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Review

The Role of Climate Control in Monogastric Animal Farming: The Effects on Animal Welfare, Air Emissions, Productivity, Health, and Energy Use

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Abstract: In the last decades, an engineering process has deeply transformed livestock houses by introducing fine-tuned climate control systems to guarantee adequate indoor climate conditions needed to express the maximum genetic potential of animals and to increase their productivity. Climate control, hence, has strong relation with productivity but also with other livestock production domains, outlining a web of mutual relations between them. The objective of this work is to understand the actual role of climate control in intensive livestock houses by unpicking this web of mutual relations through a literature review. The results show that climate control plays a key role in intensive livestock houses since it has strong relations with animal welfare, air emissions, productivity, health, and energy use. These relations make it essential to adopt an integrated approach for the assessment of the effectiveness of any proposed improvement in the different domains of livestock production. This is especially true considering aspects such as the expected increase of livestock production in developing countries and global warming. For this purpose, integrated climate control models of livestock houses are needed, representing a challenging opportunity for performing investigations in this research field.

Keywords: indoor climate conditions; environmental control; agricultural buildings; poultry; pigs; animal production; sustainable agriculture

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1. Introduction

According to the FAO (Food and Agriculture Organization of the United Nations), increasing agricultural production with the aim of meeting future food demand is one of the most important challenges for the 21st century [1]. Global human population is projected to reach—with a certainty of 95%—between 9.4 and 10.1 billion people in 2050, and between 9.4 and 12.7 billion people in 2100 [2]. This significant increase of global human population will cause a rise in food demand [3]. As a consequence, agricultural production should increase by about 70% over 2005–2007 levels [1], maintaining high quality products but using the minimum amount of resources [3]. This increase will also regard livestock products. Before 2050, the demands of meat and dairy products are expected to increase by about 70 and 60%, respectively, in comparison with the levels at the beginning of this century [4].

Currently, food from animal sources represents 18% of the kilocalories consumed worldwide and it provides various micro-nutrients, such as vitamin A and iron, that are difficult to obtain in adequate quantities exclusively from plant-source food [5]. In addition, animal proteins are considered of high quality since their amino acid pattern is closer to the human body requirements [6]. Animal proteins are also more easily digestible and available for humans [7]. For these reasons, 25% of the total amount of proteins consumed worldwide are derived from animals [5] that have been farmed by humanity for this specific purpose for millennia. As agriculture developed, it became evident that controlling the thermal environment in which animals are farmed contributes materially to their production [8]. Thus, animals started being farmed in confined systems, i.e., livestock houses, to providing them an environment of controlled temperature and humidity. In this way, the environmental extremes—such as very low/high air temperatures—that are typical of outdoor weather conditions are considerably reduced, increasing productivity [9]. In addition, in the last decades, livestock houses have been subjected to a continuous engineering process that has strongly transformed them, by introducing new technologies. Currently, many livestock houses are fully-mechanically controlled and equipment for supplemental heating and cooling are usually adopted. Supplemental heating systems can be classified into localized heating and space heating systems. Localized heating systems create temperature variations in the zones where animals are reared, while space heating systems create a more uniform thermal environment. The most adopted technologies for localized heating are infrared lamps or infrared gas catalytic radiant heaters, which emit 70% of their heat by radiation. In contrast, the most adopted solutions for space heating are technologies based on convection systems, such as air heaters [10]. Inside livestock houses, free cooling systems are often present. The needed ventilation air flow rate is provided by fans, whose design and energy efficiency have considerably changed during the last decades. In modern livestock houses, fixed angular speed fans equipped with brushless motors are adopted. These motors are characterized by less maintenance, reduced overheating, and increased safety regarding fire risk, compared to brushed motors. A new technology regarding ventilation that is gaining ground in livestock houses is variable angular speed fans [11] that enhance a refined control of the ventilation flow rate with reduced energy consumption.

The engineering process that is transforming livestock houses is also affecting control and monitoring systems. In fact, the continuous innovation in information and communication technologies is spreading the adoption of precision livestock farming (PLF) technologies, based, for example, on wearable Internet of Things [12] and new artificial intelligence algorithms [13]. Finally, a deep transformation also concerns the energy systems of livestock houses, which are gradually moving from fossil fuels toward more sustainable and low-carbon energy sources, such as photovoltaic, solar thermal energy and geothermal energy.

As a consequence of this engineering process, current livestock houses are intensive livestock systems that are designed and operated to minimize costs and to maximize production [14], respecting normative requirements, such as the minimum standards in terms of space allowance for animals [15–17]. The high productivity of livestock houses has led to an increase in their numbers in the last years [18], in an attempt to cover the increasing demand of livestock products. Currently, more than 70% of poultry, about 55% of pork and over 60% of eggs produced worldwide come from intensive livestock houses [19].

The presented picture shows a strong relation between climate control and productivity in livestock houses. Nevertheless, productivity is not the only area of study—also defined as "domain"—of livestock production that is affected by climate control. Existing works in literature, in fact, highlight relations between climate control and other domains of livestock production, such as animal welfare and air emissions. Consequently, a web of mutual relations between climate control and other domains of livestock production can be outlined. This web shows that the role of climate control in livestock houses is not trivial and it has not yet been totally understood. The objective of this work is to understand the role of climate control in livestock houses by unpicking the web of mutual relations with other livestock production domains, providing an innovative holistic approach to the farm concept. This objective is achieved through a literature review that is exclusively focused on monogastric animal farming, mainly poultry and pigs. This choice is due to the high sensitivity to the thermal environment that characterizes monogastric animals, making climate control an essential element for their farming. Specific investigations on biological and engineering aspects related to climate control are widely developed in literature. Nevertheless, a deep understanding of the complex relationships among biological and engineering aspects needs further development with the aim of improving the farm system by adopting a holistic approach.

