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Life cycle assessment of the manothermosonication of liquid whole egg: A comparative evaluation with conventional thermal preservation

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ABSTRACT

Manothermosonication (MTS) is a promising alternative to thermal preservation of liquid whole egg (LWE) in terms of safety level and improved quality. However, energy and sustainability assessment of MTS are not well described. This study compared the energy balance and life cycle assessment (LCA) of MTS to traditional thermal preservation of LWE, considering equivalent microbial inactivation levels and a production capacity of 100 kg/h within a “gate to gate” approach.

Results of the energy assessment indicated that MTS preservation consumed 15% less energy (2.00 kWh/kg of LWE) and water compared to thermal preservation (2.36 kWh/kg of LWE). This reduction is attributable to cavitation, the mechanism of action in MTS, which eliminates the need of pre-homogenisation stage and water for heating. Concerning the environmental impact, MTS scored lower in all impact indicators, mainly due to reduced electricity and water usage. For instance, carbon footprint of CO_2 emissions from LWE processing were 57.3% for MTS and 61.8% for thermal preservation, with the environmental impact of the pasteurisation stage being 4.1-fold lower in MTS. This study suggests MTS preservation of LWE is a viable alternative to thermal methods, offering safety, quality, and improved energy and environmental benefits.

1. Introduction

Food processing involves a range of mechanical, thermal, and special processes used for different purposes to convert often non-edible raw materials into edible and safe nutritious foods (Augustin et al., 2016; Knorr & Augustin, 2021). These processes are applied for increasing safety and shelf-life, removal of certain compounds, manipulation of particle size, enrichment of certain compounds, modification of structure of food, and other purposes (Tscheuschner, 2004). Traditional thermal technologies are widely adopted and used for many years mostly due to their high efficiency in food preservation, perceived environmentally friendly aspects, and a relatively inexpensive approach compared to some other preservation technologies. However, thermal technologies are also reported to be one of the most energy-intensive processes in the food industry (Giner et al., 2019), especially in recent time due to fluctuating energy prices obtained from fossil fuels. As a result, food sector actively explores alternatives to traditional thermal treatments which would deliver same level of food safety, same or improved product quality, and improving the overall energy efficiency of the process with a lower environmental impact (Aganovic & Smetana, 2022). Traditional thermal treatments mostly utilise a heating medium, such as steam or hot water generated by the combustion of fossil fuels, which is used to heat up food either indirectly or directly through conduction and convection processes. This approach presents certain challenges related to heat transfer, such as heat losses from equipment surfaces and overheating and quality damage to the food product (Pardo & Zufía, 2012; Pereira & Vicente, 2010). Anyhow, this contributes to additional expenditures of natural resources, resulting in a substantial

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environmental impact, mainly arising from the generation of thermal energy by fuel combustion processes and the atmospheric emissions of carbon dioxide (CO_2) impacting global warming (Mi et al., 2021).

Consequently, a group of technologies commonly called “emerging food processing technologies” have been intensively investigated for a long period of time with the purpose to produce safe and high-quality food products, while representing environmentally friendly processing options. This mostly lies in their different mechanism of action by using mechanical, electrical, electromagnetic, and other forces, which in turn can result in lower energy consumption compared to thermal energy required in some thermal treatments (Aganovic et al., 2017). Manothermosonication (MTS) is an example of emerging food technology based on the combination of ultrasound (US), heating at mild temperatures (40–70 °C), and treatments at elevated pressure (200–500 kPa) (Beitia et al., 2023; López et al., 1994). The simultaneous action of these three hurdles induces a rapid and violent collapse of cavitation bubbles, which constitutes the primary mechanism for microbial inactivation in US treatments (Lorimer & Mason, 1987; Muthukumaran et al., 2006; Raso et al., 1999; Whillock & Harvey, 1997), leading to a more rapid microbial inactivation, while minimising the thermal impact on the food’s heat-sensitive compounds, such as proteins. Consequently, MTS emerges as a promising alternative to the traditional thermal pasteurisation method for liquid food products, such as liquid whole egg (LWE).

Life cycle assessment (LCA) is a methodology used for assessing the environmental impact of products, processes, or services (Andersson et al., 1994). Concerning food technologies, LCA also serves as a methodology to assess the direct environmental influences and to estimate the indirect impacts occurring through the supply chain of a product or a technology (Aganovic et al., 2017). Herein, results of different environmental impact categories can be obtained and integrated into single units as an overview of the technological food process as part of a complex supply chain (Goedkoop et al., 2013; Goedkoop & Spriensma, 2001; Jolliet et al., 2003). Additionally, the stages in food processing where a notable environmental impact, commonly referred to as “environmental hotspots”, can be identified with the LCA analysis (Andersson et al., 1994; Guinée et al., 2011). With this tool, food producers can consider improvements to decrease the overall environmental footprint of food production chains. This is highly attractive for consumers who seek minimally processed food with improved quality attributes and an environmentally friendly production (Devlieghere et al., 2004).

However, to the best of the author’s knowledge, very few studies are available concerning LCA and food processing, in particular emerging technologies (Aganovic et al., 2017; Arnal et al., 2018; Cacace et al., 2020; Pardo & Zufía, 2012), and no studies so far assessed the MTS treatment in terms of environmental impact. Limited number of studies report the advantages of MTS as preservation technology in LWE processing in terms of microbiological food safety (Beitia et al., 2024, 2024b; Mañas et al., 2000) and as a technology that can improve functional properties of egg proteins (e.g., ovalbumin) (Beitia et al., 2025; Sánchez-Gimeno et al., 2006), but the environmental impact of LWE preservation by MTS is currently lacking. Therefore, this study aimed to perform an energy balance and LCA comparison of LWE processing using traditional thermal and alternative MTS preservation technologies on pilot-scale units.

