

Review

Energy Footprint of Cheese: A Critical Review of the Environmental Impact and Opportunities for Sustainability

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Abstract

Cheese production is an ancient practice that is associated with the food and cultural identity of different peoples. There are over 500 cheese types globally, including 207 with protected denomination of origin (PDO) and 70 with protected geographical indication (PGI) status in the European Union (EU). Each cheese has various biochemical compositions, production methods, and maturation environments. This study has provided a critical review of the environmental impacts of cheese production, focusing on energy consumption, greenhouse gas (GHG) emissions, and the integration of renewable energy sources as sustainable strategies for this sector. Based on case studies and life cycle assessment (LCA) methodologies, the analysis revealed significant variability in energy use (3.0 to 70.2 MJ/kg) and GHG emissions (up to 22.13 kg CO₂ eq/kg), influenced by factors such as the cheese type, production complexity, system boundaries, and the technological or geographical context. Particular attention was given to heat treatment, refrigeration, and maturation processes, which contribute substantially to the overall energy footprint. The paper also discusses the methodological challenges in LCA studies, including the role of co-product allocation and database limitations. Finally, strategic renewable energy options, such as biogas recovery and solar thermal integration, are discussed as sustainable alternatives to reduce the environmental footprint of the dairy sector and support its sustainability.

Keywords: cheese ripening; renewable energy; ecological footprints; life cycle assessment

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1. Introduction

During the last Ice Age, adults could not digest milk—more precisely, lactose [1]—due to their lack of the lactase enzyme. In around 9500 BC, rapid climate warming enabled the rise of agriculture and the domestication of animals such as goats and sheep, which were initially valued for their meat, hides, and milk. Cattle were domesticated later, mainly for labor, and only became a milk source more recently [2,3]. As farming spread in the Middle East, dairy fermentation (yogurt and cheese) made milk tolerable. A genetic mutation in Europe about 7500 years ago allowed lifelong lactase production, boosting milk consumption.

Between 7000–6500 BC, ceramic technology emerged, allowing milk storage and aiding cheese production. Perforated ceramic sieves, which have been linked to early dairying, were likely used primarily for cheesemaking [2]. In Ancient Rome, agronomists such as

Varro and Columella documented cheese production methods and optimal practices [4]. Today, cheeses showcase numerous unique tastes, textures, scents, rinds, and shapes, which are shaped by their biochemical composition, manufacturing techniques, the aging process, and culture [5]. It is believed that over 500 unique types of cheese are presently manufactured across the globe, of which 207 have protected denomination of origin (PDO) and 70 have protected geographical indication (PGI) recognition in the European Union (EU) [6]. Despite many efforts to categorize the diverse range of cheeses, they are generally grouped by species, coagulants (Figure 1), texture, or ripening agents [3].

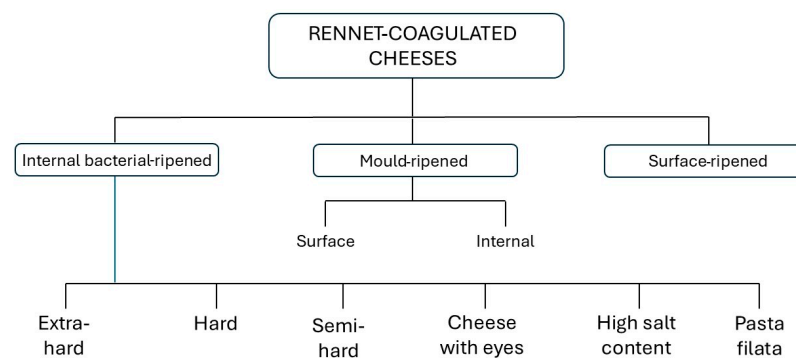


Figure 1. Diversity of rennet-coagulated cheeses [3].

According to FAO [7], global milk production was close to 950 million tons in 2023—an increase of 1.3% compared to 2022—from which around one quarter was used for cheese production [8], thus requiring a significant amount of energy to meet such an increase.