2. Scope of the Work

Before analyzing the web of relations of climate control, it seems worthwhile to define the term "climate control" since, in literature, it is often used as a synonym for "environmental control". Nevertheless, important differences can be highlighted between the two terms.

According to Clark [9], the environment in livestock production is the sum of the elements that influence animal performance in a direct or indirect way. When livestock production is carried out in confined systems, i.e., livestock houses, the indoor environment corresponds to the enclosure delimited by the building envelope [10]. The indoor environment can be modified actuating on the "indoor environmental conditions" that, contextualizing ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) terminology [20] for this specific application, can be defined as the conditions of air and radiation prevailing around an animal. Indoor environmental conditions, hence, include parameters such as indoor air temperature, relative humidity, air speed, Indoor Air Quality (IAQ) and light and noise levels [21]. The term "indoor environmental control" is often used in the agricultural engineering sector referring exclusively to the thermal environment—defined as "the environmental factors that influence the body heat balance" [22]—and "gaseous environment" [23], or IAQ, without considering lighting and acoustic environments. Probably, this simplification in the use of the term "indoor environmental control" is because agricultural engineers and researchers in this area have historically focused mainly on thermal and the gaseous environments, neglecting further aspects. Considering the presence of emerging studies and investigations focused on aspects such as light and acoustics in livestock houses [24–27], it seems more appropriate to also adopt a definition of indoor environment that includes thermal, gaseous, light and acoustic environments in the agricultural engineering sector. When only thermal and gaseous environments are considered, it would be clearer to adopt the term "climate control".

The previous concepts are schematized in Figure 1, where the action area of climate control is figured out in the context of the entire livestock production environment, referring to the definition proposed by Clark [9]. The figure shows that climate control depends only on thermal and gaseous, i.e., IAQ environments, while indoor environmental control also depends on acoustic and lighting environments. In addition, Figure 1 shows that the indoor environment is characterized by other elements that are not directly related to the indoor environmental control, such as feeding system, human-animal interactions and water supply. Finally, the indoor environment—delimited by the house envelope—represents only a part of the environment in which livestock production takes place. Other elements, such as parasites, rainfall and altitude should be considered.

Given this framework, the present work will focus exclusively on climate control, intended as the control of thermal environment and IAQ. Some reference to acoustic and lighting environments will be provided, but these specific research fields are considered beyond the scope of the present work.

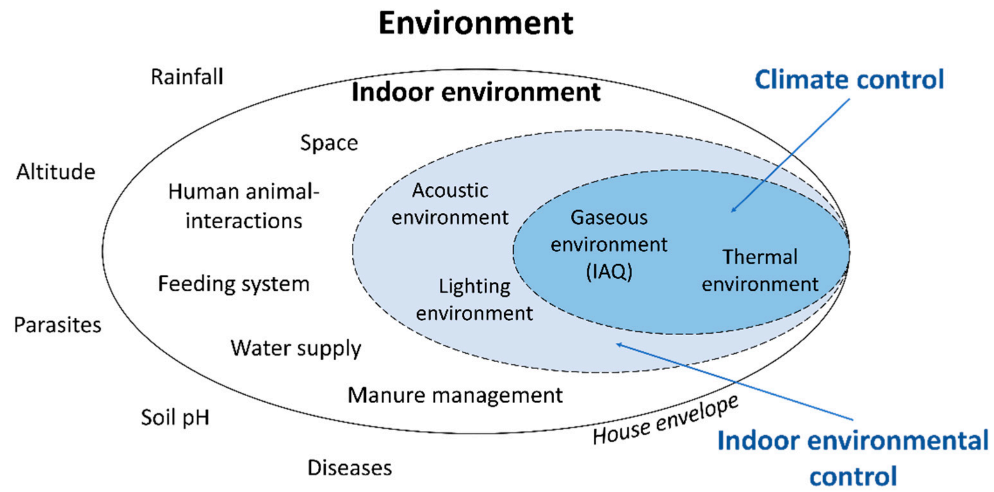

Figure 1. Elements of livestock production that are affected by indoor environmental control and climate control, respectively, among all the livestock production elements. The figure shows only part of the elements of the environment as an example.

3. Analyzed Works

To understand the mutual relations between climate control and other domains of livestock production, an analysis of the existing scientific literature was performed. The literature review was carried out by searching for information in ScienceDirect and Scopus databases, combining the following keywords: climate control, livestock houses, temperature, relative humidity and ventilation. The obtained papers were scanned as follows:

- Phase 1: the duplicate papers between the two analyzed databases were eliminated;
- Phase 2: the papers which predominantly in English were excluded;
- Phase 3: the titles were scanned and the papers that were not focused on monogastric animals or that were from other research areas were excluded;
- Phase 4: the papers were read and those in which no relations between climate control and other domains of livestock houses stood out where not considered as a contribution and excluded;
- Phase 5: the references of the remaining papers were read to find further papers that relate to the previously presented criteria.

After this selection process, the remaining papers were grouped according to the domain of livestock production that was found to have a relation with climate control. The considered domains are animal welfare, air emissions, productivity, health and energy use, as reported in Table 1. Other relations with further domains could be highlighted, but they are considered beyond the scope of the present work. Table 1 shows that this analysis encompasses scientific works published in the last 20 years in international scientific journals, books, conference proceedings and scientific reports. As stated before, this literature review was focused only on monogastric animals due to their sensitivity to climate conditions. Nevertheless, climate conditions are also important for the farming of ruminants, but they are considered beyond the scope of the present review.