2. Material and methods

2.1. Liquid whole egg preparation

Fresh large-grade “A" eggs produced in Germany were purchased from a local supermarket (Quakenbrück, Germany), from which fresh LWE was prepared. At first, the eggshells were washed with tap water and left to air-dry for 10 min. Afterwards, eggs were opened, and the egg chalazae were filtered out from the samples to directly treat the fresh LWE by manothermosonication (see section 2.2.1).

2.2. Preservation treatments of liquid whole egg

2.2.1. Manothermosonication

A pilot scale MTS equipment was used for the treatment application, as described in Beitia et al. (2024, 2024b). The system consists of (i) US-probe setup (UPI2000, Hielscher, Berlin, Germany) with an 18 mm tip diameter sonotrode (BS2d18, Hielscher, Berlin, Germany), operating at a constant frequency of 20 kHz and with a probe depth of 1.20 cm, (ii) water bath (DIL e.V., Quakenbrück, Germany) as a temperature control system with circulating hot water through the US chamber (closed double jacket cell with 170 mL of capacity), and (iii) valve to increase the pressure in the chamber. The MTS treatment involved a wave amplitude of 132 μm and pressure of 300 kPa, corresponding to a US intensity (UI) of 277.56 W/cm^2. These conditions applied under dynamic thermal conditions were previously determined as optimal for achieving a 5.0 Log_{10} CFU/mL reduction of *Salmonella* Enteritidis DSM 17420 in LWE (Beitia et al., 2024, 2024b). Treatments were applied semi-continuously with recirculation of 500 mL of LWE (initial temperature 40 °C) through the processing chamber (30 s retention time) until reaching a final temperature of 57 °C (3.5 min treatment time), followed by cooling on ice.

2.2.2. Thermal treatment

The traditional thermal pasteurisation treatment of LWE was based on the combination of temperature and time (60 °C for 3.5 min) as recommended by the processing guidelines to achieve the target microbial food safety level, i.e., 5.0 Log_{10} CFU/mL reductions of *Salmonella* spp. (Froning et al., 2002; United States Department of Agriculture - Food Safety and Inspection Service, 2017). The thermal treatment was considered under a theoretical industrial scenario.

2.3. Energy assessment and data collection

Energy required for the preservation of LWE using MTS was experimentally obtained and empirically calculated for the thermal treatment, considering the same microbial inactivation level of *Salmonella* spp. (5.0 Log_{10} CFU/mL) and the same production capacity (100 kg/h) for both treatments. Fig. 1 shows the processing diagram for the MTS and thermal preservation of LWE.

2.3.1. Manothermosonication

Energy requirements for MTS preservation consist of electrical energy consumed by the (i) ultrasonic generator, which is the energy transformed by a piezoelectric transducer into mechanical vibrations, i.e., acoustic waves that propagate through the liquid food product (Beitia et al., 2023), and (ii) energy required to pump the product through the system. The calculation of the energy consumption in the MTS stage was performed for UI of 277.56 W/cm^2 for a front face of 2.5 cm^2 of the sonotrode (18 mm tip diameter). As mentioned in section 2.2.1., treatments were applied in a semi-continuous way, but to perform the energy assessment, continuous processing was assumed where after 3.5 min treatment (theoretical residence time of the product in the MTS treatment chamber), the product reached a temperature of 57 °C and the MTS treatment applied was sufficient to achieve the targeted inactivation (Beitia et al., 2024, 2024b).

As mentioned above, the MTS pasteurisation was applied under dynamic thermal conditions, assuming the LWE processing conditions that would be used in the industry. Moreover, a theoretical optimum scenario with a heat recovery rate of 100% was considered, with values of up to 80% typically found in food processing systems to recover energy losses being more realistic (Mardiana-Idayu & Riffat, 2012; Silva et al., 2023). The “fresh LWE pre-heating” and “LWE pre-cooling” stages (Fig. 1) assumed the 100% heat recovery by (i) reaching the initial temperature of the LWE (40 °C), before the application of MTS, during the “fresh LWE pre-heating” stage, and by (ii) using fully the thermal load after MTS preservation (57 °C) to reduce the temperature of the

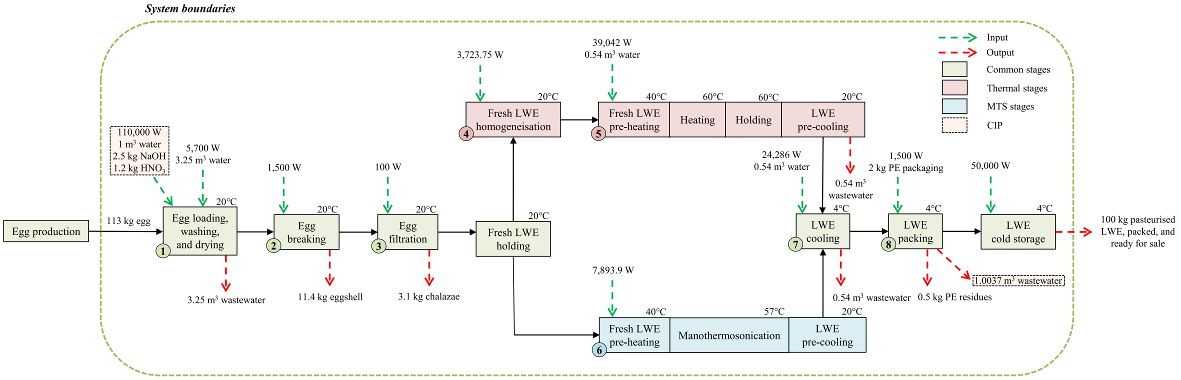

Fig. 1. Representation of "gate-to-gate" system boundaries with the flow chart of the LWE processing (production capacity of 100 kg/h) using MTS (blue boxes) and thermal (red boxes) treatments as preservation technologies, showing the common stages for both scenarios in grey boxes. Inputs (green arrows) and outputs (red arrows) for each stage are shown according to the LCI table (Table 1); inputs and outputs of the CIP procedure appear in a discontinue-line box. The equipment considered for each stage is shown with numbers, according to Table 1.

