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Cost-Engineering Analysis of Radio Frequency Plus Heat for In-Shell Egg Pasteurization

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Abstract

Salmonella spp. is a pathogenic microorganism linked to eggs and egg products. In-shell eggs are not required to be pasteurized in any country before they reach the consumer. The use of an emerging technology known as radio frequency has been successfully used to inactivate this pathogen inside in-shell eggs and claim pasteurization standards (5 - log reduction). The objective of this manuscript was to conduct the engineering cost of egg processing using a radio frequency pasteurizer and compare the processing cost to conventional thermal pasteurization for in-shell eggs. The ARS-patented radio frequency pasteurizer was used (40.68 MHz, 35 W) to pasteurize eggs in 24.5 min. The conventional thermal pasteurization (56.7 °C) required 60 min for the same level of inactivation. The techno-economic analysis (TEA) included information from stakeholders, egg processors and equipment manufacturers and was used together with energy balances and some key assumptions. Calculations for the engineering cost were made based on the required energy for each system, showing that the radio frequency required a third of the total cost of electricity to pasteurize eggs in a year compared with thermal, based on utilities costs in PA. Other utilities such as water and steam were also minor for radio frequency pasteurization. After two years of operation, the projected additional cost of processing is ~USD 0.19 per egg for the radio frequency system, compared with USD 0.22 per egg for conventional thermal treatment, largely due to volume-based amortization of capital costs and lower annual operating costs for the RF process. Radio frequency thus could be an option to pasteurize eggs in farms from PA and potentially in other states, using the system developed by our research team, while reducing energy consumption and increasing return on investment.

Keywords: economic analysis; pasteurization; emerging technology; poultry

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1. Introduction

Statistics show the high production of eggs worldwide; in the USA, the annual production was 93.1 billion eggs in 2024 [1], and in the EU, the yearly production in 2021 was 74.4 billion eggs [2]. The presence of the human pathogen *Salmonella* Typhimurium in foodborne outbreaks is commonly associated with eggs and egg products [3,4]. However, in-shell eggs are not required to be pasteurized in any country; only a small fraction of in-shell eggs in the US are sold pasteurized. Pasteurized eggs are considered a premium product, with higher cost and focused on special sectors of the population [5].

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Radio frequency is one of the innovative food technologies that have been successful in microbial inactivation in several food commodities [5–7]. Radio frequency allows a fast volumetric of the product using the dielectric and thermal properties of the food, minimizing overheating from conventional thermal processing [5,6]. In-shell eggs have been successfully pasteurized with radio frequency plus heat, achieving a 5 - log reduction in *S. Typhimurium* inoculated inside the eggs. No sublethal injured cells were detected after pasteurization, and no cell survivors were recovered after a week under refrigerated conditions [5]. In addition, the egg quality after radio frequency pasteurization plus heat is well preserved [8]. This new radio frequency pasteurization process for in-shell eggs is completed in 24.5 min, reducing the processing time when compared with conventional thermal egg pasteurization (60 min). Currently, the trend is moving to research those low-energy, low-cost food technologies that can be transferred to the food industry [9].

The research conducted with emerging technologies for food processing and preservation has been widely published. However, the scale-up and costs of these technologies are not well documented [10]. In addition, the transfer from lab bench to industry scale of emerging technologies is usually a slow process. Priyadarshini et al. [11] mention this transfer as an organizational change with two main stages, initiation and implementation. Several reasons delay the transfer from lab to industry such as the initial investment, the time-consuming process validation with specific microorganisms, equipment designs and the lengthy process request for regulatory approval [11,12]. More evidence is required about the efficiency, processing costs and benefits of switching from conventional to emerging technologies to persuade the food industry about the implementation of these innovative interventions [12]. A techno-economic analysis (TEA) is usually conducted to evaluate the economic benefits of a new process [9]. The TEA not only evaluates the economic viability of the process but also quantifies capital and operational costs, helps with price estimation, can evaluate financial performance of the technology and is a useful tool to make critical decisions regarding processing equipment design [13]. Several examples of novel food technologies, sanitizers and treatments have been analyzed using a TEA, exploring feasibility, profitability, adoption and scalability [9,13,14].

The TEA of radio frequency processing for high moisture food, such as eggs, has not been reported to the best of our knowledge. The aim of this work was to conduct a systematic TEA of radio frequency plus heat processing that achieves egg pasteurization and compare it with conventional thermal pasteurization. The TEA focuses only on the process(es) that achieves microbial inactivation and does not consider those pre—and post—activities during the egg processing cycle. The TEA will be evaluated based on information from a large egg farm in Pennsylvania, with the desired annual production of 14 million pasteurized eggs.

