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Global Population, Carrying Capacity, and High-Quality Foods in the Industrial Revolutions Era

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Abstract: The report discusses food availability and demands in the Anthropocene era, considering the links to global population growth and the extended concept of Cohen's Condorcet equation for carrying capacity estimations. It recalls the Super-Malthus and Verhulst-type scalings, and the recently introduced analytic relative growth rate. Particular focus is on the ongoing 5th Industrial Revolution (IR) times and its feedback interplay with the Sustainable Civilization concept. In such context, the significance of innovative food preservation technologies that can yield high-quality foods with pro-health features, simultaneously increasing food quantity and reducing adverse environmental impacts, is discussed. For this trend, high-pressure preservation and processing (HPP) plays a dominant role. The high-pressure 'cold pasteurization,' related to room-temperature processing, has already achieved a global scale. Notable are superior features, fairly correlated with social expectations of the Sustainable Society and the technological tasks of the 5th Industrial Revolution. The discussion is based on the authors' experiences in HPP-related research and application experiences. The next breakthrough can be HPP sterilization. The innovative path developing the barocaloric effect supporting concept is presented. The mass implementation of HPP sterilization can lead to milestone societal, pro-health, environmental, and economic benefits.

Keywords: global population; Industrial Revolutions; carrying capacity; food resources; Condorcet equation; innovative high pressure processing/preservation of foods.

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1. Introduction

Twelve thousand years ago, the last Ice Age - lasting ~100,000 years - terminated. Global Warming freed Eurasia and North America from the ice sheets. The mild climate and vast, uninhabited areas, along with rich food resources, yielded exceptional opportunities for hunter-gatherers. The Anthropocene era began [1]. During only 12 millennia, the global population rose from $\sim 2\, millions$ (10 000 BCE) to $\sim 8.23\, billions$ in June 2025 [2-4]. This population success was significantly due to the millennial access to 'infinite' food resources for an ever-increasing population.

Food is a vital source of energy and health maintenance. Providing food for oneself and one's family is a challenge for every person, every day. The question arises about the impact of this essential resource on global population changes in the Anthropocene, up to the present days. The preliminary response is the target of this report.

The answer may seem extremely puzzling due to the vast and multidimensional scope of changes and the heterogeneity of issues involved in the mentioned period. However, such data can be hidden in the global population growth scaling patterns, significantly shaped by access to food resources.

For millennia, the exponential pattern of global population growth has been dominant. It is also known as geometric growth, in which the growth rate is proportional to the current population size or, alternatively, to the same relative percentage in each subsequent time period [2-4]. Recently, explicit evidence for such a trend has been shown, also in the period particularly significant for modern times: from the mid-medieval to the onset of the Enlightenment epoch [2]. However, since ~1700, the qualitatively new 'boosted' scaling of global population growth emerged [2-4]:

$$P(t) = P_0 exp(rt) = P_0 exp\left(\frac{t}{\tau}\right) \Rightarrow P(t) = P_0 exp\left(\frac{b't}{T_C - t}\right) = P_0 exp(bT^{-1}) \quad (1)$$

$$\sim 1100 - 1720 \ ('Malthus') \Rightarrow \sim 1720 - 2024 \ (\text{'constrained-criticality'})$$

where $P(t)$ denotes the global population, t is the time since the Anthropocene onset, 12 000 BCE; $b' = const$, $T_C \approx 2216$ is the extrapolated, singular 'Dooms-year', $T = (T_C - t)/t$ is the relative distance from T_C; $r = const$ is for the Malthus population growth rate parameter, and $\tau = 1/r$ means the relaxation time. The latter was introduced in ref. [2].

Sojecka and Drozd-Rzoska obtained the above result by introducing the Super-Malthus scaling equation, supported by distortion-sensitive analysis [2-4]. Notably, simple exponential behavior given on the left side of Equation (1) is common in nature: from microbiology [5-8] and biology [9-11] to dynamics of physical processes [12-14], chemical reactions [15,16], nuclear reactions, and nuclear fission reactors [17-19]. For the latter, the term' chain reaction' is used to describe the increasing impact of neutrons in subsequent steps [20]. However, over the last two centuries, the global human population has increased significantly stronger, as indicated on the right side of Equation (1).

Providing food for a growing population has been a concern and challenge for millennia [21,22]. Over the past two centuries, the global population has grown at an unprecedented rate. However, instead of food shortages, there has been an (apparent ?) surplus of food on the shelves of hypermarkets. This extraordinary situation can be explained by technological and societal changes during the Industrial Revolution (IR) era [23-26]. It is driven by the development and mass implementation of groundbreaking technological innovations in feedback interplay with socio-economic 'innovations' that support and organize technological development. The progress in IR times is so rapid that the world can change beyond personal recognition during one man's lifetime. An example can be qualitative civilizational changes during the reigns of two symbolic persons: Emperor Franz Josef I of Austria (1848–1916) and Queen Victoria I of the United Kingdom (1837–1901) [27].

Food productivity increased due to the implementation of innovative technologies in agriculture, as well as advancements in food processing and logistics. The rising amount and assortment influenced demands. But such a process is 'elastic' only to a certain level. Finally, a relative decrease in food prices and lower expenditure are necessary. The funds released to consumers in this way could be spent on other goods and services, stimulating broader economic development. These processes also led to a qualitative decline in agricultural employment. In highly developed countries, only about 10% of all employees work in agriculture nowadays [28-30]. A further significant decrease can be expected, for example, due to the use of Artificial Intelligence (AI) for fieldwork. For instance, the future can be associated with autonomous agricultural machines that cultivate fields and are controlled with the support of Artificial Intelligence. Such a picture of the future is shown, for example, in Christopher Nolan's phenomenal film *'Interstellar'* (2014).

Specific to the Industrial Revolution's time is the 'feedback mechanism' between science, technology, and socioeconomic issues. In these innovation-driven times, developing methods to ensure food safety and extend shelf life with minimal impact on the products' native forms is essential.

Of particular importance are the works of Louis Pasteur (1863), who recognized spontaneously developing parasitic microorganisms as a crucial hazardous factor to human health and product safety and quality [31]. He solved the challenge by discovering 'thermal pasteurization', i.e., heating the product to $\sim 85\,^oC$, for a few minutes [32], essentially reducing the number of parasitic microorganisms In the second half of the 19th century, chemical preservation additives also began to be widely implemented for ensuring long-term microbiological safety [33]. During that time, the foundations of refrigeration technology were also developed, making the mass-scale implementation of refrigerators and coolers possible since the first half of the 20th century [34]. The pioneering works of Pierre Curie and Marie Curie-Skłodowska led to the use of ionic irradiation as a physical factor destructive for microorganisms,…. [35-37]. These IR-times developed food preservation technologies, resulting in an extraordinary abundance and diversity of foodstuffs on supermarket shelves. To achieve this 'plenteousness' of food products, essential was also the logistics chain extension, often on a global scale, which additionally motivated the search for effective food preservation methods.

However, in recent decades, the dark side of IR-developed innovative food preservation methods has been revealed. The accumulation of parasitic side effects has even led to dangerous and harmful global-scale pandemics related to obesity, numerous allergies, and certain types of cancer [38-44].

