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Review

An Overview of Poultry Greenhouse Gas Emissions in the Mediterranean Area

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Abstract: The growing population and income drive the rapid increase in food demand. Greece and a few other Mediterranean countries are characterized as countries with a high proportion of mountains favoring goat and sheep breeding; however, poultry breeding is also important, and production is increasing rapidly. Poultry breeding is characterized by the millions of birds reared with increased quantities and prices of feedstuffs. There is a parallel increase in greenhouse gas (GHG) emissions., since poultry production generates a significant amount of GHG. The aim of the present study was to provide an overview of poultry GHG in the Mediterranean area. Emissions' sources and mitigation practices are presented. Future is promising given that sustainable practices are implemented.

Keywords: soybean replacement; manure management; Mediterranean; biogas production; novel feeding; poultry; sustainable farming

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1. Introduction

The global population, estimated at nearly 8 billion people worldwide in 2022, tends to approach 9.7 billion by 2050 and 10.4 billion by 2100 [1]. Likewise, in 1950, 30% of the population lived in urban areas, in 2000 47%, while 68% is foreseen by 2050 [2]. This alteration led to a more fast-paced way of life and to a shift in food habits more western-based, abandoning the Mediterranean diet concept, as well as to considerable levels of animal-derived protein consumption [3]. Besides that, there is a trend in shift from red to white meat [4], especially towards poultry. Thus, to meet the demand, poultry farming grows constantly [5]. This leads to thriving environmental concerns about animal production [6], hence setting the development of sustainable animal diets as a top priority.

In terms of environmental concern, climate change severely affects livestock. On the other side, concurrently livestock farming is one of the main contributors to greenhouse gas (GHG) emissions [7], either through the animal physiological processes or the food supply chains. Thoroughly, the three so-called GHGs, which customarily contribute to this phenomenon, are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [8], while others such as ozone (O_3), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF_6) have a slighter contribution [9].

Nevertheless, the concerns over the impact of the livestock sector om climate change have led to a plethora of studies aimed at improving the scientific knowledge over this [10–14]. Moreover, there is a great need for further research, not only on the impact of poultry farming on GHG emissions, but more importantly on the mitigation practices that need to be established for lessening such environmental burden. It is important to note that even though the food systems have a major contribution to the GHG emissions

(~30%), the opportunity for reducing them has received less attention, partly because it seems like an unavoidable burden for meeting the nutritional global demand [15]. Nonetheless, at the same time, consumers' demand for products with a low environmental footprint [16] and that promote animal welfare [17] appears to be increasing.

Greece and a few other Mediterranean countries in the European Union (EU) are characterized as countries with a high proportion of mountains favoring goat and sheep breeding; however, poultry breeding is also important, and production is increasing rapidly. Moreover, the production system established in countries of the Mediterranean region is generally based on intensive production, thus the application of GHG mitigation strategies could be more holistic and irreversible. As a result, it could be more efficient compared to ruminants' sector, where the variety of production systems make difficult the application of such strategies. In addition, the EU Mediterranean countries share not only similar climate conditions and farming systems, but more importantly share common policies under the auspices of the European Union, potentially establishing a more unified approach. Considering the above evidence and due to the specific socioeconomic aspects analyzed below, we chose to study poultry, aiming to explore options to help lessen the environmental impact associated with poultry production in EU Mediterranean countries.

2. Greenhouse Gas Emissions

2.1. Calculation of the GHG Emissions

A widely described term is that of "Carbon Footprint" (CF), a reference to the sum of GHG emissions generated and associated with any activity by a product or service system [18]. Contrary to what the word implies, the CF includes CO_2, N_2O, and CH_4 emissions expressed in carbon dioxide equivalents (CO_2-eq) [19].

Likewise, several methodologies have been applied to assess the environmental impact of livestock production systems [7]. The LCA (Life Cycle Assessment) is an ISO-standardized environmental accounting tool (14040 and 14044 ISO standards) used to evaluate the environmental impact generated through the different life-cycle stages of a product "from raw material acquisition, via production and use stages to waste management" [20]. The methodology has also been applied to livestock and food production systems [21,22]. However, for conducting a holistic approach, the keynote is the inclusion not only of the in-farm emissions but also the emissions contained in each stage of production as fertilizer, crop or feed production, animal facilities, processing, transportation, market distribution, product consumption, and waste management [23].