Although there is a vast array of cheese types, the manufacturing process follows a generally similar method (Figure 2). The initial phase in production involves transporting milk to the factory at low temperatures (4–7 °C). In large-scale production, the solids content must be adjusted to achieve the desired fat-in-dry matter level and fat-to-protein ratio by utilizing creaming, incorporating skimmed milk, or adding milk powder. Pasteurization or other heat treatments might also be implemented to meet hygiene standards. Nonetheless, such standardization and thermal processing methods are almost absent among most small-scale producers utilizing raw milk. The third step includes the coagulation of casein to create a gel through the processes of acidification, proteolysis, or heating along with acidification. Subsequently, the curd is extracted from the whey, shaped, and salted. The ripening process initiates a series of biochemical alterations that affect texture, aroma, and flavor, increasing the sensory complexity of each cheese. Nonetheless, depending on the cheese variety, particular environmental conditions in the ripening room must be fulfilled, specifically, ventilation, temperature, and humidity [8].

Cheese production usually necessitates thermal energy, mostly from fossil sources and electrical power. Thermal energy, which is produced from natural gas or propane, is employed in methods such as pasteurization, coagulation, and sanitation, whereas electricity is used in mechanical processes and lighting [8].

Previous reports on energy use in Dutch dairy farms pointed to milk pasteurization and cheese storage as accounting for the highest share of the overall energy consumption—above 40% of the total energy use. Likewise, studies regarding the cheese sector in California have highlighted thermal processes (pasteurization, heating systems, evaporators, dryers, and sterilization) as the most energy-intensive methods, making up 40% of the total energy use, whereas refrigeration processes constituted 20% of the overall energy consumption [8].

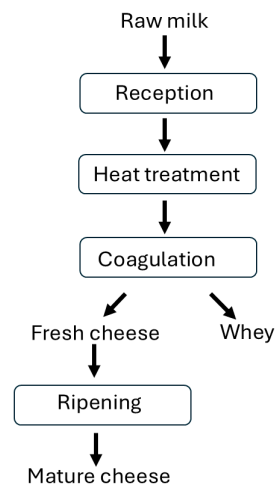


Figure 2. General procedure for cheesemaking [3].

2. Heat Treatment of Milk

The pasteurization of cheese milk became standard practice in around 1940, primarily for public health reasons, but also to guarantee a milk supply with more consistent bacterial quality and to improve its shelf life. Although a substantial amount of cheese is still produced from raw milk, especially in southern Europe, pasteurized milk is now primarily used, particularly in large production facilities [3]. During heat treatment, most of the advantageous bacteria essential for cheese production are also destroyed (e.g., lactic acid bacteria), along with specific milk enzymes such as lipases. The temperatures and durations used for heating milk are based on the cheesemaker's objectives. Consequently, lower temperatures, such as 65 °C, could deactivate specific coliforms while maintaining lipase enzymes, yet may not be adequate to eradicate the vegetative cells of pathogens. The minimum thermal processing required to achieve this objective is a treatment at 71.7 °C for 15 s, or an equivalent [9]. The heating fluid consists of water, which is changed into steam in boilers that utilize fossil fuels and is conveyed to the processes via a network of pipes [10].

Milk pasteurization became common in around 1940 to improve public health, ensure consistent bacterial quality, and extend shelf life. While raw milk is still used in local cheese production, especially in southern Europe, large-scale production relies on pasteurized milk [3]. Temperature and duration vary based on the desired outcomes—lower heat (e.g., 65 °C) may preserve enzymes but may not eliminate all pathogens. Standard pasteurization requires heating to 71.7 °C for 15 s [9]. The heating system uses steam generated from fossil-fuel-powered boilers, distributed through a pipe network [10]. Heat treatment is essential in milk processing, but its impact on quality must be assessed to choose the best method, as it may range from mild thermization to ultra-high-temperature treatment (Table 1).

Table 1. The main categories of the heat treatment of milk [9].

Treatment	Temperature (°C)	Time
Thermization	63–65	15 s
LTLT pasteurization	63	30 min
HTST pasteurization	72–75	15–20 s
Ultra pasteurization	125–138	2–4 s
UHT	135–140	1–5 s

The primary systems utilized in the dairy sector for heat transfer during milk processing include [9] the following: (1) Direct heating systems, involving the direct contact of the heating medium (steam) with the product. (2) Indirect heating systems, where the heating

medium and cold milk are divided by a barrier and categorized into plate heat exchanger, tubular heat exchanger, or scraped-surface heat exchanger.