2. Materials and Methods

2.1. Cost Analysis

The TEA of egg pasteurization (radio frequency plus heat or conventional thermal) included costs related to equipment purchase (capital), utilities (electricity, steam, water), equipment maintenance and labor. The calculations for TEA were based on several previous experiments reported by Bermudez-Aguirre et al. [5,8] and additional tests that were focused on the improvement in equipment performance, microbial inactivation and quality attributes of large white eggs. For example, in Figure 1, the efficiency of the system was tested using several egg weights until the maximum efficiency of the radio frequency energy was achieved. Furthermore, some technical data about egg processing was kindly provided by our stakeholders. The boundaries of the systems to conduct TEA will be described in Sections 2.3 and 2.4.

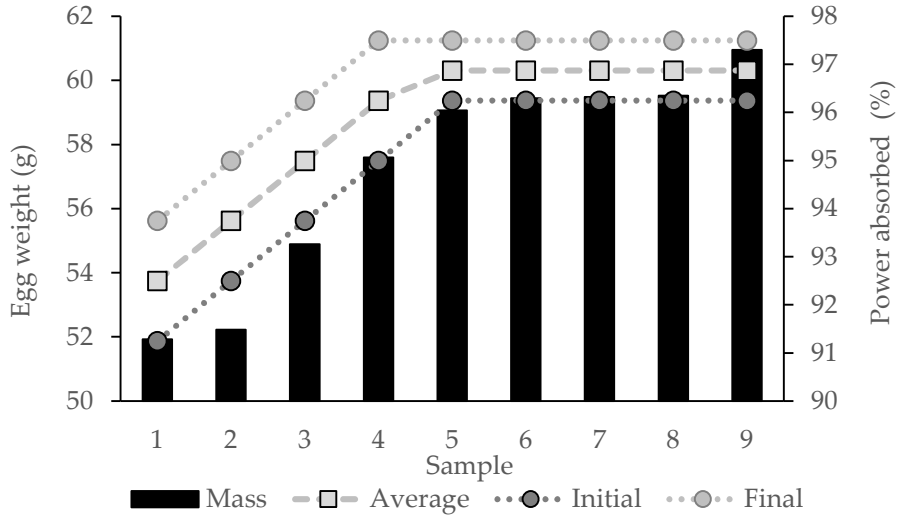


Figure 1. Efficiency (power absorbed %) of the radio frequency pasteurizer according to egg weight.

2.2. Eggs

Large white eggs (average weight 58 ± 1 g) were chosen to process within the radio frequency system because of the electrode paddle design, which handles and processes this specific size with the highest efficiency—minimal energy losses (Figure 1). However, larger or smaller paddles can be attached to the system to process different egg sizes and achieve similar efficiency. For practical reasons, the engineering cost will be focused on large white eggs using this approximate weight per unit.

Eggs were supplied during a time frame of four summer—fall months by a local farm in PA. The average cost of large white eggs Grade AA, unpasteurized, was calculated based on ten commercial selling points (supermarkets) in the suburbs of Philadelphia, PA and just used as reference. The prices were recorded as of 25 September 2025. Stores included supermarkets from all range prices.

Based on the input from one of our stakeholders, only a small percentage of eggs processed at one of the largest egg farms in PA will be sold as a premium product, i.e., pasteurized [15]. The estimated amount is 3 truckloads of eggs per day (~864,000 eggs/day). It is assumed that the farm will operate 2 shifts per day (16 h per day), and the egg production will be 72,000 dozen/day only for pasteurized eggs. The estimated annual production of pasteurized eggs was set as 14 million units.

Egg Processing

The conventional processing of eggs in farms (without pasteurization) has the following steps. Eggs are laid at an approximate temperature of 37.7 °C and then washed and disinfected using warm water with a sanitizing agent (43.3 °C, 30–45 s, chlorine solution 200 pm). Afterwards, eggs are checked for quality at room temperature for a further sorting process based on weight. Later, eggs are packaged and sent for distribution and stored at <7.2° C [15]. Pasteurization of eggs should be conducted after sorting large eggs (58 ± 1 g) and when the internal temperature of the eggs is around 35 °C. In Figure 2, the egg processing cycle is shown. Based on the developed radio frequency system to pasteurize large eggs (58 ± 1 g), after sorting and weighing, eggs can follow two routes. If the eggs are smaller or larger than 58 ± 1 g, they can go for commercial processing for regular commercialization (packaging, transportation). If the eggs are 58 ± 1 g, the eggs can go for radio frequency plus heat pasteurization.

