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Sustainable Innovations in Steam Generation for Food Sterilization Processes: A Review

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Abstract: The current review aimed to identify the recent developments in sustainable steam generation and its applications in food sterilization. Fuel, gas, and coal boilers are the traditional methods for producing steam. Recently, innovative methods of steam generation include electrodes, solar, natural gas, nano-electric, biogas, biomethane boilers, and sustainable steam generation through heat pump (heat pump is an energy-efficient device that transfers heat from one location to another, typically using electricity). The calories in the 100% saturated steam are higher than steam saturation by 95%. The solar parabolic dish system includes biaxial tracking mechanism that ensures increased efficiency and useful energy production due to the increased radiation. Electrode boilers generate steam using electric current, offering simplicity, reliability, and efficiency. Nano-electric boiler boasts a high-power density, minimal carbon emissions, great physical stability, and high-power factor and electric conversion efficiency. The efficiency of natural gas, biogas and biomethane boilers ranges from 94% to 95% with an economizer. The air-source heat pump boiler provides stable system output with high energy efficiency, generating steam at temperatures exceeding 120°C. Water content below 0.01% mass is necessary for steam purity to prevent overheating. The thermal treatment of canned food should reduce bacteria levels by 12 log cycles in low-acid foods to meet safety limits. The container contains 1 spores for Clostridium botulinum for thermal treatment (sterilization) at 121°C. The process involves sterilizing materials at 121°C for 15 min, killing most heat-resistant microorganisms. The innovative steam sterilization methods aim to advance industrial uses that fulfill net-zero emissions and sustainable development goals (SDG).

Keywords: Boiler, Biogas, Biomethane, Electrodes, Solar concentrator, Superheated steam.

Introduction

Recently, heating, cleaning, distillation, and other important industries utilize the steam (Baetens *et al*., 2019). A boiler produces steam by converting the chemical energy of fuel into heat energy, which is then transferred to the water through conduction, convection, and radiation. Boilers with fire tubes and water tubes are the two primary varieties utilized in industrial applications (Kumar *et al*., 2022). Boilers can operate using many types of fuels, including fossil fuels, biomass, natural gas, and gas oil. Bioliquid flames in pilot furnaces are clearer and have higher gas temperatures. (Park *et al*., 2020). Boilers are categorized into several types: industrial, agricultural, and domestic. Their heating methods include direct or indirect heating, oil, coal, wood, gas, and electricity. Electric boilers have lower soot and environmental issues (Kim & Kim, 2021). The generation of solar steam requires the use of solar thermal energy, which can be achieved through parabolic trough collectors (Pal & Ravi; Kumar, 2023). Moreover, Steam can be generated by several methods, such as solar power towers, linear Fresnel reflectors, and parabolic dish systems (Hamidinasab *et al*., 2023; Ouyang *et al*., 2023; Vengadesan *et al*., 2023). These techniques require vacuum or expensive high optical concentrations that cause heated surfaces and hot bulk liquids to lose heat. Therefore, new solar energy receptors have appeared, such as volumetric solar receptors or nano-fluids, to reduce energy losses (Mohammed *et al*., 2023). Al-Hilphy *et al*. (2022) stated that steam can be generated using solar energy and used to extract oils from aromatic plants. The researchers explained that the application of solar energy achieves sustainable energy goals.

Electrolytic steam produced can be easily implemented in the industry. Finally, it could save up to 1.84 × 10^8 kg CO_2/year in greenhouse gas emissions (Sanaye *et al*., 2020). The Scheduled maintenance work helps the boiler operate at its peak efficiency, and boiler efficiency can increase to 90.98% (Madejski & Żymełka, 2020). One of the advantages of the electric boiler is its excellent thermal efficiency, pollution-free operation, and rapid load regulation when the load demand changes (Teng *et al*., 2019). Li *et al*. (2021) depicted that the regenerative electric boiler provided with an energy storage device used to produce steam with lower energy.

Green technologies represent a critical approach to addressing environmental challenges while fostering a sustainable future. Green technologies are becoming increasingly interested in ohmic heating. It is an advanced thermal process that generates heat through alternating current, due to its potential for efficient heating (Shao *et al*., 2020). Ohmic heating is a low-energy technique where heat is internally distributed throughout the mixture (salt water) (Abdulstar *et al*., 2020). An alternative to traditional heat treatment is ohmic heating (D’cruz *et al*., 2023; Nemati et al., 2021). Ohmic heating is one of the electrothermal technologies used to disrupt microbial and enzymatic activity (Al-Hilphy *et al*., 2023). Electrode boilers, used in industrial, and manufacturing facilities. Electrode boilers generate hot water and steam using the flow of electric current. They offer advantages such as simplicity, reliability, efficiency, automation, and ease of maintenance (Manni *et al*., 2022). Thermal sterilization of cans is a method of food preservation for long time. Most of the world's population benefit greatly from its widespread use and large contribution to nutritional well-being (Teixeira, 2019). Numerous food companies employ heat treatment because it is an affordable method of processing and preservation (Pursito *et al*., 2020). This technique is crucial because it can improve food quality, prolong shelf life, and boost food availability, safety, and cost .(Dash *et al*., 2022;Huang *et al*., 2016). This method uses a specific amount of heat to preserve food and prevent the growth of undesirable microbes (Dash *et al*., 2022). Canned food is a mixture of liquid and solids, heat treatment is used to sterilize it when it contains water and additives

(Rodríguez- Ramos *et al*., 2021). According to Ziaiifar & Nedamani (2023), thermal methods in the food business are used to prepare ready-to-eat food and remove harmful microbes for consumer safety. The purpose of the current review is to identify recent advancements in steam generation and its use in sterilizing canned food processes .

Steam generation

The three primary processes in the steam generation process include preheating, which raises the water's temperature to the boiling point, and continually adding heat to convert the water into steam. Finally, superheating, which heats steam beyond boiling temperature. Steam is defined as water vapor, which is the gas phase of water (Fang *et al*., 2023). Steam is a convenient way to transfer heat from fuel to desired areas. This is because it contains both sensible and latent heat emitted while maintaining a steady temperature (Mallick, 2023). The term "wet steam" refers to steam that has droplets of water in it. This means that one kilogram of steam has a liquid portion that symbolizes water. Dairy and food companies are the main sources of these. The degree of saturation (vapor quality) determines how many water droplets are presented. If the vapor is reported to have a 95% saturation degree, it implies that 5% of it is composed of water droplets created by the liquid. When performing heating activities, this issue needs to be considered since one kilogram of 95% saturated steam has fewer calories accessible than one kg of 100% saturated steam. This is because that's the difference occurs in that 0.05 kg (Sree & Deepika, 2023).

Steam boilers

A boiler, also known as a steam generator, is a device that produces steam from water by burning fuel to release thermal energy. The thermal energy is transmitted to the water by radiation, convection, and conduction (Rao, 2023). Boilers produce steam at low to medium pressure (7-2000 kPa), including boilers with two primary varieties for industrial use: water-tube and fire-tube. They can be classified into industrial, agricultural, and domestic applications, and can be heated directly or indirectly. Other types include petroleum, briquettes, wood, gas, and electric (Kim & Kim, 2021). Boilers are categorized based on multiple parameters. While heat is produced by all boilers, the classification is only for convenience's sake. In Fig. (1) the classification of boilers is shown (Rao, 2023).