2.2. Mediterranean Statistics for Livestock GHG

The principal sources for GHGs involved in livestock are N_2O from fertilizer application, during cultivation, and manure management [24]; CH_4 originates from enteric fermentation and manure management plus the CO_2 mainly from fuel combustion on-farm, such as from heavy farm machinery operations, heating, electricity, fertilizer production [25], and land-use change (LUC) for feed production [26]. In detail, a FAO report [27] described that livestock accounts for 14.5% of total anthropogenic GHG emissions or 7.1 Gt CO_2-eq. Of this total, the share of feed production and processing is about 45% or 3.2 Gt CO_2-eq; enteric fermentation about 39% or 2.8 Gt CO_2-eq, being the second-largest source of emissions; and manure management about 10% or 0.71 GtCO_2-eq. The remaining 6% or 0.42 Gt CO_2-eq is due to the processing and transportation of the animal products. The largest contributor of livestock emissions globally is the cattle production with a contribution of 4.6 Gt CO_2-eq or 61%, while other species generate much lower emissions, such as poultry 0.7 Gt CO_2-eq (8%) [19,27]. By accounting only for the direct CH_4 and N_2O emissions from enteric fermentation and total manure management, the contribution is estimated at 5.4 Gt CO_2-eq [19,28].

Specifically for the EU countries, agriculture constitutes 11.4% of total GHG emissions [29], from which CH_4 from enteric fermentation accounts for 42% while manure management 14% [30]. Combining CH_4 from enteric fermentation and N_2O emissions from soils, a sum of 81% of the total agricultural emissions results [30]. However, the quantities of GHG emissions differ between species, regions, or production systems, as organic systems tend to produce higher GHG emissions [31] (Figure 1 and Table S1 in the Supplementary Materials). Moreover, farm-gate emissions have increased by up to 11% from 2000 to 2019, mainly attributed to livestock (~55%) [32]. Therefore, each production system should be studied separately, requiring a different approach for mitigation options [33].

Nevertheless, agriculture in Greece accounted for 8.84 million tonnes CO_2-eq in 2010 but 7.78 million tonnes CO_2-eq in 2019 [34], Croatia and Malta being among the countries presenting a substantial decrease within the EU [30]. Furthermore, emissions from agriculture accounted for 9.2% of total emissions in 2018 and decreased by 22.19% compared to 1990 levels [34]. This outcome is due to the reduction of N_2O emissions from soil because of the reduced use of synthetic nitrogen fertilizers and the animal population number. Furthermore, in Greece, CH_4 represents the main GHG from agriculture, in a range of 48% to 58% of total GHG [34].

Hence, greater interest should be given to research in mitigating GHG emissions. According to Gerber et al. [27], good practices and technological application in animal nutrition, health, as well as manure management can help to improve livestock production and reduce global GHG emissions by 30%. For this purpose, in turn are described some mitigation practices that can be adopted for poultry farming applied in the EU Mediterranean countries and include—but are not limited to—feed management, feed production options, manure management for fertilization, and energy mitigation on site.

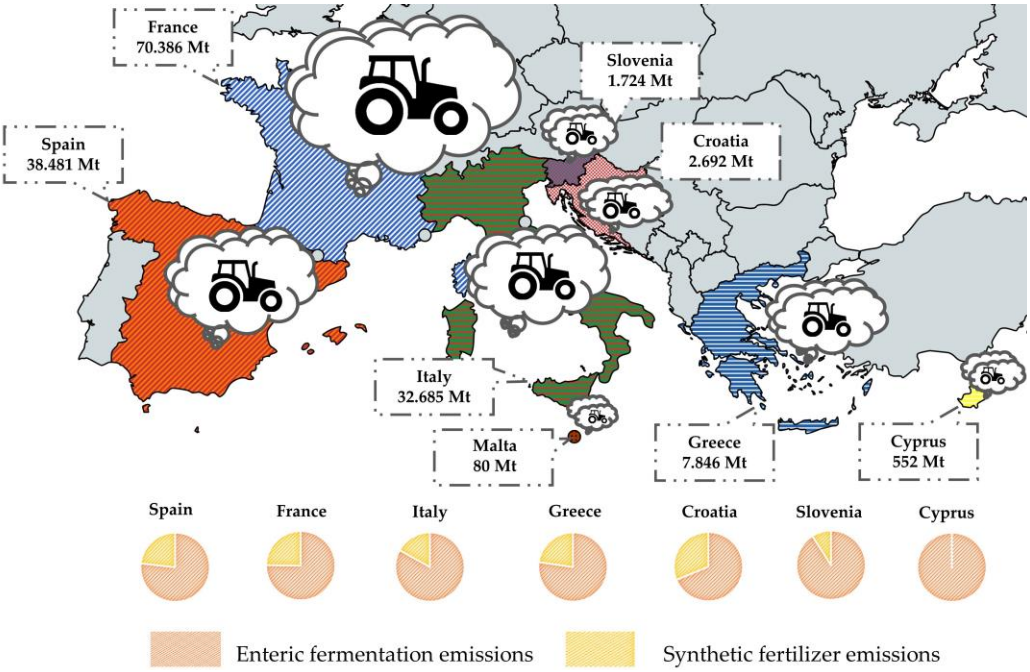

Figure 1. Emissions, in EU Mediterranean countries, originating from agriculture sector, expressed as total of CO_2-eq and as ratio of enteric fermentation to synthetic fertilizers emissions (only total emissions are presented for Malta, Supplementary Data at Table S1) [32].