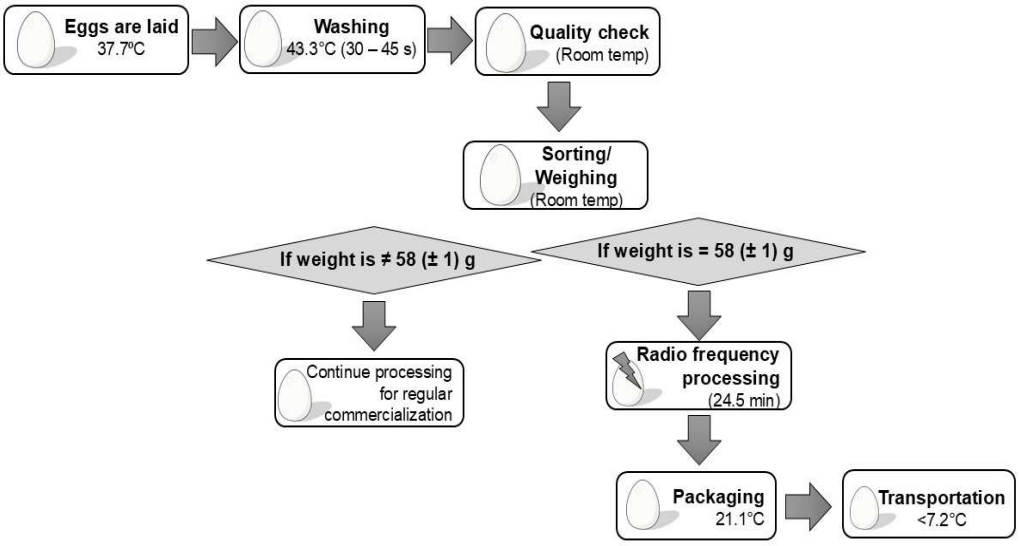


Figure 2. Egg-processing cycle showing the steps for conventional processing and for radio frequency plus heat pasteurization.

To calculate the engineering cost of the radio frequency and thermal processes to pasteurize eggs, some assumptions are made:

(a) constant tap water temperature: 20 °C
(b) constant internal egg temperature after sorting: 35 °C

2.3. Radio Frequency Plus Heat Pasteurization

The use of radio frequency plus heat to pasteurize in-shell eggs has been previously described in detail [5,8]. Briefly, the radio frequency pasteurizer is based on an ARS—patented equipment that has been re-designed and improved in the last four years. The new system operates at 40.68 MHz and 35 W. The system contains 3D custom-printed paddles that hold copper electrodes (5 cm × 2.5 cm × 0.2 cm). The gap between the electrodes corresponds to the diameter of a large egg (4.32 ± 0.05 cm). Eggs are placed on top of silicone rollers and allowed to rotate during processing (42 rpm), permitting homogeneous volumetric heating. The eggs are sprayed with a nozzle system during radio frequency with water (38.5 °C ± 2.9, 14 L per minute) to prevent overheating of the albumen (Figure 3). After 4.5 min of radio frequency processing, eggs are moved into the hot water spray system (Kuhl Corporation, Flemington, NJ, USA) and processed at 56.7 °C ± 0.7 for 20 min to finalize the microbial inactivation. The temperature is monitored inside the egg yolk and albumen using fiber optic sensors.

The full radio frequency plus heat process will be divided into three sub-processes for cost analysis and calculations using system boundaries as set in Figure 4a.

The three sub-processes are the following:

(a) Process #1: Eggs are processed using the radio frequency system for 4.5 min to increase the internal temperature;
(b) Process #2: Simultaneously, to process #1, eggs are water-sprayed (38.5 °C) to equilibrate and keep the albumen temperature, avoiding degradation;
(c) Process #3: Eggs are treated with a hot water spray (56.7 °C) for 20 min to complete microbial inactivation.

The total processing time of the three processes together is 24.5 min. The list of processing conditions for radio frequency plus heat pasteurization are listed in Table 1.