In the conceptualization of Figure 2, the mutual relations between climate control and the domains of livestock production that are considered in this work are shown. As visible from Figure 2, climate control has a mutual relation with animal welfare. This is since adequate indoor climate conditions are essential to improve the welfare of the farmed animals. Improved animal welfare could have positive impacts from the point of view of ethics and it may contribute to increasing the social acceptance of intensive animal faming systems that, nowadays, are more and more criticized. Animal welfare can have further connections with two other important pillars of livestock production, namely, feeding and genetics. As an important component of animal environment, climate control critically affects how farmed animals express their genetic potential using feed efficiently and without disease. Therefore, investigations aimed at analyzing these three aspects—climate control, genetics and feeding—should be performed considering all of them together in a holistic way.

Table 1. Domains of livestock production that have a mutual relation with climate control and scientific works from literature—with publication year and type of source—that highlight that mutual relation.

Domain	Reference	Year	Source [1]
Animal welfare	Broom [28]	1996	J
	Blokhuis et al. [29]	2013	B
	Mellor [30]	2016	J
Air emissions	Huynh et al. [31]	2005	J
	Blanes-Vidal et al. [32]	2008	J
	Groot Koerkamp et al. [33]	2008	P
	Knížatová et al. [34]	2010	J
	Banhazi [35]	2013	J
	Winkel et al. [36]	2014	P
	Thorne [37]	2019	B
	Costantino et al. [38]	2020	J
	Rodriguez et al. [39]	2020	J
Productivity	Grieve [40]	2003	J
	St-Pierre et al. [41]	2003	J
	Lu et al. [42]	2007	J
	Daramola et al. [43]	2012	B
	Kilic and Simsek [44]	2013	J
	Barrett et al. [45]	2019	J
	Bilardo et al. [46]	2019	P
	Settar et al. [47]	2019	J
	Liu et al. [48]	2020	J
	Moreno et al. [49]	2020	J
Health	Kristensen and Wathes [50]	2000	J
	McGovern et al. [51]	2001	J
	Donham et al. [52]	2002	J
	Beker et al. [53]	2004	J
	Olanrewaju et al. [54]	2007	J
	Olanrewaju et al. [55]	2008	J
	Smit et al. [56]	2008	J
	European Commission [57]	2012	R
	Aland and Banhazi [58]	2013	B
	Ngajilo [59]	2014	J
	FAO [60]	2016	R
	O'Neill [61]	2016	R
	Yi et al. [62]	2016	J
	Hristov et al. [63]	2018	J
	Laurent [64]	2018	R
	Ranjan et al. [65]	2019	J
	Yasmeen et al. [66]	2020	J
Energy use	Thornton and Herrero [67]	2010	R
	El Mogharbel et al. [68]	2014	J
	Fabrizio et al. [69]	2014	J
	Costantino et al. [70]	2016	J
	Costantino et al. [71]	2017	P
	Zhou et al. [72]	2017	P
	Costantino et al. [73]	2018	J
	Costantino and Fabrizio [74]	2019	P
	Xie et al. [75]	2019	J
	Lee et al. [76]	2020	J

[1] B: book, J: journal, P: conference proceeding, R: scientific report.

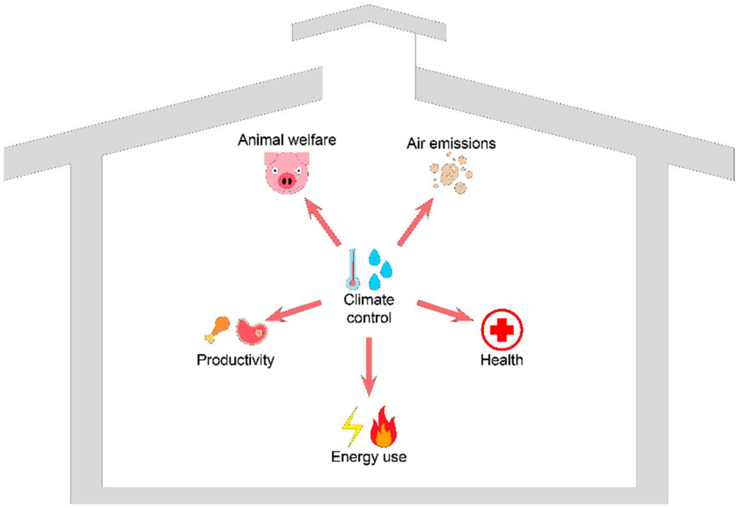

Figure 2. Conceptualization of the relations between climate control and the considered domains of livestock production.

Figure 2 highlights a strong relation between climate control and air emissions. Ventilation has a dual role in controlling the pollutant concentration and in affecting their emission rates. The same ventilation—type and airflow rate—can modify emission patterns. For example, the NH_3 emission process is enhanced when turbulence—air velocity—and temperature increase above manure surfaces. By contrast, high ventilation flow rates may reduce the humidity of litter inside livestock houses, thus reducing potential emissions in subsequent phases. This mutual relation and the real effect of ventilation, hence, is however difficult to predict since it depends on factors such as the airflow rate, building geometry and manure management system. Furthermore, it may be affected by other environmental parameters, such as temperature and relative humidity. These are relevant topics which need further research to be understood with the aim of improving emission abatement techniques.

Climate control also has a mutual relation with productivity and with health. The former relation—with productivity—is because inadequate indoor climate conditions can jeopardize farm production from the quantitative and the qualitative point of view. The latter relation—with health—is because climate control maintains adequate thermal and gaseous environments that contribute to assured hygienic conditions and, hence, to reduction in health risks for both animals and humans.

The last relation that is shown by the conceptualization of Figure 2 is that of energy use. Many livestock houses for monogastric animal farming are characterized by high energy consumption due to the use of mechanical equipment needed to maintain the adequate indoor climate conditions. Moreover, this energy consumption entails considerable greenhouse gas (GHG) emissions since fossil fuels are mostly adopted in the agricultural sector.