3. Cheese Ripening

The biochemical processes observed during cheese ripening are typically classified as (1) glycolysis of residual lactose, lactate catabolism, and citrate metabolism; (2) lipolysis and fatty acid metabolism; and (3) proteolysis and amino acid catabolism. The flavor and texture of a cheese is enhanced by proteolytic and lipolytic processes, along with the generation of volatile compounds by the bacteria and fungi found on a cheese's surface [11]. The growth of microflora and biochemical processes is tightly associated with the ripening temperature, as it affects the generation times of bacteria according to their growth phase. Generally, cooler temperatures inhibit bacterial growth and biochemical reactions in the curd. The factors that condition ripening are tightly connected to tradition, location, and the distinctive characteristics of a cheese. For instance, cheeses with blue veins, such as Cabrales and Roquefort [12,13], are typically aged inside caves to enhance the growth of *Penicillium roqueforti*. Until the mid-20th century, the ripening of sheep cheeses in specific regions of southern Portugal took place in temporary adapted rooms inside a manor house, where temperature management entailed using braziers for heat and opening windows for cooling. This depended on practical knowledge and needing extensive experience. Today, the ripening phase takes place in climate-regulated rooms, with insulated walls and automatic control of the temperature and humidity [14], where refrigeration is mechanically processed.

Cheese ripening involves key biochemical processes, such as glycolysis, lipolysis, and proteolysis, which enhance both flavor and texture through the generation of volatile compounds by the bacteria and fungi found on the cheese's surface [11]. The ripening temperature is crucial as it affects bacterial growth and biochemical activity, which is slowed by lower temperatures. Ripening methods vary by tradition and region, for instance, blue cheeses such as Cabrales and Roquefort are aged in caves to support mold growth [12,13]. Until the mid-20th century, cheese ripening relied on empirical temperature control, however, today it is processed inside climate-controlled facilities, with automated temperature and humidity systems [14].

Vapor-compression refrigeration systems (VCRS) are presently the most common refrigeration systems in both residential and industrial sectors, using a liquid refrigerant inside a closed-loop system through four stages (expansion, evaporation, compression, and condensation), as represented in Figure 3, alternating successively from low to high pressures [15,16].

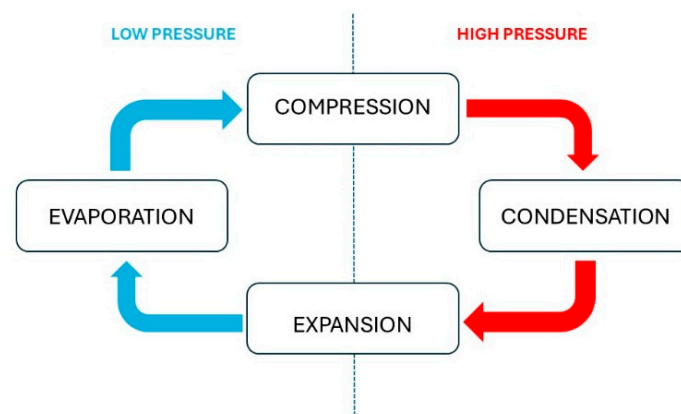


Figure 3. Stages of a vapor-compression refrigeration system.

As the refrigerant enters the evaporator, heat is absorbed from the cold space, causing the liquid to vaporize, which is then compressed to a significantly high temperature and pressure [15,17]. The performance of a VCRS is identified by the coefficient of performance (COP), an adimensional parameter relating to the heat removed and the energy input. It is influenced by factors such as pressure, power, heat transfer, and environmental conditions [15].

A thermoelectric cooler (TEC) is a semiconductor device with a solid state, where the Seebeck and Peltier effects are the basic principles [18,19]. A standard TEC contains multiple P-type and N-type semiconductor junctions that are connected in series through metallic interconnects, generally composed of copper [20]. However, due to the low COP—around 0.6 [18,21]—the use of TEC is still limited to small-scale applications, such as portable refrigerators, automobile seat cooling, battery cooling, medical applications, and electronic devices [22,23]. An eventual increase in the application of TEC in the food industry would require a significant increase in COP to compete with VCRSs. Eventually, using novel thermoelectric materials or configurations that exhibit significantly higher figures of merit than those presently attainable with conventional Bi_2Te_3 -based bulk substances will need to be used. Additional efforts would also be needed to enhance the efficiency and integration of heat exchange systems on the hot and cold sides, aiming to decrease temperature differentials across modules [21].

