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Environmental sustainability in dairy production: A comparative life cycle assessment of conventional and ozone-based ripening for 'Toma Piemontese' raw milk cheese

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ABSTRACT

Ozone technology enhances cheese ripening, thereby improving shelf life, food safety, and reducing waste. Traditional methods, such as manual brushing for controlling microbial growth, are time-consuming and less effective than modern techniques such as gaseous ozone treatment. A Life Cycle Assessment (LCA) method was applied to compare the environmental impacts of a conventional and an innovative ozone system for Toma Piemontese cheese ripening. Our analysis includes three functional units (FU). Results show small differences in the ecological footprints of the compared systems for 1 kg of ripened cheese, with slight increases in impacts for the innovative system in non-carcinogenic toxicity (+4.0 %) and fine particulate matter formation (+2.0 %). Ozone treatment extends the shelf life of cheese by 21 days, leading to about a 25 % reduction in overall impact per lifespan unit compared to the conventional system. Despite a 32.1 % increase in technology investment, automation leads to notable operational savings, improving environmental and economic performance. Accordingly, the innovative system reduces supply costs and improves energy efficiency, improving its impacts per economic unit by 8.2 % compared to those of the conventional system. In general, findings reveal that energy for thermal conditioning remains a major contributor to the ecological footprints of both systems. We argue that the innovative system offers clear ecological, economic, and social benefits, positioning ozone technology as a viable solution for sustainable production, especially for raw milk cheeses. However, future research should explore consumer acceptance of ozone technology and the integration of renewable energy sources to further improve sustainability.

1. Introduction

The agri-food sector directly affects global health and society through food production, processing, and distribution. Nutrition-related diseases often stem from unsustainable food systems, while cultural and traditional factors limit dietary change [1]. Promoting healthier food systems and diets is crucial to addressing these challenges [2]. The sector also drives economic growth through employment, exports, and value chains. For small farms in rural areas, it ensures livelihoods, food security, and local sustainability [3]. In light of climate and resource challenges, sustainable dairy systems aim to meet rising demand while reducing environmental impacts [4,5]. Milk and dairy products are key to a balanced diet due to their high nutritional value, digestibility, and efficient nutrient absorption [6]. Cheese, in particular, is among the most widely consumed dairy products globally [7]. However, ensuring their safety requires strict processing standards [8], requiring significant resources and energy and contributing to substantial environmental impacts [9]. Notably, dairy production accounts for 27 % of food-related GHG emissions in Europe [10,11].

In Italy, the dairy sector is one of the most significant branches of the food industry. According to Ismea, in 2023, the milk and dairy products sector contributed 8.5 % of Italy's total export value—a trend that continues into 2024, with a 9.6 % increase in the first months of the year compared to the same period in 2023 [12]. The rise in milk production has increased its availability [13]. Most of the milk produced is destined for processing into more stable and long-lasting products, many of which carry certifications such as Geographical Indication (GI), a key driver of the national economy. GI-related value is unevenly distributed, with 20 % of provinces generating over 80 % of the total, with the North-East and North-West regions leading [14]. The Protected Designation of

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Origin (PDO), one of the most important GI certifications, has grown for the third consecutive year in the food sector, reaching €9.17 billion in production value in 2023 (+3.5 % annual growth, +44 % since 2013) and generating nearly €18 billion in final consumer sales (+3.6 %). Cheese performed exceptionally well, with a 5.3 % increase, surpassing €5.5 billion for the first time and achieving the highest production levels in the last five years [15]. The competitiveness of Italian dairy farms is supported by innovative technologies that improve energy efficiency. In this context, sustainable innovation strengthens bio-cultural heritage, economic resilience, and environmental protection [16], with energy management playing a crucial role due to the high demands of dairy processing [17]. However, dairy farms face barriers such as limited awareness of energy efficiency measures, operational heterogeneity, and the lack of quantitative data on energy consumption. These challenges, along with the structural paradigm shift in energy markets, highlight the critical role of balanced policies and supportive mechanisms such as energy audits in driving energy efficiency improvements and economic sustainability [18]. In this context, the new Regulation (EU) 2024/1143 introduces measures to foster sustainability in GIs, mainly through more effective tools supporting the competitive and sustainable development of high-quality production [19].

In dairy systems, several conventional methods are adopted to optimize energy consumption, particularly for milk thermal treatments [20,21], such as pasteurization, sterilization, and Ultra High Treatment (UHT) processing to control pathogenic and microbial contaminants [22]. Additionally, traditional methods without thermal energy during ripening, e.g. the use of saline solutions and cheese brushing, are commonly applied to raw milk cheeses to ensure proper aging and microbial stability. However, these methods may prove ineffective due to labor, supply issues, and potential quality concerns [4,23], leading to i) additional production costs, ii) losses of merchantable product iii) cumulative ecological risks across further environmental domains and iv) shortened product shelf life. In this regard, thermal treatments of milk can be fully or partially offset by adopting modern technologies that are considered more beneficial for consumers, eco-friendly, and cost-effective for food processing and preservation [24]. Ozone, a triatomic form of oxygen molecule with an oxidation potential of −2.07 V, offers innovative solutions for addressing environmental and production challenges due to its antimicrobial sanitization efficacy and absence of harmful residues, promoting it as a sustainable option [4]. While its use in production may require initial investment [25], studies confirm its effectiveness in cheese making against spoilage microflora and pests, without compromising quality [23,26–29]. As early as 2001, the Food and Drug Administration (FDA) classified ozone as a food additive, recognizing it as a GRAS (Generally Recognized As Safe) element [30]. To date, the EU regulatory framework has recognized ozone as a biocidal substance under Regulation n° 528 [31]. Disinfectants like ozone can only be manufactured, marketed, and used in the European Union based on authorization under this regulation and relevant national laws of each Member State. Regarding workplace safety, its oxidative properties may pose potential toxicity risks at low concentrations (0.02–0.04 ppm in air) and exposure duration. Therefore, several limitations on the use of ozone have been imposed for human safety, e.g. 0.1 ppm for gaseous ozone in food industry workplaces and 8 h of exposure by the Occupational Safety and Health Administration [32] and 0.3 ppm twice daily for 15 min by the Comitato Nazionale per la Sicurezza Alimentare (CNSA) of the Italian Ministry of Health [33]. To avoid any potential health risk, high-concentration ozone treatments can be conducted without the presence of workers, e.g., by night or during weekly closures [4].

Given this context, the sustainable development of dairy systems and the use of modern technologies call for an integrated evaluation of ecological, economic, and socio-cultural factors to balance environmental performance, food safety, and farm profitability [34,35]. Life cycle Assessment (LCA) is the most widely used methodology for assessing the sustainability of dairy systems [9,36–39]. This method offers the great advantage of analysing the environmental impacts of a product system both throughout its whole life cycle and in relation to specific production processes. LCA helps identify environmental hotspots (i.e., where the most significant environmental impacts occur) and understand impact drivers to guide sustainability improvements [40]. It also enables comparisons between conventional and innovative systems and is widely used to assess the effectiveness of technological innovations in agri-food (e.g., [41]). Üçtuğ et al. [9] found cheese to be the most studied dairy product in LCA, with carbon footprint (CF) being the most common indicator. Using 1 kg of aged cheese (2–3 months ripening) as a functional unit (FU), Rossi et al. [42] reported a CF of 15.34 kg CO_2 eq.—the highest among milk-based products. Over 50 % of the GHG emissions occurred during cheese making, primarily due to energy consumption for manufacturing operations and cold storage. Electricity consumption, heating and refrigerants are the key impacting factors affecting the aging/storage phase, as observed by Ramirez et al. [43], Xu et al. [44], and Kim et al. [45]. In the study by Dalla Riva et al. [46], the environmental analysis of Asiago PDO cheese focused on manufacturing processes. Energy and fuel consumption were identified as key processes for improving efficiency and developing mitigation strategies. Although LCA analyses are increasing, comparative studies between traditional and modern technologies remain limited, hindering a full understanding of their role in sustainable dairy development. Most research focuses on ecological aspects, overlooking the broader potential of LCA to address economic and social dimensions. Using different FUs, for instance, could offer more comprehensive impact assessments [47,48].

By adopting an LCA method, the present study aims to assess the environmental impacts of a conventional and an innovative Toma Piemontese raw milk cheese ripening. Specifically, the conventional ripening method, which involves cheese brushing to prevent microflora spoilage, is replaced by an innovative approach using gaseous ozone as a microbial control agent. Using a comparative approach and three different FUs, our research proposes to evaluate the potential benefits of adopting a non-thermal technology in cheese production systems to achieve ecological, social, and economic sustainability. The main outcome of the research is to contribute to the current scientific knowledge supporting the modernization of agri-food industry through sustainable models. These models are oriented towards small-medium farms' food systems and their impacts on environmental, social, and governance spheres. The LCA method was applied using the SimaPro software, following the ISO 14040–14044 [49,50] series standards. The results are presented as the comparison between the environmental impacts of the conventional and the innovative systems basing on i) an equal amount of manufactured biomass, ii) identical monetary gross profit from the ripening process and iii) an equal entity of shelf life of cheese. Finally, main findings of this research are discussed, highlighting the strengths and weaknesses of each compared process, and concluding from a sustainable development perspective.

2. Materials and methods

2.1. Life cycle assessment

2.1.1. Goal & scope definition

This study is part of several experimental research activities conducted in a small-size dairy farm in the Piemonte region, northern Italy (S-O_3-SDairy, I TESORI DELLA TERRA s.c.a.s. ONLUS, Cervasca, Italy), which produces Toma Piemontese Protected Designation of Origin (PDO) cheese made from raw cow's milk. As a PDO-certified product, it embodies the region's heritage and complies with strict standards that balance the risks of raw milk with the added value of traditional cheesemaking, allowing it to command premium prices [51]. The Life cycle Assessment (LCA) method was used to assess the environmental impacts and damages of two different ripening systems of Toma Piemontese cheese. In particular, the environmental performance of a conventional ripening (CR) system, which involves regular manual brushing of cheeses to prevent molds and spoilage microflora, was compared with an innovative ripening (IR) system involving the use of gaseous ozone to control microflora growth. LCA analysis complies with the international standards of the ISO 14040–14044 [49,50] series, respecting the four phases foreseen by the framework rules defined by the international ISO standard.

The LCA analysis focuses exclusively on cheese ripening, the final stage of the dairy production system, as shown in Fig. 1. Cheese ripening begins with its storage in thermal conditioning facilities and it ends after an aging period of 40 days (i.e., medium ripening cycle by the producer) at low temperatures. Both the CR and IR systems implement measures to prevent microflora spoilage during aging. The LCA analysis includes all material and energy flows linked to cheese ripening and related environmental impacts. In contrast, environmental impacts related to transport, distribution, consumption and waste management (organic left-over materials and packaging) are excluded from the LCA analysis.