3. Poultry

Primarily, poultry meat represents a major part of the total amount of meat produced [35] and is projected to represent 41% of all meat sources protein by 2030 [5]. Over the last 50 years, the average annual growth for poultry meat has been 5%, while it has been 3.1% for pork, only 1.5% for beef, and 1.7% for small ruminant meat [36], operating as a forerunner of the total meat production. Additionally, the rapid increase in poultry production is further supported by the increased poultry population from 4.2 billion birds in 1961 to more than 35 billion birds in 2020 [32]. Similarly, egg production was 15 million tonnes in 1961, while in 2018 it exceeded 92 million tonnes [32]. Likewise, poultry production is also a major agricultural sector in the Mediterranean area (Table 1), and a substantial source of GHG emissions for Greece [37], compared to other Mediterranean countries.

Table 1. Population and production (meat and eggs) of poultry in 2020, in EU Mediterranean countries.

	Poultry	
Countries	**Meat Production (Thousand Tonnes)**	**Eggs Production (Thousands of Tonnes)**
Croatia	54	30.1
Cyprus	27	10.5
France	1121	786.1
Greece	228	74.3
Italy	1055	717.4
Malta	4	5.5
Slovenia	64	24.8
Spain	1412	810.9

The data were collected by FAO [32].

The sources of the emissions derive from feed production, LUC, and the energy use during the operations in and out of the farms (international trade, slaughterhouse, feed production, hatchery). It has been vastly reported that feed production is the most important source of GHG emissions [33,38–40], and the rate varies widely in the literature from 45% to 93.7% [41–43]. For example, the major environmental cost from an intensive egg production system was feed production in Spain [44], while comparable results were found in Netherlands [45], Iran [46], and Canada [42], implying an independence for each country.

As for the broiler sector, the most is related to LUC and animal feed [6] while the rest to performance objectives, use of energy, the handling of litter, and the stocking density [47,48]. Energy combustion is an important source of GHG in poultry production, both for eggs and meat [45,49,50], required for the ventilation, feeding, lighting, egg collection, sorting, heating, and operation of the mechanical equipment.

As a result, it is essential to mention that the differences in emissions sources, for meat and eggs, result in different values for emissions, as well as in different ways of expressing the rate of GHG emissions. For instance, in a meta-analysis study, with protein as a basis of calculation, 100 g of poultry meat protein accounted for 5.7 kg CO_2-eq, while 100 g of egg protein accounted for a lower rate of 4.21 kg CO_2-eq [6]. On the other hand, Clune et al. [51] reported values based on the kg of product at a rate of 3.65 kg CO_2-eq/kg BFM (bone-free meat for chicken) and 3.46 kg CO_2-eq/kg eggs.

3.1. Greenhouse Gas Emissions

3.1.1. CO_2 Emissions

Carbon dioxide emissions originate mainly from fuel consumption [52] and electricity [53] and are attributed to the appropriate machinery, transportation, and ventilation equipment used in the animal houses and the crop production. Notwithstanding, respiration is not considered a source of emissions, because the emitted and absorbed quantities of CO_2 are equivalent [54]. As for the crop production, this turns on the cereal production, a major and necessary part in poultry feed and diets, as well as on the LUC and the transportation of other essential feedstuff. Nevertheless, the cereal production is of great concern and concurrently a potent area for further research, as has been extensively reviewed by Różewicz [55].

Moreover, the health of birds highly depends on the temperature in the poultry house, with emissions deriving from the need for optimal temperature conditions and the adjustments needed to achieve this. For instance, in poultry houses there is the need for heating in cold months of the year but also the need for cooling during hot months, to avoid heat stress [56]. This is even greater for small chicks that lack proper thermoregulation mechanisms. To properly establish such thermal systems, a significant amount of CO_2 emissions may be generated, due to energy consumption.

Besides, more CO_2 emissions are generated from hatchery processes due to extensive energy consumption. In detail, a range of 12–23% was reported by Usubharatana and Phungrassami [57].

Last, the international trade in poultry meat contributes to significant emissions of CO_2 by fuel use for the shipping and total transportation of poultry meat, estimated at 256,000 tonnes of CO_2 [58]. Emissions are proportional to the use of fuel and strictly related to the distance travelled [39]. Therefore, the potential lack of availability of local feed is a major challenge for producers due to the increased need for fuels.

3.1.2. CH_4 Emissions

Methane is the most important greenhouse gas related to animal agriculture with a global warming potential that is 28-fold that of CO_2 [59], mainly coming from ruminants' enteric fermentation and manure storage [60]. Conversely, poultry as monogastric do not pose a significant share from enteric fermentation, so the CH_4 originates mainly from the management of waste and excreta generated. The type of litter, moisture, and temperature affect the emissions and concentrations of gases [61]. Egg production includes a variety of housing systems and litter-processing practices. The waste which is produced from the various operations of poultry farms are liquids, the litter, dead birds, broken eggs, and the eggs discarded during the packaging process in larger production units.