The absorption refrigeration systems (ARSs) operate based on the absorption of the refrigerant, commonly ammonia–water or lithium bromide–water solutions, requiring a high-temperature heat source to separate the refrigerant from an absorbent mixture [24], such as steam, waste heat, natural gas, exhaust gases [25], propane, or solar [26]. ARSs are becoming more interesting as they offer viable alternatives to VCRSs by utilizing working fluids that have zero ozone depletion potential (ODP); zero global warming potential (GWP); and, additionally, can operate using waste heat [27] or solar energy [24,26]. Kori and Lux [28] reported the development of a solar–biogas hybrid absorption refrigeration system, combining the heat from solar radiation and the combustion of biogas, presenting a COP of 0.106. While the combination of thermal energy from solar–biogas achieved the highest economic returns, the stand-alone solution using biogas presented the highest temperature control.

The primary obstacles to the adoption of ARSs in the food industry include their higher cost relative to VCRSs, the small number of manufacturers, the low COP (up to 0.7), distribution networks that are not yet fully developed, the high temperature of the evaporators, and a lack of experience and performance data from commercial applications [21].

Dairy products are among the most environmentally impactful food products, particularly regarding their carbon footprint, which is generated by milk production, dairy farming, and the growth of feed crops. Industrial milk processing is the second largest determinant of greenhouse gas emissions. In fact, in the dairy industry, significant amounts of energy are used for milk pasteurization and heating, on the one hand, and for refrigeration on the other. Depending on the cheese type and ripening time, the specific values of the electric energy consumption of raw milk treatment may range from 0.72 to 10.8 MJ/kg of the final product [1 kWh = 3.6 MJ], as reported in the literature. Moreover, the thermal energy consumption is reported to vary from 0.1 MJ/kg to almost 8 MJ/kg of the final product, with values at the lower end of the range generally reported for soft cheeses with short ripening times and high water content [29].

4. Environmental Footprint and Life Cycle Assessment in Cheese Production

The quantification of consumed and available environmental resources is essential in supporting sustainability in the production sector. It facilitates the implementation of improvements, ensures the alignment of activities and products with current legislation,

and supports the acquisition of important certification labels [30]. Environmental indicators point to the growing scarcity of resources, making sustainability the central focus of discussions across all production sectors. The concept of the ecological footprint emerged in the 1990s, with the doctoral work of Wackernagel and William Rees [31] introducing a new method to measure humanity's demand for finite natural resources. This concept evolved into specific indicators, such as the carbon footprint, energy footprint, and water footprint [32]. These metrics reflect resource use across different domains, where detailed indicators are applied to quantify the utilization of natural resources in specific activities or product development, taking into account the complexity of the processes involved.

The ecological footprint of the cheese production sector is categorized by various factors within the production cycle. A widely adopted tool to assess such impacts is the life cycle assessment (LCA), which evaluates environmental burdens across the production chain. It follows a "gate-to-gate" approach, from the acquisition of raw materials (input flow) to gas emissions and waste (output flow), contributing to the identification of used resources and aiming towards more sustainable practices [33]. A study conducted in a small cheese factory in southern Spain identified the main subsystems involved in the LCA of cheese production, namely the energy cycle, water, packaging materials, raw materials, cleaning products, transportation, waste, and gas emissions. This indicated an average carbon footprint of 10.2 kg of CO₂ eq/kg of cheese [34].

The average water consumption required to produce 1 kg of cheese depends on the type of cheese and the processing methods used. Most of the ecological footprint generated during cheese production results from the agricultural phase, specifically from milk production. Studies indicate that approximately 80% of the greenhouse gas emissions from cheese production are linked to on-farm milk production, including animal feeding and management [34]. The ecological footprint is lower when considering only the cheese factory processes, excluding the environmental impacts of milk production. However, the energy footprint during cheese processing remains substantially high due to the energy required for processes such as refrigeration, pasteurization, and cheese maturation [35].

For a more precise approach, it is crucial to define the scope of a study, avoiding dispersion and emphasizing the most relevant results according to the analysis objectives [36]. For instance, when considering a cheese factory, the study boundaries can be set from milk acquisition to the final product if the focus is on the ecological footprint. However, if the objective is to analyze the energy footprint of cheese production to improve sustainability within the facilities, it is appropriate to structure the investigation from the reception of raw materials in the factory, as what precedes this stage would be unnecessary for the intended audience.

Several studies have emphasized the environmental impacts of cheese production linked to energy use, particularly during the maturation and sterilization phases of the raw materials. The study by Silva et al. [37], analyzed the production of Minas Frescal and Minas ripened cheese using the LCA methodology, and compared the impacts caused during the production of each. The results showed that Minas ripened cheese has a higher impact due to higher milk consumption.