In this section, a general overview of the mutual relations that exist between climate control and the considered domains of livestock production was provided. The presented relations will be discussed in-depth in the following sections.

4. The Central Role of Climate Control

4.1. Climate Control and Animal Welfare

Animal welfare has always been associated with coping with the environment, as highlighted by the definition of animal welfare provided by Broom [28]. In addition, the second domain of animal welfare proposed by Mellor [30] is focused on the environment, highlighting that uncomfortable or unpleasant physical features of the environment are negative for animal welfare. In this context, hence, climate control is fundamental since it provides adequate thermal and gaseous environments inside livestock houses. The importance of an adequate thermal environment in terms of animal welfare is also highlighted by the protocol for the overall assessment of animal welfare developed by the Welfare Quality Network [29]. One of the 12 principles at the basis of this protocol specifically regards animal thermal comfort.

To understand the deep relation between climate control and animal welfare, the changes that happen to animals' metabolisms when the thermal environment is not adequate should be understood. Indoor effective environmental temperature is the main parameter that can be considered for evaluating if the thermal environment is adequate for animal farming. This parameter depends on air temperature, relative humidity and air velocity [77] and it has to be maintained within the thermoneutral zone (TNZ) to guarantee the animal's thermal comfort. When the effective environmental temperature is within this range, the animal is in thermal comfort and most of the intake energy is used for growth and production. When the effective environmental temperature is lower than the TNZ, the animal can suffer from cold stress—with potential hypothermia—and its rate of metabolic heat production must be increased by adopting different strategies, such as behavioral modifications or the increase of feed intake. By contrast, values of effective environmental temperature higher than TNZ can cause heat stress that can lead to potential hyperthermia. In this situation, the animal should increase its heat losses to maintain the thermal balance by adopting behavioral strategies, reducing feed intake or sweating [22].

Another condition related to indoor climate that can jeopardize animal welfare is poor IAQ. The indoor air of livestock houses is characterized by high concentrations of different types of pollutants such as gases, vapors, bioaerosols and particulate matter. These pollutants originate from animals, feed, manure and from microorganisms that are associated with manure [37]. They can impair animal welfare with further negative consequences on health and productivity. To improve IAQ and to consequently enhance animal welfare, European regulation sets threshold limits for certain noxious gases in livestock houses. For example, NH_3 and CO_2 concentrations should be maintained below 20 ppm and 3000 ppm, respectively, in European broiler houses with stocking densities higher than 33 kg m^{-2} [16]. Nevertheless, values over these limits were reported in commercial poultry houses. Knížatová et al. [34] measured NH_3 concentrations up to 29 ppm in a broiler house in different periods of the year. NH_3 concentrations up to 39 ppm were found by Costantino et al. [38] in a broiler house in the Mediterranean area. The analyses performed in that work show that the previously mentioned thresholds of NH_3 and CO_2 were exceeded during 60% of the monitored period. The control of CO_2 concentration represented a mayor issue at the beginning of the production cycle, when broilers were chicks, while the control of NH_3 became a mayor issue as broilers grew.

4.2. Climate Control and Air Emissions

As just stated, gases, vapors, bioaerosols and particulate matter worsen IAQ of livestock houses, with detrimental effects on animal welfare. To avoid similar problems and to improve IAQ, contaminant concentrations are usually controlled through natural or mechanical ventilation, a strategy that has a dual effect. On the one hand, ventilation dilutes and removes contaminants, improving IAQ. On the other hand, ventilation can enhance the same air emissions, increasing the contaminants that are emitted inside and outside the livestock house. A clear example of this dual effect can be found, for example, in broiler houses. The high ventilation flow rates that are usually adopted in this type of livestock house during warm seasons decreases the NH_3 concentration, but, at the same time, these high ventilation flow rates favor the NH_3 volatilization from litter with a consequent increase of air emissions. By contrast, in cool periods, ventilation flow rates are considerably lower to minimize the ventilation heat losses. Consequently, NH_3 is not diluted and concentration increases [34]. This dual effect shows that techniques for emission reduction should be implemented in broiler houses. Groot Koerkamp et al. [33], for example, proposed the installation of air circulation units for drying the litter and, hence, decreasing NH_3 and odor emission. Winkel et al. [36] proposed decreasing the emission of particulate matter through an optimized oil spraying method.

A similar relation between the increase of ventilation and the consequent increase of air emissions can also be found in pig houses, especially in the ones that are equipped with a partly slatted floor. According to the analyses of Blanes-Vidal et al. [32], ventilation air flow is one of the three main parameters that affect NH_3 and CH_4 emissions in pig houses, together with the type of rooting material and animal activity. High ventilation air flow rates entail high air speeds, a parameter that is positively related with the mass transfer coefficient from manure to air [78]. When air characterized by a high speed passes over the free surface of the manure, the emissions increase. Rodriguez et al. [39] found an inverse behavior between NH_3 concentration and relative humidity, and a direct relation between NH_3 concentration and indoor air temperature in weaning rooms, results that are similar to the ones of Banhazi [35].

Air emissions inside livestock houses could also increase due to the adoption of mechanical equipment for providing supplemental heating to the farmed animals. A commonly adopted strategy to provide supplemental heating in livestock houses is to place combustion air heaters directly inside the enclosure. This configuration is favorable since installation is cheaper and all the heat produced is released directly into the enclosure, with benefits from the energy and financial points of views. By contrast, this solution is detrimental for IAQ since the combustion fumes are exhausted directly into the enclosure, further increasing air emissions, mainly CO_2. Better solutions should be considered for providing supplemental heating without further increasing the air emissions inside the same enclosure. Valuable options could be the adoption of other technologies, such as electrical heating lamps or radiant floors, or exhausting fumes directly outside the enclosure.