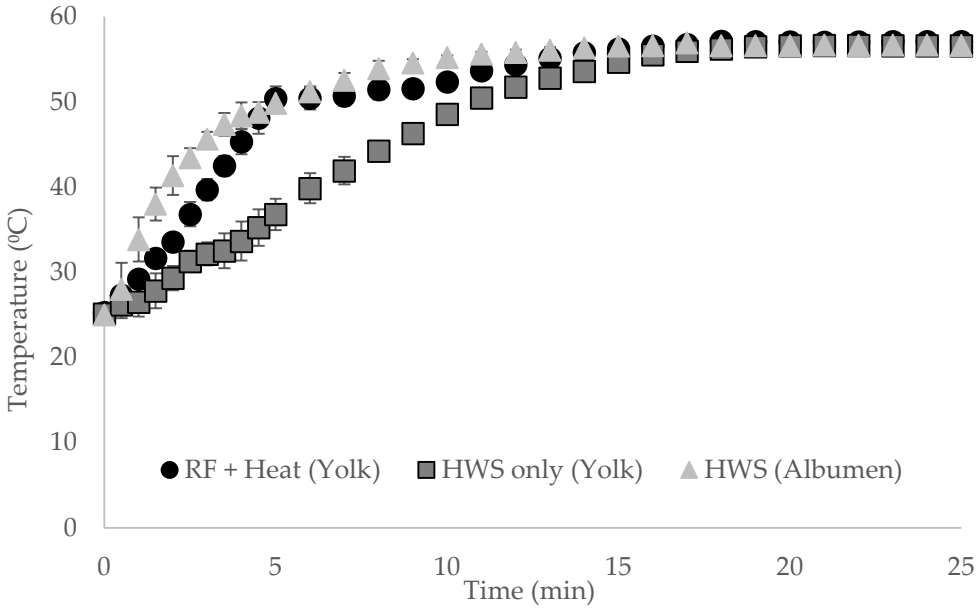


Figure 3. Heating profile in egg processing using radio frequency plus heat and hot water spray (HWS: conventional thermal processing).

The electric cost of the radio frequency plus heat processing, C_{RF}, including processes #1, #2 and #3, is equal to the addition of the individual costs (C_1, C_2, C_3) and expressed as follows:

$$C_{RF} = C_1 + C_2 + C_3 \quad (1)$$

To calculate the electric cost of process #1, C_1, the energy applied during radio frequency processing (Q_1) is calculated as follows:

$$Q_1 = P \times t \times n \quad (2)$$

where P is the power applied per egg (W), t is the processing time (s) and n is the efficiency. The efficiency of the radio frequency was experimentally evaluated and was between 97 and 99% (Figure 1). For practical reasons, the efficiency was set as 98%.

Table 1. Radio frequency (RF) plus heat processing conditions to achieve pasteurization standards (5 - log reduction) of *Salmonella* Typhimurium in intact eggs.

Description	Operating Processing Conditions
Process #1: RF only	
Working frequency	40.68 MHz
Input Power	35 W
Time	4.5 min
Process #2: Water spray during RF	
Temperature	38.5 °C
Time	4.5 min
Water flow rate	14 lpm * (0.58 lpm/egg)
Process #3: Hot water spray (HWS)	
Temperature	56.7 °C
Time	20 min
Water flow rate	14 lpm * (0.58 lpm/egg)

* lpm: liters per minute.