The standards ISO 14040:2006 (LCA-Principles and framework) and ISO 14044:2006 (LCA-Requirements and guidelines) are internationally validated methodologies that provide the necessary guidelines for applying LCA to a wide range of processes and products. The main difference between the two standards is that ISO 14040:2006 outlines the principles and framework of an LCA study, while ISO 14044:2006 provides the guidelines and requirements for conducting the assessment [38]. According to these standards, LCA is structured into four main phases: (i) the definition of the objective and scope; (ii) the inventory analysis (LCI); (iii) the impact assessment (LCIA); and (iv) the interpretation of the results. In defining the objective and scope, the boundaries of the system and the

processes included are established. LCI involves collecting quantitative data on input and output flows, with modelling in specific software.

When there is co-production, it is necessary to apply criteria for allocating environmental impacts, preferably avoiding allocation through subdivision or the expansion of the system. As the use of the LCA method became more widespread, the need for a complementary technique arose to ensure data robustness and the reliability of the conclusions. The study by Kim et al. [39] applied LCA to cheese and whey production, following ISO 14040 and ISO 14044. The system covered all stages, from milk production to final disposal, and, in the case of whey, up to its delivery to the first customer. Whey was treated as a co-product, requiring the allocation of impacts based on ISO guidance. The main method used was mass allocation, considering milk solids as the relevant basis. When more detailed data were available, allocation was conducted by engineering estimates or by revenue, depending on the nature of the input. These choices affect the share of environmental impact assigned to whey and, by extension, to cheese, particularly in categories such as energy demand and eutrophication. Selecting appropriate allocation criteria, as defined by ISO 14044, helps to improve consistency and comparability in LCA studies involving dairy products.

Another important element of these methodologies is the use of databases such as “Ecoinvent”, a comprehensive source that provides inventory and input–output data for a variety of processes and services. Although access to its content requires a license, “Ecoinvent” is adopted by academic institutions and private companies, allowing the comparison of data and facilitating the rapid calculation of components belonging to the study being analyzed [38]. However, it should be noted that part of the datasets are based on generalized European conditions, which may not fully include regional variations in production processes, energy sources, or the lower production scales typical of artisanal production, thus influencing the accuracy and transferability of the results when applying the database outside its primary context.

As environmental analysis has become increasingly necessary, specific indicators for each resource have emerged, such as the energy footprint, carbon footprint, and water footprint. These indicators now complement LCA and are also supported by alternative tools, such as environmentally extended input–output (EEIO) analysis, expanding the analytical scope of environmental assessments in the cheese sector [40].

5. Energy Footprint

The concept of the energy footprint is based on an indicator focused on the energy required for a process, from the acquisition of resources to the end of its life cycle, including intermediate stages [32]. There are several methodologies for calculating the energy footprint, such as the LCA mentioned previously. However, it is also possible to adopt a simpler approach, as illustrated below. Figure 4 presents a simplified methodology for assessing the energy footprint of cheese production, focusing on key steps such as data collection, unit conversion, and energy allocation. In addition to the elements shown, more detailed analyses may also consider upstream energy and material inputs, such as those related to equipment manufacturing, infrastructure, and transport, which contribute indirectly to the total environmental load of cheese production.



Figure 4. Simplified illustration of the process for calculating the energy footprint (adapted) [41].

In the context of the cheese industry, the energy footprint is particularly prominent in the operation of refrigeration, pasteurization, coagulation, and ripening. It may also be used to compare different production methods, such as large-scale industrial production versus artisanal methods. The ripening chamber requires continuous control to ensure optimal environmental conditions, specifically temperature and humidity, which can account for up to 30% of the total energy consumption in the cheesemaking process [42]. A comparative analysis of the energy consumption among different types of cheese is presented in Table 2 and, as shown, the results are quite heterogeneous.

Table 2. Energy consumption required to produce 1 kg of cheese.

