Zhang Z, Li K, Li S, et al., Thermal batteries based on inverse barocaloric effects. Sci Adv. 2023; 9:eadd0374. DOI: 10.1126/sciadv.add0374