Three different functional units (FU) were adopted in the LCA analysis in order to evaluate impacts and damages from different perspectives. In accordance with the Product Category Rules [52], which assumes biomass or volume as default units for assessing the environmental performance of agri-food products, the first FU of this study is one kilogram of ripened Toma cheese (1 kg of cheese). The development of innovative sustainable solutions in agri-food systems has implications for key social aspects of sustainability, such as improving food safety and extending shelf life [4]. This topic is particularly addressed for fresh foods with a high microbiological value and rapid spoilage, such as dairy products [53]. The ongoing scientific debate is exploring several strategies to minimize microbial levels of ripened cheese, extending its shelf life, reducing consumer health risks, and lowering food waste [20]. Therefore, a second FU, representing one day of lifespan of a Toma piece (1-day piece^{-1}), was chosen to evaluate how an extended shelf life could affect the environmental performance of the production system. To carry out the ripening trial for the IR system, the availability and usage of additional appliances and energy were required. As a result, dairy farms are often involved in relevant investments, amortizing them over time through the sale of products with anticipated improvements in both quantity and quality. In the agri-food sector, there is increasing emphasis on minimizing environmental impacts of product systems while maximizing farm profits, promoting both environmental and economic sustainability [54]. Accordingly, a business-based FU was adopted to evaluate potential improvement of the system efficiency from an economic perspective. The third FU chosen for the LCA analysis refers to one hundred thousand euro of operating farm profit related to the ripening process (100 K € *rel*-OP).

2.1.2. Life cycle inventory

As stated by the LCA framework based on the ISO standards, primary and secondary data about the CR and IR systems are inventoried. Information was collected from questionnaires administered to farmers during the trial activities, and the Life Cycle Inventory (LCI) of the compared systems was designed as shown in Table 1. Overall, the LCI mostly consists of primary data, which was supplemented with some information from international libraries. Specifically, a streamlining

Table 1
Life cycle inventory (LCI) of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system). Dataset refers to an entire ripening cycle of 15 batches of Toma Piemontese cheese, each batch containing 40 pieces. The ripening process lasts 40 days.

	TECHNOSPHERE		UNIT	CR system	IR system
	Input	Output			
MATTER	*Fresh cheese*		*kg*	2168.7	2117.6
	Water (softened)			167.9	25.0
		Ripened cheese		1800.0	
		Steam (cheese drying)		325.3	317.6
		Waste (cheese decay)		43.4	-
		Ozone gas		-	3.6
		Water (waste)		167.9	25.0
FACILITIY	*Thermal conditioning*		*Piece*	0.0435	
	Ozone device appliance			-	0.0024
	Brush			0.5	-
ENERGY	*Natural gas (combustion)*		*mc*	1.7	-
	Electricity (med. voltage)		*kWh*	2880	2925.6

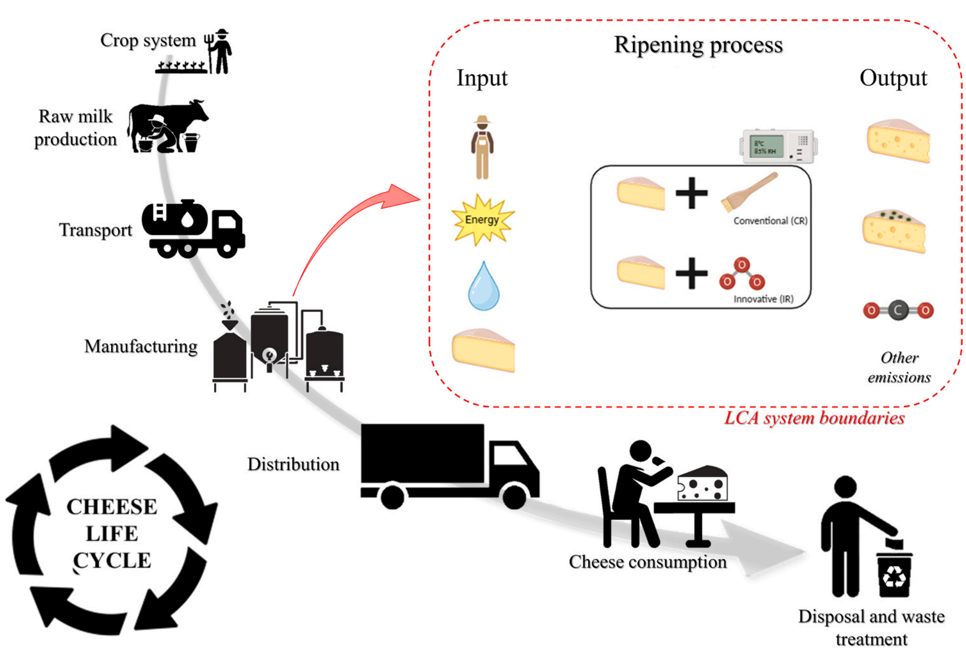


Fig. 1. Definition of system boundaries for the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in Toma Piemontese cheese production.

approach was used during the LCI assembly, involving the use of a few surrogate processes to replace the original ones based on physical, chemical, and functional similarity to the unavailable data. The adoption of the streamlining technique was considered a valid methodological approach considering that the surrogate processes were identified and selected following an expert-based evaluation for the close similarity to the actual processes [55]. As a result, the environmental impact estimates from the LCA analysis have a high level of precision.

The ripening system investigated consisted of a 40-day aging cycle of 15 batches, each comprising 40 pieces of cheese. The ripening system is characterized by two key practices. The first practice refers to thermal conditioning, i.e., storing the cheese at 8°C temperature and 85 % relative humidity. Thermal conditioning is common to both ripening systems. Regarding the second practice, microbial and fungal growth management during the aging period is implemented to prevent the occurrence of molds and spoilage microflora on the surface of stored cheeses. Biochemical dynamics during cheese ripening are critical for product safety, quality and marketability [53]. In the CR system, manual brushing of cheese is performed once a week throughout the entire ripening period. Materials and resources used (i.e., brushes consumption, water, and natural gas for their cleaning) are therefore included in LCI. This traditional method for preventing microbial contamination involves significant time and cost for most small dairy farms, as it requires many work hours from the operators. For this reason, the manual brushing of cheese of the CR system is replaced by the use of an innovative ozone technology in the IR system. An electronic appliance equipped with a central body (ozone generator) and a series of tubes was used to consistently distribute 4–30 g hr^{-1} (400 ppb, 0.856 mg mc^{-3} concentration) of ozone on cheeses stored in the cold room, preventing sediments and residues. Furthermore, the ozone device is equipped with a fan system for room aerating at the end of each treatment. Ozone was administered in 6-hour treatments on alternate days during the night. This scheme avoided any risk to the operators' health [4]. Materials and resources (i.e., ozone appliance and electricity consumption) are therefore included in the IR system LCI.

2.1.3. Impact assessment

For the present study, the SimaPro software version 9.4.0.2 was used, in compliance with the ISO 14040–14044 [49,50] regulation. The reference database used is the Ecoinvent 3.3 database. The impact assessment method chosen for this study is the ReCiPe 2016 method, which allows for the characterization of impacts and damages at three levels of detail (i.e. the midpoint level, which represents the environmental impact on specific environmental issues of high interest; the endpoint level, which represents the consequences in terms of damages on three different global compartments; and the single score level, which represents an overall impact score linked to all environmental consequences), facilitating the interpretation of the results. Specifically, starting from the input/output flows of materials and energy included in the product system inventory, the SimaPro model estimates emissions produced in air, water, and soil compartments by the investigated systems. Based on the estimated emissions, the ReCiPe 2016 method evaluates impacts on 18 environmental issues, referred to as intermediate indicators, defined as "midpoint". In accordance with the EPD [52] procedure, the most relevant impact categories based on the normalised and weighted results of the representative product recalculated after the remodelling were considered for their cumulative contribution to at least 80 % of the total environmental impact. Eight relevant impact categories (midpoints) were identified for the LCA analysis. Due to their specific measurement units, midpoints are not directly interoperable. Through standardization coefficients, midpoint units are converted into units referring to three main damage categories. Damage categories are i) human health expressed in DALY (disability-adjusted life years, representing days of human life lost and/or lived with disabilities), ii) ecosystem quality in species.yr (the number of animal and plant species disappeared globally) and iii) resource depletion in USD (the total value in US dollar of non-renewable terrestrial resources lost). The set of standardization coefficients in this LCA analysis is the "World 2010 H/Official". In this way, through cause-effect chains that link each intermediate impact to one or more final damages, midpoints are aggregated into three endpoint categories by summation. Finally, an overall score of each product system is calculated. This score represents the sum of the three endpoints of the analysed product system. For this purpose, endpoint indicators were normalized into impact scores expressed in points of impact (Pt) through defined normalization factors. All indicators are reported in Table 2. More details about the ReCiPe 2016 Midpoint/Endpoint method can be found in the technical report of Huijbregts et al. [56].

2.2. Shelf life

The use of gaseous ozone to control microflora spoilage and maintain the cheese quality was investigated. In particular, during the ripening phase, the levels of microorganisms, molds, and yeasts on the surface of Toma cheese samples were assessed. The samples were treated using both traditional brushing (control) and the innovative gaseous ozone method, followed by microbiological analyses. Subsamples from the crust area of each cheese sample were collected for microbiological analysis at each ripening time, following the National Organization for Unification and European Standardization (UNI EN) ISO 4833–1 standard [57] for total microorganism counts at 30°C and CCFRA G43 method 2.1.1: 2007 [58] for yeast and mold counts. All analyses were performed in triplicate, with results expressed as Colony Forming Units per gram of product (log_{10} CFU g^{-1}). Key research findings reveal that the use of gaseous ozone during the ripening process significantly affects microflora growth, enhances overall product quality, and notably delays spoilage. Based on the study results, this work attempted to evaluate microbial growth in ripened cheeses from the two systems, in order to assess potential shelf-life extension. The evaluation considered all microbiological indicators (i.e., microorganisms, molds, and yeasts) at 0 (T_0), 10 (T_{10}), 20 (T_{20}), and 30 (T_{30}) days of cheese ripening, with T_{30}

Table 2
ReCiPe midpoints and endpoints considered for the impacts and damages characterization of the compared conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system).

LEVEL	DESCRIPTION	IMPACT/ DAMAGE CATEGORY	UNIT
MIDPOINT	*Intermediate indicators of environmental impact that reflect the changes in the natural environment caused by emissions or resource use*	*Climate change*	kg CO_2 eq
		Fine particulate matter formation	kg $PM_{2.5}$ eq
		Ozone formation	kg NO_x eq
		Terrestrial acidification	kg SO_2 eq
		Human carcinogenic toxicity	kg 1,4-DCB
		Human non-carcinogenic toxicity	kg 1,4-DCB
		Depletion of fossil resources	kg oil eq
		Water consumption	Mc
ENDPOINT	*Final indicators of environmental impacts on three higher aggregation compartments*	*Human health*	DALY
		Ecosystems	species. yr
		Resources	USD
SINGLE SCORE	*Weighted value that combines results of all impact categories into one overall index*	*Total impact*	Pt

representing the minimum ripening period required by farm to place the product on the market. Furthermore, the highest significance for modelling the microbiological growth curves was found in the time interval T_0-T_{30}. Results of the three indicators were standardized to an intermediate indicator with a value of 0–0.3 (recurring decimal) through a min-max method [59]. Finally, an overall 0–1 microbiological index (m-IND) was calculated as the sum of the three intermediate indicators for each system and for each T_n, for a total ripening period of 30 days (T_0-T_{30}). m-IND values are reported in Table 3.