This problem is closely associated with the rich offer of so-called ultra-processed foods, often chemically modified, containing a set of chemical preservatives and other supplementary artificial additives to make them taste appealing and addictive. These include numerous carbonated drinks, sweet or salty packaged snacks, ice cream, chocolate, sweets (confectionery), mass-produced bread and rolls, margarine and spreads, cookies (biscuits), numerous energy cakes and bars, energy drinks, milk drinks, 'fruit' yogurts and 'fruit' drinks, cocoa drinks, meat, and chicken extracts and prepared sauces, infant formula, milk substitutes and other products for children, 'quasi-healthy' and 'slimming' products such as powdered or 'fortified' meals and meal substitutes, as well as many ready-to-heat products, including pre-prepared cakes, pasta dishes and pizza, poultry and fish 'nuggets' and 'sticks', sausages, burgers, hot dogs and other reconstituted meat products, and powdered and packaged 'instant' soups, dumplings and desserts. It is an offer of products at surprisingly low prices, which may immediately raise suspicions of a connection with the so-called 'junk food' [45].

Studies have shown that ultra-processed foods increase the risk of obesity by 55%, sleep disorders by 41%, anxiety disorders by 53%, type 2 diabetes by 40%, and depression and premature death by 20%. It also presents strong evidence of a 50% increase in the risk of death from cardiovascular disease. It is estimated that approximately 70% of all food in the United States is ultra-processed. Its consumption is responsible for ~6% in Brazil or Chile but around 14% in the US or England of total health problems [45,46].

Then, it is not surprising that food waste reaches $> 40\%$ (!) globally [47,48].

Minimizing these losses is the simplest and most environmentally friendly way to increase the global food supply. Avoiding the catastrophic impacts of 'junk food' and the side effects of food preservatives is also essential for the health and well-being of modern societies. These benefits can introduce precisely incalculable but evidently huge contributions to the World Economy.

In the current era of the 5th Industrial Revolution, it is not only essential to ensure the quantity and variety of foods and support logistics requirements. Offering food that avoids the mentioned harmful 'side effects' has become essential for modern, sustainable societies. It also includes respect for the Environment and the Circular Economy, thanks to obtaining greater food resources without increasing the carbon footprint and reducing the disposal of 'unnecessary foods'.

The basic response to these challenges and civilizational needs is the concept of 'High-Quality Foods' defined as '*food produced using specific agricultural production methods, in particular in terms of food safety, traceability, authenticity, labeling, nutritional and health values, as well as respect for the environment and animal welfare, the sustainability of agricultural production and distinctive qualities, in particular quality and taste*' [49-51].

The fundamental problem is the implementation of these expectations in practice. It can be achieved by developing new-generation food preservation concepts that explore different scientific bases than the 'standard' methods (recalled above), which have been developed since the 19th century and are still dominant.

Below, high-pressure preservation and processing (HPP) for foods are presented. It is also called 'cold pasteurization' or 'radicalization'. It has already passed the market test and seems to meet all expectations as the next-generation technology for high-quality foods [7,8,52-63]. Original solutions for the next-generation HPP sterilization are also shown. The preliminary part of the report presents the conceptual background for the above issues through a new discussion on food needs and requirements in the Anthropocene. It focuses on the carrying capacity concept as its key metric, including some new interpretations, particularly the Condorcet equation, which links it to population growth.

2. Materials and Methods

Regarding global population data, the report recalls the findings of recent studies by authors regarding global population growth since the onset of the Anthropocene, but in the given case, focusing on available, particularly food, and more generally, the system carrying capacity as the synthetic metric including also other resources, related to energy, or ecological issues, for instance.

For the population data, the report recalls the recent set of population data developed by the authors and given in the Supplementary Information of ref. [3]. This set was prepared by collecting population data from different sources and then subjected to numerical filtering using the Savitzky–Golay principle. Notably, the discussion in the given report includes years 2023 and 2024, which are absent in the references. [2-4]. The report recalls the analytic reasoning that extends the standard Malthus and Verhulst models towards the so-called Super-Malthus and Verhulst-type models [2-4]. It includes the distortions-sensitive and derivative-based analysis, recently introduced in refs. [2,3]. Results of refs. [2-4], are in the given report extended towards the significance of food resources and the more general carrying capacity concept.

Recalling expectations and demands of the ongoing 5th Industrial Revolution era, new demands for food with health-promoting properties, requirements of a sustainable society, and circular economy are further discussed. They are exemplified by high-pressure preservation and processing (HPP) technology, which uniquely fulfils emerging expectations.

3. Results

3.1. Global population, carrying capacity, and Condorcet criterion

The 17th century was a time when the Scientific Method was shaping [64,65], laying the conceptual foundation for the emerging Industrial Revolution era. It emphasizes the importance of critically analyzing observations, formulating hypotheses, conducting experimental verifications, analyzing output data using analytic equations, and drawing critical conclusions. Isaac Newton's great works significantly contributed to their universal recognition [65,66]. He used it to discover impressive universal laws of nature expressed by functional scaling equations. An example can be the Laws of Dynamics and the Law of Gravity in physics. The latter links seemingly distant phenomena such as an apple falling from a tree and movements of planets or comets 'in the sky'. Isaac Newton introduced differential analysis to show in-depth model assumptions and derive final scaling equations [65,66].

In 1798, Thomas Malthus recalled Isaak Newton grand legacy inspiration when introducing the first analytic model describing human populations growth ($P(t)$) [67]):

$$\frac{dP(t)}{dt} = rP(t) \;\Rightarrow\; G_P(t) = \frac{1}{P(t)}\frac{dP(t)}{dt} = \frac{dlnP(t)}{dt} = r \tag{2}$$

$$P(t) = P_0 exp(rt) \tag{3}$$

where $r = const$ is the Malthus growth rate parameter, t is the time since the Anthropocene onset and the prefactor P_0 is related to $t = 0$. Note the introduction of the relaxation time $\tau = 1/r$ in refs [2], as noted in Equation (1).

The left side part of Equation (2) and Equation (3) recalls the basic Malthus report [67]. The right side part of Equation (3) explores the concept of the relative growth rate (RGR) G_P, recently discussed in refs. [3,4].

Malthus also stressed the meaning of available food resources amount $F(t)$ for the population growth, introduced via a supplementary equation that assumes [67]:

$$F(t) = A + Bt \tag{4}$$

Considering the interplay of Equations (3) and (4) heuristically, Malthus concluded [67]: 'The population increases in a geometrical ratio, and the subsistence rises only linearly, which finally leads to '*times of vice and misery*'. It leads to the famous Malthus Trap (Catastrophe), when the quantity of food becomes increasingly insufficient for the growing population. Malthus advised population constraints or extra rise in subsistence (food) to escape the trap disaster [67]. Unfortunately, the simplistic escape concept, like the conquest of other countries, has often been implemented [68-70].

A few decades later, Pierre François Verhulst (1838) introduced a model in which food requirements are explicitly included in the scaling equations [71]:

$$\frac{dP(t)}{dt} = rP - sP^2 \;\Rightarrow\; G_P = \frac{1}{P(t)}\frac{dP(t)}{dt} = r - sP = r \times \left(\frac{K-P(t)}{K}\right) \tag{5}$$

$$P(t) = \frac{1}{1+C exp(-rt)} \tag{6}$$

where the parameter $C = 1/P_0 - s$; s is the Verhulst parameter showing the impact of necessary resources, originally food, and the carrying capacity: $K = s/r$.