thermally pasteurised product in the "LWE pre-cooling" stage, before the "LWE cooling" stage. For this last stage, the specific energy (E) needed to reach the product's final temperature (4 °C) was calculated considering an initial temperature of 20 °C in the "LWE cooling" stage, i.e., final temperature after the "LWE pre-cooling" stage, by using equation (1).

$$E = C_p \times \dot{m} \times \Delta T \tag{1}$$

where C_p is the specific heat capacity, being 3.80 J/kg °C for the LWE (Góngora-Nieto et al., 2003), $\dot{m}$ is the mass flowrate (100 kg/h), and ΔT is the required change of temperature (°C).

2.3.2. *Thermal treatment*

Energy requirements in the thermal pasteurisation of LWE were also calculated using equation (1), similar as for MTS requirements (see section 2.3.1). In the "heating" stage, an initial temperature of 40 °C (the final temperature at the "fresh LWE pre-heating" stage) and a final temperature of 60 °C were considered for calculations. However, the same calculation of energy requirement for the "LWE cooling" stage as in MTS and the 100% heat recovery rate for the "fresh LWE pre-heating" and "LWE pre-cooling" stages were considered for the energy requirements.

2.4. *LCA methodology*

The LCA methodology is a standardised approach based on life cycle thinking, employed for evaluating the sustainability of food technologies that follows guidelines established by ISO (International Organization for Standardization) standards (ISO 14040, 2006; ISO 14044, 2006). The design of an LCA study can be approached from three perspectives: responsibility, time frame, and product or technology orientation (Pardo & Zufía, 2012). The current study is based on a technology orientation perspective.

2.4.1. *Type and goal*

The LCA methodology could be split in two types of studies based on the analysis objective. On the one hand, attributional studies focus on determining the environmental load of a product's life cycle. On the other hand, consequential studies report on the environmental impacts of a product or technology resulting from decision-making that influences market changes (Guido & Vigon, 2011). In this study, as Hospido et al. (2010) recommended for non-thermal technologies, a prospective attributional LCA study was followed to assess and compare traditional and alternative preservation technologies for LWE processing.

2.4.2. *Scope and boundaries*

Different LCA approaches can be mentioned depending on setting distinct boundaries in the analysis, spanning from raw material extraction to the product's end-of-life, which includes equipment manufacturing and transportation stages (Aganovic & Smetana, 2022). Consequently, the LCA analysis can be categorised into three scopes: "cradle-to-gate," "gate-to-gate," or "cradle-to-grave", depending on the consideration of the raw material production in preceding processes from the technological treatment ("cradle"), the transformation of raw materials into food ("gate-to-gate"), or the end-of-life phase, involving product consumption and waste treatment ("grave"). In this work, the "gate-to-gate" approach was used (Fig. 1), as only the impact from processing stages of LWE production was considered; thus, the environmental impact of each processing stage in the production chain was identified.

2.4.3. *Design of the life cycle inventory*

The life cycle inventory (LCI) used for the LCA performance gathers the inputs (energy, materials, and resources) and outputs generated throughout the preservation process for both technologies (Table 1). As previously described (see section 2.3), the data at the pasteurisation stage were either experimentally measured or theoretically calculated, and data from the other processing stages were taken from industrial devices available online, technical documents, and scientific literature sources. The ecoinvent 3.2 database (ecoinvent, Zurich, Switzerland) was also used for background and missing data. As mentioned, this study aimed to compare the environmental impact of two preservation technologies (traditional thermal and emerging MTS) in LWE considering same capacity continuous production, and using 1 kg of pasteurised LWE, packed, and ready for further sale as a mass-based functional unit (FU). This FU was selected because of the possibility of making other comparisons on a 1 kg basis and further comparisons in future studies. Consequently, the environmental impact obtained by the LCA was expressed per 1 kg of pasteurised LWE, considering equal in both preservation scenarios the raw material input, pre-processing and storage conditions, packaging system using low-density polyethylene (PE), and cleaning-in-place (CIP) procedure. For the CIP data, information from the literature related to milk processing was used (Eide et al., 2003), which included quantities of 2.50 kg of NaOH, 1.20 kg of HNO_3, and 4.25 m^3 of water, assuming that comparable values would be needed in the LWE production. This selection was based on the similarity of processing, conditions, and requirements observed experimentally in previous studies (data are not shown).

Furthermore, different assumptions were made for both treatments to obtain a fair comparison of the LCA studies. First, a baseline scenario of the LWE production in Germany was established (Quakenbrück,

Table 1
Life cycle inventory (LCI) with the main inputs in the processing of LWE by thermal and MTS preservation treatments used for the LCA study ("gate-to-gate" system boundaries), per FU (1 kg of pasteurised LWE, packed, and ready for sale).