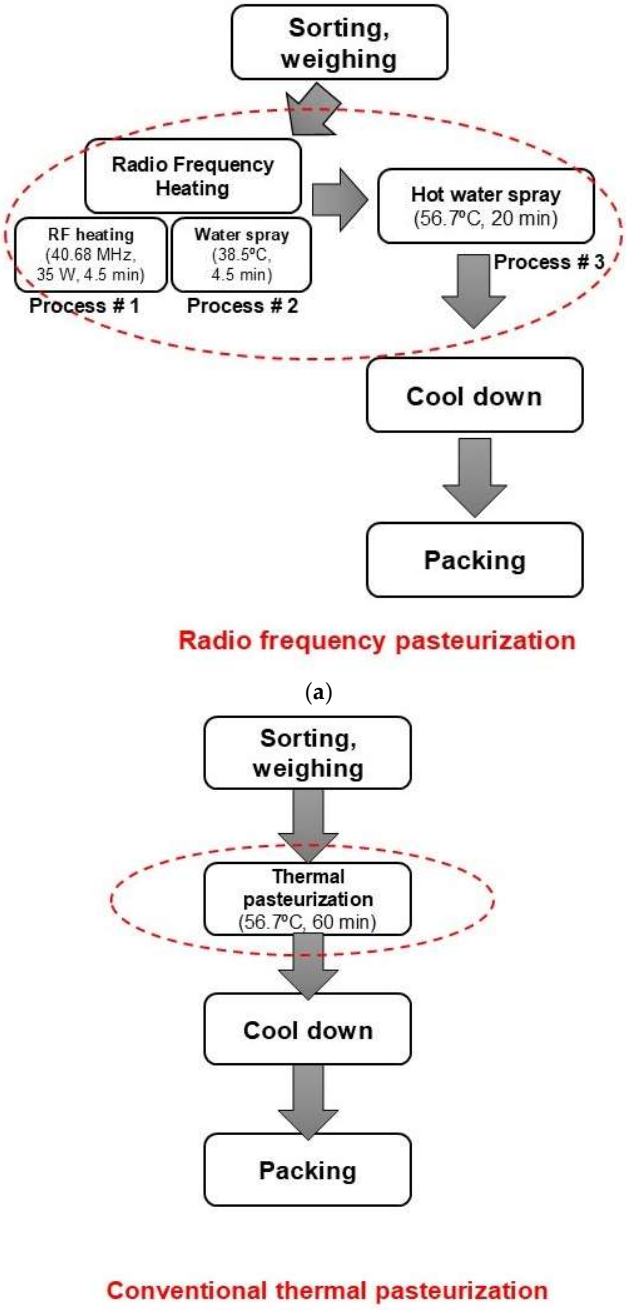


Figure 4. Representation of the steps to conduct radio frequency pasteurization (**a**) and conventional thermal egg pasteurization (**b**). Dotted lines refer to the process(ess) in which microbial inactivation occurs (system boundaries).

For processes #2 and #3, the required energy (Q) was calculated based on the following equation:

$$Q = mC_p\Delta T \quad (3)$$

where m is the mass of water (kg) used during the process, C_p is the specific heat of water (kJ/kg °C) at the required temperature and ΔT is the difference in temperature (°C) between the inlet and outlet. Water properties at specific temperatures were used and are listed in Table 2. The efficiency for all thermal processes used in this work (excluding radio frequency processing) was set at 90%.

Table 2. Physical properties of water used for calculations for the engineering cost of radio frequency plus heat and conventional thermal pasteurization of eggs [16].

Property	Value
Specific heat (kJ/kg °C)	
38.5 °C	4.175
56.7 °C	4.180
Density (kg/m^3)	
38.5 °C	992.76
56.7 °C	985.69
Latent heat of vaporization (kJ/kg)	
38.5 °C	2409.5
56.7 °C	2365.7

2.4. Conventional Thermal Pasteurization

To compare the costs between regular thermal and radio frequency plus heat pasteurization, the processing conditions chosen for the first one are based on those achieving a 5 - log reduction in *S. Typhimurium*. So, the processing conditions are 56.7 °C for 60 min, and it is considered that microbial inactivation happens only during this process. The equipment used will be the same hot water spray system used to complete the radio frequency pasteurization. So, to calculate the required energy and electricity cost to pasteurize eggs using only thermal processing, Equation (3) was used, and the efficiency was set as 90%. The boundaries for this system are shown in Figure 4b.

2.5. Additional Costs and Assumptions

The cost related to raw material, washing, quality check, weighting, sorting and packing are not included in the process, because it is the same for radio frequency and thermal pasteurized eggs and out of the boundaries of the evaluated system. Furthermore, the cost for cooling down the eggs after thermal or radio frequency pasteurization is assumed to be the same and is also not included in this evaluation.

The amount of water to process eggs was calculated based on the required amount of water during radio frequency processing (sprayed water) and that required during the hot water spray. For thermal processing, the volume of water was required to process eggs for 60 min. The required steam for processing was calculated with the following equation:

$$Steam\ required = \frac{Q}{\lambda} \quad (4)$$

where λ is the latent heat of vaporization (kJ/kg) at the specific temperature for each process.

The cost of utilities was obtained from different sources based on the USA. First, for electricity, the rate was USD 0.0986 per kWh [17] for industrial use in Pennsylvania. Meanwhile, for steam the average rate was USD 0.24/klbs for industrial applications [18]. Finally, the cost of industrial water varied depending on the provider and the location in PA; based on several industrial rates, the final price was set as USD 1.49/m^3.

Maintenance costs were added to the TEA, using 3.0% of capital costs for radio frequency plus heat and 2% for conventional thermal processing, as suggested by [10]. Labor costs included the hire of two plant operators, each one in an 8 h shift. Salaries are based on the Philadelphia pay area as of 2026, for persons with the required skills to operate a fully automatized system.

Lastly, the amortization of capital costs was calculated using Equation (5) as follows:

$$C_E = \left(C_{Con} \times E + C_{Cap}\right)/E \quad (5)$$

where C_E is the cost per egg, C_{Con} is the consumables cost per egg, C_{Cap} is the capital cost of the equipment and E is the total number of eggs processed.

2.6. Statistical Analysis

All the experiments were conducted at least by duplicate in different weeks. Eggs were used from the different batches received during the summer and fall months, but all the samples were within the required weight range from the same farm in PA. Basic statistical analysis (average, standard deviation) was conducted using Microsoft Excel (Version 2501, Seattle, WA, USA), and one-way ANOVA (a = 0.05) was conducted to find significant differences.