The left side parts of Equation (5) and (6) are related to the original Verhulst model formulation [71]. The right side part side shows the re-formulation exploring the RGR parameter, as proposed recently [3]. It includes the carrying capacity factor (K), originally introduced by Pearl and Reed [72,73], as a metric of available foods and other necessary resources, from energy to those related to ecological capacities. Following Equation (5), the carrying capacity parameter K can be interpreted as the maximal population in a given system, which is allowed for all available 'resources', mentioned above [3].

Equation (6) presents the Verhulst model equation, which describes population growth, derived from Equation (5).

The comparison of Equations (2) and (5) indicates that one can consider the apparent growth rate: $r'(r,t) = r(1 - P(t)/K)$. It shows that for the Verhulst model behavior (i) $P(t)$ first follows the Malthus pattern (Equations (2) and (3)), (ii) next the continuous decrease of the apparent growth rate r' occurs, and finally (iii) the stationary phase related to $r'(r,t)\to 0$ and $P(t)\to K$ occurs. The appearance of the apparent Malthus and stationary 'phases' led to the name ' bimodal behavior' for the Verhulst equation [74,75].

Note that the behavior discussed above applies to systems with a constant amount of resources (food) despite population growth. It means that resources, including food, are renewable, up to reaching a possible level in the given system. For systems with non-renewable resources, their amount decreases as the population rises. In such a case $P(t)$ reaches maximum and subsequently the population diminishes, down to the 'death phase'.

There are numerous population growth models [74-85], critically discussed in refs. [2,3]. In this report, we focus on the Malthus and Verhulst models, which remain a significant reference [86-94] in population studies and directly address the impact of food resources. Their extension yields a unique possibility to the distortions-sensitive analysis, detecting local $P(t)$ changes, recently introduced by the authors [2-4].

Figure 1 presents global population evolutions since the Anthropocene onset. It is based on data developed by the authors [2,3] recently. The plot explores a semi-log scale, for which the basic Malthus behavior is visualized via a linear dependence, namely: $lnP(t) = lnP_0 + rt = lnP_0 + (1/\tau)t$, and $log_{10}P(t) \approx 0.434 lnP(t)$. Note the explicit indication of subsequent historical periods.

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It reveals the simple behavior of Malthus over the enormous period of the first 9 millennia in the Anthropocene. Such behavior is manifested via linear changes for the applied scale.
For such pattern, global population has risen following a simple 'geometric' growth, as described by the Malthus model (Equations (2) and (3)). It also means no food restrictions over this period, following the Malthus and Verhulst models discussion above.
The Malthusian growth accelerates approximately $4.6\times$, on passing the crossover correlated with the transition from the Early to the Late Neolithic epoch. It is manifested by a change in the slope of the lines in Figure 1. Notably, it occurred soon after the Doggerland flood and the formation of the North Sea [95]. It was accompanied by a rise in sea levels, a further retreat of ice sheet remnants, and a warming of the climate.
Figure 1 illustrates that this behavior persists even beyond the Bronze Age, encompassing the periods of the first great civilizations in ancient Egypt, the Middle East, the Mediterranean, China, and India.

Significant irregularities in $P(t)$ changes appear in Antiquity times. For the authors, this should not be linked to food shortages. This was the time of the formation of great empires, of which the Roman Empire was the most famous. Almost 1/3 of the global population lived there at the time, for $\sim 500\ years$, from Julius Caesar's times to the fall of the Western Empire, the global population [6,97]. It may suggest reaching those mentioned above 'stationary phase' in the Verhulst model scaling, related to the limited availability of food. For the authors, the dominant cause was different and probably unique in history. The Empire's economy was primarily based on exploring slaves as a 'human energy source', on an enormous scale. For example, in the giant silver mines in the La Tinto region (present-day Spain), where tens of thousands of slaves worked.

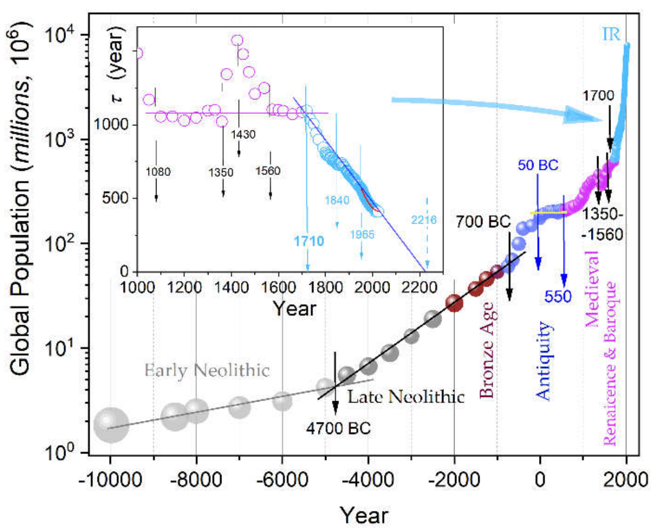

Figure 1. The global population has undergone significant changes since the onset of the Anthropocene. The size of points reflects the error estimations. Different colors are for subsequent cultural periods: grey is for Neolithic (in light grey, and late in dark grey), brown is for the Bronze Age, darker blue is for Antiquity times, violet is for the subsequent period Medieval to Enlightenment onset, and the light blue is for modern times (Industrial Revolutions: IR). Characteristic dates are indicated. Note the semi-log scale for visualizing the basic Malthus equation, which illustrates a linear dependence. The inset shows the changes in relaxation time, determined using Super-Malthus Eq. (7); for this presentation, the basic Malthus evolution is expressed via the horizontal line. The plot was prepared using the author's data [2,3].

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Their average survival time was only $\sim 3\,months$ [97,98]. The Empire's weakening and 'barbarian' neighbors civilizational progress effectively limited the 'supply' of this 'raw material', so cruelly exploited. The global population began to grow again after the fall of the Roman Empire.

Starting with the advent of the Medieval times, permanent population growth occurred, as visible in Figure 1. For portraying the visible nonlinear pattern, the Super-Malthus (S-M) relation with time-dependent growth rate $r(t)$ was proposed in ref. [2]. It is given in the left-hand part of the relation below:

$$P(t) = P_0 exp(r(t) \times t) = P_0 exp\left(\frac{t}{\tau(t)}\right) \Rightarrow \tau(t) = t \times ln\left(\frac{P_0}{P(t)}\right) \quad (7)$$

Notable that for $r(t) = r = const$ the S-M relation simplifies to the basic Malthus Equation (3). The next unique feature of this S-M relation is the time-dependent relaxation time, $\tau(t) = 1/r(t)$. This magnitude, commonly used for testing dynamics in physics [12-14], enables a direct estimation of the time required for 50% changes from the population at a given moment, namely: $t_{1/2} = \tau \times ln2$. Nevertheless, direct parameterization of $P(t)$ changes via this S-M Equation (7) (left part) can be puzzling, since it requires in prior knowledge of $r(t)$ or $\tau(t)$ evolutions.