Processing stage	Input	Unit	Thermal preservation/MTS preservation		Reference	
			Thermal preservation	Reference	MTS preservation	Reference
Egg loading, washing, and drying	Egg	kg	1.13		Own calculation	
	Energy	W	57		OM-EGGW, Yaoji Industrial Investment, Shenzhen, China Eide et al., 2003 (1)	
	Water	m^3	0.03		Eide et al., 2003; OM-EGGW, Yaoji Industrial Investment, Shenzhen, China (1)	
Egg breaking	Energy	W	15		BT 14, Avitec Srl, Milan, Italy (2)	
Egg filtration	Energy	W	1		FS, OVO-TECH, Boczna, Poland (3)	
Fresh LWE homogenisation	Energy	W	37.24	Ayari et al., 2020; ETKF-M, ERDURO, Selçuklu, Turkey (4)	–	–
Thermal treatment - *Fresh LWE pre-heating* - *Heating* - *Holding* - *LWE pre-cooling*	Energy	W	390.42	TEK-PH-M, SIPE TEKMASH Institute, Ukraine (5); ETKF-M, ERDURO, Selçuklu, Turkey (5); own calculation	–	–
	Water	m^3	0.01	Gut et al. (2003)	–	–
MTS treatment - *Fresh LWE pre-heating* - *MTS* - *LWE pre-cooling*	Energy	W	–	–	78.94	TEK-PH-M, SIPE TEKMASH Institute, Ukraine (6); own calculation
LWE cooling	Energy	W	242.86		Ba-60-50, NordicTec EU, Szydłowiec, Poland (7); ETKF-M, ERDURO, Selçuklu, Turkey (7); own calculation	
	Water	m^3	0.01		Gut et al. (2003)	
LWE packing	Energy	W	15		AUSIV-3220L, Azeus Food Machines, Zhengzhou, China (8)	
	Packaging	kg	0.02		Own calculation	
LWE cold storage	Energy	W	500		Evans et al. (2015)	
CIP	Energy	W	1100		Eide et al. (2003)	
	Water	m^3	0.01			
	NaOH	kg	0.03			
	HNO_3	kg	0.01			

Lower Saxony), which included the use of a mix of energy and water from the grid, considering the cut-off approach (residual approach), as the waste generated through the process can be recycled, but without the same interest as in the production of animal feed and PE (Williams & Eikenaar, 2022). Furthermore, the labelling of the final product post-packing fell outside the scope of the LCA study, as it could have encompassed different types of labelling without significantly impacting the final result. Concerning the organic waste (eggshells and chalazae) generated from the production steps, a biowaste treatment was considered up to the point of industrial composting, and the recycling option of unsorted PE waste was selected from ecoinvent 3.2. However, the environmental impact associated with the production of raw material (e.g., enriched cage egg production in Europe) was not considered in this study, as it was found to represent more than 98% of the total environmental impact from the LWE production (data are not shown).

2.4.4. Life cycle impact assessment

The IMPACT WORLD + methodology V1.02 (the updated version of IMPACT 2002+ methodology) was employed, basing the results analysis on the main weighted midpoint impact categories, such as climate change, freshwater ecotoxicity, or non-cancer human toxicity (Bulle et al., 2019). The selection of this methodology and the associated environmental impact categories was based on previous studies that compared emerging sustainable food technologies, like high-pressure processing and pulsed electric fields, with conventional thermal methods (Aganovic et al., 2017). The LCA study used SimaPro 9.5.0.2 software (PRé Consulting, Amersfoort, The Netherlands) and the ecoinvent 3.2 database (ecoinvent, Zurich, Switzerland). From the different results obtained in the study, Monte Carlo Simulation analyses with 10,000 rounds were used for the uncertainty calculations, leading to comparisons between LWE preservation by MTS and thermal treatments.

3. Results and discussion

3.1. Energy assessment and comparison

From the energy assessment, the energy requirements for the LWE processing by MTS and thermal preservation treatments for reaching the targeted microbial inactivation were found to be 200.98 and 235.85 kWh, respectively. Considering a production rate of 100 kg/h, the energy consumption for thermal preservation was determined to be 15.25% higher compared to MTS preservation.

The lower energy consumption associated with MTS processing can be attributed to several factors. Firstly, thermal preservation includes a pre-processing "fresh LWE homogenisation" (usually between 10 and 25 MPa) (Ayari et al., 2020), required to homogenise the egg components (egg white and egg yolk) to (i) prevent their post-processing separation and (ii) control the LWE viscosity, reducing overheating during the high-temperature application. However, the MTS processing does not need that homogenisation because of the cavitation. This phenomenon involves continuous cycles of microbubble creation and implosion cycles in the product medium, allowing the breakage of the fat particles into smaller particles. Consequently, there is a mixture of the egg white and egg yolk which limits its post-separation and allows to obtain a product with a controlled viscosity (Modarres-Gheisari et al., 2019; Taha et al., 2020). Additionally, as a result of cavitation, there is a release of large amounts of energy called "hot spots," associated with sudden pressure rises to 100 MPa and high temperatures of around 5000 K that result in an increase of the product temperature (Ferrante et al., 2007; Herceg et al., 2013; Scherba et al., 1991). Consequently, no additional thermal energy is required to be applied to reach the target final temperature of the product in MTS (57 °C). In contrast, in thermal pasteurisation, the temperature required during the holding stage needs to be at least 60 °C, which is 3 °C higher than in MTS treatment. Furthermore, the thermal gap between the product under analysis (in this case LWE) and heating mediums (such as water), measured at 6 °C in this study, needs to be considered for the comparison. This gap leads to higher energy consumption in traditional thermal processing compared to novel MTS methods.