The estimation of m-IND was then used to build two differentiated microflora growth curves during Toma cheese lifespan (Fig. 2). Starting from the m-IND values of CR and IR systems, exponential functions for the period T_0-T_{30} were extracted to reproduce the trend of microflora levels over time for each system. The exponential functions obtained for the CR and IR systems had an R^2 equal to 0.96 and 0.93, respectively. As previously described, the research was conducted in a small-size typical dairy farm of northern Italy. In these farm patterns, dairy systems are usually based on traditional production schemes (i.e., using methods passed down through generations) and local supply of raw materials. In our case, the dairy farm produces Toma cheese from raw milk, i.e. using limited heat treatments before its transformation. The adoption of this procedure contributes to adding cultural value to the produced cheese. However, raw-milk products decay faster, reducing their shelf life from 90 days (as seen with pasteurized-milk cheese) to 60 days for raw-milk cheese, which is the shelf life threshold considered by the producer. Therefore, the m-IND value reached by the CR system microflora curve at T_{60} was assumed as the maximum merchantability threshold (i.e., its best before). Starting from this threshold, the moment T coinciding with that m-IND threshold was also identified on the IR system microflora curve. The methodological approach lastly assessed an increase in the shelf life of cheeses ripened with ozone gas treatment of 21 days compared to cheese ripened with traditional brushing.

2.3. Relative operating farm profit

Table 4 presents the economic incomes and expenditures of the CR and IR systems, aiming to estimate the operating profit (OP) for the two differentiated ripening processes. OP serves as an effective alternative to gross profit as an economic indicator, given that gross profit may not always capture useful insights into the future profitability of system improvements [60]. Given the technological development focus of our research, combining operational and production costs with gross profit provided a more reliable approach to assess the economic sustainability of the investigation.

Similarly to the LCI designing, interviews with the farm operators were conducted to establish a farm budget analysis specifically for the cheese ripening period. Market data (e.g., wholesale cheese selling price at the end of dairy production) and the costs incurred for thermal conditioning and ripening practices in both the CR and IR systems were analysed. Moreover, data relating to dairy farm investments in infrastructure and their usage, maintenance, and lifespan were collected. The gathered information was primarily used to estimate the farm's gross income from cheese sales. For each system, operational costs, along with depreciation and amortization of infrastructure investments, were subtracted from the gross income. As a final point, estimates of the farm OP, specifically for the ripening process for both CR and IR systems, were calculated.

Table 3
Estimates of microbial indicators (i.e., microorganisms, molds, and yeasts) through a min-max standardization method of the microbiological values. Starting from indicators, a single microbial index (m-IND) was then calculated for both conventional ripening system (with brushing; CR system; control) and innovative ripening system (with gaseous ozone use; IR system; ozone) for each time interval of the ripening process.

RIPENING PERIOD	SAMPLE	MICROORGANISMS	MOLDS	YEASTS	m-IND
T_0	*Control*	0.227	0.00	0.00	0.23
	Ozone	0.231	0.00	0.00	0.23
T_{10}	*Control*	0.069	0.24	0.13	0.44
	Ozone	0.000	0.16	0.09	0.26
T_{20}	*Control*	0.176	0.25	0.17	0.60
	Ozone	0.137	0.19	0.12	0.45
T_{30}	*Control*	0.275	0.26	0.28	0.81
	Ozone	0.173	0.24	0.16	0.57

Note: 0 (T_0), 10 (T_{10}), 20 (T_{20}), and 30 (T_{30}) days of cheese ripening.

3. Results

3.1. Ecological footprints of the conventional and innovative ripening system

Table 5 shows the environmental impact characterization of both the conventional (CR) and innovative (IR) ripening systems. In general, for the same amount of biomass produced, the ecological footprints of the IR system are very close to those of the CR system, with slight impact differences ranging from 0.8 % to 4.0 % at the expense of the IR system.

Regarding the three inventory subjects, energy (i.e., natural gas and electricity) accounts for over 95 % of the total impact, representing the largest share of the ecological footprints of both systems. In detail, for 1 kg of ripened cheese, the ecological footprint related to the matter subject for the IR system is approximately 85.1 % lower than that of the CR system. In relation to the facility subject, the IR system displays lower impacts than the CR system on climate change (-28.1 %), fossil resource scarcity (-28.7 %), and water consumption (-24.8 %). On the other hand, the impacts of the IR system on fine particulate matter formation and non-carcinogenic human toxicity are, respectively, 29.9 % and 90.8 % higher than those of the CR system. For the most impactful subject (i.e., energy) of the two ripening systems, the ecological footprints of the CR and IR systems for an equal unit of biomass produced are very similar, with slight differences of 1.0–1.6 % at the expense of the IR system.

Overall, the damage characterization of the compared ripening systems concerning a biomass functional unit (FU) confirms what was observed for their ecological footprints. The Life cycle Assessment (LCA) analysis of the CR and IR systems indeed reveals very similar endpoint values. Specifically, Table 6 shows that, for 1 kg of ripened cheese, the IR system results in 1.8 % more damage to human health, 0.4 % more damage to ecosystems, and 0.2 % less damage to resources.

When comparing the specific subjects, energy once again represents the most damaging one, accounting for between 97.6 % and 97.9 % of the total damages in both ripening systems. While the IR system's matter subject causes 85.1 % less damage than the CR system's for an equal amount of ripened cheese, the damages caused by energy subject in the IR system are greater. Specifically, energy of the IR system results in 1.4 %, 1.3 %, and 0.6 % more damage to human health, ecosystems, and resources, respectively, compared to energy of the CR system. Finally, the facility of the IR system causes 21.2 % more damage to human health than the CR system facility. Conversely, for 1 kg of ripened cheese, the facility of the IR system causes 40.4 % less damage to ecosystems and 37.8 % less damage to resources, respectively, compared to the facility of the CR system.

As shown in Fig. 3, global warming and fine particulate matter formation represent the ecological footprints with the greatest environmental weight on the cheese ripening process for both investigated systems. Specifically, the carbon footprint (CF) accounts for 38.2 % of the environmental performance of the energy subject in both the CR and IR systems. For the matter and facility subjects, the CF contributes 17.3 % and 22.4 % in the CR system, and 17.3 % and 13.6 % in the IR system, respectively. Environmental impacts from fine particulate matter correspond to 25.8 %, 29.6 %, and 39.3 % of the total impacts from the matter, facility, and energy subjects of the CR system, and to 25.8 %,

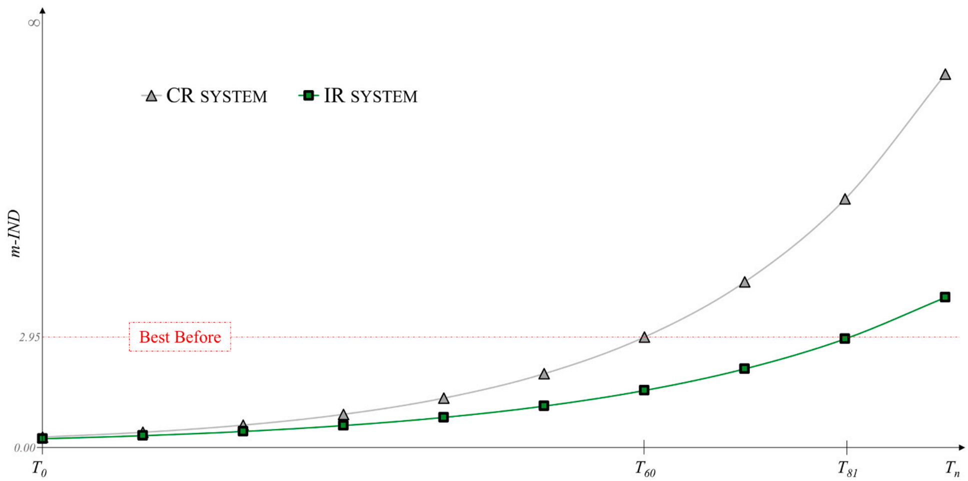


Fig. 2. Growth curves of the microbial index (m-IND) of both conventional ripening system (with brushing; CR system) and innovative ripening system (with gaseous ozone use; IR system) and assessment of the shelf life extension for cheeses ripened with ozone treatment. The m-IND value of the CR system curve at T_{60} is assumed as the maximum merchantability threshold (i.e., its best before) of Toma Piemontese cheese.

Table 4
Inventory of monetary values about inputs and outputs of both conventional ripening system (with brushing; CR system) and innovative ripening system (with gaseous ozone use; IR system), operational information of the two ripening processes, and depreciation/amortizing costs of infrastructures used. Below, the Relative Operating Profit (Rel-OP) is calculated. Monetary values refer to four main items, i.e., Product (main good assessed for its environmental impacts over its entire life cycle), Structural (physical and/or human supports involved in the production system), Supply (provision and availability of resources required for the production system), and Energy (functional power used during the production system). For each investigated system, the dataset refers to a 40-day ripening cycle of 15 batches of Toma Piemontese cheese, each batch containing 40 pieces.

ITEMS				UNIT	CR system	IR system
Budget	*PRODUCT*	*Cheese*	*Selling price*	*€/kg*	13.00	
	STRUCTURAL	*Thermal conditioning*	*Investment*	*€*	96	
		Ozone device appliance		*€*	-	57
		Brush		*€*	19.95	-
	SUPPLY	*Human*	*Labour cost*	*€*	1687.56	-
		Water (softened)	*Service*	*€*	0.13	0.02
		Natural gas (combustion)		*€*	0.72	-
		Waste treatment		*Kg*	563.9	-
	ENERGY	*Electricity (med. voltage)*		*€*	345.6	351.1
Operational	*STRUCTURAL*	*Thermal conditioning*	*Consumption*	*Hours*	960	
		Ozone device		*Hours*	-	120
		Brushing		*Hours*	57.4	-
	SUPPLY	*Water (softened)*		*Lt*	167.9	25.0
		Natural gas (combustion)		*Mc*	1.71	-
	ENERGY	*Electricity (med. voltage)*		*kWh*	2880.0	2925.6
Amortizing	*STRUCTURAL*	*Thermal conditioning*	*Amortizing*	*Hours*	150,000	
		Ozone device	*(lifespan)*	*Hours*	-	50,000
		Brush		*Pieces*	0.5	-
			Revenue	*€*	23,400.00	23,400.00
			Operating Expenses		2034.01	351.09
			Depreciation		563.86	0.00
			Amortization		115.95	153.12
			Relative Operating Profit (Rel-OP)		20,686.18	22,895.79

Table 5
Impact characterization of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in relation to a functional unit equal to 1 kg of ripened cheese.

IMPACT CATEGORY	UNIT	CR Matter	CR Facility	CR Energy	IR Matter	IR Facility	IR Energy
Global warming	*kg CO2 eq*	7,72E−05	7,67E−03	6,29E−01	1,15E−05	5,51E−03	6,37E−01
Ozone formation	*kg NOx eq*	4,93E−07	3,69E−05	2,34E−03	7,34E−08	3,49E−05	2,37E−03
Fine particulate matter	*kg PM2.5 eq*	1,78E−07	1,57E−05	9,52E−04	2,65E−08	2,04E−05	9,66E−04
Terrestrial acidification	*kg SO2 eq*	4,62E−07	3,57E−05	2,38E−03	6,88E−08	3,80E−05	2,42E−03
Human carcinogenic tox.	*kg 1,4-DCB*	4,27E−05	2,78E−03	4,45E−02	6,36E−06	3,05E−03	4,52E−02
Human non-carcinogenic tox	*kg 1,4-DCB*	3,21E−04	2,41E−02	8,47E−01	4,78E−05	4,60E−02	8,60E−01
Fossil resource scarcity	*kg oil eq*	1,77E−05	2,00E−03	1,73E−01	2,64E−06	1,43E−03	1,75E−01
Water consumption	*m3*	1,04E−05	8,41E−05	1,24E−02	1,55E−06	6,33E−05	1,26E−02

Table 6
Damage characterization of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in relation to a functional unit equal to 1 kg of ripened cheese.