However, one can apply the above S-M calculate temporal changes in the relaxation, as shown in the right-hand part of Equation (7). The evolution of this magnitude is shown in the inset in Figure 1. For such a plot the horizontal line is related to the basic Malthus Equation (3), with $r(t) = r = const$, or $\tau(t) = \tau = const$. Such behavior has been visible since the Middle Ages (~1100) until the onset of the Enlightenment period (~1700), with a distortion coinciding with the impact of the Black Death pandemic [2-4]. For the authors, the extension of this 'distortion' into the 16th century can be related to the enormous population catastrophe in South America resulting from the Spanish conquest.

Since the year ~1710 till nowadays, emerges the linear trend described via $\tau(t) = a - bt$, as evidenced in the inset in Figure 1. Substituting it into the S-M Equation (7) (left part) yields the unique crossover to the constrained critical scaling equation, as given in Equation (1) (right part). It has been derived and extensively discussed in refs. [2,3].

How did food resources and their availability influence population development during this period?

Generally, such a discussion over a long period can be puzzling due to significant changes in civilization, cultural diversity, wars, and conquests, ... However, the Malthus-type trend for the first period, as indicated in the inset of Figure 1 (1100–1719), suggests no essential global food availability problem, following the above discussion regarding the Malthus and Verhulst models. Of course, numerous famines and local population catastrophes are known in this period, but their global impact appeared relatively weak.

The measure of food availability can be the standardized income of a well-defined but relatively large group of employees, optimally in a country where such distortive factors as wars, conquest, and changes in borders are negligible. Such conditions can be considered in England, for which almost constant earnings of building workers from ~ 1200 to ~ 1840 is evidenced Only later does a systematic increase in earnings appear [99-101]. For the authors, this can suggest a large 'rent of benefits' for industrialists in the 1st Industrial Revolution era since the enormous increase in productivity had a negligible impact on wages, the relative size of which had remained unchanged since the Middle Ages.

The Verhulst model approach might seem beyond the global population growth shown in Figure 1. However, one may consider a Verhulst-type equation associated with a set of (r, s)associated with crossing subsequent barriers, occurring well before approaching the stationary phase. The effective portrayal of global population data since the onset of the Anthropocene was considered by Lehman et al. [102], who linked the crossover of subsequent eco- and bio-barriers. The problems and challenges of such an approach were further discussed in ref. [3]. Worth recalling here is the report by Cohen [79], who suggested that the fundamental Verhulst model dependence (left

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side of Equation 5) can yield a link between population growth and carrying capacity (K, metric of available resources), he named the Condorcet equation [79]:

$$\frac{dK(t)}{dt} = c(t)\frac{dP(t)}{dt} = \left(\frac{L}{P(t)}\right)\frac{dP(t)}{dt} \Rightarrow \quad (8a)$$

$$\Rightarrow \frac{dK(t)}{dt} = L\frac{dlnP(t)}{dt} = LG_P(P,t) = L'exp(bP) \quad (8b)$$

where the coefficient 'c' is the basic Condorcet metric; $L' = La$, $b = const$.

Equation (8a) is for the basic Condorcet equation formulation introduced by Cohen [79]. It includes the suggested by Cohen 'dilution' of the carrying capacity metric by the rising population via assumption $c(t) = L/P(t)$, where $L = const$ [79]. Cohen also suggested that the parameter L can be a measure of the total available resources.

Equation (8b) is for the new development of the Condorcet equation, considered in this report. It explores the general functional link $dP/P = dlnP$ and the recent finding of the analytic per capita global growth rate (RGR) G_P, including its expoennetial parameterization [2]. Equation (8b) opens the route for the direct estimation of carrying capacity evolution via an integrating exploration of Equation (8b).

Recalling the above dependenceies, starting from $c = 1$, the parameter decreases in each subsequent time t, i.e., $c < 1$. Finally, it reaches $c = 0$, yielding the Verhulst model's stationary state. For $c < 0$ carrying capacity, food resources, and consequently population diminishes. When $c > 1$, each additional person in the population introduces additional values to the system carrying capacity above their own needs, thus yielding conditions to accelerate population growth, even a boost to infinity. Here, Cohen [79] attempted to establish a connection to von Foerster et al. Doomsday equation that suggests an infinite global population in 2026 (!) [74]. When publishing in 1960 it offered an impressing simple scaling equation of $P(t)$ changes since 400 BCE [76]. However, this scaling failed when more past data became available and as the approach to the hypothetical Doomsday in 2026 [2,3,75].

Cohen in ref. [79] offered an inspiring picture, although heuristic, expressed via Equation (8a), and by introducing Condorcet parameter c, which can change in subsequent stages of population growth.

A further development of problem offers Equation (8b), as discussed above. To continuous this issue one can recall the recent authors' report [3] which develop the discussion on the per capita global population rate (RGR), initiated in ref. [102], by introducing its analytic: $G_P(t,P) = (1/P)(dP/dt)$ for the population growth was shown [3,4]. Next the analysis directly resulted from the Verhulst model reference derivative Equation (5), explored via the plot $G_P(t,P)$ vs. P, revealed significant inconsistencies between model expectations and 'empirical' global population data [3,4]. It led to showing the prevalence of portrayal via the next, 'empowered' Super Malthus relation [2]:

$$P(t) = P_0 exp(t/\tau)^{\beta} \quad (9)$$

In refs. [2,3] the distortions-sensitive, derivative-based analysis directly applied to discrete 'empirical P(t) data, for testing subtle local changes was introduced. In the most recent ref. [3] it is shown that it is directly related to testing changes of RGR $G_P(t,P)$ factor.

It enabled insight into a subtle 'bending up' discrepancy from the general trend visible in the inset in Figure 1, after 1965. It has been shown that in Industrial Revolutions era, the following behavior took place: from ~1710 till ~1965 − 1968: $\beta > 1$, and later, till nowadays: $\beta < 1$. At the indicated crossover the transition from $\beta \approx 1.5$ to still lasting domain described by $\beta \approx 0.85$ took place. [2,4]. This unique crossover even stronger manifests for $G_P(P)$ dependence, linking it to the global population $P(t) = 3\,bilions$ [3,4]. Notable that the empowered exponential behavior is relatively common for complex physical systems, where the exponent $\beta > 1$ is related to the 'amplified' development, associated with the 'ordered nucleation centers' and 'internal energy' creation. The

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stretched-exponential case $\beta < 1$ is related to multichannel energy dissipation and is observed as a dominantly disordered system [2].

Considering these, we can further reformulate the basic Cohen's Condorcet implementing RGR factor for the empowered exponential Equation (9):

$$\frac{dK(t)}{dt} = L\frac{dP(t)/P(t)}{dt} = L\frac{dlnP(t)}{dt} = LG_P(t) = \frac{L\beta}{\tau}\left(\frac{t}{\tau}\right)^{\beta-1} \quad (10)$$

Notably, the right-hand part of the above relation correlates with the so-called hazard rate of the Weibull distribution for complex dynamics [2].