Fire tube boilers

The boiler tubes in a fire tube boiler are filled with hot combustion gases (Fig. 2a). The water that will be heated surrounds the tubes. The tube system is within a huge pressure vessel filled with steam and water (Tognoli *et al*., 2022). Boilers using fire tubes that have pressure outputs between 103.4 and 2413 kPa, produce high-quality steam to power from 10 to 1100 kW. They require larger water content and require a larger vessel space. With numerous tubes and large heat transfer area, they increase boiler efficiency. Flue gases are moved through pipes to the stack exit during the burning of fuel in a lined furnace. The boiler uses single-pass, four-bath, baffles, economizers, and tube surface area to efficiently redirect hot gases, minimizing heat loss in the chimney (Woodruff *et al*., 2017).

Water tube boilers

Combustion gases are fed through tubes filled with water in water tube boilers (Fig. 2b), which are threaded on both the feed and vapor sides (Sathish *et al*., 2021). At higher pressures in power plants, a safety boiler, also known as a water tube boiler, is used to reduce the risk of accidents. It connects the steam and clay

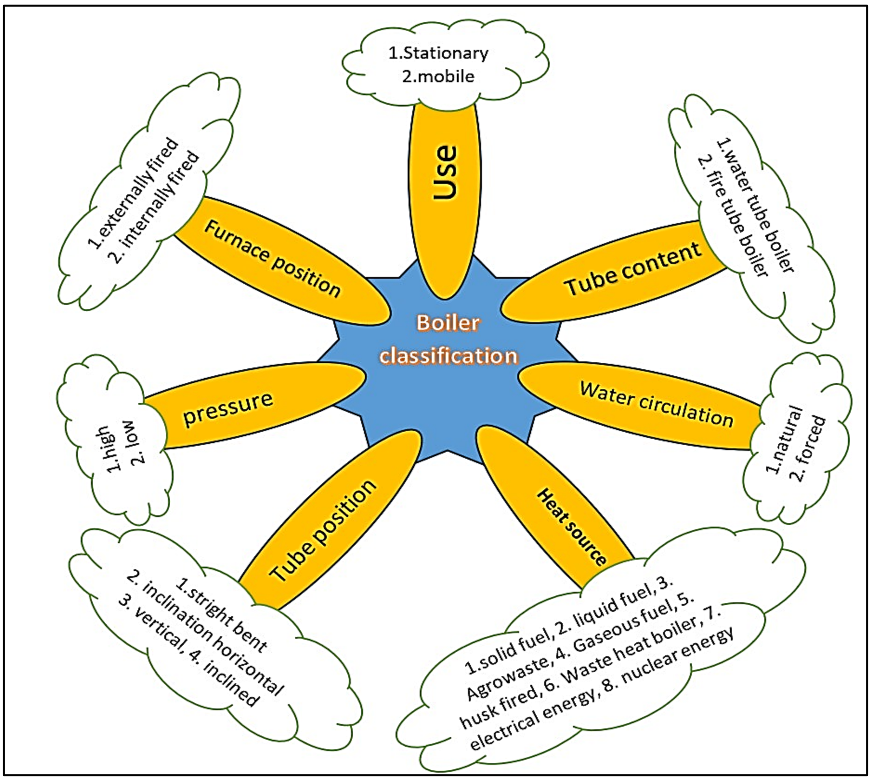

Fig. (1): Boilers classification

drums, producing steam between 4500-61000 kg/h. Although their water content is small, they can still overheat (Munda *et al*., 2018). The main drawback of water tube boilers is the deterioration of the seals and their exposure to attack by the chemicals used in boiler treatment. There may be a leak between the parts that are sealed together by the gaskets.(Sree & Deepika, 2023). Stress corrosion cracking is one of the most crucial elements affecting boiler performance limitations (Subramanian *et al*., 2022). When using the boiler, unexpected cracks occur in the water pipe wall, making it susceptible to harsh weather (Kim & Kim, 2021).

Solar steam generation

The sun is the only renewable energy source located at the center of the solar system. Solar energy is emitted as electromagnetic radiation continuously and constantly throughout the year. This energy is released at a rate of, 1367 W/m^2 as a solar flux (Widén & Munkhammar, 2019). Solar energy is a sustainable and abundant energy source. It can be utilized in various processes such as solar thermal conversion, artificial photosynthesis, and photovoltaics (Wang *et al*., 2022a). The solar parabolic dish system, and solar collector system, utilize various types of concentrators to generate steam with solar energy. This system includes biaxial tracking mechanism which ensures increased efficiency and useful energy production due to the increased radiation (Kumar *et al*., 2022; Malik *et al*., 2022). The second system utilizes a cavity receiver, pressure system, solar tracker, modular dish, solar receiver (helical coil), and measuring devices for steam generation. The pressure works on the steam flow through the pipe, and the solar collector maintains the pressure and flow rate. The aperture is positioned at the traditional dish's pivot point (Swanepoel *et al*., 2021). The temperature steam of this type of boiler reach to 365 °C (Lorfing *et al*., 2021).

Electrode and Natural gas steam generators

Electrode and natural gas steam generators saving 1.84 × 10^8 kg CO_2/year (Sanaye *et al*., 2020). Recently, there has been a rise in the interest in green technology due to ohmic heating or electrical conduction heating. Through the use of an alternating current, samples are heated through the novel and cutting-edge technology known as ohmic heating (Shao *et al*., 2020).

The samples' electrical conductivity and intensity of the electric field are two significant factors affecting the ohmic heating process's effectiveness (Hashemi & Roohi, 2019). The input voltage and the strength of the electric field are related. Chemical additives during ohmic heating lead to an increase in the conductivity of food samples. Ionic species-containing salts and acids are among these additions. Nowadays, the food industry utilizes ohmic heating for various processes such as blanching, evaporation, drying, fermentation, extraction, pasteurization, and sterilization (Al-Hilphy & Khaneghah, 2023; Gavahian *et al*., 2020; Schottroff *et al*., 2020; Moreno *et al*., 2016).

Electrode water heating boilers generate steam using electric current, offering simplicity, reliability, and efficiency. However, defects include symmetrical electrode arrangement, reduced device and electrode manufacturability (Manni *et al*., 2022). Giladi (2019) developed an electric water-heating boiler with electrodes, insulated vessel, and separation circuit for safe and efficient heating. It features a timer, thermostat, hot water exit hole, and water entry hole. Kim & Kim (2021) designed a boiler with electrodes that heated electrolyzed water to a boiling point by means of electrodes. Heated electrolyzed transferred to a heat exchanger by means of a pump to heat water and use it in industry. The temperature is controlled using electronic sensors.