3. Results and Discussion

3.1. Egg Pasteurization

Thermal pasteurized eggs are considered a premium product in the USA and although it is not common to find pasteurized eggs in supermarkets, sometimes it is possible to find a few dozen with slightly higher costs (about USD 2–3/dozen on top of average price). The current price of unpasteurized large white eggs (AA) in ten selling points of the suburbs in Philadelphia was USD 3.97 ± 1.27 per dozen, as at September 2025.

3.2. Equipment Processing

3.2.1. Electric Cost

The first part of the cost analysis was focused on the calculation of the electrical cost of the radio frequency plus heat and conventional thermal pasteurization of eggs based on the annual production of 14 million units. Based on the egg load required to be processed, the radio frequency system should be able to process 86,400 eggs per day, 54,000 eggs per hour (16 h/day) and 4500 eggs per cycle, considering 12 full cycles per day (4 h/day are for other activities pre- and post-processing, such as cleaning and sanitation) and the work week includes 6 days.

Using the electric design of the USDA ARS—a patented radio frequency pasteurizer and several improvements that have been made in the last few years—each egg will receive 35 W, working at 40.68 MHz. Calculating the required energy for each process: 1, 2 and 3, (Figure 4) and using the latest reported cost of industrial electricity in Philadelphia, PA, as USD 0.0986/kWh [17], the cost of a radio frequency pasteurized egg dozen will be USD 4.69. Comparing this price with unpasteurized eggs (USD 3.97/dozen) and those pasteurized thermally (USD 5.89/dozen), the use of radio frequency plus heat is not only reducing processing times but also offering an affordable cost for pasteurized eggs with a slight increase in price, compared with regular eggs, of about 72 cents per dozen (Table 3). These results present radio frequency plus heat as a low-energy, low-cost option to pasteurize eggs.

Table 3. Comparison of the approximate cost of pasteurized eggs using radio frequency plus heat and conventional thermal pasteurization (considering only electricity charges).

Cost for Processing	Radio Frequency Plus Heat (USD)	Conventional Thermal Pasteurization (USD)
Process #1	3700	-
Process #2	86,000	-
Process #3	756,000	-
Total cost [a]	846,000	2,270,000

Table 3. *Cont.*

Cost for Processing	Radio Frequency Plus Heat (USD)	Conventional Thermal Pasteurization (USD)
Added cost per egg	0.06	0.16
Added cost per dozen	0.72	1.92
Final cost per egg dozen [b]	4.69	5.89

[a] Considering annual production of 14 million pasteurized eggs. [b] Using as base the commercial cost for fresh unpasteurized eggs in Philadelphia, PA (USD 3.97 per dozen, AA large white eggs, September 2025).

3.2.2. Capital Costs

The second part of the engineering cost included the capital costs. The initial investment of a radio frequency system has been included in the capital costs. Based on the internal designs, configurations and scale-up options designed by this research team, the initial cost of the pasteurization system to process 4500 eggs per cycle will be about USD 1.5 million. It is worth mentioning that the engineering cost does not include the land and construction of the facilities because the cost could be the same as the one for a thermal pasteurization processing plant. In addition, radio frequency is a single technology that does not involve specific requirements for installation (i.e., deep excavation or a complex piping system). Several equipment configurations were evaluated according to the required annual egg production, considering the dimensions of current egg processing lines in large farms to minimize scale-up constraints. The best configuration based on that was chosen for the present analysis. The radio frequency system has been designed to be attachable to/detachable from current egg processing lines and pasteurize the required egg load depending on the farm needs. If the system is incorporated as part of commercial egg processing lines, there is no investment in land or construction of facilities.

Capital costs also include the purchase of heat exchangers, a hot water spray system, loaders and conveyors to move the eggs during production. Other capital costs were calculated as suggested by Sampedro et al. [10], using twice the cost of equipment. These costs are related to the final engineering design and installation of the systems. It is important to notice that the radio frequency system plus heat is a fully automatized process that will require minimum supervision.

3.2.3. Other Utilities Cost

The electric costs are reported in Section 3.2.1 to show the energy savings of using radio frequency instead of conventional thermal pasteurization for in-shell eggs. Besides electricity, the process relies on water and steam, so these costs are discussed in this section. Even though, during the initial experiments, eggs needed to be warmed up (35 °C) because they were previously stored under refrigerated conditions after inoculation to prevent microbial growth (4 °C), in practice, eggs will be processed soon after they are laid. So, eggs out of hens are about 37.7 °C; they are washed with hot water and sanitized (43.3 °C) for 30 to 45 s. Then, they move for quality check, sorting and weighing at room temperature [15]. So, the heat from inside will dissipate during the quality check and sorting and will be ready to start the processing at around 35 °C. No required initial warming up is required and no cost has been added for this step.