DAMAGE CATEGORY	UNIT	CR Matter	CR Facility	CR Energy	IR Matter	IR Facility	IR Energy
Human Health	*DALY*	4,21E−10	3,19E−08	1,54E−06	6,27E−11	3,86E−08	1,56E−06
Ecosystems	*species.yr*	6,87E−13	7,12E−11	3,14E−09	1,02E−13	4,25E−11	3,18E−09
Resources	*USD2013*	4,69E−06	6,48E−04	3,20E−02	6,98E−07	4,03E−04	3,22E−02

32.5 %, and 37.4 % of the IR system, respectively.

Including only 0.7 % of the total impacts of both the CR and IR systems, the water footprint represents one of the least impactful ecological footprints of the ripening process. Despite the water demand for cleaning and maintaining tools and infrastructure, the use of water therefore has negligible environmental consequences for the matter subject. Finally, ozone formation represents the least relevant ecological footprint, with a weighted environmental impact equal to 0.2 % of the total impacts of both the CR and IR systems.

3.2. Effect of an extended shelf life on the environmental performance

According to the Fig. 2, the cheeses ripened with ozone gas treatment (IR system) showed an increase in shelf life of 21 days compared to the control (CR system). Exploring the comparison between the two systems in relation to a FU equal to one day of life of cheese (1-day piece^{-1}) (Table 7), the environmental performance of the IR system was overall better than that of the CR system for all the midpoint indicators considered (all impacts lower by 23.0–25.4 %).

Energy is confirmed as the most impactful process subject for both ripening systems, accounting for 94.0–99.5 % of environmental impacts of the entire process. Relating to the 1-day piece^{-1} FU, the midpoint indicators of the IR system for the matter subject are 89.0 % lower than those of the CR system. As for the facility subject, the environmental impacts of the IR system are generally lower than those of the CR system, except for the Human non-carcinogenic toxicity category. For a same unit (i.e., 1-day piece^{-1}), the CR system shows an impact on Human non-carcinogenic toxicity of 1.20E-03 kg 1,4$^{\text{-DCB}}$, while the corresponding impact of the IR system is 1.70E-03 kg 1,4$^{\text{-DCB}}$, which is 41.3 % higher. Finally, all energy-related impacts in the IR system are 24.8–25.1 % lower than those of the CR system for 1-day piece^{-1}.

In absolute terms, the ripening process mainly causes damages to human health (Fig. 4). For an identical shelf life unit of the ripened cheese (i.e., 1-day piece^{-1}), the damages to human health, ecosystems and resources in the CR system amount to 1.31 mPt, 0.04 mPt and 0.01 mPt, respectively. Meanwhile, the IR system causes 0.99 mPt, 0.03 mPt and 0.01 mPt of damage to human health, ecosystems, and resources, respectively. For 1-day piece^{-1} unit, the damages to human health, ecosystems, and resources in the IR system are therefore lower than those in the CR system by 24.6 %, 25.6 %, and 26.1 %, respectively.

Focusing on the three process subjects, the IR system consistently displays improved environmental performances compared to the CR system for an equal shelf life unit. Furthermore, the energy subject remains the most damaging of the three inventory subjects, accounting for 97.9 % of the total damages in the CR system and 97.6 % of the total damages in the IR system. For 1-day piece^{-1} unit, the facility damages in both CR and IR systems represent only 2.0 % and 2.4 % of the total damage in the two systems, respectively. On the other hand, the damage caused by the matter subject is negligible in both ripening systems.

Comparatively, the total damage of the matter, facility, and energy subjects in the IR system decreases respectively by 89.0 %, 12.1 %, and 24.9 % with respect to the CR system.

3.3. Environmental and economic profitability of ozone use

Considering a monetary FU equal to one hundred thousand euro of operating farm profit relating to the ripening process (100 K € rel-OP), the IR system has all the ecological footprints (here observed as normalized midpoint indicators) between 8.2 % and 8.4 % lower than those of the CR system (Fig. 5). For both investigated systems, the energy item represents the most impactful farm cost item, including between 93.9 % and 98.7 % of the total impacts for each system.

Comparing the two ripening processes, the transition from the CR system to the IR system results in a reduction of all impact indicators for all farm cost items in relation to 100 K € rel-OP unit. As for the structural item, the midpoint categories of the IR system are between 2.6 % and 17.6 % lower than the corresponding ones of the CR system in relation to an equal unit of operating profit (OP). Concerning supply items, the impacts of the IR system for 100 K € rel-OP are lower than those of the CR system for all categories, with a reduction between −2.9 % and 83.5 % among different midpoints. Specifically, the impacts of the supply item of the CR system for 100 K € rel-OP are equal to 0.032 mPt, 0.015 mPt, and 0.004 mPt, respectively, in the categories Human carcinogenic toxicity, Human non-carcinogenic toxicity, and Water consumption. Otherwise, results of the corresponding impacts of the IR system display midpoint values of 0.014 mPt (-55.4 % respect to CR), 0.006 mPt (-60.2 % respect to CR), and 0.001 mPt (-83.5 % respect to CR), respectively. Finally, with regard to the most impactful farm cost item (i.e., energy), the IR system shows a reduction in impact of −8.2 % for all categories compared to the CR system in relation to an equal unit of OP.

In relation to an economic FU, the damages from the most impactful farm cost item (i.e., energy) represent the largest share of the total damage. For 100 K € rel-OP, the energy item of the CR system causes damages equal to 1.3E-02 DALY to human health, 2.7E-05 species.yr to ecosystems, and 2.8E+ 02 USD to resources. Meanwhile, the damages from the energy item of the IR system for the same profit unit to human health, ecosystems, and resources are 1.2E-02 DALY, 2.5E-05 species.yr, and 2.5E+ 02 USD, respectively. For 100 K € rel-OP, the supply item of the CR system causes damages of 2.4E-05 DALY to human health, 6.4E-08 species.yr to ecosystems and 2.6 USD to resources. On the other hand, the damages from supply item of IR system for 100 K € rel-OP decrease by 12.9 % on human health, 8.6 % on ecosystems, and 8.2 % on resources, compared to the corresponding impacts from the CR system. Lastly, the structural item of the CR system causes damages to human health, ecosystems, and resources equal to 2.8E-04 DALY, 6.2E-07 species.yr, and 5.6 USD, respectively, for 100 K € rel-OP. The damages to human health, ecosystems, and resources from the structural item of the IR system are reduced, in relation to the same FU, by 8.6 %, 42.7 %, and 12.6 %, respectively.

In general, when comparing the CR and IR systems on the basis of a business-based FU, the IR system shows better environmental performance on all damage compartments and on the overall impact (Fig. 6). As shown in the table "d" of the Fig. 6, referring to an equivalent OP, the environmental performances of the IR system improve by 8.2 % on the total damage to human health, 9.0 % on the total damage to ecosystems, 8.2 % on the total damage to resources and 8.3 % on the overall impacts of the ripening process.

4. Discussion

Ozone technology offers an eco-friendly, low-cost method for food

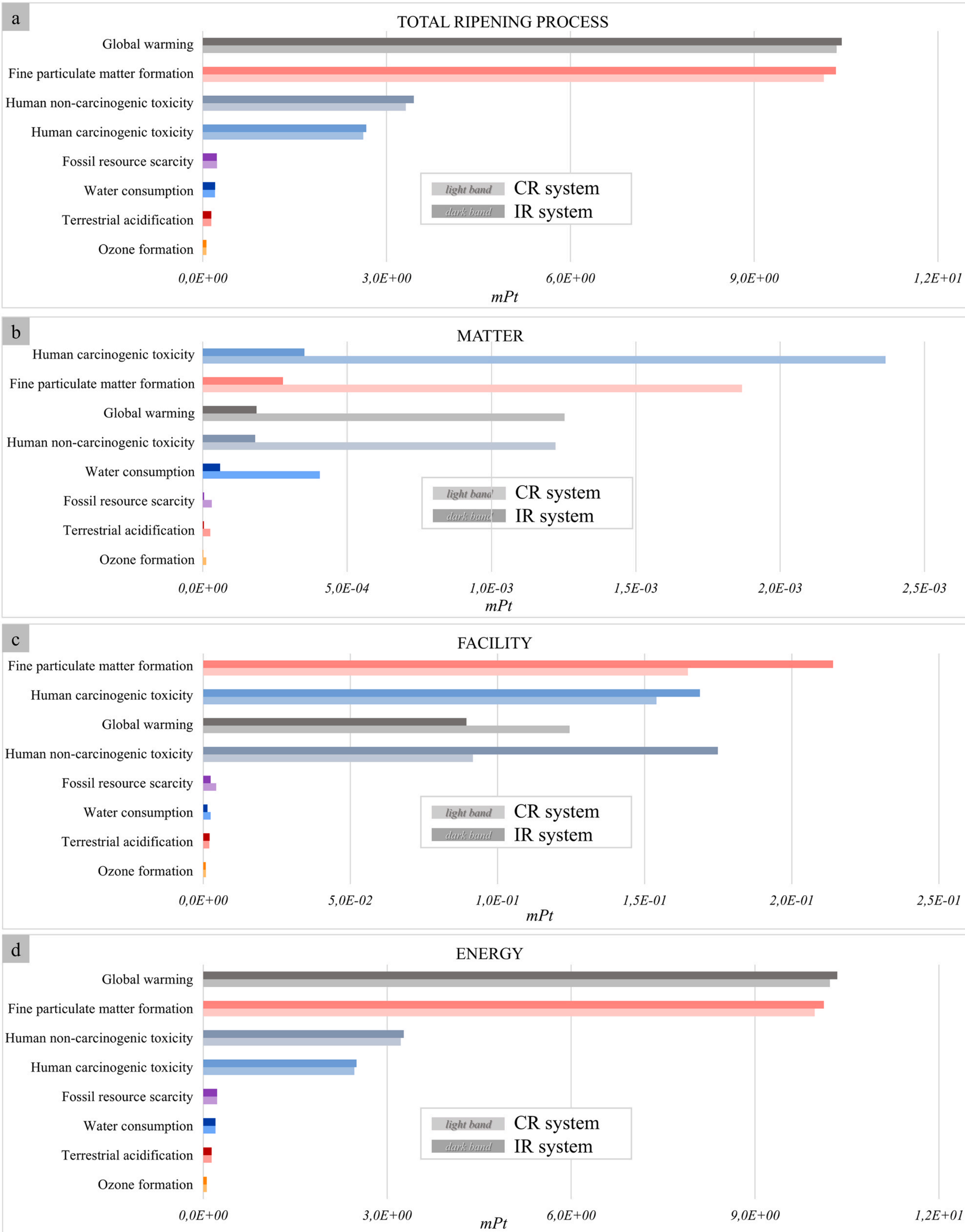


Fig. 3. Single score standardization of the eight midpoint indicators adopted for the assessment of the ecological footprints of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in relation to 1 kg of ripened Toma Piemontese cheese. The weighted values of midpoints are exposed both with respect to the whole ripening process (a) and with respect to matter (b), facility (c), and energy (d) subjects.