Hybrid steam generators are systems that can alternate between using electricity and natural gas to produce steam (Hybrid steam generators are systems that combine multiple technologies to produce steam more efficiently and sustainably. These generators typically integrate different types of boilers, such as electric, gas, or biomass boilers, allowing for flexible operation and optimized energy use). There are different sets of possibilities for the hybrid boiler (Toropov, 2023). Hybrid boilers come in four varieties. The first is an electric air heater parallel to the firebox, and the second is the presence of electrical resistance elements in the boiler to heat water. The third is the presence of an electric flow heater to heat the water flowing into the boiler. Finally, placing an electrical element in the degassed in the boiler feed water. These types use electric elements to heat water within the boiler, ensuring efficient operation and maintaining proper water temperature. Another system was proposed (Verschuur ,2019).

For natural gas steam generation, boilers can be classified into boilers with fire and water tubes. In the first instance, steam is frequently produced by combustion boilers for use in industry and power generation. Water in the boiler tubes is heated by the combustion gasses that are present outside the tubes. In contrast, the latter scenario sees the water flow out of the tubes while the combustion gasses remain inside (Dorotić *et al*., 2020). Accumulator is necessary to place a steam collector because of the variation between the process's steam supply and demand.

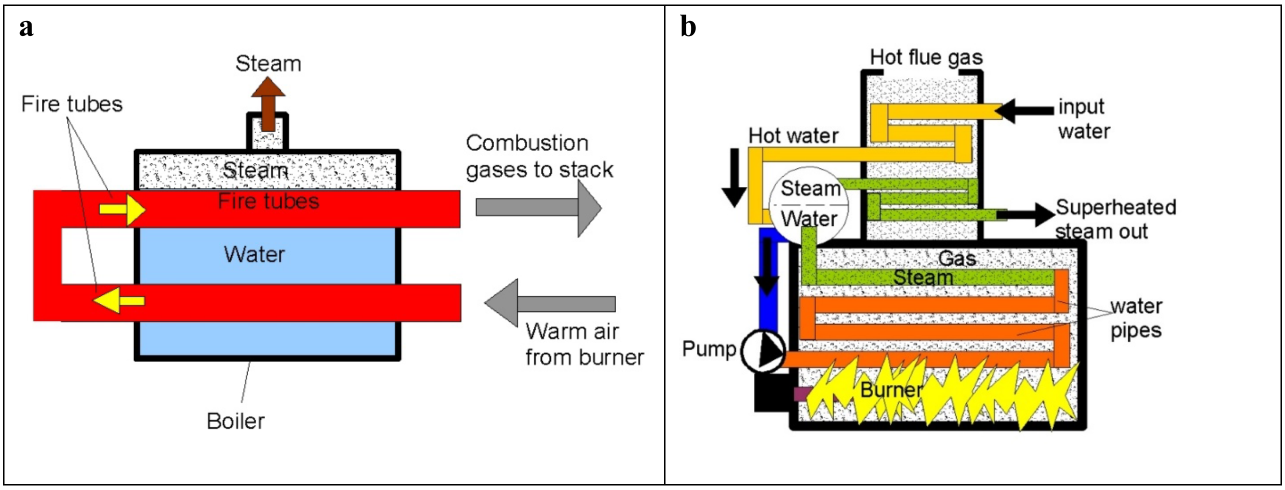

Fig. (2): Fire tube boiler (a) and water tube boiler (b) (Tognoli *et al.*, 2022).

The vapor collector charges when production exceeds demand, raising the internal pressure while also causing some vapour to condense. The internal pressure decreases, and some of the water evaporates when the steam collector is released due to insufficient production of steam. Hence, the vapour collector's pressure determines the storage loading level (Hechelmann *et al*., 2020).

The nanomembrane electric boiler is a new type of electric heating system. This novel nano electric boiler uses a whole new approach to heating. Moreover, chemical energy is not used to produce heat. Conversely, heat is produced immediately from the electrical energy. With the help of computers and a sophisticated control system, this revolutionary nano-electric boiler can be fully automated. It boasts a high-power density, minimal carbon emissions, great physical stability, and high-power factor and electric conversion efficiency (Shen *et al*., 2014).

Biogas and Biomethane Boiler

Natural gas, biogas, and biomethane boilers have part load efficiencies ranging from 94% to 95% when equipped with an economizer. Biomethane or biogas can be substituted, but requires a specific burner. Biogas is produced at the production site, while biomethane is fed into the public gas grid through upgrading processes. Additional steps can be taken to meet local feed-in requirements. Biomethane, if biogas is unavailable, provides a convenient alternative for natural gas users to reduce CO_2 emissions, regardless of the biomethane's production location (Hechelmann *et al*., 2020).

New and Sustainable Steam Generation by heat pump

Heat pumps are attracting interest from both researchers and industry because of their economic, environmental, and energy benefits compared to traditional heating and cooling systems, contributing to decarbonization efforts. Among various types, air source heat pumps for water heating can draw heat from the renewable resource of air and transfer it to water, thereby raising its temperature. The absorption system can generate steam at temperatures ranging from 100 to 115 °C; however, there have been limited studies conducted on this cycle (Yan *et al*., 2021). The utilization of heat pumps can not only reclaim waste heat from industrial processes and enhance energy efficiency but also decrease reliance on fossil fuels, leading to a reduction in CO_2 emissions. Essentially, by improving the technically achievable performance levels, the potential for implementing high-temperature heat pumps can be significantly expanded (Zühlsdorf *et al*., 2019). Denmark plans to lead the way in achieving carbon neutrality by 2025, while the United Kingdom and Japan have set their sights on reaching to reduce greenhouse gas emissions by 2050 (Jiang *et al*., 2022).

China has gradually restricted the use of coal-fired boilers as a result of the Paris Climate Change Agreement in an effort to manage air pollution and lower CO_2 emissions. High-temperature steam is produced by an air-source heat pump boiler, which takes thermal energy from the surrounding air. Overcoming limitations of current alternatives like gas, electric, biomass, and solar boilers. The air-source heat pump boiler provides stable system output with high energy efficiency, generating steam at temperatures exceeding 120 °C, despite ambient temperature variations. The air-source heat pump boiler has demonstrated significant advantages over other boilers in terms of technical and economic analysis and carbon trading. Heat pump powered by air In China, steam generation is a practical and environmentally friendly substitute for coal-fired boilers (Yan & Wang, 2020).

Sustainable boilers fuel

Boilers using oil and gas emit pollutants like carbon dioxide and experience gas shortages, particularly in winter when residential heating demand is high (Hannun & Razzaq, 2022). The biomass boiler offers numerous economic, social, and environmental advantages (Verma & Singh, 2015). Biomass fuel contains high levels of pollutants, high alkaline materials, volatile components, and low ash melting points. This makes it prone to producing slag and coke from combustion (Björnsson *et al*., 2021). Geothermal systems and heat boilers provide energy savings and are environmentally friendly, but their applications are limited (Petlickaitė *et al*., 2022; Nuryawan *et al*., 2021; Vusić *et al*., 2021). Heat pump technology efficiently recovers low-grade heat, upgrading thermal energy, with a higher coefficient of over 100% compared to fuel boilers. In addition, absorbing heat from the surroundings or waste sources (Souček *et al*., 2019; Woo *et al*., 2021). The study revealed that the energy of biofuel boilers is lower compared to fossil fuel boilers (Stanytsina *et al*., 2022). Table 1. Illustrates a summary of sustainable steam generation and its uses.