The above discussion facilitates an examination of the planetary carrying capacity necessary for the development of the global population based on the values of exponent β, which have been in effect since the beginning of the Anthropocene [2]. Over the millennia until ~ 1700, the dominant trend is described by the exponent $\beta = 1$. This means that both population and resources increase 'geometrically', according to the simplest scaling relation of the Malthus model (Equations (2) and (3)). This may indicate that, from the Neolithic Times to the onset of the Enlightenment, the most crucial resource remained food resources, and on a global average, each new member of the global population was able to introduce as many new resources as needed into the system. The 'disruption' in $P(t)$ changes in Antiquity times is commented in more detailed in ref. [2].

Since the onset of the Industrial Revolution, the increased population growth, following the Condorcet relation, is associated with an increased carrying capacity, where parameters L & $\beta > 1$. In this unique period, subsequent groundbreaking technological innovations solve cumulated problems that could hinder further development. The scientific and technological breakthroughs opened up areas of exploitation of previously unexploited raw materials, significantly increasing global carrying capacity. An example is the 1st Industrial Revolution period, the Steam Age. It was first driven by wood as an energy source until large areas of Europe were deforested. The exploitation of hard coal solved the problem. When it proved insufficient for new and necessary applications, the use of oil and electricity as an energy source gained importance from the mid-19th century onwards. The latter again increased the demand for coal as the most essential raw material for generating electricity. Between the years 1965-1968, the scaling of the global population changes has changed associated with the qualitative change of the Condorcet – related parameters $, L, \beta < 1$. This may represent a spontaneous reaction of the complex global population system to the global-scale constraints associated with approaching total carrying capacity limits. During this period, the world became a 'global village', and immediate contact between any two places on Earth became possible. There appeared to be a tangible limitation of available space for everyone, and the consequences of massively violated ecological constraints led to the already ongoing ecological catastrophe, including the great catastrophe of Global Warming. The answer to this great challenge, perhaps the greatest in human history, seems to be the tasks of the 5th Industrial Revolution.

Note Appendix A1, where issues related to subsequent Industrial Revolution periods are briefly concluded.

The 5th Industrial Revolution is currently underway [23,24]. It is most often defined descriptively as a period of incorporating concepts of (*i*) sustainability, (*ii*) human-centeredness, and (*iii*) concern for the environment…. matched with artificial intelligence (AI) development. This is a descriptive definition, different from the earlier stages of IR, where dominant breakthrough technologies and/or scientific innovations were explicitly addressed. However, the term sustainability seems to include issues (*ii*) and (*iii*). Maybe the term 5th Industrial Revolution – sustainable development via new generation energy sources, material engineering, and AI implementation would better agree with the subsequent IR stages' names.

Although the successive stages of the Industrial Revolution era opened up new 'raw material' resources or 'carrying capacity' [3,79] without recalling the dominant food resource in previous eras, it remained critically important, and its growth was also created by technological progress. This involves the implementation of new technologies in agriculture, directly producing food, as well as

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new food preservation technologies that ensure the health and safety of products and address the significant challenge of increasingly complex logistics with a dramatically growing population. This was related to the discovery and mass implementation of new food preservation and processing methods. Of particular importance here were the great discoveries of Louis Pasteur [31], who identified the microbiological source of health hazards in food or beverages related to the presence of parasitic bacteria, fungi, or yeast and indicated a way to reduce the hazard to a safe level by heating to a temperature of $\sim 85\,^{o}C$ [32]. Then came various chemical preservatives added to products [33], cooling and freezing [34], and radiation [35,36]. Therefore, the response to the great challenge of gigantic population growth was characteristic of the New Brave World [103] of the Industrial Revolution's times: the mass implementation of innovative technologies. Nowadays, the food problem may seem to be solved globally. The supermarket shelves show previously unknown assortment at prices accessible to the typical consumer. But this great success also has a dark side. New methods of food preservation and processing have been identified as a contributing factor to the pandemic on a global scale. New food preservation and processing methods can also be considered a significant cause of food waste, reaching $> 40\%$ globally [49-51]. Reducing it is the simplest and most environmentally beneficial way to significantly increase available food resources and carrying capacity.

For the Industrial Revolutions' era, the fundamental response to the following significant challenges is the implementation of breakthrough technologies. [23-28]. Below, we present the current state of the art and emerging possibilities for solving the food quality challenge and creating high-quality foods with explicit pro-health properties and pro-environment features. This is high-pressure preservation/processing (HPP), which nowadays enables 'cold' pressure-assisted pasteurization, and for emerging innovations [5,7,8,52-63], sterilization is also used [7,8].

3.2. High Pressure Preservation / Processing of food

Already in the Middle Pleistocene, pre-humans began to prepare food using fire [104,105]. This improved digestive properties but also reduced the impact of harmful microorganisms or worms. It, therefore, had a pro-health effect. It also extended durability, i.e., the time of consumption. These are the basic goals of all food preservation methods up to today. In subsequent times, increasingly complex methods appeared. This was probably fumigation and then pre-smoking [104,105]. Then, methods using natural environmental conditions, such as low temperatures (freezing) or wind and low humidity (pre-freeze-drying), are probably employed [106]. In the Anthropocene, more complex methods of food preservation appeared, mainly related to the processing of its form. For milk, it was sour milk, yogurts, butter, and buttermilk or cheeses, for which records appear as early as $\sim 7000\, BCE$ [106-108]. Then, it was pickling, marinating, using salt and honey (sugar), ... Increasingly complex recipes were also developed for the long-term use of meat in the form of hams or sausages [108]. It is also, in fact, the result of implementing 'innovative technologies' developed by generations of trial-error approaches and the extraordinary talents of generations of cooks. This massive set of products shapes today's cuisine, which can be included in the category of 'high-quality foods' without exception, as long as natural products are used, as in the old days.

The Industrial Revolution began only 2 centuries ago. During that time, the global population has increased from $\sim 600\, million$ to $\sim 8.3\, billion$. It was also a time of previously unknown growth in agricultural productivity, resulting from the implementation of broadly understood technological, biotechnological, and socio-economic innovations. On a global scale, a significant surplus of food appeared, and in the majority of countries, stores with previously unknown abundance and variety of products. Numerous massive urban centers have emerged in response to the implementation of new technologies. For this '*New Brave World*', the supply of food, in adequate quantities and at least acceptable quality, has become a particularly significant task. In addition to the direct increase in agricultural production, it has become essential to extend the product's shelf life and safety in increasingly complex logistics conditions. There has also been an increasing range of new and highly processed food products. There has been a need for a new generation of food preservation methods

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that ensure the health safety of the product with minimal impact on its 'native' form. They are thermal pasteurization and sterilization, a wide range of chemical preservatives, cooling, and freezing [32-38]. These methods, whose references date back to the 19th century, are important factors in the current 'abundance' of food. However, these methods have become increasingly apparent over the past few decades that their mass implementation has led to new and dangerous problems on a global scale, namely [38-46]:

- ✓ Thermal pasteurization ensures microbiological safety, but at the same time, it often reduces the nutritional, vitamin, and bioactive properties of the products
- ✓ Chemical additives appeared to be directly related to pandemics of obesity, some types of cancer, allergies, skin problems, and intestinal problem
- ✓ Cooling and freezing are excellent preservation methods; however, the use of technological solutions can contribute to global warming.
- ✓ irradiation can effectively extend shelf life and improve safety by killing pathogens and insects. However, there are problems related to nutrient degradation and changes in taste and texture.