Often, although the term chicken manure is used, it represents a general term including but not limited to chicken slurry, dry chicken excreta, chicken manure, and fresh chicken excreta [62]. In a biological production system, excreta in piles are composted, which increases aeration and reduces anaerobic CH_4 production.).

3.1.3. N_2O Emissions

The N_2O emissions are generally produced due to the high use of N fertilizers for the feed production, slightly more than 35 percent of emissions [27], and the spreading of the animal manure on the field. Under this context, it is necessary to divide the source of the fertilisers into artificial and natural manure, not only under the strict limits of GHG emissions but also based on a more sustainable production activity [63]. For fertilizer manufacturing, 0.7% of total GHG emissions or 0.41 Gt CO_2-eq were reported [64]. Excess of N can be converted to N_2O through the nitrification–denitrification process, where ammonium (NH_4^+) or organic N is converted to NO_3^- and NO_2^- during nitrification, and then via anaerobic treatment NO_3^- and NO_2^- are reduced to N_2, while through denitrification N_2O and nitric oxide (NO) are produced [9].

4. Mitigation Strategies

To lessen the environmental burden, a variety of strategies should be addressed. Mitigation strategy is a group of practices that need to be implemented for GHG emissions' reduction. In general, it is crucial to separate the mitigation practices in different sections according to their aim. In poultry, the practices are related, but not limited to, feed utilization, manure management through utilizing it for energy production or as a fertilizer, as well as energy management through cost effective solutions and renewable energy sources, and data collection for extra data analysis, a novel way of predicting the environmental impact. Moreover, feed efficiency and growth rate are related to the quantity and quality of generated excreta [65]. FAO [66] estimates that available improved-farming practices can lower emissions by up to 30%, including mitigation for feed production, nutrition, energy combustion, and faecal management. However, management practices can only lower GHG emissions up to a specific point. For any further mitigation, livestock reduction is needed or an increased efficiency.

4.1. Poultry Feed Formulation and Additives

A summary of the mitigation strategies related to poultry nutrition is presented in Table 2 and presented in detail in the following sections.

Table 2. Summary of the dietary practices applied to lessen the GHG emissions.

Dietary Strategy	Nutritional Practice	Effect-Impact	Supporting Evidence	References
Replacement of soybean	Peas	↓ 8.21% GHG	Local availability reduces the transportation emissions	[67]
	Semi-leafless peas			[68]
	Domestically peas and rapeseed			[49]
	Cottonseed meal			[69]
Replacement of palm oil	Cotton seed oil	↓ 22% CF		[70]
Alternative protein sources (insects)	Mealworm	↓ LUC	- Welfare, growth performance or any other physiological or morphological feature	[71,72]
	Black soldier larvae fat		No alteration on performance or meat and carcass quality	[73]
Balance low-protein diets	Amino acids	↓ Loss of nutrients	↓ Energy demand	[74]
Improve bioavailability of nutrients	*E. coli* phytase	↑ Bioavailability		[75]
	Zn and phytase		↑ Body weight and nutrient usage	[76]
	Decrease or replace the amount of soybean meal with protease and corn gluten meal			[77]
Waste valorization	Hotel food residues	↓ Loss of nutrients ↓ Energy for feed production ↑ Supply of bioactive compounds	No impact on FCR, mortality, carcass, or breast yield	[78,79]
	Vinification by-products (ground grape pomace, wine lees extract and grape stem extract)		- Feed intake, FCR, carcass yield, and the weight of the internal organs not affected	[80]

	Wine lees extract rich in yeast cell walls, and grape stem extracts	- Improvement of the broilers' oxidative status	[81]

↑ =Increase, ↓ = Decrease.