Finally, indoor climate conditions can affect air emissions in an indirect way since they have a strong impact on the urination and defecation behavior of reared animals. According to Huynh et al. [31], indoor air temperature is positively related to the pig urination and defecation frequencies that, in turn, affect NH_3 emissions.

4.3. Climate Control and Productivity

Climate control helps to guarantee adequate thermal and gaseous environments with a consequent increase of the productivity in both quantity and quality terms. Animal productivity can be seriously jeopardized by heat stress, which is particularly detrimental in poultry. Broilers and laying hens are characterized by a low ability to dissipate body heat, a physiological feature that makes them extremely sensitive to heat stress [48]. Broilers exposed to heat stress decrease feed intake for reducing metabolic heat production, with a consequent lack of essential nutrients that causes a growth reduction. This condition is further worsened considering that, in heat stress conditions, most of the energy intake from feed is expended in panting to dissipate excess heat [43]. Consequently, broilers that suffer from heat stress require more time to reach the final live weight target in comparison with broilers reared in a more adequate thermal environment. The work of Daramola et al. [43], for example, highlighted that broilers in heat stress conditions took 84 days instead of 42 days to reach the final live weight target of around 4 kg. This issue is particularly evident in broilers with high growth rate potential, as highlighted by the study by Settar et al. [47] on the effects of the interaction between genotype and environment on the performance of commercial broilers. An inadequate thermal environment frustrates the efforts carried out in the genetic selection of the reared breeds. In addition, the heat stress exposure of broilers could also affect the quality of production. According to Lu et al. [42], chronic heat stress can negatively affect the fat deposition in broiler meat. Furthermore, seasonal heat stress has been reported to accelerate postmortem glycolytic metabolism, leading to biochemical changes in muscle and to the production of pale, soft and exudative meat characteristics in chickens [43].

Heat stress is also detrimental in laying hen farming since it causes performance decreases, blood chemistry alterations and mortality increases, as reported by Kilic and

Simsek [44]. The effects of heat stress in laying hens is chronologic [43], meaning that the effects appear sequentially in time. First, heat stress causes a reduction in egg size, then a lowered egg production and, finally, a reduced quality of the egg shell [40]. The effect of ambient temperature on the average egg weight appears to be cumulative. When hens are kept at 26 °C, the mean egg weight increases by 1 g per week, whereas when kept at 35 °C, the average egg weight remains constant for a period of six months [43].

Pig productivity can also be affected by heat stress. According to the experimental results of Bilardo et al. [46], growing-finishing pigs tend to not feed when indoor air temperatures are excessively high. Furthermore, growth performance and intestinal function of pigs can be affected by the increased gut permeability and inflammation caused by heat stress [43]. Heat stress exposure can even be detrimental in pigs for meat quality due to the high production of free radicals and reactive oxygen substances [49] and by changes in the distribution of adipose tissues as body fat shifts towards internal sites [43].

Heat stress, hence, considerably affects farm productivity and the financial losses attributable to heat stress-related problems are significant. According to St-Pierre [41], losses each year in the US in the growing-finishing pig sector amount to around USD 202 million. The economic losses are relatively lower in the poultry sector, being around USD 98 million in laying hen production and around USD 51.8 million in broilers [41,45].

4.4. Climate Control and Health

Climate control has a strong relation with both animal and human health, as shown by the schematization presented in Figure 3. Climate control provides the adequate thermal and gaseous environments necessary to maintain animal health and avoiding health problems, such as hypothermia and keratoconjunctivitis, as better described in Section 4.1. Furthermore, an adequate climate control contributes considerably towards reducing the spread of infections inside livestock houses. This aspect is of the foremost importance for both animal and human health, especially considering the One Health approach, as specified later in Section 4.4.2. Finally, Figure 3 shows that climate control has further positive impacts on human health at a local level by reducing potential respiratory problems for farm workers, as highlighted in Section 4.4.3.

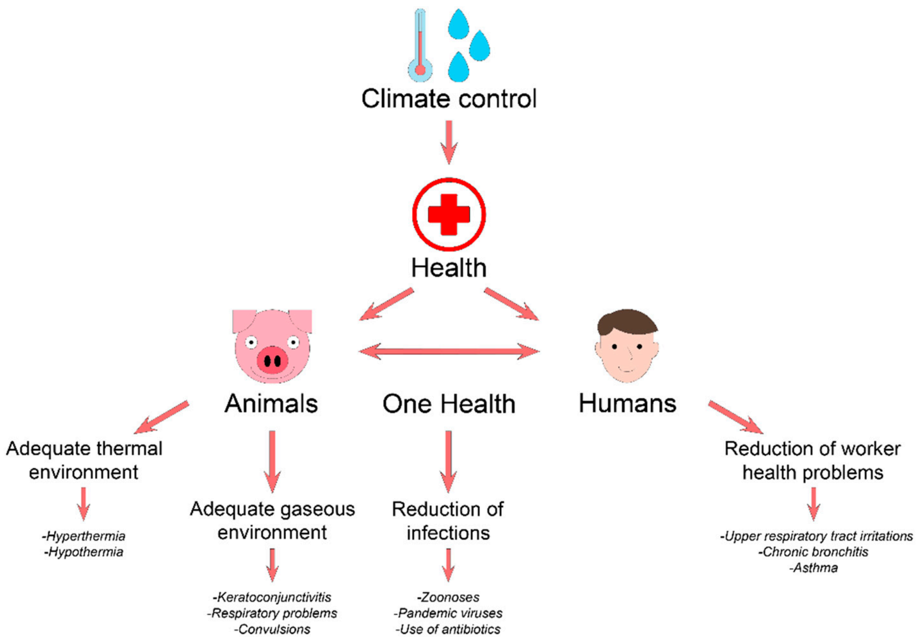

Figure 3. Relation between climate control and health of both humans and animals.