When considering the energy requirements at the "pasteurisation" stage for both treatments, the same egg pasteuriser (No 5 for thermal treatment and No 6 for MTS in Fig. 1) was used in this study. This decision stems from the current unavailability of industrial equipment for continuous microbial food preservation of LWE using MTS. However, currently, different companies offer US equipment at an industrial scale. Detailed energy requirements at the "pasteurisation" stage involve 7.2 kWh for the pasteuriser operation and pumping system for both processing lines (MTS and thermal) and 31.84 kWh for the heat exchanger operation (including pumping system and warming up the heating medium) for the thermal scenario. Similarly, the highest rate of energy recovery (100%, as an ideal scenario) was assumed for (i) "pasteurisation" stages; (ii) "fresh LWE pre-heating" stages of the non-pasteurised LWE (20 °C) with the pasteurised LWE at high temperature; (iii) "LWE pre-cooling" stages of the pasteurised LWE at high temperature with the non-pasteurised LWE (20 °C) before cooling. Regarding the "pasteurisation" stage in the MTS scenario, crucial processing parameters for the technology need to be considered for maximising the energy efficiency and achieving the target microbial inactivation level, such as the UI, which is directly related to the processing parameters of wave amplitude and pressure applied during the treatment.

Pasteurisation of LWE is targeted to achieve a microbial inactivation level of *Salmonella* spp. of 5.0 Log_{10} CFU/mL, which was the basis for comparing both technologies in this study. However, other quality aspects need to be considered in the design of the preservation process of LWE, such as protein quality and potential denaturation due to the exposure to high temperatures. For example, conalbumin (ovotransferrin) is considered to be the most sensitive heat-sensible egg protein, starting to denaturate at 57 °C and being completely insoluble and precipitates after its coagulation at approximately 63 °C (Arzeni et al., 2012; Higuera-Barraza et al., 2016). The MTS treatment in this study achieved the target inactivation after 3.5 min from an initial temperature of 40 °C, and a final temperature of 57 °C. The treatment ended after reaching the temperature threshold for protein denaturation (57 °C), without requiring additional holing time at such temperature, due to the benefits of cavitation and its lethal microbial effects. However, in the case of conventional thermal processing, higher temperatures of up to 60 °C are required, for which an isothermal scenario is considered, which accounts for microbial inactivation. As a result, the protein denaturation of LWE during thermal pasteurisation needs to be monitored over LWE processing, resulting in the most frequent stops during production due to occasional blockages of the pipes in egg pasteurisers, which seizes operation for hours while cleaning takes place (Hamid-Samimi et al., 1984).

Consequently, this situation leads to a more frequent application of the CIP procedure in the thermal treatment than in MTS, influencing a higher energy consumption and consumption of chemical products, which have a direct environmental impact and can slow down LWE production. Additionally, the CIP procedure has an important contribution to the environmental impact of a food processing chain; for example, CIP is known to be one of the most environmentally impactful stages in dairy production for the entire life cycle (Eide et al., 2003). The energy assessment and the LCA in this study was based on a 100 kg/h production capacity. The real issues and consequences resulting from the protein denaturation should be considered in terms of energy consumption and environmental impact with a more detailed information and for a larger industry-relevant production capacity.

3.2. *Life cycle impact assessment*

Results obtained from the LCA studies of LWE processing with thermal and MTS preservation are presented by comparing the environmental impact indicators with its uncertainty analysis.

3.2.1. *Environmental impact indicators*

The analysis of the midpoint environmental impact indicators obtained from the LCA studies (Table 2) revealed that LWE preservation by MTS was beneficial in all studied categories compared to LWE thermal preservation. In this sense, Figure S1 (see Supplementary) shows a comparison of the obtained environmental indicators for the MTS preservation scenario compared to a 100% score for the indicators resulting from the thermal preservation scenario. As mentioned before, the thermal preservation line accounted for "fresh LWE homogenisation", "heating", and "holding" stages and then demanded higher energy consumption than the MTS preservation line, as mentioned in section 3.1. Consequently, this higher energy demand may be the reason for a high environmental impact score in LWE processed by traditional thermal treatment.

The environmental indicator "climate change", which is associated with the carbon footprint and CO_2 emissions, has often been proposed in the scientific literature as a representative impact category for the environmental contribution of the food sector because of its significant global relevance (Arnal et al., 2018; Bartocci et al., 2020). Consequently, by looking at the midpoint indicator of climate change (short term), in the case of LWE processing with MTS, where 0.51 kg CO_2 eq/kg of LWE is generated, 42.7% of the CO_2 emissions can be attributed to the CIP procedure, delivering the rest of the CO_2 emissions from the processing stages (57.3%). From them, the stage with a major contribution to climate change was found to be the "LWE cold storage" stage (19.2%), followed by the "LWE packing" stage (14.1%), where the production and use of the packing material (PE) represented the 9.4% of the CO_2 emissions in the processing. However, just 3.3% of the CO_2 emissions were attributed to the MTS pasteurisation treatment. Similarly, Tsai

Table 2
Environmental impact indicators of the LWE processing with thermal and MTS preservation treatments obtained in the LCA study using the IMPACT WORLD + methodology V1.02 (FU: 1 kg of pasteurised LWE, packed, and ready for sale).