4.1.1. Unconventional Feed Formulation

Under this context, total or partial replacement of ingredients in diets can be applied. During volatile ingredient markets, when there is pressure to reduce diet costs, or when common ingredients become scarce, there is a need to use alternative feed ingredients considering potential limitations. Likewise, the high demand for protein supply for livestock led to the constantly increasing global production of soy products, which is severely related to deforestation and soil degradation. Poultry production uses 37% of soybean [82], the largest amount of any livestock sector in Europe. Therefore, great interest should be given to soybean that highly contributes to LUC [83]. It is important to note that a 1% soybean reduction can decrease more than 10% N excretion [84]. Most notably, soybean can be replaced by semi-leafless peas [68], domestically cultivated peas, and rapeseed [49]; however, the local availability and presence of antinutritional factors should be taken into account. A beneficial strategy for the poultry sector with a crucial impact is the cultivation of legumes, a practice under serious development. The locally produced legumes not only provide poultry with an efficient amount of protein but also have the potential for substituting imported soybean. For instance, under the perspective of reducing the global transportation emissions due to soy imports from south America, the cultivation of legumes, such as faba bean or lupine, can be turned into a viable solution [85]. A decrease of 8.21% for total GHG was reported by Fatica et al. [67] by examining the total for the replacement of soybean with peas, in broiler diets in Italy, suggesting it as a means for reducing the GHG emissions in the Mediterranean area. Moreover, Abín et al. [70] substituted palm oil with cotton seed oil, which reduced the CF by 22%, ensuing a CF of 2.3 kg CO_2-eq per kg of eggs. Furthermore, Ceylan et al. [86] tested sunflower, fish, linseed, and rapeseed oil while Yuan et al. [69] replaced soybean meal with expanded cottonseed meal in laying hen diets at the levels of 6, 8, and 10%. The benefits of these substitutions are not solely related to the use of feed with lower CF but also to changes within the cropping systems [49]. Under this scope, using good quality non-contaminated feed which does not contain an excess of minerals such as copper or zinc but those quantities that are required for animal health could be a beneficial strategy [58].

The prospect of using alternative protein-rich feed ingredients in poultry diets may benefit global food security and demand for protein. Apart from that, they do not compete with the use of arable land, a crucial benefit on the effect of climate change. Some suggestions with environmental potential for upcoming use in poultry nutrition include but are not limited to micro- and macro-algae, duckweed, yeast protein concentrate (YPC), bacterial protein meal (BPM), leaf protein concentrate (LPC), and insect meal [87]. However, their role in mitigating GHG emissions needs to be clearly evaluated, but it seems promising since, for example, insects can turn low-grade biowaste into proteins [88]. Under this context, insects are acknowledged as a natural feed for wild-grown chickens that can further be used in organic systems, so a modest hypothesis is whether the inclusion of insects in poultry diets would benefit, in terms of sustainable production, animal welfare and with reduced environmental impact [89]. Since insects are high in protein, fat, essential amino acids, and micronutrients [90,91], a promising option for soybean replacement is the use of insects, such as black soldier fly larvae, maggot meal and mealworm, as protein sources [92–94]. For example, mealworms' crude protein content (~50.4%) is at the same level as or even higher than soybean (~49.5%) but less than fishmeal (~69%). In addition, saturated and monosaturated fatty acids are also present in high levels [88]. As for the feed efficiency, the mealworm inclusion in poultry diets did not affect the welfare, growth performance, or any other physiological or morphological feature in free-range chickens

[71] or broilers [72]. Mealworms are a better option than maggot and silkworm as they improve both broiler performance and meat quality [95]. However, Biasato et al. [96] suggested inclusion at a low level (~5%), due to risks for the intestinal morphology. Moreover, the substitution of 50% and 100% of soybean meal with the same level of black soldier larvae fat did not present any alteration on performance or meat and carcass quality [73], prompting an innovative and promising feed-supplementation method. Nevertheless, insects require special treatment for growth and development [87] for heating and drying, so the energy demand needs to be limited, as reported by de Boer et al. [97]. Tallentire et al. [87] reported that LPC had the lowest GHG emissions, followed by YPC and insect meal. However, the potential of future growth in insect meals has some crucial limitations, since it is not only limited for the large volume the market needs but also in relation to the substantial ingredients for the poultry feed, mainly amino acids and trace elements [98], issues which need to be resolved. Nevertheless, more research is needed for the examination of the economic viability [99].

4.1.2. Feed Production Practices

Feed production is the biggest opportunity to reduce GHG emissions in poultry farming, since it constitutes a major emissions factor. In that part, the main target is to reduce the need for nitrogen fertilizer added on soil or use the least amounts that can be handled without compromising N emissions. That could be achieved through pruning and management systems that increase nitrogen yield in crops. Also, a good option is the use of crops that require less N per unit of yield compared to conventional crops. Moreover, soil management using suitable cultivation techniques (e.g., minimum slope), integrated pest management, and targeted use of fertilizers is a practice not only good for GHG emissions but also with advantages for soil and total crop production [58].

4.1.3. Amino Acids

It is essential to provide poultry diets that meet the nutritional requirements in their production and development stage to reduce the loss of nutrients and balance the direct consequences on profit [100] as well as preserve welfare. Furthermore, for low protein diets, it is crucial to supplement the ratios with additional essential amino acids or to modify them to balance amino acids and avoid reduced-feed intake resulting, in turn, in reduced production [101,102]. Although amino acids appear to have the greatest carbon intensity among other feed constituents, they have low impact due to the small quantities used [103]. Amongst others, the use of amino acids may result in a viable replacement of soybean in poultry meat production [104]. Moreover, feeding with the digestible amino acids tend to reduce not only the environmental impact but also the cost and the energy demand for their production [74]. That is why the use of amino acids is highly related to precision feeding as a technique.