Type of Cheese	Energy Consumption (MJ/kg)	Country	System Boundaries	References
Beira Baixa PDO	3.8	Portugal	Cradle-to-gate	[35]
Industrial cheese	5.1			
Artisanal cheese	3.0	Portugal	Gate-to-gate	[43]
Mozzarella	45.1	Italy	Cradle-to-grave	[44]
Cheddar	48.5	USA	Cradle-to-grave	[39]
Mozzarella	45.4	USA	Cradle-to-grave	[39]
Multiple types of cheese with sheep's and goat's milk	52.1	Italy	Gate-to-gate	[29]
Asiago PDO	70.2	Italy	Cradle-to-gate	[45]

The lowest specific energy consumption values were observed for artisanal cheese producers in Portugal (around 3.0–3.8 MJ/kg), followed by industrial producers (5.1 MJ/kg) from the same study region. According to Nunes et al. [43], the lower values for artisanal producers result from the use of raw milk, limited mechanization, the small size of ripening rooms, the lower electric power of the compressor, the more efficient use of storage space, and seasonality. In contrast, cheeses such as Asiago PDO (70.2 MJ/kg) and USA industrial cheddar (48.5 MJ/kg) showed higher consumption, which can be attributed to the cradle-to-grave system boundaries, long maturation periods, and the intensive use of thermal and electrical energy in refrigeration, packaging, and storage. A study in Sardinia, for instance, reported a value of 52.1 MJ/kg, which was largely influenced by outdated equipment and limited energy efficiency. These variations highlight the influence of production scale and technology, as well as how boundaries are defined in each study.

Mozzarella cheese exhibited similar energy consumption across different countries (45.1 MJ/kg in Italy and 45.4 MJ/kg in the USA) due to the standardization of the processing conditions. The differences observed in the comparative analysis for the cheese sector (Table 2) are a consequence of the type of cheese, the complexity of its production process, the definition of LCA system boundaries, the geographical location, and the technology applied. As highlighted by Öztuna [46], optimizing energy use according to production levels contributes to both sustainability and competitiveness. Furthermore, according to Chinese et al. [29], energy type is a major source of environmental impact, with fossil fuels still dominant in steps such as pasteurization and ripening. Despite the growing adoption of renewable sources, the sector continues to rely heavily on fossil fuels, which hampers efforts to improve its environmental performance. These findings indicate the importance of interpreting comparative data and of considering methodological frameworks and contextual variability.

6. Carbon Footprint

Like other environmental metrics, the carbon footprint is a specific indicator used to quantify the emission of greenhouse gases (GHGs). According to Hansen et al. [47], carbon dioxide (CO₂), primarily originating from the burning of fossil fuels and industrial activities, is the largest contributor to global warming, followed by methane (CH₄), which is largely emitted by agriculture and livestock. Another important group of GHGs includes nitrogen oxides (NO_x), which, although emitted in smaller quantities, also contribute to the increase in atmospheric temperature [48]. These indicators have been developed to achieve more reliable results, despite the complexity and variability of GHG emissions. They can be applied to processes and products, and can even be used to determine the amount of GHGs emitted by a nation, providing greater accuracy in the implementation of strategies to mitigate environmental impacts. In the context of cheese production, the carbon footprint is most significant during the milk production stage, accounting for 86% of the emissions [33]. Enteric methane (CH₄) emissions from ruminants are a major contributor to the carbon footprint of milk production. According to Laca et al. [49], dietary modifications—such as replacing conventional forages with high-sugar grasses—can help to reduce CH₄ emissions. These strategies act on the fermentation process in the rumen, influencing microbial activity, thus reducing methane output. This type of intervention complements broader sustainability measures at the farm level, contributing to the reduction of the GHG emissions associated with dairy supply chains.

In the context of the cheese industry, refrigeration is responsible for a significant portion of the emissions associated with the product's life cycle. According to Canellada et al. [33], energy consumption during storage and distribution can account for up to 6% of the total CO₂ eq. emissions related to cheese production. Moreover, as noted by Laca et al. [49], the refrigeration systems used in the stages following milk production are electricity-dependent, which further increases emissions when non-renewable energy sources are utilized.

The discussions around climate change and its causes have raised concerns across various industrial sectors, including the food industry, leading to increased research into technologies that reduce GHG emissions. Several LCA studies have been carried out with the objective of quantifying GHG emissions across diverse geographical and technological contexts. Table 3 summarizes some of the results from different case studies, expressed in kilograms of CO₂ equivalent per kilogram of product. However, the studies used in Tables 2 and 3 adopted different LCA boundaries and analytical frameworks, which can influence the reported values and should be considered when comparing results across sources.

Table 3. Documented case studies on GHG emissions associated with cheese production.