However, during radio frequency pasteurization, it is important to keep the temperature of the egg albumen low to prevent any protein degradation. The heating profile using radio frequency and conventional heating (hot water spray) of the egg yolk and albumen is shown in Figure 3. Because of that, there is a need to spray the eggs with water at 38.5 °C. For the cost of water in the utilities section of Table 4, it is considered that new fresh water

is used for every cycle. However, water can be recycled and reused for further cycles or applications representing a reduction in the cost of the utilities. Further deeper analysis can be conducted regarding this utility. However, it is important to highlight that the water used during processing must meet the criteria of potable water (free of microorganisms and chemicals), because it will be in direct contact with eggs. So, the options could be to install a treatment plant for recycling water and use some methods such as filtration, reverse osmosis or ultraviolet to ensure the microbial and chemical quality or use new fresh water for every cycle. The cost for the treatment plant is not included in the present manuscript.

Table 4. Cost comparison between radio frequency plus heat and conventional thermal pasteurization of in-shell eggs including capital and utility costs.

Processing Parameter	Units	Radio Frequency Plus Heat	Conventional Thermal Pasteurization
Number of eggs	Eggs/year	14,000,000	14,000,000
Hours of production [a]	h/year	4800	4800
Capital costs			
Heat exchangers	USD	20,000	20,000
Radio frequency system	USD	1,500,000	0
Hot water spray system	USD	15,000	15,000
Loaders and conveyors	USD	12,000	12,000
Other capital costs	USD	1,547,000	47,000
Total capital cost	USD	3,094,000	94,000
Utility costs			
Electricity cost	USD/year	846,000	2,270,000
Steam cost	USD/year	1000	6800
Water cost	USD/year	292,000	716,000
Total utility cost	USD/year	1,139,000	2,993,000
Maintenance costs			
Equipment maintenance	%Capital	3.0	2.5
Maintenance costs	USD/year	108,290	2350
Labor costs [a]			
Plant operator	Per shift	1	1
Labor costs	USD/h	35	35
Total labor costs	USD/year	140,000	140,000
Total annual costs	USD/year	4,481,000	3,230,000
Additional cost per egg	USD/egg	0.32	0.23

[a] 6 day–week, 16 h, two 8 h-shifts.

3.2.4. Maintenance Cost

The maintenance cost has been calculated as suggested by [10] using 3% of capital costs for radio frequency and 2.5% for thermal processing. The required maintenance for radio frequency includes new electrodes after they reach the end of their useful life, some repairs in the electrical system and wiring. The approximate amount is shown in Table 4, as USD 108,290 annually. For thermal processing, the cost is inferior because of the low maintenance that is required—about USD 2350 per year.

3.3. Other Related Costs

The labor cost was calculated based on the hiring of two technicians to operate the system. It is expected to have two 8 h shifts. Salaries are based on average pay rates in Philadelphia, PA, in 2026 for people with the required skills to operate the system. It is worth mentioning that radio frequency processing is fully automatized and requires minimum supervision from a technician who can be the same employee on a regular farm with adequate training.

The final cost comparison between the radio frequency and the conventional thermal pasteurization is shown in Table 4. Calculations were made based on the required number of eggs per year (14 million) and the process(es) involved in each category. It is clear that capital costs for the radio frequency pasteurizer are high (USD 3,094,000) compared with conventional thermal processing (USD 94,000), mainly because of the initial investment in the novel equipment. However, the utilities costs and other annual operating expenses are more than double for conventional pasteurization (USD 3,135,350) when compared with radio frequency (USD 1,387,290), again showing radio frequency as a low-energy, low-cost option to process eggs. As with any capital-intensive process, the cost per unit decreases with production, i.e., as more eggs are processed. Figure 5 shows the cost per egg for the RF plus heat process compared with conventional thermal, incorporating amortization of the capital costs over continued production, calculated with Equation (5). Using the summary data (Table 4), the average unit processing cost per egg for the first year is USD 0.32 for radio frequency and USD 0.23 for thermal pasteurized. By the second year of production, the processing cost per egg drops to USD 0.19 for radio frequency while remaining at USD 0.22 for thermal pasteurized. With higher annual operating expenses and lower initial capital costs, the unit cost for conventional thermally processed eggs is not as responsive to amortization as the RF process. The turnover point at which favorable cost per egg shifts from conventional to RF processed is at a total volume of 22 million eggs. Based on an annual processing volume of 14M eggs (Table 4), this is approximately 1 year and 7 months.