Boiler Efficiency

The efficiency of the boiler is the ratio of the thermal energy supplied by the steam divided by the energy input to the boiler. The efficiency of the new boiler ranges from 85% to 95% depending on the type of fuel and the characteristics of the boiler. Boiler losses can be attributed to hot flue gas, hot surfaces, and discharge, with the most critical gas being hot flue gas. Usually, the boiler's flue gas temperatures range from 133.6 °C to154.7 °C

Table (1): Summary of sustainable steam generation and its uses.

Sustainable steam generation	The uses	References
interfacial Solar steam generation	Interfacial Solar steam generation offers fast, energy-efficient, and fast-responsive sterilization, superior to conventional methods. The key solar absorber is biochar, and a proof-of-concept system with a 10.5 L autoclave operates at low cost and minimal carbon footprint.	(Li *et al*., 2018)
High-temperature solar steam generation	A photothermal membrane, composed of polystyrene foam, bubble wrap, and coated cloth. It generates high-temperature steam (around 90 °C) for efficient sterilization of microbes like *Staphylococcus. aureus*, *Escherichia coli*, and *Geobacillus*. *Stearothermophilus*, and clean water.	(Noureen *et al*., 2023)
2steam generation by self-floating electrically driven interfacial evaporator	The evaporator achieved a 90% electrical-to-steam. The energy conversion efficiency is higher at a 10 kW/m^2 heating power density and a 20 s thermal response through localized heating of wicked water. The interfacial evaporation design modifies the ratio of vapor outflow evaporation surface area. This is to achieve high temperature and efficiency at low heating power densities. The system, which incorporates an interfacial evaporator within a sanitizer, offers faster steam temperature rise. Also, superior steam sterilization performance compared to commercial bulk heating methods.	(Xu *et al*., 2019)
Superheated steam	Superheated steam aids in enhancing product quality through functional protein denaturation, proper starch gelatinization, nutrient loss reduction, and improved physicochemical properties of foodstuffs.	(Fang *et al*., 2023)
Biogas and Biomethane Boiler	A boiler using natural gas, biogas, and biomethane with an economizer has an efficiency of 94% to 95%.	(Hechelmann *et al*., 2020)
induction-heated autoclave	The induction heating mechanism is advantageous for compact and efficient autoclaves, reducing total sterilization time by 40-80% compared to conventional autoclaves.	(Kameda *et al*., 2014)

(Madejski & Żymełka, 2020). Efficiency measures how well fuel chemical energy is converted into heat in steam, with boiler efficiency and fuel utilization being crucial selection criteria. It ranges from 72-83% and operates according to fundamental thermodynamic principles (Chao *et al*., 2017).

Energy Associated with Steam and Steam purity

Steam is a powerful heating agent due to its high heat per kg. At atmospheric pressure, 1 kg of vapor releases 2252.4 kJ when condensed. When energy is added, water heats up, causing it to evaporate. Dry vapor, lighter than air, rises and condenses on cool objects. To heat 1 liter of water to 100 ºC, the water must absorb 418.7 kJ. Water requires an energy of 2257.15 kilojoules to convert into steam. Water requires 2 kJ of energy to raise its temperature by 1 ºC. Superheated steam with a temperature higher than 100 degrees Celsius transfers all its energy to the condensation surface (Sanchez Vega, 2016). For steam purity, the steam's water content must be substantially lower than 0.01% mass. When water contains pollutants such as sulfates (SO_4) and carbonates (CO_3), they lead to the formation of deposits with low thermal conductivity. Impurities accumulate on the pipes and cause a significant increase in the heater's temperature. Impurities will also accumulate on the turbine blades, and the most dangerous pollutants for steam turbines are Na+ and K (Vakkilainen, 2017).

The use of steam in food processing

Heat is still one of the most often used methods for lowering foodborne microbiological risks. In addition, heat is required for additional procedures like cleaning, sanitation, and sterilizing equipment and packed food. The heat generated in the boiler furnace is transferred through the hot flue gases to the liquid. This technology is widely used in the food and beverage industry to provide superheated hot water and steam (Jung *et al*., 2022; Xu *et al*., 2019a). Xu *et al*., (2019b) stated that the adhesiveness of rice cooked with high pressure steam increased by 24.2% to 76.9%. In addition, the hardness decreased by 19.6% to 41.6% compared with the control sample. The researchers illustrated that high pressure steam cooking leads to a thicker sponge-like texture in the external layer of the rice, contributing to its stickiness. Moreover, the higher-pressure steam disrupts the starch-protein framework, allowing for more even moisture distribution, which enhances softness. The content of simple sugars and free amino acids in the camellia seed cake decreased, along with a reduction in the lightness of the camellia seed powder. Overall, steam explosion effectively modifies the functional properties of camellia seed powder, enhancing its solubility, foaming, and emulsifying abilities while altering its structural characteristics (Zhang *et al*., 2019).

Applications of steam generated using solar energy

Solar thermal is used for pre-heating, heating, drying, and cleaning at low temperatures in industrial heat processes. They have shown feasibility evaluations in the food and beverage sectors, making them economically and practically feasible (Ismail *et al*., 2021). For the extraction, Al-Hilphy *et al*. (2022) developed a solar steam generator using a flat solar collector and stainless-steel plate. The steam is sent to an essential oil extraction unit, which condenses the steam and oil, collecting them in a separation funnel. They found that the primary component of clove, cinnamon, eucalyptus, and cardamom essential oils was oxygen compounds. The researchers found the terpene content of orange and lemon essential oils was high. For pasteurizing milk using steam generated by solar concentrators, Franco *et al*. (2008) developed a method for pasteurizing goat's milk using solar energy. They used a deep conical center, a mirror, and a stainless-steel boiler to absorb solar radiation. After 10 min, the milk reached 65 °C. A galvanized iron pasteurization cylinder and another tank were also used, with the milk heated by steam. For solar interstitial steam generation for sterilization, steam sterilization is a reliable public health method, but in developing countries, electricity is scarce, necessitating off-grid solutions to prevent epidemic diseases solar interstitial steam generation, using biochar as a solar absorber, offers rapid and energy-efficient sterilization, with a capacity of 10.5 liter. This method is a promising and complementary solution that is particularly useful for off-network areas due to the effective sterilization, which reaches 99.99% kill of pathogenic bacteria (Li *et al*., 2021).

Steam generated using ohmic heating for desalination

Abdulstar *et al*. (2020) designed a system to evaporate non-potable water and convert it into distilled water using ohmic heating. The system consists of a heat-resistant plastic container containing two electrodes made of stainless steel, through which an alternating electric current passes. After that, the steam is transferred to a heat exchanger to be condensed into distilled water. The researchers found that the highest water distillation productivity was achieved at 500 mL/h using vertical electrodes. The electrical conductivity and TDS values significantly decreased.

Debacterisation of food surfaces by steam

Biglia *et al*. (2017) utilized steam to remove bacteria from cocoa beans through a thermal process. The system included a steam boiler, accumulator, and bacteria removal tank. After roasting, bacteria were reduced by steam treatment. The beans are collected in a tank and heated to 90-100 ºC by pumping steam for 3-5 s with continuous stirring. This method ensures quality, and safety in food production.