4.4.1. Climate Control and Animal Health

Climate control contributes strongly to maintaining the health of farmed animals. As previously specified in Section 4.1, an inadequate thermal environment can be detrimental for animal health, leading to hypothermia and hyperthermia with severe consequences, including death. An inadequate gaseous environment is also detrimental for animal health especially when high NH_3 concentrations are present inside the house. Being a water soluble gas, NH_3 can be absorbed into the mucus membrane and can increase susceptibility of poultry to respiratory diseases [53] and to the development of infections [50]. High NH_3 concentrations can also cause keratoconjunctivitis—ocular damage [54]—and other ocular disorders [53]. In addition, broilers exposed to high NH_3 concentrations had a higher expression of genes potentially inhibiting both growth and development of breast muscle [62]. Even high CO_2 concentrations can have negative consequences on broilers. This is due to both the negative effects of this gas and the consequent decrease in O_2 concentration [51]. Concentration of CO_2 over 90,000 ppm can cause gasping and convulsions in broilers. Long exposure times, even in the presence of lower CO_2 concentrations, can decrease body weight and increase mortality [55], with negative effects on productivity.

4.4.2. Climate Control and the One Health Approach

Climate control can further contribute towards improving animal health by assuring hygienic conditions inside livestock houses. In this way, the risk of introduction and spread of infections in herds and flocks can be reduced with positive impacts for animal health. By reducing the infections of farmed animals, the broad use of antibiotics in the livestock sector could be reduced with potential benefits for human health at a global level [64]. According to the US Food and Drug Administration, over 70%—by weight—of the antibiotics that are considered as medically important for humans are sold to be used in animals, often with the aim of preventing infections or promoting growth rather than treating sick animals [61]. This massive use of antibiotics fosters the mechanism of resistance acquisition of bacteria [60] with the consequent development of drug-resistant infections in humans that kill at least 700,000 people every year [61]. This shows that animal and human health are closely connected. According to the European Centre for Disease Prevention and Control [79], around 60% of all the human diseases have animal origins. For this reason, the World Health Organization developed the One Health approach that considers human health, animal health and environmental health to be interconnected. The One Health approach aims at "designing and implementing programs, policies, legislation and research in which multiple sectors communicate and work together to achieve better public health outcomes" [80]. This approach is particularly focused on food safety, zoonoses control and antibiotic resistance with important impacts at a global level. The role of climate control in the framework of the One Health approach will be even most important considering that climate change is leading to the rise of new pathogens and diseases [63,65]. These diseases are not only a problem for livestock production, but also for humans. This is because there are high probabilities that emergence of new diseases may act as a mixing vessel between human and livestock, facilitating combination of new genetic material and their transmissibility [81].

4.4.3. Climate Control and Worker Health

Human health can benefit from climate control in livestock houses not only at a global level, as shown in the previous section, but positive effects can also be obtained at a local level. Climate control can contribute towards guaranteeing the health of farm workers, as reported in the schematization of Figure 3. According to the European Commission, being a farmer is historically one of the most hazardous occupations in the European Union with 400–500 fatalities per year, due to accidents with animals or zoonotic diseases [57]. Workers of intensive livestock houses are particularly exposed to zoonosis with higher risk of contracting a pandemic virus, such as swine or avian flu and psittacosis. This risk can be minimized through frequent vaccinations, quarantining of sick animals and efficient ventilation able to guarantee adequate IAQ levels [57]. Efficient ventilation also contributes towards decreasing the respiratory exposures and health risks of farm workers. Workers of intensive livestock houses are particularly exposed to respiratory problems, such as upper respiratory tract irritations, chronic bronchitis and asthma [66]. This is because these building enclosures are characterized by high concentrations of noxious gases—e.g., NH_3 and H_2S—and dust that represent potential health hazards for humans. Inside livestock houses, gases are generated by the decomposition of animal urine and feces, while dust particles have different origins, such as animal dander, feed and insects. The size of these dust particles ranges from less than 2 to 50 µm in diameter and they can absorb noxious gases, increasing their potential hazards when inhaled [58]. This potential hazard further increases considering that endotoxin and mycotoxin can be present within these particles [59]. Recent studies demonstrated that the exposure to this mix of gases and dust results in 2–4 times the respiratory health hazard—measured by the decline in pulmonary function over a period of work—than under normal conditions [52]. Undoubtedly, the risk of acute and chronic respiratory diseases in intensive livestock house workers depends on the individual's relative genetic susceptibility to endotoxin [56] and other features, such as a pre-existing respiratory condition, the duration of the working time in the enclosure and the concentration of pollutants inside the house [58]. In this sense, an appropriate ventilation of the enclosure able to dilute the contaminant concentration can strongly contribute to improving the workers' health and safety, providing an additional benefit for farmers: healthy and safe workers are more productive than stressed or injured ones [57,58].