Midpoint impact categories	Units	Thermal preservation	MTS preservation
Climate change, short term	kg CO_2 eq	0.58	0.51
Climate change, long term	kg CO_2 eq	0.55	0.48
Fossil and nuclear energy use	MJ deprived	9.15	8.15
Mineral resources use	kg deprived	0.01	0.01
Photochemical oxidant formation	kg NMVOC eq	$1.00 \bullet 10^{-3}$	$9.00 \bullet 10^{-4}$
Ozone layer depletion	kg CFC-11 eq	$2.63 \bullet 10^{-8}$	$2.36 \bullet 10^{-8}$
Freshwater ecotoxicity	CTUe	9023.93	7640.73
Human toxicity, cancer	CTUh	$7.04 \bullet 10^{-8}$	$6.11 \bullet 10^{-8}$
Human toxicity, non-cancer	CTUh	$1.40 \bullet 10^{-7}$	$1.21 \bullet 10^{-7}$
Freshwater acidification	kg SO_2 eq	$3.34 \bullet 10^{-9}$	$2.98 \bullet 10^{-9}$
Terrestrial acidification	kg SO_2 eq	$2.99 \bullet 10^{-6}$	$2.69 \bullet 10^{-6}$
Freshwater eutrophication	kg PO_4 eq	$2.45 \bullet 10^{-5}$	$2.20 \bullet 10^{-5}$
Marine eutrophication	kg N eq	$3.10 \bullet 10^{-4}$	$2.79 \bullet 10^{-4}$
Particulate matter formation	kg PM2.5 eq	$1.22 \bullet 10^{-4}$	$1.11 \bullet 10^{-4}$
Ionising radiation	Bq C-14 eq	9.62	8.38
Land transformation, biodiversity	m^2yr arable	$7.68 \bullet 10^{-5}$	$6.61 \bullet 10^{-5}$
Land occupation, biodiversity	m^2yr arable	0.01	0.01
Water scarcity	m^3 world eq	0.16	0.15

et al. (2021) also reported that the refrigerated storage of final products was one of the major contributors to the environmental impact of egg yolk powder production because of the electricity consumption. In the case of thermal processing, a higher score of 0.58 kg CO_2 eq/kg of LWE was obtained, resulting in 61.8% of the CO_2 emissions from the processing stages (38.2% attributed to the CIP procedure), supposing a higher environmental impact in the climate change indicator than in the processing by MTS. In the thermal LWE processing, the pasteurisation treatment represented 13.5% of the contribution, which means 4.1-fold more than the MTS pasteurisation treatment. However, similar as in MTS processing, the cold storage of the pasteurised and packed LWE represented the highest contribution among the processing stages (17%). A comparison between the contribution in the climate change indicator of the different processing stages and the CIP procedure of the MTS and thermal LWE processing is presented in Fig. 2.

Furthermore, electricity consumption was the main factor in the LWE processing chain for the climate change indicator contribution, representing 0.40 and 0.47 kg CO_2 eq/kg of LWE for the MTS and thermal scenarios, respectively (Fig. 3). Hence, the lower electricity consumption in the LWE processing by MTS would result in lower CO_2 emissions. However, it is not only electricity consumption that influences the climate change indicator; scores on other environmental indicators may also be affected. For instance, high electricity consumption is also related to a high score of non-cancer human toxicity due to using resources such as lignite and coal and the large pollutant emissions delivered from the energy generation in the combustion process (Tsai et al., 2021). Consequently, a higher environmental impact of the non-cancer human toxicity category was found in the thermally ($1.40 \bullet 10^{-7}$ CTUh/kg of LWE) than in MTS preserved LWE ($1.21 \bullet 10^{-7}$ CTUh/kg of LWE). Herein, the use of renewable energy sources, such as wind, solar, and hydroelectric energy, may reduce the overall environmental impact associated with the use of energy, i.e., climate change and non-cancer human toxicity, among others, as suggested by Tsangas et al. (2020) and Zdravkovic et al. (2021). Moreover, Tsai et al. (2021) found that the introduction of such renewable energy sources (electrical heating, solar heating and pumping, and membrane treatment of wastewater) as technology to incorporate in the CIP stage is supposed to result in a slight overall environmental improvement because of the replacement of the polluting nature electricity supply (coal-fired).

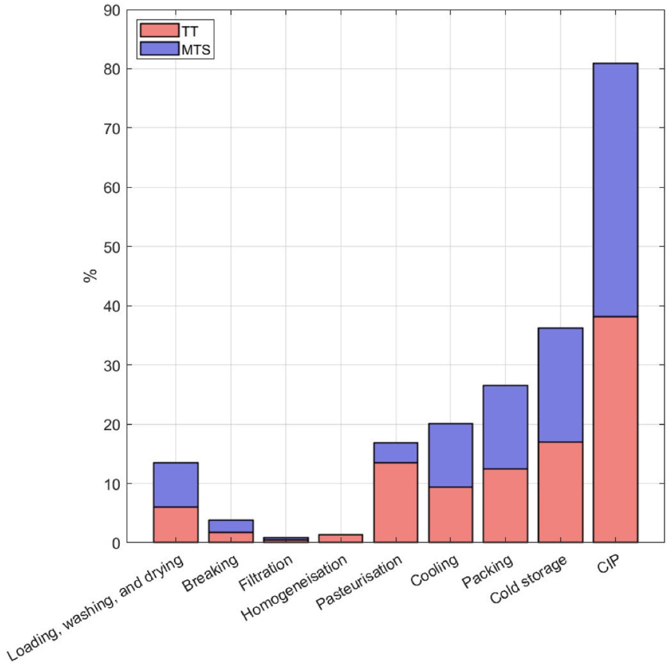

Fig. 2. Comparison of the contribution to the climate change (short term) indicator, in %, of the different stages and the CIP procedure for the LWE processing with MTS (in blue) and thermal (in red) preservation treatments.

Regarding the residues generated during the LWE processing (e.g., eggshells, chalazae, wastewater, and PE), a higher wastewater generation is expected in thermal preservation due to increased water consumption. However, the analysis assumes certain operational conditions that may not fully reflect real industrial processes, such as variations in cleaning cycles or water reuse strategies, potentially leading to discrepancies in actual wastewater volumes and affecting the environmental impact assessment. As a result, for the water scarcity and freshwater ecotoxicity indicators, the “egg loading, washing, and dying” stage is supposed to make the highest contribution in both processing lines, followed by the wastewater generated after the CIP procedure. However, the thermal processing line accounts for an extra stage where wastewater is generated, i.e., the “pasteurisation” stage. Higher water scarcity and freshwater ecotoxicity scores are expected in thermal processing (0.16 m^3 world eq/kg of LWE and 9023.93 CTUe/kg of LWE, respectively) than in MTS processing (0.15 m^3 world eq/kg of LWE and 7640.73 CTUe/kg of LWE, respectively), as the MTS “pasteurisation” does not require the use heating medium to increase the temperature of the product. This is particularly significant given that water usage represents a significant challenge for the food industry (Pardo & Zufía, 2012).