Zion *et al*. (2021) stated that the sterilization process involved a thermal trap surrounded by steam-pumped holes and a chain conveyor. This is ensuring the sterilization of products at a specific temperature. (Anwar *et al*., 2020) used saturated steam at a temperature of 100 °C for 6 s to kill *Listeria innocua* bacteria on food surfaces, where it decreased by the logarithm of 2.4.

Removal of microbial contamination using steam and ultrasound

Musavian *et al*. (2022) conducted a study on the decontamination of chicken meat using ultrasonic waves and steam. They found a decrease in *Campylobacter jejune* bacteria by 0.8, 1.1, and 0.7 logarithms in the back skin, breast, and neck samples, respectively. Moreover, Enterobacteriaceae decreased by 1.6, 1.9, and 1.1 logarithms and TVC by 2.0, 2.4, and 1.3 in the back, breast, and neck, respectively. The researchers explained the rapid treatment of at least 1.5 s in the treatment room. This method makes this technology suitable for modern and fast poultry processing lines.

Rapid Hygrothermal Pasteurization (RHP)

Tirawat *et al*. (2010) designed a device for rapid thermosetting. A cylindrical treatment chamber with a 1 m diameter and 0.3 m inner diameter is used for sterilizing fresh fruits and vegetables. It has two heating vents connected to a steam boiler, allowing 5-7 kg/h of steam flow. Samples are dropped through the chamber. The researchers found that RHP decreases mesophilic bacteria, changes color and stability, and retains ascorbic acid, ensuring minimal quality changes.

Liquid Food Sterilization by Steam Jet

In order to quickly raise the temperature of the product, direct steam injection is frequently used. Steam temperature significantly impacts heat transfer, with the highest Nusselt number observed at 120 ºC for liquid food. Huber and Viskanta correlations' Nusselt numbers were lower at steam Reynolds numbers greater than 25,000, 40,000, and 60,000 for 120 ºC, 125 ºC, and 130 ºC (Ranjbar, 2019). In many industrial applications, jet impingement has been shown to be an efficient way to shorten process times and enhance product quality (Nurhikmat *et al.*, 2021).

Culinary Steam

Culinary steam is the appropriate steam for direct injection into food products. For the purpose of the application, culinary steam must adhere to all applicable codes of the relevant regulatory bodies (such as the FDA and USDA). The high temperatures and moisture levels needed to sterilize enclosed surfaces of food processing equipment. For instance, closed tanks, pipelines, and valves, are achieved using culinary steam (Wang *et al.*, 2022).

Superheated Steam

Superheated steam (SHS) is an advanced technique that has a lot of potential applications in food manufacturing. Superheated steam has greater heat transfer coefficients than traditional processing techniques, which effectively lowers the number of microbes on food surfaces. Furthermore, SHS creates an environment with minimal oxygen that inhibits the oxidation of lipids and the production of dangerous compounds (Fang *et al.*, 2023). Superheated steam (SHS) is a new method of sterilization that inactivates the bacteria in dry food processing settings by using high temperature steam. SHS preventing condensation on surfaces. This type of steam is heated to a temperature higher than saturation at a specific pressure (Sarifudin *et al.*, 2022). Condensation of saturated steam occurs when its temperature drops below the saturation point. Because its temperature is higher than that of saturated steam. In dry conditions, superheated steam can inactivate germs without providing moisture. Hence, superheated steam has been used to remove contamination from various food processing surfaces (Nafissatou *et al.*, 2020; Rohaman & Siregar, 2020). Kurniadi *et al.* (2017) found that increasing peanut butter's water activity and roasted steam temperature led to a decrease in *Enterococcus faecium* D-value. Jia *et al.* (2021) found that ultra-heated steam treatment at 155-190 °C and 5-10 s improved the lipid stability of dried whole wheat noodles. This led to increase fatty acid content, decreasing unsaturated fatty acids, and increasing 2-pentylfuran, tocopherol, and total volatile compounds.

SHS is a crucial drying medium due to its non-toxic, fire-resistant, antioxidant properties, compatibility with food products. Also, it improved energy efficiency through energy recycling, and partial exhaust use (Cowan, 2004). SHS with its high specific heat, has excellent potential as a drying medium. Many drying systems, including fluidized bed dryers, vacuum dryers, rotary dryers, flash dryers, impact dryers, and spray dryers, can use it (Cowan, 2004). Huang *et al.* (2021) indicated that treating wheat flour with superheated steam for 6 s at a temperature of 150 °C and a moisture content of 13.5% was the ideal period. Maximum viscosity increased to 2560 CP, and enthalpy of gelatinization (ΔH) dropped to 5.67 J/g as a result of these conditions. Moreover, maintaining the granular microstructure and crystalline structure of starch while enhancing protein ordering.

Direct steaming of oil palm sterilization

Fresh fruit bunches in a palm oil mill need to be sterilized before the oil is extracted. A boiler and a sterilizer that steams food are located apart but linked by pipes in a typical industrial sterilization system. Water is used in this operation in enormous quantities. An average conventional sterilizer uses 0.256 kg of water per kg of fresh fruit bunches. The boiler and the sterilizer would be incorporated into one unit in an integrated design. Using integrated design as a single unit saves water consumption and maintains certain sterilization conditions through continuous sterilization. The findings indicated that the duration of sterilization, particularly between 30 and 45 min, has a greater impact on fruit-bunch separation than pressure selection. 2.5 bars and 60 min were the ideal parameters for excellent fruit-bunch separation. This gave an acceptable free fatty acid, and deterioration of the bleachability index of crude palm oil standard, together with little water usage. The specific water consumption at this operating position was 0.0587 kg-water/kg, or almost 4.34 times less than the conventional use (Lawson *et al*., 2007).

Steam sterilization of canned food

Canning relies on the method of thermal sterilizing food, packing it in vacuum-sealed containers, and sealing it tightly to eliminate pathogenic microorganisms and spoilage-causing enzymes (USFDA, 2022). Canned food can be preserved for 1–5 years, depending on the type of canned food, heat treatments used, and sterilization time (Maikanov *et al*., 2019). Studies have stated that through canning, the shelf life of meat and fish can be prolonged (Parija, 2023). It was recommended to use appropriate temperatures and times for heat treatments to maintain food nutritional value. Avoid negative interactions with can metals, and eliminate microbes (Lerouge, (Morya *et al*., 2020; Shawaqfeh *et al*., 2019). There is strong evidence that thermal process pollutants cause adverse toxic effects and pose 2019; Niinomi, 2019; Mohapatra, 2017). The USDA approved two methods of canning: water bath canning, which raises the internal temperature to 212 °C, and steam pressure canning, which pumps steam into a closed chamber under pressure to reach temperatures up to 240 °C, commonly used for low-acid foods (Niinomi, 2019).

The sterilization process eliminates all types of pathogenic bacteria that cause product damage.