4.1.4. Exogenous Enzymes

Another option is to improve the digestibility of feed and the bioavailability of nutrients using exogenous enzymes, such as phytases and proteases, and to ensure a balanced microflora (eubiosis) in the digestive system of the bird. The idea of including exogenous enzymes in poultry diets is to decrease the feed's protein level without affecting the growth performance and improve the environmental impact as a result. For example, Al-Harthi et al. [75] described some broiler feeding scenarios and reported that the diet consisted of olive cake supplemented with 500 FTU of *Escherichia coli (E. coli)* phytase was the most beneficial and economically competent scenario among those they examined without affecting performance. Also, improved body weight and nutrient usage was indicated in wheat–soybean meal-fed broilers supplemented with Zn and phytase [76]. Besides, Giannenas et al. [77] examined some scenarios, decreasing the amount of soybean meal with the addition of protease or replacing soybean meal by corn gluten meal and including a protease, providing potential environmental benefits.

4.1.5. Waste Valorization

Food waste has generally been considered as a great loss of nutrients, so a modest proposal could be the optimization of such novel feeding technique, especially for poultry. Thus, the incorporation of food waste or by-products could imply a potent material for further utilization [105], contributing to both the circular economy and upcycling. In experiments performed in broilers, the results from incorporating vinification waste by-products [80,81] and hotel food residues [78,79] depicted some promising results. Apart from the concept of sustainable production and the lack of contradiction with human food consumption, there are some vital points to emphasize on this promising strategy. For example, it is of utmost importance to preserve the presence of beneficial bioactive compounds in food waste by examining the proper method of transforming waste into animal feed [106]. Also, to abate the potential hazards of food waste as feed supply, several techniques have been studied and evaluated in recent research [107].

As far as the performance concerns, in an experiment conducted by supplementing 15% of the ration with hotel residues, in broiler diets there was no impact reported on the feed conservation ratio (FCR), mortality, carcass, or breast yield [78]. Moreover, there was no biochemical parameter examined implying any physiological malfunction due to the food-waste incorporation. In another study, Giamouri et al. [79] examined not only the supplementation of hotel food residues in broiler diets, but also the condition of supply, sterilized or non-sterilized. The broilers were supplied with four different treatments: a control, non-meat treatment (100 g dehydrated food residues without any meat), non-sterilized treatment (NS) (100 g non-sterilized dehydrated food residues/kg feed), and sterilized treatment (100 g sterilized dehydrated food residues/kg feed). The results from this study suggested the significance of such treatments as feedstuffs for broilers. In depth, the performance, body weight, FCR, mortality, carcass yield, meat quality, weight of organs, as well as a plethora of biochemical and hematological parameters examined, presented no effect from meat treatment, suggesting the sterilization as a good means for maintaining high levels of hygiene. In addition, the treatment with no meat even resulted in lighter broilers, and a worsening in FCR showed no impact on meat quality, indicating space for optimization.

Furthermore, in an experiment conducted by Giamouri et al. [80], broiler diets were supplemented with three kinds of vinification by-products such as ground grape pomace, wine-lees extract, and grape stem extract. The results depicted the feed intake, FCR, carcass yield, and the weight of the internal organs as not having any significant difference. However, a lighter color was observed for the treatment groups compared to the control. Lastly, the ground grape pomace group demonstrated higher levels of polyunsaturated fatty acids and lower saturated fatty acids compared to the other groups. Nevertheless, these results come in combination with another study by Mavrommatis et al. [81] where the incorporation of wine-lees extract rich in yeast cell walls and grape-stem extracts in broiler diets led to a considerable improvement in the broilers' oxidative status. The use of specific by-products can not only contribute to the purpose of a circular economy but also in supplying diets with significant bioactive compounds, which in another way would have been lost. Although the valorization of food waste and agro-industrial by-products is mostly related to an environmental approach, under the perspective of a circular economy, some parallel effects on GHG emissions can also be unveiled. More specifically, by applying this novel feeding practice, a significant decongestion of the environment using organic wastes can be achieved. Combined with that, the utilization of a plethora of bioactive nutrients, contained in waste, reveals the potential for improving the animal performance and concurrently to further minimize the CF of poultry meat products per unit of protein.

Finally, any process of transformation of food waste to poultry feed needs to produce low carbon emissions. In this regard, Georganas et al. [106] reported an energy-efficient and cost-effective transformation process of food waste from hotels into animal feed by applying solar energy for pasteurizing and drying of the food waste.