Table 7
Impact characterization of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in relation to a functional unit equal to one day per piece of ripened cheese.

IMPACT CATEGORY	UNIT	CR Matter	CR Facility	CR Energy	IR Matter	IR Facility	IR Energy
Global warming	*kg CO2 eq*	3,86E−06	3,83E−04	3,15E−02	4,26E−07	2,04E−04	2,36E−02
Ozone formation	*kg NOx eq*	2,47E−08	1,84E−06	1,17E−04	2,72E−09	1,29E−06	8,78E−05
Fine particulate matter formation	*kg PM2.5 eq*	8,91E−09	7,86E−07	4,76E−05	9,83E−10	7,56E−07	3,58E−05
Terrestrial acidification	*kg SO2 eq*	2,31E−08	1,78E−06	1,19E−04	2,55E−09	1,41E−06	8,96E−05
Human carcinogenic toxicity	*kg 1,4-DCB*	2,14E−06	1,39E−04	2,22E−03	2,36E−07	1,13E−04	1,67E−03
Human non-carcinogenic toxicity	*kg 1,4-DCB*	1,61E−05	1,20E−03	4,23E−02	1,77E−06	1,70E−03	3,19E−02
Fossil resource scarcity	*kg oil eq*	8,87E−07	1,00E−04	8,64E−03	9,78E−08	5,28E−05	6,46E−03
Water consumption	*m3*	5,22E−07	4,21E−06	6,22E−04	5,75E−08	2,34E−06	4,68E−04

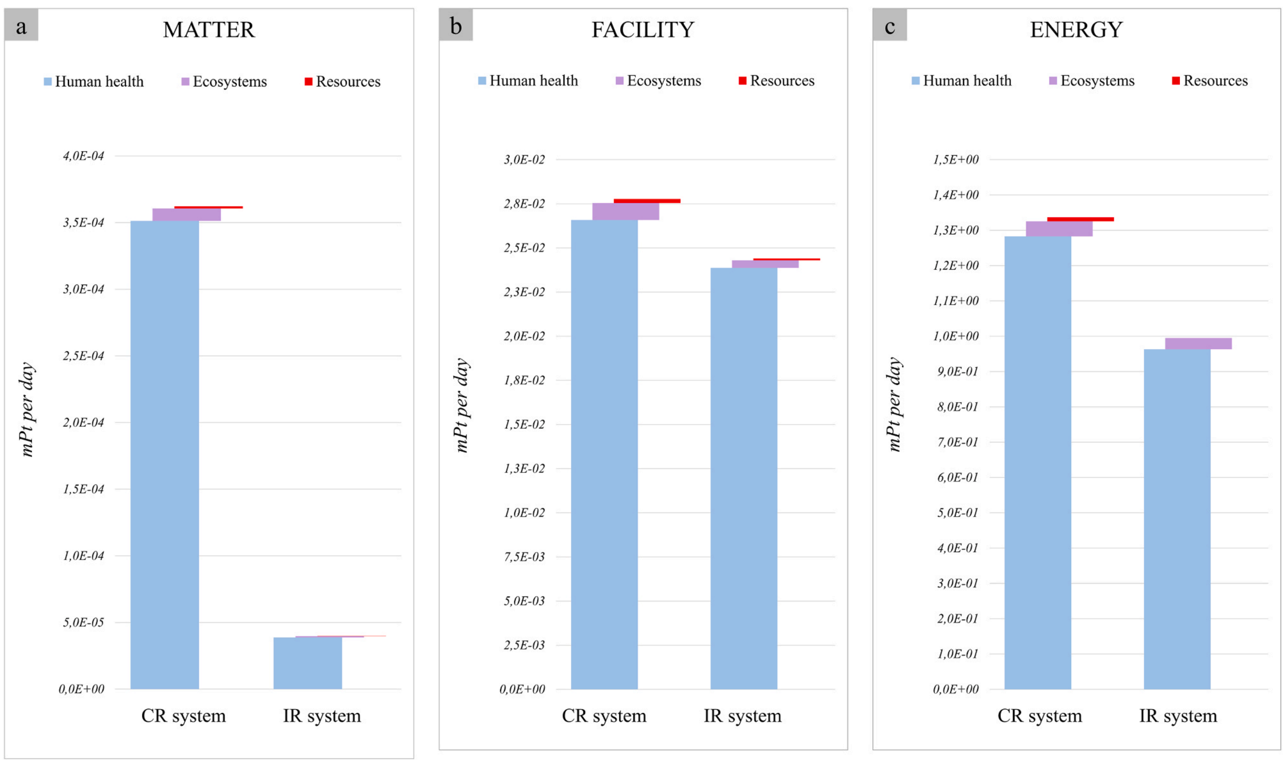


Fig. 4. Environmental performances of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in relation to a functional unit equal to one day per piece of ripened cheese. The environmental performances of the two compared systems are allocated according to three key process inventory subjects, i.e., matter (a), facility (b), and energy (c).

preservation and pest control [20,25,61]. Yet, studies rarely address its economic feasibility or long-term effects on quality and consumer acceptance [62]. In this context, the most innovative aspect of the present work lies in providing a much more comprehensive cost-benefit analysis to assess the feasibility of this technology. Our main findings show that the adoption of the innovative technology with gaseous ozone in place of conventional techniques brings clear advantages in improving the environmental performance of the ripening process. Despite slight increases in specific impact categories in relation to 1 kg of aging cheese, the IR system offers substantial benefits extending product shelf life of approximately 21 days and reducing damages per unit of operating profit (OP) due to lower labour requirements and reduced waste production.

Considering 1 kg of aging cheese, conventional ripening (CR) and innovative ripening (IR) systems show very small differences in environmental impact, which are almost negligible. This means that a switch from a traditional ripening method of Toma cheese to an innovative system that involves an ozone technology would not compromise the ecological footprints of the product. The IR system shows increases in specific impact categories, such as non-carcinogenic toxicity (+4.0 % compared to the CR system) and fine particulate matter formation (+2.0 % compared to CR system). As previously described, gaseous ozone is a highly toxic and corrosive compound with a pungent odour that causes irritation to the throat and eyes [25]. Ozone can be toxic depending on concentration and exposure time. In this context, using ozone destructors could be beneficial when applying high concentrations [63]. Moreover, gaseous ozone can interact with environmental components (e.g. reaction with volatile organic compounds, potentially producing substances that may contribute to non-carcinogenic toxicity, and interaction with other atmospheric components, maybe resulting in the generation of fine particulate matter). In the atmosphere, oxidants like hydroxyl radicals and ozone play a key role in forming pollutants (fine particulate matter and photochemical smog) that negatively impact air quality and public health. Air pollution can affect health, and short-term exposure to air pollutants is associated with respiratory issues (e.g., cough, asthma) [64,65]. To mitigate these effects, effective measures should include optimizing ozone concentration, regulating treatment frequency, and improving air filtration and environmental control. For this reason, in the operational design i) the quantities and related impacts of emitted gas are very low in absolute terms, and ii) the

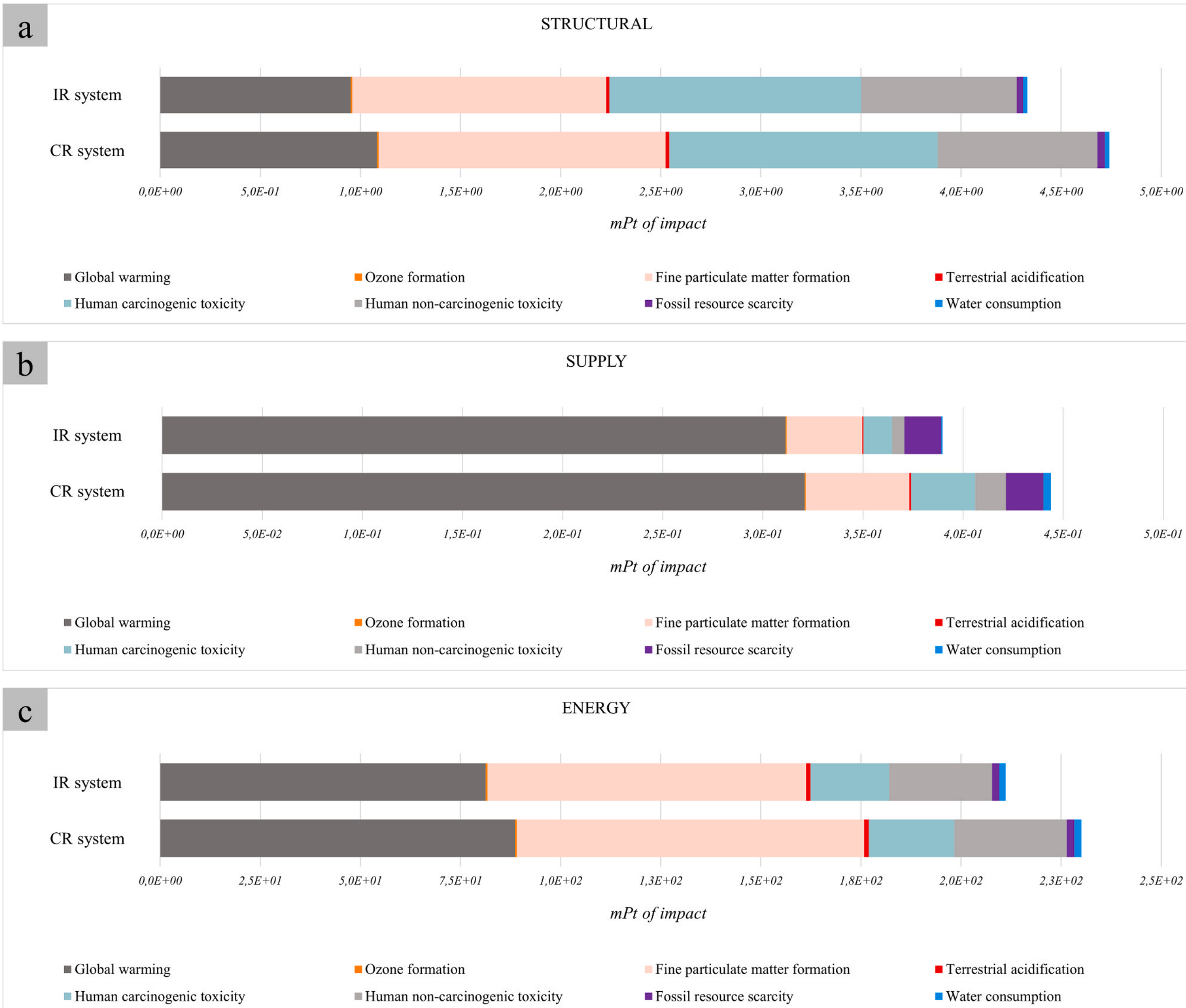
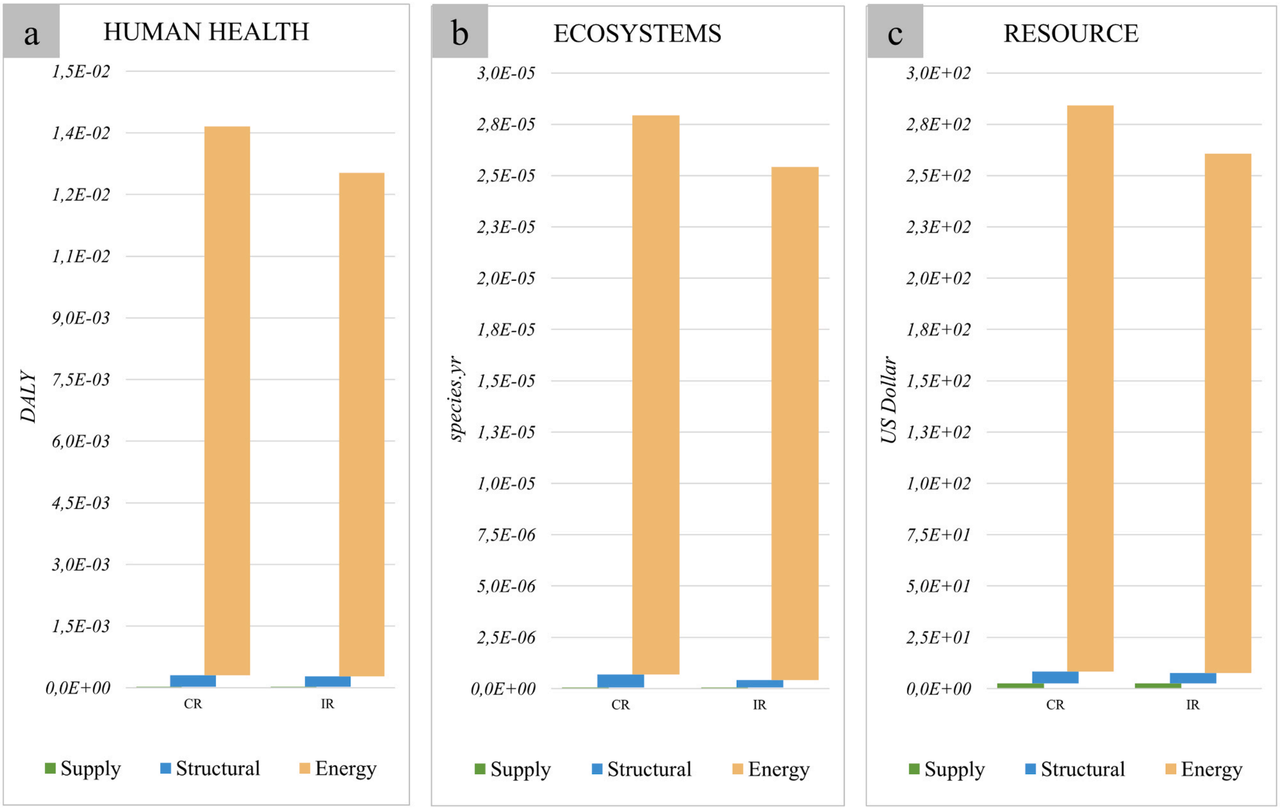