As mentioned in section 2.4.3, the production of raw materials (egg production) was not considered in the LCA study, as its environmental impact contribution was shown to be around 98% of the final result. The same situation was found in other LCA studies conducted previously, with the highest environmental impact found in raw material food production, e.g., fruit cultivation, rather than in technological processing (Aganovic et al., 2017; Doublet et al., 2013; Khanali et al., 2020; Zdravkovic et al., 2021). Concerning the production of eggs, the study of Pelletier et al. (2013) evaluated the carbon footprint of intensive egg production and egg processing supply chains in the Midwestern United States during the year 2009 to quantify life-cycle greenhouse gas emissions and recommend measures to achieve a more efficient egg industry standards. Results obtained from their study found that the production of eggs (feeding of hens) had the highest environmental impact, resulting in the highest emissions in egg production. However, stages related to egg processing and breaking, i.e., stages covered in the current study, are supposed to be just 3% of the total egg chain emissions. Similarly, further LCA studies conducted in the egg production field agreed that the production and formulation of animal feed represented one of the major negative environmental contributions throughout the processing chain (Abín et al., 2018; Ghasempour & Ahmadi, 2016; Guillaume et al., 2022).

To the best of the author’s knowledge, this is the first LCA study considering the preservation of egg products inside the egg processing, with both traditional (thermal) technologies and emerging technologies, MTS, in this case. Additionally, there is a lack of studies on egg processing that have been subjected to LCA studies. For instance, Tsai et al. (2021) performed an LCA study on producing egg yolk powder by spray drying, especially in the CIP operations in the dryer stage. In the study, two scenarios of applying the CIP procedure were investigated (intermittent flow of aqueous NaOH cleaning solution *vs.* standard, continuous, and steady cleaning solution flow), resulting in the intermittent flow in the reduction of the environmental impact in all of the study categories by approximately half score. These refer to emissions delivered from thermal energy and wastewater that are significant in food processing. Previous LCA studies of two novel technologies which are already in an industrial state (high-pressure processing and pulsed electric fields) were performed in fruit and vegetable juice (Aganovic et al., 2017; Cacace et al., 2020; Davis et al., 2010) or ready-to-eat meal processing (Pardo & Zufía, 2012), for which an environmental benefit was reported with the introduction of such technologies in the food processing. Concerning US technology, only LCA studies in food applications can be found in the extraction of valuable food compounds, like

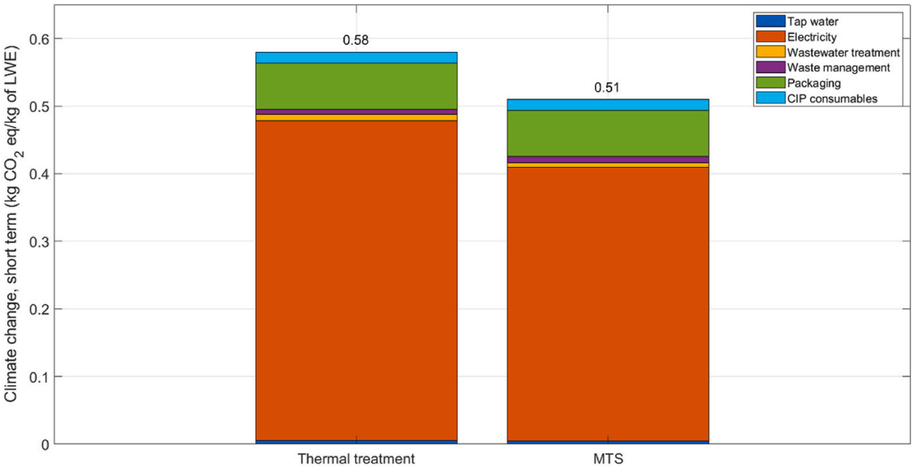

Fig. 3. Comparison of the contribution to the climate change (short term) indicator, in kg CO_2 eq/kg of LWE, of the main factors (inputs and outputs) of the LWE processing with thermal and MTS preservation treatments. The different factors are shown in the bars with different color: tap water (in dark blue), electricity (in red), wastewater treatment (in orange), waste management (in purple), packaging (in green), and CIP consumables (in light blue).

β-carotene from carrots and microalgae (Kyriakopoulou et al., 2015) and polyphenols from chicory (Vauchel et al., 2018), obtaining better environmental indicators in the extraction process assisted by US.

3.2.2. Uncertainty analysis

The uncertainty of the midpoint environmental indicators obtained from the Monte Carlo analysis performed for the two LWE processing line scenarios is presented in Figure S2 (see Supplementary). As can be seen, no significant differences ($p > 0.05$) were found in all the environmental indicators investigated between the LWE processing lines with MTS and thermal treatments. Moreover, a low uncertainty was obtained in most of the environmental categories, indicating an accurate dispersion of the LCA results. However, the human toxicity (cancer and non-cancer), ionising radiation, and water scarcity indicators showed higher uncertainty results. The increased dispersion in these environmental indicators can be explained by the variability in some of the background data sourced from the database used for the LCA study, which may include diverse geographic, technological, or temporal conditions that impact these categories.