Therefore, there are expectations for the implementation of food preservation methods based on new, previously unused physical bases in applications. Examples include technologies based on (*i*) ultrasound, using micro-scale cavitation, (*ii*) pulse electric field (PEF) impacts, where the perforation of cell membranes is important, (*iii*) fast deep cooling, surface-related, (*iv*) 'cold' plasma surface action, (*v*) ultraviolet surface action, ….

The resume of innovative methods for food preservation can be found in numerous review reports [7, 50-52, 61, 63].

However, none of these methods are characterized by the particularly desirable 'universality' - i.e., the effect on both liquid and solid products in their entire volume, the definitive avoidance of chemical preservatives (including salt and sugar), or the uncompromised preservation of the fresh product's qualities over an extended time period. Such a set of preferred features, and, even a significantly larger one, is only achieved by the action of high pressure on food products. Furthermore, it is an innovative method that has already undergone a successful global market test.

High-pressure preservation (HPP) technology, implemented for over 3 decades, offers a positive impact on the product without the above negative impacts, namely [7,8,52-63]:

- shelf-life extension to even up to 180 days!
- high microbiological safety
- fresh product taste, flavour, and texture
- fresh product vitamin composition
- bioactive and nutritional properties maintenance
- no chemical preservatives
- activation/deactivation of selected enzymes
- salt- and sugar limited/free products
- for 'fluid' and 'solid foods
- application to packed food, reducing the risk of secondary contamination
- environment-friendly technology: (*i*) limited requirements for electric energy- (*ii*) practical lack of waste during processing, (*iii*) reduction of 'expired products' amount, and then disposal problems
- 'clean label', innovative technology

The HPP technology implemented on the market consists of the impact of high-pressure $P = 300 - 600MPa$ for 3 to 15 minutes, generally at room temperature. Figure 2 shows HPP facility with the pressure chamber working volume $V = 50L$ operating at arbitrary pressure up to $P = 600MPa$.

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Figure 2. HPP processor with the large volume pressure chamber ($V = 50L$), max pressure $P = 600MPa$. The central part of the system shows the pressure chamber, and on the right side, there is a mechanism for closing and opening the chamber, as well as for product replacement. It is part of the HPP pilot line in the X-PressMatter Lab of IHPP PAS (Warsaw, Poland). Designed & constructed by UnipressEquipment (IHPP PAS, Poland).

It shows the main pressure chamber body and the automated system for closing and opening the chamber, as well as loading the product. The pressure is supplied from an external high-pressure large-volume pump. The automated system is controlled from a panel in an adjacent, safety-isolated room.

Figure 3 shows the conceptual basis of HPP technology, showing an elliptical curve in the pressure-temperature ($P - T$) plane describing the limits of protein denaturation. The first point on this curve was observed by Louis Pasteur (1863), which gave rise to the technology of thermal pasteurization of food. It consists of reaching the denaturation limit ('clumping') of protein structures, which occurs at a temperature of $\sim 85\ ^oC$. Such thermal treatment of the product leads to the denaturation of proteins in the parasitic organisms present, from worms to microorganisms. Today, the denaturation curve is associated with a 5-decade (10^{-5}) reduction in the number of microorganisms [32] when presented on a logarithmic scale leads to the jargon term 5-log reduction.

The next point in the above curve can be linked to Percy W. Bridgeman compressing of the egg albumin under room temperature [109,110]. Smeller and Heremans plotted the denaturation via modelling using the Clausius-Clapeyron equation, implemented for the given process [111-116]:

$$\frac{dT_D}{dP} = T_D \frac{\Delta V}{L} = \frac{\Delta V}{\Delta S} \tag{11}$$

where T_D is for the denaturation temperature at the given pressure and $L, \Delta V, \Delta S$ is for the latent heat, volume change and entropy change when passing $T_D(P)$ curve.

In ref. [116] the elliptic curve was obtained by assuming pressure-dependent evolution of $T_D(P)$, $\Delta V(P)$, $\Delta S(P)$. It is worth recalling here that the Clausius-Clapeyron equation was originally introduced for the melting-freezing discontinuous transition, i.e., $T_m(P)$. Thus, Smeller and Heremans [115,116] essentially considered denaturation as a specific discontinuous phase transition. Notably, HPP technology, which is essentially the pressure counterpart of pasteurization, does not act effectively on viruses. Significant impact appears for pressures above 1GPa, generally destructive for a product and also hazardous and non-convenient in applications [117].

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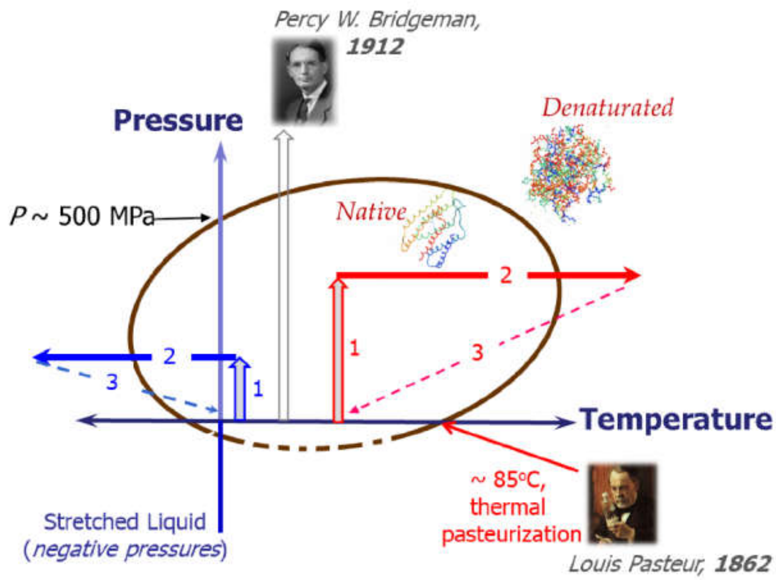

Figure 3. The denaturation/pasteurization curve in the pressure-temperature ($P-T$) plane. The forms of the native and denatured protein is shown. Links to discoveries by Louis Pasteur (thermal pasteurization under atmospheric pressure) and Percy W. Bridgeman for the first denaturation under isothermal compressing (white egg) are indicated. The plot also contains paths showing innovative Colossal Barocaloric Effect (CBE) supported solutions: (**1**) compressing, (**2**) CBE-based temperature changes, (**3**) decompression, and return to ambient conditions. The red color is related to the CBE support with $dT_m/dP > 0$, where 'heat' is released on compressing, and the blue one is for the CBE-support with $dT_m/dP < 0$, where 'cool' is released on compressing; T_m is for the discontinuous phase transition, melting or order-disorder type, being the base of the Barocaloric Effect phenomenon.

The vertical arrows in Figure 3 shows standard paths related to HPP technology. Most often it is related to near-room temperature compressing, but generally operations in the range from $\sim 4\ ^oC$ to $\sim 50\ ^oC$ are considered. Notable that the thermal processing, recalled the thermal pasteurization, is related exclusively to passing the denaturation curve under atmospheric pressure.