Type of Cheese	GHG Emissions (kg CO ₂ eq/kg)	Country	System Boundaries	References
Cheddar	8.6	USA	Cradle-to-grave	[39]
Mozzarella	7.3			
Artisanal	16.6	Spain	Cradle-to-retail gate	[49]
Parmigiano Reggiano PDO	16.1	Italy	Cradle-to-gate	[30]
Organic Parmigiano Reggiano	8.1	Italy	Cradle-to-grave	[50]
Oaxaca cheese	15.6	Mexico	Cradle-to-retail gate	[51]
Cheddar	14.0	United Kingdom	Cradle-to-grave	[52]
Pecorino Toscano PDO	22.13	Italy	Cradle-to-gate	[34]

Similarly to what was observed in the analysis of energy consumption, the GHG values associated with cheese production vary depending on factors such as the type of product, the complexity of the production process, the definition of system boundaries (LCA), and the technological and geographical characteristics of the units analyzed. In addition, in the case of emissions, the origin of the energy used, the inclusion of credits for co-products (such as the use of whey), and the specific methodologies adopted in each study also have an influence. The variations observed between the cases reflect both structural differences in the production systems and methodological choices in the design of the inventories and borders, which is why the results reported are only comparable when contextualized from this perspective.

In summary, applying the LCA methodology to the cheese industry provides a detailed and structured framework for assessing the environmental impacts of each stage of the production process. By identifying the most critical phases of the production process, it becomes possible to implement targeted strategies to reduce the ecological footprint. In addition, the integration of complementary approaches and reliable databases, such as “Ecoinvent” [38], strengthens the accuracy of the assessments, offering relevant information to improve sustainability practices in the sector. These efforts not only contribute to reducing environmental degradation but also support the industry’s alignment with the global sustainable development goals.

7. The Use of Renewable Energy in the Dairy Industry

Today, certain environmental issues arise from inadequate policies or the inadequate management of energy resources. Fossil fuels play a key role in global energy management as they are a non-renewable source that may be utilized alongside or substituted with renewable sources. The route to addressing the current energy predicament appears to depend on adopting various strategies. In recent decades, a range of technologies aimed at different levels of energy efficiency have been implemented across different processes and industries, except for some specific industrial sectors, such as wood processing [53].

In the last decades, such systems have been adopted by a large number of dairies and livestock farms for the production of biogas, which has been transformed onsite into heat and electricity [54] through combustion, or treated for the production of methane and injected into pipelines of natural gas [55]. However, this is only possible when the network is at a short distance from the production plant. The pursuit of profitable gas utilization often makes burning the gas more practical than investing in a combined heat and power (CHP) unit. The primary factors that limit the economic viability of biogas include its low energy potential per unit of volume, the complexities associated with its liquefaction, the small production scale [56], and the excessive maintenance [57]. Camarillo et al. [57] studied the economic sustainability of the production of energy in livestock facilities using

biogas generated from the flush wastewater of seven dairies across the USA. The results suggested that energy production can be economically sustainable; however, it depends on competing factors, such as electricity pricing and plant capacity. According to the study, the development of energy production using biogas could benefit from grants, tax incentives, environmental policies, and also from a higher level of technical assistance for operation and maintenance.

Solar thermal energy is advancing, with innovations leading to lower operating costs with higher overall efficiency. The use of solar energy in the dairy industry is typically focused on specific processes that require heating, however, its application may also be extended to cooling processes [10], such as absorption systems. A benefit of solar energy is the capacity to integrate it into existing conventional systems. This minimizes the need for technical changes in thermal equipment such as pasteurizers or boilers, therefore, it avoids disruptions in production during the installation phase and eliminates the need to reorganize control systems. For instance, solar energy would be an option for producing steam at a higher temperature, reducing it later to 80 °C–150 °C to meet production requirements such as cleaning processes or heat treatment. In fact, the critical temperature is established by the pasteurization units at approximately 85 °C, which can be supplied by non-concentrating solar collectors to reduce the cost of solar energy integration [10].

Examples of the integration of solar energy in milk processing include the testing of a low-cost solar concentrator in Amblayo (Argentina) to pasteurize goat's milk at 63 °C for 30 min. The system used a Fresnel-type concentrator to produce steam from sunlight, which was then injected into the pasteurization device. The condensation of steam and the consequent transfer of latent heat were used to heat the water used for the pasteurization of milk in a double-wall tank. The design of the concentrator was optimized for ease of use and the efficient manual tracking of sunlight, reducing the need for automatic systems. The experimental results indicated that such a system could pasteurize 10 L of milk per hour [58].