Furthermore, the comparison of the uncertainty for both scenarios in LWE processing made with the Monte Carlo approach is presented in Fig. 4. As can be seen, the obtained score of all impact categories was higher for processing with thermal preservation, considering a 100% impact score, except for the non-cancer human toxicity and water scarcity categories, where thermal preservation was higher at 83.3% and 56.2% than MTS preservation, respectively. Regarding the significance of these two last environmental indicators, the use of electricity and water for the processing by MTS is still required, but such demand is expected to be lower than in thermal processing, as discussed in previous sections. Consequently, the production of LWE using novel MTS as a preservation technology may suggest a more sustainable option than conventional thermal, as lower scores in the evaluated environmental impacts were obtained because of the reduced electricity and water consumption during processing.

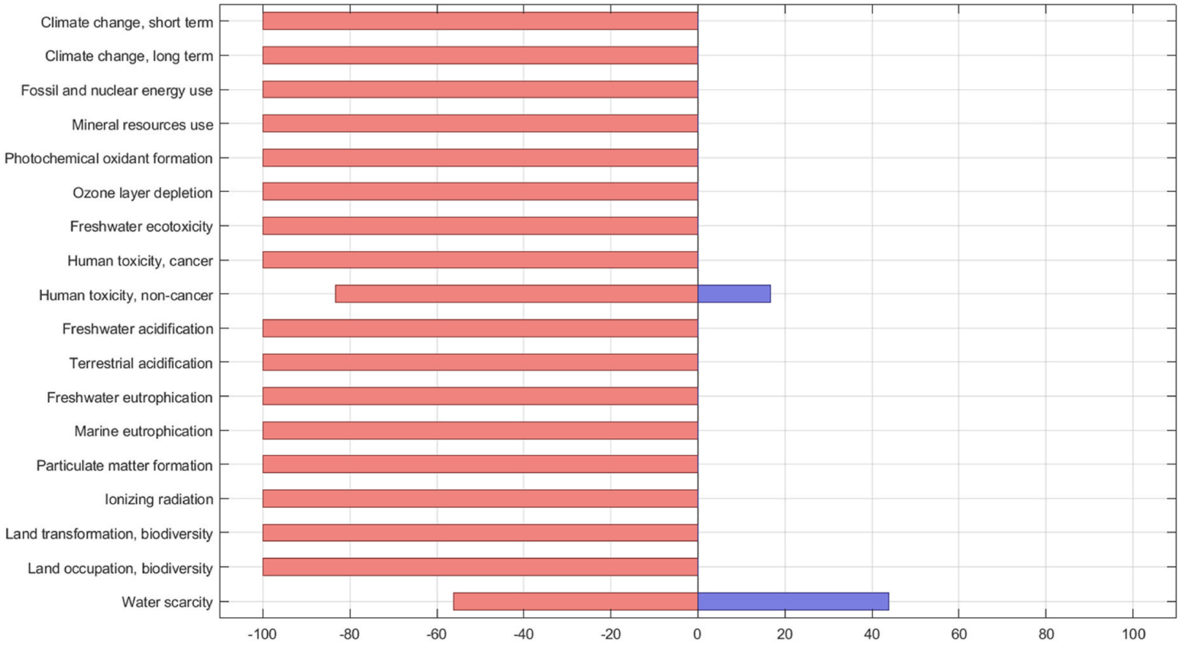

Fig. 4. Comparison of the uncertainty after the Monte Carlo analysis (10,000 runs) for the environmental midpoint indicators obtained for the LWE processing with MTS (in blue) and thermal (in red) preservation treatments by using the IMPACT WORLD + methodology V1.02.

4. Conclusions

The environmental impact comparison of the LWE processing, including the MTS and conventional thermal treatment for the preservation of liquid whole egg, was conducted for a 100 kg/h production capacity. A 15.25% lower energy requirement was found in MTS processing (2.00 kWh/kg of LWE) than in thermal processing (2.36 kWh/kg of LWE). The lower energy demand in MTS was related to the absence of the “fresh LWE homogenisation” stage and differences in the water as a heating medium needed for the “pasteurisation” stage. From the LCA perspective, lower scores in all environmental midpoint indicators were obtained in the MTS processing with “gate to gate” system boundaries, mainly because of lower electricity and water requirements during LWE processing. For instance, for the climate change factor (carbon footprint), 0.51 kg CO_2 eq/kg of LWE is expected in the MTS processing, where a higher 0.58 kg CO_2 eq/kg of LWE will be obtained from the thermal processing. In this sense, the CO_2 emissions from the processing stages were found to be 57.3% in the MTS scenario and 61.8% in the thermal scenario, being the “LWE cold storage” of final products in the processing stage with the largest environmental impact in both cases. However, the “pasteurisation” stage was found to represent a low overall environmental impact, but thermal preservation had 4.1-fold higher CO_2 emissions than MTS preservation.

Consequently, innovative technologies, like MTS in LWE processing, may reduce energy and water consumption, leading to a lower positive environmental impact. Additionally, MTS has shown potential advantages in preserving and improving LWE techno-functionality while maintaining the same level of food safety as traditional thermal treatments. However, a sensitivity analysis on different heat recovery rates (e.g., 50%, 70%, or 90%) could provide valuable insights into how varying recovery efficiencies impact the overall energy savings and environmental benefits of MTS compared to conventional thermal methods. Likewise, further studies collecting experimental industrial data are necessary to confirm these results, particularly in terms of product and technology safety, product quality, and sustainability.

CRediT authorship contribution statement

Enrique Beitia: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Beatriz Q. Silva:** Writing – review & editing, Software, Methodology, Formal analysis. **Sergiy Smetana:** Writing – review & editing, Software, Methodology. **Volker Heinz:** Writing – review & editing, Resources, Funding acquisition. **Vasilis Valdramidis:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Kemal Aganovic:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2024.116953.

Data availability

Data will be made available on request.

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