The standard method for sterilizing low-acid foods is usinng stationary retort at high temperatures to extend their shelf life (Pommerville, 2022). In the food preservation sector, heat sterilizing canned food is a common practice. This process maintains the food's nutrients, helps identify its organoleptic qualities, and guarantees the microbiological integrity of the products. However, sterilization requires a lot of energy, affecting the final product’s cost (Musavian *et al*., 2022). High temperatures (120–130 °C) applied for an extended period of time (usually more than 60 minutes). Theses temperatures represent the major treatment conditions used for ensuring a safe and long-lasting product for low-acidity foods. At the same time, food's texture, taste, flavor, and nutritional value are greatly influenced by the treatment conditions (time and temperature). The treatment conditions cause food microstructure to be weakened and damaged (Norman-McKay *et al*., 2022; WHO., 2004). Nevertheless, a chemical reaction also occurs amongst the different nutrients that are now free and able to combine to generate other molecules in food. Some of which are harmful to human health and are referred to as thermal process pollutants

potential health risks to humans (Prabawa *et al*., 2022). The most toxic compounds are furans, acrylamide, and advanced end products that disrupt the biomolecular function, resulting in health risks (Owusu-Apenten & Vieira, 2023). Khunprama *et al*. (2022) sterilized fried rice, revealing a slight decrease in L*, a*, and *b values, and increased pH, fat, ash, moisture content, water activity index, protein, and carbohydrate content.

Sterilization methods by steam

Thermal treatment is a crucial method for food preservation. In canning, the aim is to manage infections and break down anti-nutritional elements like lectins in red beans (Saha *et al*., 2022). There are many types of heat sterilization, are:

Wet steam sterilization

Steam under pressure sterilization is a method used to heat aqueous solutions and heat-perishable materials. The autoclave, invented by Charles Chamberland in 1879, is filled with wet steam at a higher pressure than atmospheric pressure. The process involves sterilizing materials at 121 °C for 15 min, killing most heat-resistant microorganisms. Some blackboards can withstand boiling water for several hours (Peesel *et al*., 2016). For prion disposal, the recommendations are to use temperatures of 121-132 °C for 60 minutes or at least 134 °C for 18 minutes and the prion (Strain 263K). It can be eliminated relatively quickly by sterilization in this way. The time required to complete the sterilization process varies according to the type and quantity of the material to be sterilized. In addition, the temperature of all solution parts to reach the sterilization temperature. Sterilizers can reach 121.6 °C under normal conditions, but open containers cannot be heated above 100 °C. Closed containers like autoclaves maintain temperature. Steam generates steam, raising the boiling point and expelling air through valves, ensuring efficient sterilization. Sterilization typically occurs at a temperature of 121 °C for 15 minutes, followed by separation of the heat source, cooling of the sterilizer until pressure drops to normal atmospheric pressure, and opening (Deeth & Lewis, 2017).

Determining factors for heat treatment selection

The factors that determine the choice of thermal treatment are the type of food, the chemical composition, the type of microorganisms present. As well as the initial number of microorganisms, the microbial death curve, and the heat sensitivity of the nutrients.(USFDA, 2022). The safety limits for thermal processing of canned foods are to reduce bacteria count by 12 logarithmic cycles in low-acid foods. Thermal processing of food must eliminate pathogenic bacteria and their toxins. For example, *Clostridium botulinum* and *Clostridium thermosaccharolyticum*, which cause spoilage and spore formation in low-acid foods. It can grow at room temperature (the optimum degree of growth is 37 ºC). To achieve the necessary thermal treatment at 121.1 ºC, the number of spores the container is 1 spores/gram for *Clostridium botulinum*. The value of D for *Clostridium botulinum* = 0.23 min at a temperature of 121.1 ºC and heat resistance (Z) = 10 ºC (Maikanov *et al*., 2019).

Table (2): Summary of the effect of retort conditions on the quality of different foods.

Product	Type and volume of can	Conditions	The effect	references
Beef Rending	130×180 cm, flexible pouch bags	Pressure=1.3 bar, T=121°C, time=42 min,	Sterilization value ($F_{o)}$=5.6 min, predict process time (Pt)=28 min, Estimating the sterilization value of beef rendang in a retort pouch using either the general method or the ball formula yields accurate results.	(Praharasti *et al*., 2020)
Mushroom	300×407 mm can.	115, 121, and 130 °C, processing time from 2-97min	With increasing retort temperature, steam consumption decreased in the opposite direction; by increasing the temperature from 115 °C to 130 °C and from 115 °C to 121 °C, the energy efficiency of up to 72.9% and 58.1% per batch of retorting was achieved at the same F-value	(Pursito *et al*., 2020)
Tuna fish	Jar 9.2×6.5 cm.	115 ºC for 60 min	Ash, protein, and fat comprised 2.18 %, 17.74 %, and 21.0 % of the product's water content. The pH was 4.85, the peroxide value was 5.87 %, and the TPC of the products were less than $1 \cdot 10^{1}$ CFU/g. According to a heat penetration study, the F_o of canned cooked	(Anwar *et al*., 2020)
Yellow fin Tuna	3.7×5.6 cm can	T=121.1°C for 50 min	Lethality using Palm oil and brine were 2.52 and 8.69 min during the heating stage, respectively. At the holding temperature stage F=121.1°C , the death rates for palm oil and brine were 38.96 and 49.23, respectively. Both brine and palm oil had a closed	(Hasan *et al*., 2018)

Dike kernel (ogbono) soup	Tin-plate steel cans 63×75 mm	T=110, 116, and 121 °C	After heat processing the canned soup at 110, 116, and 121C, the spores of *Bacillus stearothermophilus* that remained decreased by 54%, 71%, and 75%, respectively. The soup was canned at 121C for approximately 31 minutes according to heat penetration	(Fasogbon *et al.*, 2022)
Mango and Pineapple	Cylindrical metal with a capacity of 454-457 ml	T=115, 120, 125, and 130 °C	Canned pineapple pieces retained more vitamin C than canned mango pieces did. Heat treatment quickly reduced leached vitamin C. The activation energy needed to break down beta-carotene and vitamin C in mangos was greater than that needed to break down	(Arampath & Dekker, 2020)
Starch	Can with 6*10 cm, 10*6, and cone with ten heights and five diameter	T=121 for 15 and 30 min	During sterilization, the cone-shaped container transferred to heat the quickest. Additionally, the shape, position, final temperature, j, L, and F-value of the slowest heating zone are significantly influenced by container geometry.	(Ranjbar, 2019)
Traditional Indonesian Foods	cans	T= 121 °C for 15 min	The food product's color, seen as vibrant and interesting, received a score of 4-5 for this attribute. The food product's flavor, which received a score of 4, had a more flavorful aroma, a score of 4-5, and a riper texture, which received a score of 4.	(Nurhikmat *et al.*, 2021)
Dry Bean (dynasty variety)	Can 307*407 mm	soaking and blanching condition+ T=121.1°C for 19 min	The canning process has had little effect on the quality of canned beans. Appearance=2.4, texture=52.3 kg, hue angle=19.7, Chroma=19.1, and L*=19.3.	(Wang *et al.*, 2022b)