4.2. Manure Management

Manure management, including collection, storage, treatment, transportation, and the final utilization, can lessen the burden of environmental pollution and on public health through specific actions. Any efficient system aims to prevent manure and its constituents from accessing the environment, as well as being profitable. Moreover, by applying the manure under specific requirements to avoid CH_4 and N_2O formation [108] for fertilization and feed production, a diminished use of nitrogen fertilizer and, subsequently, nitrogen loss can be achieved. Specifically, poultry manure consists of many essential macronutrients and micronutrients, functioning as a rich organic nutrient for plant growth [109]. However, there is great concern over the overuse and improper application, resulting in severe environmental and health hazards [110]. The spread of manure on crops and fields, although representing the simplest and a low-cost method of manure management, and apart from the high emissions of N_2O and ammonia levels, reveals a high handicap over the unutilized energy coming from manure [111]. Therefore, the ease of collection combined with the prevention of evaporation, runoff, and leaching to prevent losses are keys to an efficient system.

Spreading broiler manure, without any treatment or any further process on the fields, is the simplest paradigm of manure handling. After cleaning the stable, the manure is stored for a limited amount of time and then distributed to the field. The main advantage of this approach is the relatively low costs. Apart from the space needed for manure storage (usually a concrete structure), only a small amount of equipment for transport and distribution (generally manure spreader) is required. Despite this, this kind of manure handling is vastly associated with NH_3 and N_2O emissions; hence, the energy potential of the manure utilization remains unused [111].

4.2.1. Storage

The frequent removal from animal houses is appropriate for avoiding manure fermentation and GHG emissions, as extended storage may increase CH_4 emissions [112]. Therefore, the area manure is intended to be stored in should meet the proper period boundaries. Additionally, the duration of storage is highly dependent on the climate conditions, and consequently different limitations are set due to the conditions, from 3 months in drier countries such as Greece to even 10 months in Finland [113].

An option that is not so expensive and can be widely used is the cooling of the slurry channels [114]. As for the appropriate temperature, the cooling of slurry below 10 °C tends to reduce CH_4 emissions at a rate of 30% to 46% compared with no cooling conditions [65] and can also mitigate NH_3 emissions from in-house manure storage [115]. The combination of frequent removal and cooling by taking it to an outside storage is based on the premise of significant temperature-difference conditions [116] and can be used in cold or mild climates.

4.2.2. Process

Anaerobic digestion is important. Since there is a great need for renewable fuel sources worldwide, the interest aims on efforts such as biogas produced under the anaerobic digestion (AD) process. Anaerobic digestion is the degradation of microorganisms in organic matter under anaerobic conditions producing CH_4, CO_2, and other gases as by-products. The output of this process is the utilization of biogas over heat and electricity on the last level of process, thus indicating one of the most efficient methods for emissions reduction both from manure and energy [117]. The biogas digestate may also replace the use of mineral fertilizers, especially if it is kept in closed tanks, with CH_4 at low rates [111]. The composition of raw biogases is generally 55–70% CH_4, 30–45% CO_2, nitrogen (0–15%), O_2 (0–3%), H_2O (1–5%), hydrocarbons (0–200 mg m^{-3}), hydrogen sulphide (0–10,000 ppmv), NH_3 (0–100 ppmv), and siloxanes (0–41 mg Si m^{-3}) and the heating value of the gas varies from 18 to 30 MJ/m^3 [118]. Biogas can be efficiently used for replacing electricity or fuel combustion on the farm, since poultry excreta produce 310 m^3 biogas/tonne on dry matter basis [119,120]. In an experiment conducted in Greece, biogas from chicken manure was implied to reduce the CF of the farm from 1.38 to 0.49 kg CO_2-eq/head, also demonstrating the economical aspect of the payback for the farm in around 8 years [121]. Production of biogas via anaerobic digestion of biodegradable materials such as biomass, manure, sewage, municipal waste, green waste, plant material, and energy crops [122–124], is a technology that can be implemented at the industrial, village and farm-household scales [120]. Moreover, this technique over waste can effectively reduce odor emission or contaminants making it a promising solution for the utilization of waste from slaughterhouses [125]. However, there is a limitation due to high levels of ammonium, which is toxic for biogas bacteria, and may contain sand and other materials; hence, it should be used in small quantities [120].

Composting provides several benefits related to manure handling, odor, manure moisture and pathogen control, organic matter stabilization, additional farm income [126], lower density, as well as easier and longer storage than raw chicken manure [127]. Nevertheless, C and N losses are of major concern during composting; for example, N loss results either in ammonia emissions, nitrates leaching [128], or CO_2 evaporation [129]. The benefits, such as lessened odor and CH_4 emissions compared with anaerobically stored manure, make it a favorable option [126] to increase nutrient conservation and to produce stable organic fertilizer [130]. Thus, utilizing additives such as zeolite, biochar [129], vermiculite [131], or vinegar waste residues [132] have been examined.

Although on a smaller scale evaluated, the technique of gasification could be highlighted. Gasification functions a dual purpose, partially transforming carbonaceous content into syngas as fuel and generating biochar as a by-product [133].

The combustion of poultry litter can be a sustainable form of manure management [134]. Ogino et al. [135] reported a 42% reduction in GHG emissions by applying a low-protein diet combined with litter incineration compared to a conventional farming system.