Fig. 5. Impact characterization of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) in relation to a functional unit equal to one hundred thousand euro of operating farm profit relating to the ripening process. Impacts are allocated respect to the three main farm business items, i.e., structural (a), supply (b), and energy (c) costs.

farm procedures involved in the use of gaseous ozone during the ripening process are implemented in time periods and operational techniques that completely avoid risks to the human health of farm staff (i.e., during night hours and in the absence of operators). Likewise, the IR system causes more damages to human health (1.8 %), more to ecosystems (0.4 %), and less to resources (0.2 %) compared to the CR system, demonstrating that the use of gaseous ozone does not lead to substantial increases in damage when producing an equivalent quantity of cheese. The single score standardization of impacts and damages has highlighted that global warming potential and fine particulate matter formation are the most significant environmental impacts in the cheese ripening process for both systems investigated. Generally, thermal treatments, refrigerated storage, and cleaning-in-place operations contribute to GHG emissions due to the energy and water consumption, as well as the production of cleaning agents involved [66]. Our analysis highlighted that electricity demand for thermal conditioning during the cheese ripening process is very high (the entire aging period requires temperatures of about 8–10°C), likely representing the main contributor to the climate change impact category. It is interesting to observe that, although the additional electrical equipment (ozone device) results in an increase of energy inputs for the innovative system, this increase represents only 1.6 % of the overall electricity consumed. Thus, the ozone technological implementation does not pose a serious risk to the environmental performance of the IR system.

The shelf life extension achieved with gaseous ozone treatment directly enhances food safety and reduces waste, improving social performances, promoting this advance as a promising food decontamination technology [5,67]. In relation to a lifespan functional unit (FU), the lower carbon and water footprints of the IR system further contribute to its environmental performance, making it a more sustainable alternative to the conventional system. For 1 day per piece of cheese, the IR system shows reduced damages to human health, ecosystems, and resources compared to the CR system, with decreases of 24.6 %, 25.6 %, and 26.1 %, respectively. Our findings are therefore in line with other similar works on food and dairy products (e.g. [68]), demonstrating that minimal increases in environmental impacts per unit of biomass produced through an innovative technology are often justified by marked reductions of impacts by expressing the results in terms of days of product shelf life. Moreover, the demand model by Herbon [69] showed how extending the shelf life of perishable products could represent a win-win scenario for both consumers and producers. By extending product lifespan, producers could increase the prices of fresher products



d

DAMAGE CATEGORY	UNIT	CR Structural	CR Supply	CR Energy	IR Structural	IR Supply	IR Energy
Human health	*mPt*	4,63E+00	4,09E-01	2,23E+02	4,23E+00	3,56E-01	2,04E+02
Ecosystems	*mPt*	1,68E-01	1,73E-02	7,37E+00	9,60E-02	1,59E-02	6,76E+00
Resources	*mPt*	4,03E-02	1,88E-02	1,97E+00	3,52E-02	1,86E-02	1,81E+00
Total	***mPt***	**4,84E+00**	**4,45E-01**	**2,32E+02**	**4,36E+00**	**3,90E-01**	**2,13E+02**

Fig. 6. Estimates of damages on human health (a), ecosystems (b), and resources (c) of the conventional ripening system (with brushing; CR system) and the innovative ripening system (with gaseous ozone use; IR system) respect to a functional unit equal to one hundred thousand euro of operating farm profit for ripening process. In table (d), the final single score (in mPt of impact) for the two ripening systems is reported.

and, consequently, their profits. Therefore, the extended shelf life represents not only a social benefit related to the consumption of a safer product, but also a potential gain for producers, encouraging them to invest in innovative technologies that delay the lifespan of their products. In addition to extending commercial durability, the use of ozone during ripening process offers further advantages, such as of minimizing waste, requiring fewer resources for the cheese ripening, and effectively reducing emissions associated with the supply chain. In particular, the limitation of product losses during and after production processes represents a major problem of dairy products, which are one of the main categories of food lost due to microbiological contamination [70]. Although this technology is spreading throughout the food industry, we argue that the adoption of ozone-based sanitization solutions should be particularly encouraged in rapidly perishable food production systems.

When considering an economic FU, the overall findings clearly confirm the high profitability of adopting an ozone-based solution for cheese ripening. In relation to an equivalent OP, the IR system demonstrates improved environmental performance with reductions of 8.2 % in total damage to human health, 9.0 % in total damage to ecosystems, 8.2 % in total damage to resources, and 8.3 % in overall impacts from the ripening process. These results are due to the relevant savings in farming costs for the ozone ripening process. The increase in operating expenses for the IR system due to structures' costs (+32.1 % for the ozone technology) and energy consumption (+1.6 % of electricity), is largely offset by a 99.9 % discount in supply costs compared to the CR system. This is mainly because the CR system requires a significant demand of labour hours for manual brushing and cleaning-in-place operations, while these costs are eliminated in the fully automated IR system. Given the ozoniser lifespan of approximately 50,000 h, the capital investment required for its acquisition results in an incremental cost of only €57.00 per 15-batch production cycle of Toma Piemontese cheese using the IR system. Additionally, its operation entails a minimal increase in electricity expenditure, estimated at €5.50 per 15 batches, which is negligible when compared to the €345.60 spent on thermal conditioning electricity by both systems. Despite these marginal increases, the IR system enables a labour cost reduction of €1687.56 per 15-batch cycle with respect to the CR system. Accordingly, the IR system achieves an 81.4 % reduction in operating costs compared to the CR system. Energy consumption remains the largest contributor to both systems' ecological footprints, although showing an 8.2 % reduction in the IR system and highlighting improved energy efficiency. Moreover, the IR system shows an advantageous impact on human toxicity and ecotoxicity compared to the CR system. However, the greatest performance benefit is observed in the climate change category, which carries the most significant weight. As reported by Üçtuğ et al. [9], energy consumption emerged as the primary driver of the environmental footprint when considering the production processes. To date, the critical role of energy - such as natural gas, water, and electricity - remains the dominant contributor to environmental impacts, suggesting that interventions targeting these areas (e.g., energy efficiency measures) could yield significant improvements. Among cheese types, aged varieties like hard and semi-hard cheeses typically have a higher energy footprint due to longer ripening periods and controlled storage conditions [71]. The use of more energy-efficient equipment and renewable energy sources, such as photovoltaics, is necessary to achieve significant environmental advantages [72,73]. Improving the sustainability of energy (renewable energy sources) and infrastructure in the production environment can further optimize the ecological performance of the entire system. The increase in shelf life is even more important considering that effects were estimated on a product derived from raw milk, therefore subject to a rapid deterioration [74]. From a farm responsibility perspective, this finding represents key research outcome, promoting the adoption of modern technologies and driving towards sustainable development. Furthermore, observing an improvement in environmental performance with respect to a monetary FU demonstrates that the adoption of the innovative technology could represent a suitable solution from a farm business perspective.

Given the inherent complexity of sustainable development processes, this work provides valuable insights into the potential trade-offs among environmental, social, and economic priorities associated with the modernization of dairy—and more broadly, agri-food—production systems. In this sense, the use of multiple FUs in our analysis has allowed us to capture the multifaceted nature of the ozone innovation in dairy production, aligning with the recommendations of several Life cycle Assessment (LCA) practitioners [47,75-77]. As highlighted in recent literature, innovations like the use of ozone in food production systems serve multiple functions, from improving product shelf life to enhancing sustainability [4]. Therefore, adopting diverse FUs not only broadens the scope of the analysis but also ensures that specific environmental targets are properly addressed, offering a more comprehensive view of the environmental consequences. In our case, this approach could help farmers to evaluate the broader implications of technological advancements, ensuring that all relevant perspectives are considered in the move towards both sustainable development and modernization.