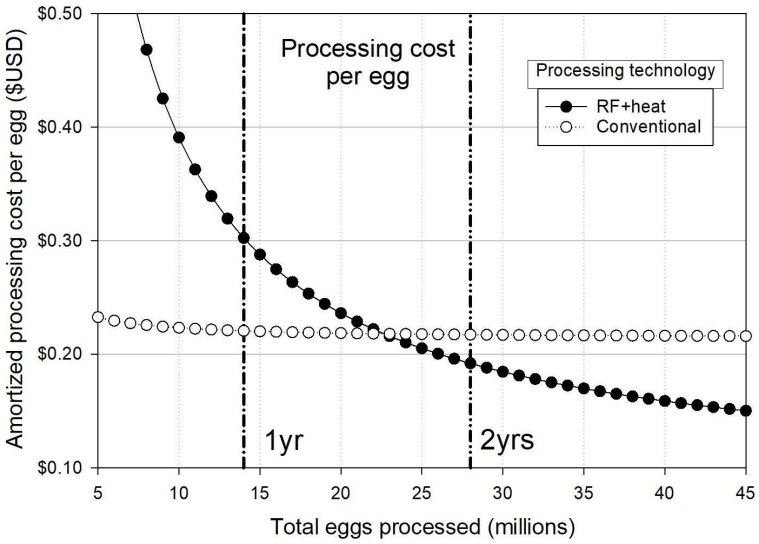


Figure 5. Processing cost per egg after the amortization cost analysis of the radio frequency plus heat pasteurization compared with conventional thermal processing.

The cost of radio frequency pasteurized eggs has not been reported before to the best of our knowledge. As such, it is difficult to compare these findings with the literature. Recently, there was a new study about the use of radio frequency to pasteurize eggs; however, the system is different from the one described in this manuscript in terms of configuration and working frequency (27.12 MHz). The energy applied to eggs is not reported, although the

authors claimed pasteurization (4.95 ± 0.53 log reduction) in 16.5 min [19]. As in many other emerging technologies, the report of processing conditions should be standardized to compare between processes from different research groups.

3.4. Cost Analysis Using Novel Food Processing Technologies

Novel technologies usually have a slow transfer to food industry because of several reasons such as regulatory aspects, consumer acceptance and initial investment. For example, in the case of high hydrostatic pressure, today is a commercial reality with hundreds of pressurized food products available in supermarkets, coffee shops and other retailers worldwide. However, back in the 1990s, high hydrostatic pressure was a technology under research with the very first commercial applications in the early 2000s. Queiros et al. [20] reported an increase in the number of high-pressure equipment worldwide from less than 20 in 2000 to 170 in 2022. The capital cost for a high-pressure equipment today goes from €700,000 to €3,500,000 (approximately USD 813,000–USD 4,064,000). The case of pulsed electric fields was also reported about ten years ago, with a capital cost of USD 988,000 for the equipment and about USD 2,100,000 as total capital cost including all the heaters, coolers and pumping systems [10]. In the present manuscript, the engineering cost of the radio frequency pasteurizer including the initial investment, the main systems and connections, the utility costs and the maintenance and labor costs for a full year of operation are about USD 4,481,000. After the first few years, the cost of radio frequency pasteurization will be based on the utilities (USD 1,139,000), maintenance (USD 108,290) and labor (USD 140,000) costs that would increase the cost of eggs to USD 0.09/egg. These numbers are important for the egg processors that often face recalls of their products because of the possible presence of *Salmonella*. These recalls result in wasted products, financial costs, damage to the brand or company and, in some cases, *Salmonella* outbreaks with illnesses and deaths. The cost of an initial investment might be high, but in the long term, egg processors can prevent these recalls in pasteurized eggs, minimizing the risks of *Salmonella* in eggs and ensuring the food safety of consumers.

4. Conclusions

Based on the TEA conducted in this research, focusing on an annual egg production of 14 million and operating the radio frequency system in PA, this novel technology could be an option to pasteurize eggs with low energy and low cost. The initial investment is high like other novel technologies such as high-pressure or pulsed electric fields, but the return of investment can be recovered after the first few years of operation because of the high production volume.

Further analysis is recommended to optimize costs, for example, including a water treatment plant to recycle the use of water during processing but ensure the microbial quality of the finished product. Furthermore, the evaluation of the life-cycle assessment for the radio frequency plus heat pasteurization is highly recommended to study the environmental impact of this novel technology.

These results offer, to large egg farmers, the option to install a system that can potentially be used to process and pasteurize premium eggs, providing the consumer with safe eggs, reducing the use of energy, water and steam, but also working towards the reduction in foodborne illnesses.

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Abbreviations

The following abbreviations are used in this manuscript:

ARS	Agriculture Research Service
BSL-1	Biosafety Level—1
EU	European Union
HWS	Hot Water Spray
lpm	Liters per minute
RF	Radio frequency
TEA	Techno-economic analysis
USA	United States of America
USDA	US Department of Agriculture

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