The effect of pressure on food and unwanted microorganisms is more complex. At room temperature, compressing to $300-400 MPa$ usually causes rupture of cell membranes surrounding microorganisms and/or organelles inside, associated with relatively weak intra-structural interactions. This is the most commonly used mechanism in HPP technology. It leads to a 3-5 decades (3-5 log) reduction of parasitic microorganisms while maintaining all the special advantages of this technology listed above [7,52]. An example is the thermal pasteurization of milk, which creates a product with a different taste than native milk and reduced nutritional value. 'Cold' pressure pasteurization at room temperature, with compressing to $\sim 400 MPa$ creates pasteurized milk with the taste and all the advantages of 'native' milk. The compression of milk to $\sim 600 MPa$, associated with achieving the denaturation curve and subsequent decompression, leads to a deeper reduction in the number of microorganisms, a change in taste, and a reduction in bio-nutritional values but a significantly lesser extent than in the case of thermal treatment at atmospheric pressure [7,52].

Thermal pasteurization, which is commonly used today, significantly reduces but does not eliminate unwanted microorganisms. A pasteurized product, therefore, has a naturally limited shelf life related to microbiological safety.

For many food products, technological sterilization is used [32], which consists of heating the product for the shortest possible time - optimally a few/a dozen seconds - to temperatures in the range of $120-150\ ^oC$. This is not full sterilization, as it requires much higher temperatures and times and is used, for example, in medicine. However, technological sterilization of food allows for extending the product's shelf life, which is safe for health to a year or more. It is also possible and

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used to 'support' this shelf life by minimizing the addition of chemical preservatives or the appropriate pH of the product [32].

Notable is the Appendix A2, further describing the unique phenomenon of the Colossal Barocaloric Effect.

3.3. Compression – related sterilization

Sterilization with the support of high-pressure compression is a problematic issue for HPP processors on a pilot or industrial scale (see Figure 2). Commercially available is a solution where the food product after heating to $\sim 90\,^{o}C$ is placed in a thermally insulated container (adiabatic conditions), which is then moved to a high-pressure chamber where compression to $P \sim 600 MPa$ takes place. This is adiabatic compression, leading to a change in the internal energy of the product and, as a consequence, a temperature increase of $\sim 30\,^{0}C$. The product under pressure reaches an effective temperature of $\sim 120\,^{o}C$ and after $10-15\,minutes$ decompression occurs, which lowers its temperature again to $\sim 90\,^{o}C$ and at this temperature the product is removed from the chamber [118].

For such a technological concept, significantly deeper 'technological sterilization' should be expected than with the standard thermal procedure described above. However, for the 'pressure assisted sterilization' technology described above, the product is at an elevated temperature for a very long time, above the denaturation limit determined by the $T_D(P)$ curve. Together with the compression and decompression time in the high-pressure chamber, this can be even several dozen minutes. Therefore, a significant reduction in nutritional value and bioactivity is likely to occur. This is no longer mild HPP technology, such as 'cold, pressure' pasteurization, with the aforementioned avoided features.

Recently, the authors of this paper have presented two innovative concepts that mitigate or even eliminate the disadvantages mentioned above, offering hope for pressure-assisted sterilization with 'mild-impact' features. It involves utilizing the so-called Colossal Barocaloric Effect (CBE) [119,120], recently discovered in certain materials from the Soft Matter family, particularly the Plastic Crystals. A strongly discontinuous phase transition is described by the Clausius-Clapeyron relation (Equation (10)), characterized by a colossal latent heat value. In adiabatic conditions (thermally insulated container), in the standard situation of the system where $dT_m/dP > 0$, this means the release of heat into the interior of the adiabatic container where the $T_m(P)$ line is exceeded due to compression. As a result, there is a substantial increase in temperature in the container where the element containing the material exhibiting the CBE phenomenon is placed. Upon decompression, there is an immediate corresponding decrease in temperature. This process is illustrated in Figure 3, which features two red arrows indicating the subsequent stages of innovative CBE-assisted compression-related sterilization. There are also Soft Matter systems with the strongly discontinuous phase transition where compressing decreases the transition temperature, i.e., they are related to $dT_m/dP < 0$ condition: this is the base of the inverse barocaloric effect [121]. For such systems, compression causes the absorption of heat energy from the environment under adiabatic conditions, which means a decrease in temperature. Decompression of course means the release of heat to the environment, when passing the $T_m(P)$ line of discontinuous phase transitions, and an increase in its temperature. Such a 'reversed CBE' process creates a unique possibility of crossing the $T_D(P)$ denaturation line when the temperature is reduced, and therefore a new type of 'truly cold' pasteurization or sterilization of food. The stages of this process are shown by two perpendicular blue arrows in Figure 3.

The authors stress the 'very cold' reversed CBE supported HPP pasteurization and sterilization (arrows on blue, Figure 3) for the first time indicated in the given report.

The feasibility analysis of CBE-assisted HPP solutions is given in refs. [7,8]. Notable is that they offer a precisely controlled process, solely by the applied pressure value, with a time-dependent temperature (high or low) that is process-significant. Moreover, it can be implemented in existing HPP industrial-scale processors. For product operations, a significant fact is that the product

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introduced to the chamber can be at near–room temperature, and it remains the same when the product is removed.

4. Conclusions

12 thousand years ago, the Anthropocene began. Thanks to increasingly favorable climatic conditions, homo sapiens gained extraordinary development opportunities. People exhibit exceptional inclinations towards strong and multidimensional mutual interactions. Consequently, as with any non-homogeneous complex system characterized in this manner, one can expect the spontaneous emergence of 'heterogenic structures,' which in this case can only mean organized clusters of people. Recent discoveries at Göbekli Tepe and Çatalhöyük (present-day Turkey) have revealed surprisingly large and highly developed quasi-urban centers that can be dated back to ~ 9,000 BCE.

For every person, both in the Neolithic era and today, the most crucial goal of each subsequent day is to provide food for themselves and their family. The answer to the question of how these needs were shaped in the Anthropocene, the 'era' of humans, is puzzling and ambiguous due to variable geographical, climatic, and cultural conditions… However, one may expect that such a message can be indirectly deduced from an appropriate scaling description of global population changes.

This issue is discussed in the first part of this paper from the perspective of Malthus [67], Verhulst [71], the super-Malthusian extension modeling [2,3], and the concept of carrying capacity introduced by Pearl and Reed [72,73]. Attention is drawn to its use via the 'Condorcet' relation concept, proposed by Cohen (1995) [79], which links carrying capacity with global population changes. In this report, the extension of this relation is proposed, utilizing the authors' recent work results, which enable the direct estimation of the Condorcet coefficient metric with the support of the Super-Malthusian description [2-4]. The presented analysis indicates that from the beginning of the Anthropocene to the end of the 17th century, a simple geometric growth of the global population dominated, although with a variable time constant (r, τ) from the beginning of the Anthropocene to the end of the 17th century, a simple geometric growth of the global population dominated, although with a variable time constant (different periods). Disturbances appeared in ancient times or during the Black Death era. They are commented on in refs. [2-4] and above in the given report.

The analysis using the 'Condorcet model' suggests that the resources (food) needed for the Malthus-type growth increase at the same rate as the population. We would like to stress new issues related to this topic associated with Equations (8b), (10) and the related discussion.