Fish Balls	pouches	T=121.1°C for 1, 5, and 10 min	Fish balls can be sterilized for 10 minutes at 121 °C. The sterilized fish ball product has a lower colour quality when sterilized for longer. After 10 minutes of sterilization at 121 0C, the texture of the fish ball can be preserved, and the sensory quality of the fish ball	(Sarifudin *et al*., 2022)
Sweet Corn Kernels	Can 73*109 mm	T=121.1 for 4 min, 118 for 40min, 121.5 for 18 min, 125 for 8 min, and 125 for 12 min	All canned sweet corn, regardless of treatment, had no microorganisms associated with food spoilage or public health concerns. The aerobic mesophilic total counts were lowest at blanching (1.8 log10 CFU/g). However, the lowest C value/F-value ratio and the highest F-value	(Nafissatou *et al*., 2020)
Corned Beef	Rectangular can 95.8*47.5*91.5 mm	T=121 for	Fo ranged from 12.08-15.72 min, moisture=66.6%, ash=2.62%, protein=11.4%, carbohydrate=11.6%, sodium=703 mg/100g, calcium=26.7 mg/100g, lead=<0.07mg/kg, zinc=16.5mg/kg, tin=<0.6mg/kg, mercury=0.0005mg/kg, spore forming thermophile	(Rohaman & Siregar, 2020)
Fried rice	Cylinder can 301*205 mm	T= 121 for 15 min, and 121 for 20 min	The total CFU/ml on the plate was 9.3 x 101. The lethal value of 3.63 min at 121°C and 15 min, and the shelf life of canned fried rice was 10.3 months.	(Kurniadi *et al*., 2017)

Factors affecting the steam sterilization process

For heat, the internal spores of bacteria are highly heat-resistant and can only reach the lethal temperature when the vapour is compressed. A temperature of 121 degrees ºC for a specified duration is sufficient to eliminate microorganisms (Barija, 2023; Xiong, 2017). Additionally, a temperature of 115.5 ºC will kill *Clostridium botulinum* spores. While high-acid foods will not support the germination of these spores, they will thrive in low-acid foods. Therefore, for safety, vegetables, meats, soups, and other low-acid mixed foods should be treated in pressure cans (Schneider *et al*., 2017)

Regarding humidity, it helps coagulate bacterial cytoplasm, and it also increases the heat necessary for protein synthesis. Overheating steam can reduce its effectiveness in killing microbes and potentially harm the sterilized materials, leading to increased exposure and duration (Mohapatra, 2017). As for pressure, it does not affect the sterilization process within the range used in autoclaves, but pressure is only required to raise the steam temperature above 100 ºC. (Lerouge, 2019; Niinomi, 2019). During the sterilization process, steam penetrates the food and heats it, but not all spores are killed at the same time. The death rate remains constant at a specific temperature, with internal spore killing taking 11-12 minutes at 121°C (Pommerville, 2022). Trapped air in sterilizers is heavier than steam, forming layers with large temperature differences. Even with air and steam, heat yield may be less than required. Complete replacement of air by steam is crucial, and a thermometer reading of 100°C indicates air removal (WHO, 2004).

Sterilizing food in small containers takes less time compared to large containers (Norman-McKay *et al*., 2022). The food was divided into two groups according to the intensity of the heat treatment it was subjected to, based on the pH number. Acidic foods had a pH equal to or less than 4.5 and were treated at 100 °C or less. Foods that are non-acidic or low-acid and have a pH of more than 4.5 are processed at temperatures greater than 100°C (Morya *et al*., 2020; Shawaqfeh *et al*., 2019). *Clostridium botulinum* spores are found in low-acid canned foods, such as vegetables and fish. Alternatively, most of the attention in the food canning industry is limited to determining the adequate treatment to eliminate the boards of this bacteria, which cannot grow and produce toxins at pH 4.5. Alternatively, these bacteria are less heat-resistant when present in a food medium with a pH of less than 4.5 (Prabawa *et al*., 2022). This is due to the fact that bacteria in acidic liquids are more readily killed by heat. Furthermore, foods with pH levels of 4.5 or below often do not support the growth of spore-forming bacteria (Owusu-Apenten and Vieira, 2023).

Ultra-high temperature heat treatment (UHT)

It is applied to liquid foods, including milk and juices, in heat exchangers, where the milk is exposed to these heat exchangers to a temperature of 126.7 C for 4 s. Sudden cooling to a degree of 5 ºC and the packaging and sealing of the containers are carried out under sterile conditions (Deeth, 2017). The main changes to proteins that arise from UHT treatment include denaturation, aggregation, and chemical changes to the amino acids in the protein. These UHT-induced changes to proteins can affect their digestibility as well as the overall biological impact of consuming them (Krishna *et al*., 2021). Ultra-high-temperature-sterilized milk types showed higher levels of saturated fatty acids such octadecanoic and hexadecanoic acid, and their lactose amounts were comparable to raw milk's (Bai *et al*., 2023).

Hydrostatic sterilizer

A hydrostatic sterilizer is an efficient continuous and agitating sterilization arrangement, consisting of four or more towers with a height of up to 20 meters. The sterilizing section directly controls temperature, while the cooling tower reduces pressure and completes cooling at atmospheric pressure. The cans rotate through the machine using stainless steel chains (Deák, 2014).

High Pressure-Assisted Thermal Sterilization

Al-Ghamdi *et al*. (2020) mentioned that in the purple potato puree treated with thermal sterilization at a temperature of 122 ºC and high pressure, the spores of *Bacillus amyloliquefaciens* were reduced by 9 log10. The researchers explained that high pressure eliminated anaerobic and aerobic microbes, and the vitamin C content decreased by 3-14%. While betalain and anthocyanin were susceptible to HPATS and considerably reduced. Total chlorophyll and β-carotene did not change ($p > 0.05$). Albahr *et al*. (2022) revealed that avocado purée's treated by HPATS made total plate count was below the detection limit during the three months of storage. The results indicated that the HPATS procedure might be used to create shelf-stable avocado purée with a short shelf life.

Microwave-assisted thermal sterilization

Microwave-assisted thermal sterilization is a technique that uses hot water immersion and long-wavelength (915 MHz) microwave radiation to sterilize food in polymeric packaging. Microwave-assisted thermal sterilization effectively eliminates pathogens and bacterial germs. It also extends the shelf life of food products without losing their flavor or nutritional value (Soni *et al*., 2020). Sarah *et al*. (2023) have sterilized oil palm fruit using a continuous microwave sterilizer. The study found that the resulting temperature of kernel nut oil varied from 39 to 97 °C. in addition, interior temperature of the kernel nut always higher than exterior temperature. The resulting temperature required a minimum power density of 300 W/kg, 6 min residence time, and 50 °C to produce palm oil with free fatty acids less than 5%.

Commercial sterilization

Rutala & Weber, (2016) and Rutala & Weber, (2023) stated that the commercial sterility is defined by FDA legislation as applying heat to food to eliminate microbes. These microbes can reproduce in food or ones that are viable and significant to public health, or by regulating water activity and heat application. The goal of thermal treatment of food is to ensure food safety from the risks of pathogenic bacteria and toxin production. It ensures the safety of food from bacteria or their spores, which can grow and cause spoilage under normal handling conditions, and inhibition of spoilage-causing enzymes (Setlow, 2014).