A parabolic trough collector was used for indirect steam production in Tunisia. It included four main components: (i) a reflector; (ii) a receiver—a vacuum tube coated with glass; (iii) a sun-tracking system, and (iv) hydraulic circuits. The incident radiation on the collector surface was reflected and concentrated onto the absorber, then the heat transfer between oil and water was conducted to attain the high temperature required for steam generation. The thermal energy efficiency varied from 22% to 32% and presented a maximum capacity of 8 kg steam/h [59]. Nielsen and Pedersen [60] also developed a system for HTST pasteurization based on low-pressure solar panels to be used in small villages in Tanzania, presenting a working capacity up to 1000 L milk per day.

The integration of solar thermal energy in a dairy plant has also been tested in the Basque Country (Spain). The aim was to replace the use of conventional fossil fuels in processes requiring low-to-medium temperatures. The Pinch analysis was used to assess the energy demands of the dairy process and to identify opportunities for optimization, concluding that a solar thermal system could significantly reduce natural gas consumption, with potential savings of up to 27.7% [56]. These strategies align with broader environmental policies, such as the European Green Deal [61], which promotes climate neutrality by 2050 and encourages the reduction of GHG emissions across all sectors, including agriculture and food processing. They are also consistent with the objectives of the EU Farm to Fork Strategy [62] and support compliance with emerging carbon pricing frameworks.

Some studies have focused on the effective utilization of renewable energy for cooling processes, where the integration of conventional vapor-compression cycles with photovoltaic panels offers an interesting solution for cooling applications. A comparative study conducted by Khan et al. [63] in Pakistan aimed to create a solar-driven milk chilling unit, operating with a 2 kW photovoltaic system, and assessing its performance with different

types of compressors. The energy consumption for reciprocating, rotary with capacitor, and rotary with variable refrigerant flow compressors was noted as 1.8 kW, 1.2 kW, and 0.8 kW, respectively. The findings demonstrated that cooling a 200 L batch of milk to the desired temperature (4 °C) needed less than 1 kW of power by extracting heat energy from the system utilizing a vapor-compression refrigeration system with variable refrigerant flow technology.

Technological progress has generated efficient and cost-effective renewable energy options. Solar systems, including photovoltaic, represent a substantial fraction of renewable energy installations in the dairy sector. They are recognized as a proven technology with reasonable costs; straightforward incorporation into existing facilities; and, in some countries, with financial incentives [64]. A suitable infrastructure is crucial for the integration of renewable energies in industrial processes. However, in some sectors this can present considerable difficulties, as forming a connection might be challenging. IoT solutions, such as smart meters, are essential instruments for assessing technical metrics and interacting with the controller, which, when integrated in a computer system, are essential for overseeing data and enabling communication for proper management. Although the scaling of RES provides several benefits, the financial factor is a crucial element in every project, therefore, cost reduction plays a fundamental role. According to previous studies, the cost relates to the use of energy for different factors, including the optimal dimension of the system and a comprehensive scenario analysis [65].

The case studies identified in this review indicate that the implementation of renewable energies in cheese production, such as solar thermal and biogas systems, can contribute to improving the environmental performance of this sector by decreasing the consumption of fossil fuels, particularly in the stages involving heat transfer, which are typically energy-intensive [54,59]. Although these systems are not yet widely implemented, particularly in small-scale facilities, they represent viable strategies for the most energy-intensive phases identified by LCA, such as thermal processing and refrigeration. Therefore, the adoption of renewable energy not only aligns with climate goals but also addresses the key hotspots identified in LCA studies of the cheese industry.

8. Conclusions

Cheese production involves multiple stages that require energy and generate environmental impacts, particularly during milk processing and maturation. The reported values for energy consumption and GHG emissions vary widely. These differences are related to factors such as the cheese type, the process complexity, the technological level, and the scope of the life cycle boundaries adopted in each study. For example, including farm-level milk production typically results in higher values, while gate-to-gate assessments that are focused on industrial operations tend to be lower.

LCA remains the most-used approach for evaluating environmental performance in this sector. Despite its advantages, the comparability of LCA studies is limited by the methodological choices, especially regarding system boundaries and the allocation of co-products. Adopting consistent criteria and using databases such as “Ecoinvent” may improve transparency and reproducibility.

Some actions may help to reduce the environmental impact of cheese manufacturing. These include improving thermal and refrigeration systems; adopting renewable energy sources, such as solar and biogas; and applying LCA to guide energy efficiency measures. Technologies such as thermoelectric cooling and absorption systems are under study, but their implementation is still limited. Future research may explore regional differences in data availability and investigate how environmental policies and certification frameworks influence the adoption of more efficient practices in the dairy sector.

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