Two centuries ago, an extraordinary acceleration in global population growth began. Despite this boost, no Malthusian Catastrophe or a generic global food shortage occurred. On the contrary, a kind of food surplus occurred. Moreover, food prices began to fall, and employment in agriculture was reduced even below 10% of the total number of employees in many countries.

The last 200 years have been a time of a new era of Industrial Revolutions. For the first time in history, massively implemented breakthrough inventions and technologies, supported by modern science based on the conceptual and philosophical basis of the Scientific Method, have solved civilizational challenges. This would not be possible without feedback interactions with the subsequently implemented 'socio-economic innovations' changing societies and managers.

At that time, the concept of carrying capacity ceased to be dominated by food, an energy source directly addressed to every person. Additionally, raw materials and energy sources became increasingly important for the 'technology' of the subsequent Industrial Revolution periods. There was also a massive impact of a resource rarely considered in earlier eras: shortages of raw materials, energy, or pollution, which have permanently devastated the planet, its climate, and the biosphere. The discussion in recent reports [2-4,7-8], briefly recalled above, shows that the complex system of the global population has been spontaneously sensing and reacting to this existential problem since the mid-1960s.

However, the current abundance of the most important resource for humans – food, might be illusory. It is mainly based on food preservation methods that have a devastating, even pandemic,

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effect on society. There is also an exceptionally unfavorable connection with popular industrial, highly processed food, referred to as 'junk food.'

However, it is possible to address these civilizational challenges within the broader context of the Industrial Revolution era – specifically, the development and implementation of Innovative Technologies.

This paper presents the basics of High Pressure Preservation/Processing (HPP) technology. The currently existing version of High Pressure 'Cold' Pasteurization has already passed the market validation test. It is a market for HPP products worth ~600 million USD, based on several hundred industrial-scale HPP processors and the industry offering solutions in this area [122]. The characteristics of products after HPP processing reveal a surprising alignment of customer and producer needs, namely the quality of a fresh product without preservatives, with extended durability. Inherent waste reduction is important for the environment, as is minimizing disposal costs. There is also an option to extend this technology, HPP – pressure-assisted sterilization, with CBE concept support, as discussed above and in the references [7,8]. It seems possible, therefore, to offer food in a scheme perfectly in keeping with the goals of a 'sustainable society' and even to fulfil the great desire of the father of medicine, Hippocrates of Kos (460-375 BCE) [123]: '*Let food be thy medicine and medicine be thy food*'.

Appendix A

A1. Industrial Revolutions resume

At the beginning of the 18th century began. In this New Brave New World, so different from previous epochs, the main factors driving progress and development were technological and scientific innovations, which were implemented spontaneously and widely. Notable is the feedback interaction with the socio-economic and political environment, which, in fact, leads to innovative progress in these areas as well.

The current era of the 5th Industrial Revolution (IR) is often defined as times of '*harmonious human–machine collaborations, with a specific focus on the well-being of the multiple stakeholders*' [23]. This is a general and also ambiguous definition compared to the earlier IR epochs, which explicitly recalled 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 4th IR times?

All the above is well visible in definitions of earlier Industrial Revolution (IR) stages, which recalling ref. [8,24] can be concluded as follows:

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, associated with AI-supported implementations.

Features and targets of the 5th Industrial Revolution significantly support the concept of a Sustainable Society, a Circular Economy, and an in-depth respect for the Natural Environment, which appear to be the goals and desires of societies around the World.

However, expectations and hopes related to the 5th Industrial Revolution times could not come true due to the destructive global disturbances caused by the madness of annexations, wars, and absurd dominations created by some countries.

A2. Comments on the Colossal Barocaloric Effect

The barocaloric effect attracted particular interest in 2019, following research in neo-pentylglycol (NPG), associated with passing by compressing and decompressing the discontinuous phase transition from the soft matter plastic crystal phase to the solid crystal phase [119-121]

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This process is described by the Clausius–Clapeyron model relation, derived in the 19th century (Equation (11)). It shows that the metric describing the 'thermal efficiency' of a discontinuous phase transition is the change in entropy. In NPG, for a compression-induced phase transition, this change can range from 300 JK/kg to even 500 JK/kg, depending on the pressure at which this process occurs. This represents an extremely large value, referred to as the Colossal Barocaloric Effect (CBE), which has not been previously recorded. This discovery coincided with a growing awareness that current refrigeration technology – commonly used in cold stores, refrigerators, air conditioners, and heat pumps – needed to be replaced by next-generation technology.

There are two factors involved. Firstly, the 'classic' and common technology is based on adiabatic decompression of the circulating fluid, with its continuous forced circulation. However, this process is effective only for some fluids, such as the commonly used hydrofluorocarbons (HFCs). For the most popular and most effective HF134A, the entropy jump value during adiabatic decompression, the process metric, is $\Delta S \sim 300 J/Kkg$ [120]. However, materials from the HFC family have a significant drawback at present – they are extremely harmful to Global Warming. It is estimated that ½ kg of the mentioned agent is as detrimental as the emission from a Diesel engine heavy-lorry for 6 months. For this reason, in many countries, less devastating replacement fluids have been used for over a decade [120]. Unfortunately, they are not associated with such high DS values, which forces increased circulation and, therefore, higher energy consumption. It is also worth noting that the aforementioned ecological substitute fluids are still not neutral in terms of Global Warming but are less harmful. Another issue worth mentioning is that, according to current estimates, coolers, refrigerators, air conditioners, and heat pumps collectively account for over 25% of global energy consumption [120]. It is also significant that the fluids used in the applications above are very volatile, so in the event of a failure, they easily escape into the atmosphere.

Therefore, there was a need to develop a qualitatively new generation of the aforementioned devices, and the aforementioned barocaloric effect is considered to be the most promising phenomenon, namely:

- Recently, in some materials from the Soft Matter family, super-Colossal Barocaloric Effect with the metric $\Delta S \sim 1000\ J/Kkg$ has been obtained [124,125]
- The process is based on cheap, widely available, and environmentally neutral
- In applications based on CBE, there is no possibility of 'escape' to the atmosphere
- Power supply is necessary only for a short compression time, and consequently, the demand for this energy is from 3x to even 10x smaller than for 'standard' currently common devices.

For innovative CBE-based facilities, the image of a relatively simple process emerges, with potentially excellent features in applications: environmental neutrality, including Global Warming, reliance on cheap and 'ecological' materials constituting the process medium, and a considerable reduction in the electrical energy required for the process. Together, this is an ideal that meets the expectations of the Sustainable Society epoch.

However, a fundamental problem persists that has hindered the practical implementation of the CBE phenomenon: the lack of a realistic and scalable concept for heat/cold exchange between the interior of the pressure chamber and its environment.

The innovative solution has been presented by the authors of this work in ref. [7]. It applies the unique features of the CBE phenomenon in a way that renders the aforementioned limitation irrelevant. Moreover, as shown in Figure 3, thanks to the support of CBE, a previously unattainable application of high-pressure technology for high-pressure sterilization has become attainable. It is worth emphasizing here – without increasing the amount of electrical energy required for processing and utilizing existing HPP processors.

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