Feasibility

The initial cost of a steam boiler plant is often more than its energy cost, making it necessary for owners to construct a new or refurbish an existing plant. The average steam generation index was 13.4 vapor units produced for each unit of fuel. While the average specific fuel consumption stood at 231.9 g/kWh. Additionally, the mitigation cost associated with the ecological footprint was decreased by $3.10 per hour (Camaraza-Medina *et al*., 2021). The autoclave sterilization process significantly contributes to production costs in canned food manufacturing, prompting a critical issue in reducing steam consumption in the process. Steam consumption is a significant factor in production costs within the canning industry. Choosing higher temperatures and shorter retorting times can positively affect commercial outcomes by lowering production costs (Pursito *et al.*, 2020). The optimal steam pressure for a meat plant is 100 psig, with a safety factor of 5%. Lowering the pressure by ten psig can save 31,910 $/year annually, resulting in a 1% energy cost reduction. This is especially important for new steam boilers, considering process temperature requirements. In vapor consumption, Pursito *et al.* (2020) suggested that using a higher temperature and shorter time in an autoclave is more economical, achieving steam consumption efficiencies of 72.9% and 58.1% per batch, respectively. The reliability-centered maintenance approach combines various maintenance strategies to optimize maintenance costs while ensuring the system's availability.

limitations and future prospectives

Steam sterilization is a common and effective method for sterilizing food. There are some foods that are sensitive to heat and some that are heat-resistant. To eliminate these problems, the type of disinfectant and the items being disinfected must be taken into consideration. UHT plants have experienced a significant increase in processing time, from 6–8 hours in the 1970s to over 30 hours due to the incorporation of a protein stabilization tube. UHT processing continues to expand the product range, focusing on environmental factors like water and energy usage and waste generation. Chemical and physical changes during treatment and storage improve the safety, and quality of UHT products (; Lewis, 2023;Deeth & Lewis, 2017).

For the future prospects, using emerging technologies such as ohmic heating, ultrasound, hydrodynamic, radio frequency, microwave, solar energy for food sterilization. For example, radio frequency with continuous steam sterilizer. As well as, using a combination of ohmic heating and microwave for sterilizing canned food. The low purity of the heating resistor, low electric conversion efficiency, poor stability, expensive acquisition and maintenance costs, and other issues are some of the drawbacks of traditional electric heating boilers.

Conclusions

Steam is generated by heating water to its boiling point or higher. The heating process is done by adding thermal energy to the water to convert it into steam. Units that generate steam are called boilers. The steam transfers the high thermal energy to the food sterilization units. There are two types of boilers used for sterilization: fire tube boilers, and Water tube boiler. The disadvantages of fire-tube boilers are that they require a large space, and a long time to produce steam. Hence, they are unsuitable for intermittent steam production. Water tube boiler defects are overheating, corrosion, creep, heat stress, and cracking. One of the modern methods of sustainable steam generation is the generation of steam by solar energy, such as parabolas, solar concentrators, and receivers with a cavity, as they use free and clean energy. The efficiency of the electrode steam boiler reaches more than 95%, and it has high thermal efficiency without causing pollution. These modern methods are environmentally friendly green technologies. Steam applications include many industrial processes, such as extraction of essential oils, water desalination, food pasteurization, and sterilization. Furthermore, the modern sterilization methods are the direct steam, steam with ultrasound, jet steam, and solar steam. Acidic foods can be sterilized at 100 °C or less, while non-acidic or slightly acidic foods can be sterilized at temperatures higher than 100 °C. Heat, humidity, time, and trapped air are essential in sterilization. At the same time, pressure has no vital role in that other than reaching a temperature higher than 100 °C in sterilizers. The cost of steam decreases by 1% when its pressure drops to 10 psig, and the sterilization process becomes more economical when using a higher temperature and shorter time. In the future, steam can be generated with fast and modern technologies such as infrared and induction heating to reduce energy costs and high steam production.

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Contributions of authors

A.A.A.: Methodology, Editing, Conceptualized.

A.R.A.: Data curation, writing—original draft, software, formal analysis.

S.M.A.: Conceptualized, formal analysis, validation.

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Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

All ethical guidelines related to meat and care issued by national and international organizations were implemented in this report.

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الابتكارات المستدامة في توليد البخار لعمليات تعقيم الأغذية: مراجعة

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المستخلص: هدفت المراجعة الحالية إلى تحديد أحدث التطورات في توليد البخار المستدام وتطبيقاته في تعقيم الأغذية. الطرق التقليدية لإنتاج البخار هي المراجل التي تعمل بالوقود والغاز والفحم. مؤخرًا، ظهرت طرق مبتكرة لتوليد البخار مثل المراجل الكهربائية والشمسية والغاز الطبيعي والنانو الكهربائية والغاز الحيوي والبيوميثان، والتوليد المستدام للبخار باستخدام المضخة الحرارية. السعرات الحرارية في البخار المشبع 100% أعلى من البخار المشبع بنسبة 95%. يتضمن نظام طبق الطاقة الشمسية الحلقي آلية تتبع ثنائية المحاور مما يضمن زيادة الكفاءة وإنتاج الطاقة المفيدة بسبب زيادة الإشعاع. تولد المراجل الكهربائية البخار باستخدام التيار الكهربائي، مما يوفر البساطة والموثوقية والكفاءة. يتميز مرجل النانو الكهربائي بكثافة طاقة عالية وانبعاثات كربون منخفضة واستقرار فيزيائي كبير وعامل قدرة عالي وكفاءة تحويل كهربائي عالية. تتراوح كفاءة مراجل الغاز الطبيعي والغاز الحيوي والبيوميثان بين 94% و95% مع مسخن اقتصادي. يوفر مرجل المضخة الحرارية ذات المصدر الهوائي إخراج نظام مستقر مع كفاءة طاقة عالية، مما يولد بخارًا بدرجات حرارة تزيد عن 120 درجة مئوية. محتوى الماء أقل من 0.01% كتلة ضروري لنقاء البخار لمنع السخونة الزائدة. يجب أن تقلل المعاملة الحرارية للأغذية المعلبة اعداد البكتيريا بمقدار 12 دورة لوغاريتمية في الأغذية منخفضة الحموضة لتلبية حدود السلامة. يحتوي العلبة على 1 سبور من البكتريا للمعاملة الحرارية (التعقيم) عند 121.1 درجة مئوية. تتضمن العملية تعقيم المواد عند 121 درجة مئوية لمدة 15 دقيقة، مما يقتل معظم الكائنات الحية الدقيقة المقاومة للحرارة. تهدف طرق التعقيم البخاري المبتكرة إلى تعزيز الاستخدامات الصناعية التي تلبي صافي الانبعاثات الصفرية وأهداف التنمية المستدامة (SDG).

الكلمات مفتاحية: غلاية، غاز حيوي وميثان حيوي، أقطاب كهربائية، موجات فوق صوتية، مركز طاقة شمسية، بخار مشبع فائق الحرارة.