5. Conclusions

Life cycle Assessment (LCA) comparison demonstrates that, for 1 kg of Toma cheese, conventional ripening (CR) and innovative ripening (IR) systems exhibit only minor differences in ecological footprints. These findings suggest that shifting from a traditional to an ozone-based ripening method does not lead to significant increases of environmental impacts on the system. Despite increases in some impact categories, such as non-carcinogenic toxicity (+90.8 %) and fine particulate matter formation (+29.9 %) when 1 kg of aging cheese is considered, the overall impact of the IR system is lower, due to its optimized operational design. In relation to the cheese lifespan unit, the environmental performance of the innovative system is significantly better than that of the conventional one. The gaseous ozone treatment has been shown to extend the shelf life of cheeses by approximately 21 days, contributing to improved food safety and reduced waste, with positive effects on social wellbeing and human health. The shelf life extension could also represent a cheese-added value, considering the greater freshness of the product and the potential increase in profit for the producer. The farm profitability of adopting an ozone-based ripening system is further supported by the impact assessment with respect to an economic functional unit (FU). The IR system demonstrated an overall reduction in environmental impacts compared to the CR system, with an 8.2 % reduction in energy impact per unit of operating profit (OP), highlighting improved energy efficiency. Energy use remains the primary contributor to environmental impacts, emphasizing the importance of integrating renewable energy sources. In conclusion, the adoption of this technology could represent a sustainable and advantageous solution, providing benefits from ecological, social, and economic perspectives. Future research should extend system boundaries to include distribution and end-of-life stages, focusing on the consumer's role. Understanding consumer awareness and acceptance of ozone-based preservation could reveal barriers and opportunities. Clear communication and education on benefits, such as shelf life extension and waste reduction, may support a broader adoption and its sustainable integration.

CRediT authorship contribution statement

Rinaldo Botondi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Marco di Cristofaro:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Vanessa Eramo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

References

[1] G. Mattarello, F. Arfelli, D. Cespi, F. Passarini, I. Vassura, Regional food consumption in Italy, a life cycle analysis, Environ. Res. 262 (2024) 119867, https://doi.org/10.1016/j.envres.2024.119867.

[2] S. Shayanmehr, S. Asumadu-Sarkodie, S. Rastegari Henneberry, M. Sabouhi Sabouni, H. Mohammadi, R. Radmehr, E.K. Ofori, N. Shahnoushi Foroushani, Market mechanisms and their role in sustainable food security: adapting to climate change in arid regions, Sustain. Futures 9 (2025) 100412, https://doi.org/10.1016/j.sftr.2024.100412.

[3] J. Wiśniewska-Paluszak, G. Paluszak, M. Fiore, A. Coticchio, A. Galati, J. Lira, Urban agriculture business models and value propositions: mixed methods approach based on evidence from Polish and Italian case studies, Land Use Policy 127 (2023) 106562, https://doi.org/10.1016/j.landusepol.2023.106562.

[4] R. Botondi, M. Lembo, C. Carboni, V. Eramo, The use of ozone technology: an eco–friendly method for the sanitization of the dairy supply chain, in: In Foods, 12, MDPI, 2023, https://doi.org/10.3390/foods12050987.

[5] V. Eramo, C. Carboni, R. Forniti, R. Botondi, Industrial pilot-scale study on the ripening and quality parameters of Toma Piemontese PDO raw milk cheese in ozone-controlled atmosphere, J. Sci. Food Agric. (2025) (Accepted - proofreading).

[6] J. Hamulka, E. Czarniecka-Skubina, M. Górnicka, J. Gębski, T. Leszczyńska, K. Gutkowska, What determinants are related to milk and dairy product consumption frequency among children aged 10–12 years in Poland? Nationwide cross-sectional study, Nutrients 16 (16) (2024) 2654, https://doi.org/10.3390/nu16162654.

[7] OECD (Organisation for Economic Cooperation and Development). (2023). OECD-FAO Agricultural Outlook 2023–2032. 〈https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2023-2032_08801ab7-en.html〉. (Accessed 6 January 2025).

[8] M.M. Delorme, J.T. Guimarães, N.M. Coutinho, C.F. Balthazar, R.S. Rocha, R. Silva, L.P. Margalho, T.C. Pimentel, M.C. Silva, M.Q. Freitas, D. Granato, A.S. Sant'Ana, M.C.K.H. Duart, A.G. Cruz, Ultraviolet radiation: an interesting technology to preserve quality and safety of milk and dairy foods, Trends Food Sci. Technol. 102 (2020) 146–154, https://doi.org/10.1016/j.tifs.2020.06.001.

[9] F.G. Üçtuğ, The environmental life cycle assessment of dairy products, Food Eng. Rev. 11 (2) (2019) 104–121, https://doi.org/10.1007/s12393-019-9187-4.

[10] P. Guzmán-Luna, M. Mauricio-Iglesias, A. Flysjö, A. Hospido, Analysing the interaction between the dairy sector and climate change from a life cycle perspective: a review, Trends Food Sci. Technol. 126 (2022) 168–179, https://doi.org/10.1016/j.tifs.2021.09.001.
[11] G. Rencricca, F. Froldi, M. Moschini, M. Trevisan, S. Ghnimi, L. Lamastra, The environmental impact of permanent meadows-based farms: a comparison among different dairy farm management systems of an Italian cheese, Sustain. Prod. Consum. 37 (2023) 53–64, https://doi.org/10.1016/j.spc.2023.02.012.
[12] Ismea – Istituto di Servizi per il Mercato Agricolo Alimentare. (2024). Report – AgriMercati n. 2/2024. ⟨https://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/13124⟩. (Accessed 6 January 2025).
[13] Ruminantia. (2024). Come se la sta cavando il comparto lattiero-caseario nel 2024? La nuova analisi di Ismea. ⟨https://www.ruminantia.it/come-se-la-sta-cavando-il-comparto-lattiero-caseario-nel-2024-la-nuova-analisi-di-ismea/⟩. (Accessed 6 January 2025).
[14] M.C. Mancini, D. Menozzi, M. Donati, B. Biasini, M. Veneziani, F. Arfini, Producers' and consumers' perception of the sustainability of short food supply chains: the case of Parmigiano Reggiano PDO, Sustainability 11 (3) (2019) 721, https://doi.org/10.3390/su11030721.
[15] Qualivita. (2024). Rapporto Ismea-Qualivita 2024. ⟨https://www.qualivita.it/rapporto-ismea-qualivita-2024/⟩. (Accessed 6 January 2025).
[16] B.D. Galli, Sustainability implications and relevance of using omics sciences to investigate cheeses with protected designation of origin, J. Sci. Food Agric. 104 (11) (2024) 6388–6396, https://doi.org/10.1002/jsfa.13403.
[17] A. Ladha-Sabur, S. Bakalis, P.J. Fryer, E. Lopez-Quiroga, Mapping energy consumption in food manufacturing, Trends Food Sci. Technol. 86 (2019) 270–280, https://doi.org/10.1016/j.tifs.2019.02.034.
[18] C. Herce, C. Martini, C. Toro, E. Biele, M. Salvio, Energy efficiency policies for small and medium-sized enterprises: a review, Sustainability 16 (3) (2024) 1023, https://doi.org/10.3390/su16031023.
[19] EUR-Lex. (2024). Document 32024R1143. ⟨https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=CELEX%3A32024R1143⟩. (Accessed 6 January 2025).
[20] V. Chiozzi, S. Agriopoulou, T. Varzakas, Advances, applications, and comparison of thermal (pasteurization, sterilization, and aseptic packaging) against non-thermal (ultrasounds, UV radiation, ozonation, high hydrostatic pressure) technologies in food processing, Appl. Sci. 12 (4) (2022) 2202, https://doi.org/10.3390/app12042202.
[21] A.Ch Stratakos, E.S. Inguglia, M. Linton, J. Tollerton, L. Murphy, N. Corcionivoschi, A. Koidis, B.K. Tiwari, Effect of high pressure processing on the safety, shelf life and quality of raw milk, Innov. Food Sci. Emerg. Technol. 52 (2019) 325–333, https://doi.org/10.1016/j.ifset.2019.01.009.
[22] P. Vashisht, D. Verma, A. Pradeep Raja Charles, G. Singh Saini, S. Sharma, L. Singh, S. Mahanta, S. Mahanta, K. Singh, G. Gaurav, Ozone Processing in the Dairy Sector: a Review of Applications, Quality Impact and Implementation Challenges. (2023), https://doi.org/10.26434/chemrxiv-2023-m3csm.
[23] C. Grasso, V. Eramo, M. Lembo, R. Forniti, C. Carboni, R. Botondi, Effects of gaseous ozone treatment on the mite pest control and qualitative properties during ripening storage of pecorino cheese, J. Sci. Food Agric. (2023), https://doi.org/10.1002/jsfa.12400.
[24] H.B. Jadhav, U.S. Annapure, R.R. Deshmukh, Non-thermal technologies for food processing, Front. Nutr. 8 (2021), https://doi.org/10.3389/fnut.2021.657090.
[25] R. Kaavya, R. Pandiselvam, S. Abdullah, N.U. Sruthi, Y. Jayanath, C. Ashokkumar, A. Chandra Khanashyam, A. Kothakota, S.V. Ramesh, Emerging non-thermal technologies for decontamination of Salmonella in food, Trends Food Sci. Technol. 112 (2021) 400–418, https://doi.org/10.1016/j.tifs.2021.04.011.
[26] V. Eramo, C. Carboni, M. Lembo, R. Forniti, R. Botondi, Microbial and fungal growth control and evaluation of quality parameters during ripening of Toma Piemontese PDO cheese treated with gaseous ozone, Ozone Science Engineering (2024) 1–12, https://doi.org/10.1080/01919512.2024.2312909.
[27] V. Eramo, M. Modesti, R. Riggi, R. Forniti, M. Lembo, V. Vinciguerra, R. Botondi, Preserving the aromatic profile of aged Toma Piemontese PDO cheese with gaseous ozone technology: a quality assessment via SPME-GC–MS/E-nose, J. Dairy Sci. (2024), https://doi.org/10.3168/jds.2024-25131.
[28] Morandi, S., Brasca, M., & Battelli, G. (2009). Impiego di ozono per il controllo di Listeria monocytogenes in diverse tipologie di formaggio. ⟨https://www.researchgate.net/publication/285842990⟩. (Accessed 6 January 2025).
[29] R. Tabla, I. Roa, Use of gaseous ozone in soft cheese ripening: effect on the rind microorganisms and the sensorial quality, LWT 170 (2022), https://doi.org/10.1016/j.lwt.2022.114066.
[30] CFR. Code of Federal Regulations. (2024). 21CFR173.368.⟨https://www.ecfr.gov/current/title-21/chapter-I/subchapter-B/part-173/subpart-D/section-173.368⟩. (Accessed 6 January 2025).
[31] EUR-Lex. (2012). Regolamento (UE) n. 528/2012 del Parlamento europeo e del Consiglio, del 22 maggio 2012, relativo alla messa a disposizione sul mercato e all'uso dei biocidi sul mercato e l'uso dei biocidi. Testo rilevante ai fini del SEE. ⟨https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32012R0528⟩. (Accessed 6 January 2025).
[32] OSHA. Occupational Safety and Health Administration. (2024). Ozone. ⟨https://www.osha.gov/chemicaldata/9⟩. (Accessed 6 January 2025).
[33] Ministero della Salute. (2010). Parere CNSA sul trattamento con ozono dell'aria negli ambienti di stagionatura dei formaggi. ⟨https://www.salute.gov.it/portale/documentazione/p6_2_2_1.jsp?id=1514&lingua=italiano⟩. (Accessed 6 January 2025).
[34] R.N. Arshad, Z. Abdul-Malek, U. Roobab, M.M.A.N. Ranjha, A. Režek Jambrak, M. I. Qureshi, N. Khan, J. Manuel Lorenzo, R.M. Aadil, Nonthermal food processing: a step towards a circular economy to meet the sustainable development goals, Food Chem. X 16 (2022) 100516, https://doi.org/10.1016/j.fochx.2022.100516.
[35] K. Arvidsson Segerkvist, H. Hansson, U. Sonesson, S. Gunnarsson, Research on environmental, economic, and social sustainability in dairy farming: a systematic mapping of current literature, Sustainability 12 (14) (2020) 5502, https://doi.org/10.3390/su12145502.
[36] J. Drews, I. Czycholl, J. Krieter, A life cycle assessment study of dairy farms in northern Germany: the influence of performance parameters on environmental efficiency, J. Environ. Manag. 273 (2020) 111127, https://doi.org/10.1016/j.jenvman.2020.111127.
[37] W. Finnegan, M. Yan, N.M. Holden, J. Goggins, A review of environmental life cycle assessment studies examining cheese production, Int. J. Life Cycle Assess. 23 (9) (2018) 1773–1787, https://doi.org/10.1007/s11367-017-1407-7.
[38] C. Ghinea, A. Leahu, Life cycle assessment of fermented milk: yogurt production, Ovidius Univ. Ann. Chem. 31 (1) (2020) 49–54, https://doi.org/10.2478/auoc-2020-0010.
[39] Ó.S. Nunes, P.D. Gaspar, J. Nunes, P. Quinteiro, A.C. Dias, R. Godina, Life-cycle assessment of dairy products—case study of regional cheese produced in Portugal, Processes 8 (9) (2020) 1182, https://doi.org/10.3390/pr8091182.
[40] V. Castellani, S. Sala, L. Benini, Hotspots analysis and critical interpretation of food life cycle assessment studies for selecting eco-innovation options and for policy support, J. Clean. Prod. 140 (2017) 556–568, https://doi.org/10.1016/j.jclepro.2016.05.078.
[41] G. Borghesi, R. Stefanini, G. Vignali, Life cycle assessment of packaged organic dairy product: a comparison of different methods for the environmental assessment of alternative scenarios, J. Food Eng. 318 (2022) 110902, https://doi.org/10.1016/j.jfoodeng.2021.110902.
[42] C. Rossi, G. Grossi, N. Lacetera, A. Vitali, Carbon footprint and carbon sink of a local italian dairy supply chain, Dairy 5 (1) (2024) 201–216, https://doi.org/10.3390/dairy5010017.
[43] C. Ramirez, M. Patel, K. Blok, From fluid milk to milk powder: energy use and energy efficiency in the European dairy industry, Energy 31 (12) (2006) 1984–2004, https://doi.org/10.1016/j.energy.2005.10.014.
[44] T. Xu, J. Flapper, K.J. Kramer, Characterization of energy use and performance of global cheese processing, Energy 34 (11) (2009) 1993–2000, https://doi.org/10.1016/j.energy.2009.08.014.
[45] D. Kim, G. Thoma, D. Nutter, F. Milani, R. Ulrich, G. Norris, Life cycle assessment of cheese and whey production in the USA, Int. J. Life Cycle Assess. 18 (5) (2013) 1019–1035, https://doi.org/10.1007/s11367-013-0553-9.
[46] A. Dalla Riva, J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi, The environmental analysis of asiago PDO cheese: a case study from farm gate-to-plant gate, Ital. J. Anim. Sci. 17 (1) (2018) 250–262, https://doi.org/10.1080/1828051X.2017.1344936.
[47] M. di Cristofaro, S. Marino, G. Lima, L. Mastronardi, Evaluating the impacts of different wheat farming systems through Life Cycle Assessment, J. Clean. Prod. 436 (2024) 140696, https://doi.org/10.1016/j.jclepro.2024.140696.
[48] C. Visentin, A.W. Trentin, S. da, A.B. Braun, A. Thomé, Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies, J. Clean. Prod. 270 (2020) 122509, https://doi.org/10.1016/j.jclepro.2020.122509.
[49] International Organization for Standardization (ISO). (2020). ISO 14040:2020 - Environmental Management — Life cYcle Assessment — Principles and framework. ⟨https://www.iso.org/standard/37456.html⟩. (Accessed 6 January 2025).
[50] International Organization for Standardization (ISO). (2020). ISO 14044:2020 - Environmental Management — Life Cycle Assessment — Requirements and Guidelines. ⟨https://www.iso.org/standard/38498.html⟩. (Accessed 6 January 2025).
[51] MASAF (Ministero dell'agricoltura, della sovranità alimentare e delle foreste). (2014). Disciplinari di produzione prodotti DOP, IGP e STG riconosciuti - 1.3 Formaggi – Toma Piemontese DOP. ⟨https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3340⟩. (Accessed 6 January 2025).
[52] EPD. (2020). PEFCR Guidance. ⟨https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf⟩. (Accessed 6 January 2025).
[53] P.L.H. McSweeney, Biochemistry of cheese ripening, Int. J. Dairy Technol. 57 (2–3) (2004) 127–144, https://doi.org/10.1111/j.1471-0307.2004.00147.x.
[54] United Nations Environment Programme (UNEP). (2011). UNEP 2011 Annual Report. UNEP. ⟨https://www.unep.org/resources/annual-report/unep-2011-annual-report⟩. (Accessed 6 January 2025).
[55] R.G. Hunt, T.K. Boguski, K. Weitz, A. Sharma, Case studies examining LCA streamlining techniques, Int. J. Life Cycle Assess. 3 (1) (1998) 36, https://doi.org/10.1007/BF02978450.
[56] M.A. Huijbregts, Z.J. Steinmann, P.M. Elshout, G. Stam, F. Verones, M.D. Vieira, R. van Zelm, ReCiPe 2016: a Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization (2016).
[57] UNI. (2022). UNI EN ISO 4833-1:2022 - Microbiologia dei prodotti alimentari – Metodo per il conteggio dei microrganismi – Parte 1: Metodo di conta su piastre. ⟨https://store.uni.com/uni-en-iso-4833-1-2022⟩. (Accessed 6 January 2025).
[58] Accredia. (2024). CCFRA G43 met 2.1.1:2007. ⟨https://services.accredia.it/accredia_labsearch.jsp?ID_LINK=293&area=7&numeroaccr=0301&classification=&isRestricted=false&dipartimento=L⟩. (Accessed 6 January 2025).
[59] P.H. Sneath, R.R. Sokal, Numerical taxonomy, Nature 193 (1962) 855–860.
[60] A.K.K.R. Jayathilaka, Operating profit and net profit: measurements of profitability, OALib 07 (12) (2020) 1–11, https://doi.org/10.4236/oalib.1107011.
[61] S. Le Féon, A. Papadakis, G. Yannou-Le Bris, J. Auberger, D. Chatzitheodorou, J. Aubin, C. Pénicaud, Life cycle inventory and life cycle impact assessment