4.5. Climate Control and Energy Use

A strong mutual relation exists between climate control and energy use. In many cases, the adoption of only passive strategies, such as natural ventilation and envelope thermal insulation, would not be enough to guarantee adequate indoor climate conditions, especially in certain periods of the year and at certain latitudes. Consequently, mechanical climate control systems—such as fans and air heaters—are adopted in livestock houses. The use of mechanical equipment entails a considerable consumption of thermal and electrical energy. Very poor information about this energy consumption is present in literature and its quantification could be a complex task as several variables should be considered. In broiler houses, for example, 96% of the total on-farm thermal energy is for supplemental heating (up to 140 kWh m^{-2} y^{-1}), while 76% of the total on-farm electrical energy is for mechanical ventilation (up to 16 kWh m^{-2} y^{-1}). In laying hen houses, around 60% of the total on-farm electrical energy is for ventilation (up to 40 kWh m^{-2} y^{-1}). In pig houses, the thermal and electrical energy consumption for climate control—supplemental heating and ventilation—represents around 70% and 50% of the total on-farm energy consumption, respectively [70]. Currently, the energy used on farms is mainly from non-renewable energy sources, a negative aspect for the environmental, social and economic sustainability of the livestock sector. In addition, the energy performance of agricultural buildings is usually low. According to the Organization for Economic Co-operation and Development (OECD) [82], the current energy performance of agricultural buildings in OECD countries is still similar to those of 1990s or 2000s because no substantial improvements have occurred in the last years. Consequently, an energy-efficient climate control of livestock houses is of the foremost importance to move towards a more sustainable agriculture. This is especially true considering the expected rise of food demand and the consequent increase of the energy consumption due to food production [67].

In this context, energy simulation models could represent powerful tools to decrease the energy consumption for climate control of livestock houses. These models enhance the evaluation of the energy performance of these buildings in standardized conditions, considering different climate change scenarios, different technologies and solutions. Nevertheless, few authors have focused on this specific topic and few ad hoc energy models developed for the estimation of the energy consumption of livestock houses are present in literature [74]. The strength of ad hoc energy simulation models developed for livestock houses is the integration of the main peculiarities of these buildings and their climate control systems. Furthermore, these models are specifically fine-tuned for the purposes of the analyses and adopt the most updated energy simulation method in compliance with the normative framework [83]. In literature, models that were developed ad hoc for the energy simulation of duck houses [76], pig houses [75] and broiler houses [73] are present. Other energy simulation models for livestock houses [68,69,72] were developed using building energy simulation (BES) tools, such as EnergyPlus (U.S. Department of Energy's Building Technologies Office, Washington, DC, USA) and TRNSYS (University of Wisconsin, Madison, WI, USA). BES tools were not specifically developed for simulating intensive livestock houses and, consequently, they cannot consider all the boundary conditions in detail that are specific to this building type, as reported by Costantino et al. [71]. Despite the differences that exist between customized energy simulation models and BES models, all these models can be used to improve the energy performance for climate control of livestock houses.

Improvements of the energy performance for climate control of livestock houses also have positive impacts on greenhouse gas (GHG) emissions. According to the FAO [84], the livestock supply chain accounts for 7.1 gigatons of CO_2-eq emissions, representing 14.5% of the total anthropogenic GHG emissions worldwide. GHG emissions of the livestock sector, hence, have become an important concern in the last years and considered more and more by society as an "enemy" of the environment, with important social impacts. Even though most of the GHG emissions of livestock sector are due to enteric fermentation and manure management, direct on-farm energy consumption represents a significant share of GHG emissions [85]. The direct on-farm energy consumption is responsible of 7.6% of the total air emissions from the chicken meat supply chain, 4.0% from eggs and 2.9% from pork supply chains. Even though the previously presented shares of emissions may seem small if compared with other ones, they are characterized by a considerable room for improvement since, currently, in livestock houses the most adopted energy sources are fossil fuels, while renewable energy accounts for less than 4% of the total energy consumed [86]. Therefore, an energy-efficient climate control based on the adoption of low-carbon and renewable energy sources could be one of the main research topics in future.

5. Discussion

In the previous sections, several relations between climate control and other domains of livestock production where shown, outlining the central role of climate control in livestock houses. This role may become even more central in future, as shown by the schematization in Figure 4. Climate change will emphasize the importance of climate control of livestock houses since global warming is opening a new long-term challenge: avoiding a perpetual food crisis [87]. Global warming increases the risk of food insecurity by intensifying the heat stress of livestock [81]. By controlling indoor climate conditions, climate-controlled livestock houses are considered resilient buildings that can mitigate the impact of climate change, contributing towards avoiding food crises [88]. As shown in Figure 4, this aspect will be of foremost importance in developing countries. These countries produce more than 50% of meat and 60% of milk that are consumed at a global level [89] and these percentages are increasing due to sociodemographic factors—such as population growth and urbanization—that foster the demand for animal products [90]. To meet this increasing demand and to guarantee the food security of these countries, climate control seems essential because most of the developing countries are in areas characterized by hot climates. Even though many factors—e.g., sanitary problems and quality of local feed—affect the productivity of livestock production in these geographical areas, adverse climatic conditions are among the most limiting factors [89]. In the past, these adverse climatic conditions had a lower impact on productivity because local livestock species were farmed as they easily acclimated to the local climate conditions. Now, the increasing demand for livestock products is turning towards the adoption of high-performance animals, typical of industrial livestock systems, that are imported from developed countries [89]. These animals were genetically selected to increase their productivity, but they are very susceptible to high temperatures due to the strong relationship that exists between production level and metabolic heat production [89]. Hence, mechanical climate control systems may spread considerably in developing countries in future. These systems would contribute towards providing adequate farming conditions, but they would also entail important energy consumption in contexts where the energy supply is often problematic. In addition, this spread of climate-controlled livestock houses would further increase the overall energy consumption of the livestock sector.