datasets of PDO Feta production in Stymfalia region, Greece, Data Brief. 48 (2023) 109207, https://doi.org/10.1016/j.dib.2023.109207.
[62] J. van Leeuwen, R. Pandiselvam, G. Jeevarathinam, Cost estimation for the preservation of selected food/crop products with ozone, J. Food Process Eng. 47 (11) (2024), https://doi.org/10.1111/jfpe.14772.
[63] F. Panebianco, S. Rubiola, P.A. Di Ciccio, The use of ozone as an eco-friendly strategy against microbial biofilm in dairy manufacturing plants: A review, Microorganisms 10 (1) (2022) 162, https://doi.org/10.3390/microorganisms10010162.
[64] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, E. Bezirtzoglou, Environmental and health impacts of air pollution: a review, Front. Public Health 8 (2020) 14, https://doi.org/10.3389/fpubh.2020.00014.
[65] M. Qin, A. Hu, J. Mao, X. Li, L. Sheng, J. Sun, J. Hu, PM2. 5 and O3 relationships affected by the atmospheric oxidizing capacity in the Yangtze River Delta, China, Sci. Total Environ. 810 (2022) 152268, https://doi.org/10.3168/jds.2023-24339.
[66] V. Vasilaki, E. Katsou, S. Ponsá, J. Colón, Water and carbon footprint of selected dairy products: a case study in Catalonia, J. Clean. Prod. 139 (2016) 504–516, https://doi.org/10.1016/j.jclepro.2016.08.032.
[67] W. Xue, J. Macleod, J. Blaxland, The use of ozone technology to control microorganism growth, enhance food safety and extend shelf life: a promising food decontamination technology, Foods 12 (4) (2023) 814, https://doi.org/10.3390/foods12040814.
[68] G. Falcone, A.I. De Luca, T. Stillitano, N. Iofrida, A. Strano, A. Piscopo, G. Gulisano, Shelf life extension to reduce food losses: the case of Mozzarella Cheese, Chem. Eng. Trans. 57 (2017) 1849–1854, https://doi.org/10.3303/CET1757309.
[69] A. Herbon, Shelf-life extension under implementation costs, Comput. Ind. Eng. 180 (2023) 109241, https://doi.org/10.1016/j.cie.2023.109241.
[70] N.H. Martin, P. Torres-Frenzel, M. Wiedmann, Invited review: controlling dairy product spoilage to reduce food loss and waste, J. Dairy Sci. 104 (2) (2021) 1251–1261, https://doi.org/10.3168/jds.2020-19130.
[71] B.B. Soares, E.C. Alves, J.A. de Almeida Neto, L.B. Rodrigues, Environmental impact of cheese production. In Environmental Impact of Agro-Food Industry and Food Consumption, Elsevier, 2021, pp. 169–187, https://doi.org/10.1016/B978-0-12-821363-6.00009-6.
[72] M. Kumar, V.K. Choubey, A Review on Life Cycle Assessment of Various Dairy Products (2022) 75–89, https://doi.org/10.1007/978-981-16-7059-6_8.
[73] C. Rossi, U. Bernabucci, G. Grossi, F. Cesarini, N. Lacetera, C. Evangelista, G. Turriziani, A. Vitali, Cradle-to-grave life cycle assessment of buffalo mozzarella cheese supply chain in central Italy, J. Agric. Food Res. 14 (2023) 100871, https://doi.org/10.1016/j.jafr.2023.100871.
[74] Y. Yoon, S. Lee, K.-H. Choi, Microbial benefits and risks of raw milk cheese, Food Control 63 (2016) 201–215, https://doi.org/10.1016/j.foodcont.2015.11.013.
[75] K. Hayashi, Partitioning product footprint changes into yield and environmental improvement effects: toward life cycle assessment of agricultural system transitions, Int. J. Life Cycle Assess. 28 (4) (2023) 336–348, https://doi.org/10.1007/s11367-022-02112-2.
[76] P. Rice, D. O`Brien, L. Shalloo, N.M. Holden, Defining a functional unit for dairy production LCA that reflects the transaction between the farmer and the dairy processor, Int. J. Life Cycle Assess. 24 (4) (2019) 642–653, https://doi.org/10.1007/s11367-018-1486-0.
[77] T. Wardenaar, T. van Ruijven, A.M. Beltran, K. Vad, J. Guinée, R. Heijungs, Differences between LCA for analysis and LCA for policy: a case study on the consequences of allocation choices in bio-energy policies, Int. J. Life Cycle Assess. 17 (8) (2012) 1059–1067, https://doi.org/10.1007/s11367-012-0431-x.