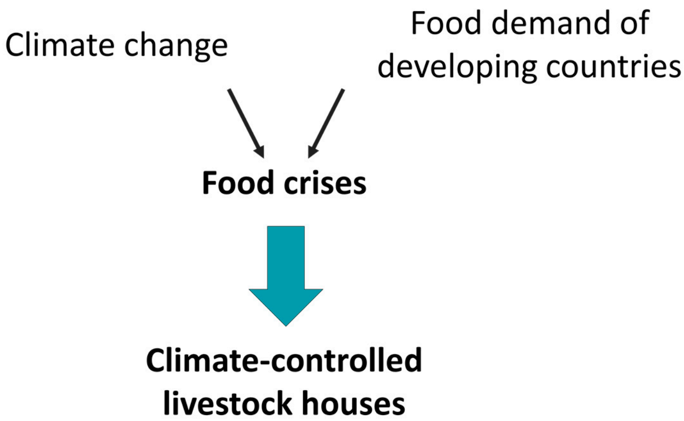

Figure 4. Schematization of climate-controlled livestock houses as a potential solution that may contribute towards avoiding food crises due to climate change and the increasing food demands of developing countries.

One of the most urgent and arduous challenges for the future is to develop an energy-efficient climate control that would have positive impacts on all the three areas of sustainability, namely, environment, economy and society [91], as shown in the schematization in Figure 5. An energy-efficient climate control would entail minimum energy consumption to maintain adequate indoor climate conditions and it would integrate energy systems based on low-carbon and renewable energy sources. These features would lead to reducing the resource depletion and to reduce the anthropogenic GHG emissions from the livestock sector, fighting climate change and the improving the environmental sustainability of the livestock sector. The economic sustainability of the livestock sector would also benefit from energy-efficient climate control since a reduction of energy consumption would lead to a consequent reduction of the farm running costs due to energy supply. The adoption of renewable energy sources represents an advantage for farmers since it would decrease their business risks in comparison to fossil fuels. Fossil fuel prices are characterized by important fluctuations that expose farmers to significant business risks and can considerably increase production costs, with a consequent rise of the final product price [19,92]. Maintaining final price stability, hence, energy-efficient climate control could further improve food security, with positive impacts on social sustainability.

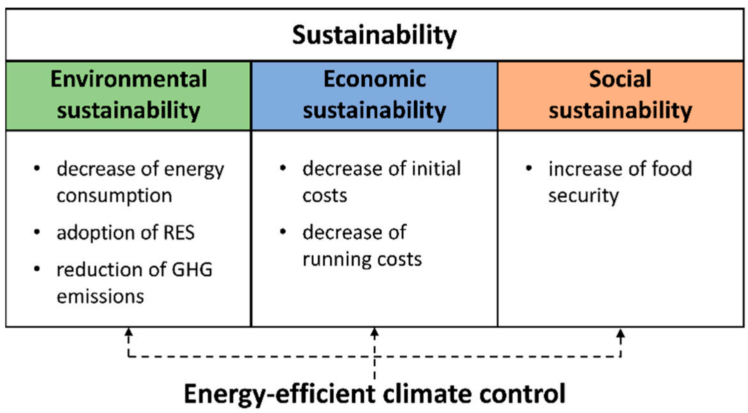

Figure 5. Positive impacts that an energy-efficient climate control of livestock houses could have on the three areas of sustainability, namely, environmental, economic and social sustainability.

An interesting question that arises from this discussion regards how to quantify the actual improvement that can be achieved through efficient climate control, considering all the analyzed domains. Such quantification is a complex task since these improvements may have a positive impact on certain domains but a negative one on others. A possible solution for this quantification may come from the adoption of precision livestock farming (PLF) technologies combined with artificial intelligence (AI) algorithms that can provide real-time data about, for example, energy consumption and animal health, requiring a minimum number of measurements. The obtained data may be merged into a single indicator that can enhance a holistic decision process in animal farms. The development of such indicator may represent an ambitious challenge for future works since the most significant parameters for each considered domain should be identified and they should be merged to obtain a single value.

6. Conclusions

In the present work, the web of mutual relations between climate control of livestock houses and other domains of livestock production was unpicked through a literature review. The results show the central role that climate control has in livestock houses and the mutual relations that interlace it with animal welfare, air emissions, productivity, health and energy use.

The web of relations that was presented in the framework of this analysis is the key to understanding the potentialities that climate control has in improving different domains of livestock production with the final aim of enhancing the development of more sustainable livestock production systems. Each one of the analyzed domains has evolved quickly for years, achieving promising advances, especially regarding sustainability. For ensuring that such advances can have the highest impact on the farms, the mutual relationships between the different domains should be deeply investigated—as done in this work—to consider farms with a holistic approach. In this framework, climate control can become a driver to push the sub-sector of livestock production in confined systems towards sustainability. Nevertheless, deep transformations are required for climate control, especially from the energy point of view. A more energy-efficient climate control is required, especially considering the increasing trends of energy consumption caused by the rising demand for livestock products. For this purpose, solutions, technologies and strategies should be developed and tested to reduce the energy consumption of livestock houses and to enhance the implementation of renewable energy technologies.

Further investigations may aim at deepening the analysis provided in this work adopting a dual approach. On the one hand, future works may expand and further unpick the web of mutual relationships considering additional domains of livestock production. On the other hand, future works may be focused on the "hardware" part of climate control by analyzing the state-of-the-art technologies that are adopted in livestock houses to control the indoor climate conditions.

This review opens interesting new perspectives for long-term research. The relations between climate control and other domains of livestock production that are highlighted in this work could be numerically assessed by developing and validating integrated climate control models. These models would encompass all the previously presented domains of livestock production and can assess how they are affected by changes in the indoor climate conditions. In addition, similar models can help to investigate the interlinking of climate control with more than one domain. They can explain, for example, how changes in one of the considered domains can indirectly affect the remaining ones. The first step for obtaining similar models is the development of reliable and robust simulation models for the estimation of indoor climate conditions inside different types of intensive livestock houses.

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