A summary of the practices applied to lessen the manure emissions is presented in Table 3.

Table 3. Summary of the practices applied to lessen the manure emissions.

Manure Strategy	Manure Practice	Effect-Impact	References
Frequent removal of manure		↓ CH_4	[112,113]
Cooling manure	Cooling < 10 °C	↓ CH_4 30–46%, ↓ NH_3	[65,115]
Biogas for energy	Producing biogas from manure	↓ GHG emissions from energy ↓ CF 1.38 to 0.49 kg CO_2-eq/head	[117,121]
Biogas digestate for fertilizer	Biogas digestate stored in closed tanks	↓ GHG fertilizer production	[111]
Composting manure	Composting and use of additives (zeolite, biochar etc.)	↓ CH_4, fertilizer production ↑ nutrient conservation	[128–132]
Incineration	Litter incineration and low-protein diet	↓ 42% GHG	[135]

↑ = Increase, ↓ = Decrease.

4.3. Energy Management and Hatchery Practices

Energy management is an important factor for livestock production and mitigation policies. First and foremost, measures should be established to improve the heating requirements of the animal houses. Moreover, the use, selection and maintenance of high-performance lighting systems, exhaust fans, and the improved building insulation appears to be of utmost importance. In addition, replacing fossil fuels with renewable energy sources, such as wind or solar energy, biomass, and the energy of biogas produced from manure, can provide immediate reduction in GHG emissions. Thus, the farm buildings should be supplied by renewable energy sources for heating, ventilation, air conditioning, and lighting [136]. In that area of interest, significant work has been made. In an experiment conducted in a cold region of Greece, the holistic approach of a heat pump for heating, ventilation, and air conditioning systems for broiler houses presented promising results [137]. In another experiment, the use of geothermal heat pumps not only reduced the cost and the fuel consumption compared to a conventional broiler house, but also lessened the CO_2 emissions, prompting a cleaner energy source [138].

As reported by Li et al. [139], solar thermal energy can be used in heating (water and space) and manure drying. Moreover, electricity through solar panels could be generated directly. Thus, a critical application is to maintain solar panels on the rooftops of the farm buildings, especially for countries with a lot of sun during the year, such as the Mediterranean ones. For this purpose, the use of combined photovoltaic panels and heat pumps could also be used, even for fulfilling the energy demand of the poultry houses [140,141]. In addition, wind turbines combined with fans can play a major part in the energy efficiency of a farm, generating electricity and ventilating the facilities [133]. Furthermore, a simple suggestion is the use of LED technology, as a more reliable, energy efficient option preserving lifetime, as well as being environmentally friendly [136].

In addition, poultry-related stakeholders should avail themselves of new hatchery techniques, including but not limited to on-tray feeding at hatchery and immediate access to feed [142,143], on-farm hatching of eggs with immediate access to feed [144], and in ovo supplementation of nutrients [145].

4.4. Data Management

Last but not least, smart technology should be included to help in precision livestock farming. The control of indoor climate conditions contributes to expressing the maximum genetic potential and increasing the productivity of the animals [146]. By installing a simple control system, with little cost, for example temperature sensors, microphones, and cameras, a farmer can preserve the appropriate conditions for the animals' welfare on a daily 24 h basis [147] and collect the proper data for extra analysis. To extend this, in the big-data world of the 21st century, the development of algorithmic models, software, image analysis tools and the collection and interpretation of such data can help the farmers to achieve the overall control of the farm and the scientists to improve their research and better analyze the animal productivity and sustainability [148–150] as well as lessen the environmental impact [10].

5. Future Prospects

Research in the accessible literature demonstrated the plethora of technical options for mitigating poultry emissions. Nutritional management, mainly through the replacement of established feed material (e.g., soybean), feed additives (e.g., amino acids), or novel feeding practices (e.g., food waste and by-products) have been cherished as the main options. Their effectiveness can be significantly increased when nutrition management is improved and productivity is increased. Diets also affect manure emissions, as they alter their content; the composition of the proportions and additives affect the form and amount of N manure. Furthermore, GHG emissions from manure can be effectively controlled by shortening storage life, ensuring proper conditions, or mainly by utilizing the unique characteristics to generate biogas. However, direct and indirect N_2O emissions are much more difficult to avoid once N is excreted. Techniques that block emissions during the early management stages retain N in the faeces that are often emitted at later stages. Another possibility from an environmental point of view could be the optimization of the productive life of the poultry species, such as broilers. In addition, various factors should be considered, such as precision feeding and the design of housing systems, to ensure that adverse effects are avoided. Another important contribution is the use of materials, equipment, and supplies with the lowest energy combustion. Not only that, but aiming for energy efficiency with a combination of renewable energy sources such as solar-wind energy, providing heating and electricity in farms, can effectively lessen greenhouse gas emissions and improve farm sustainable-energy independence. A characteristic of the Mediterranean countries is the natural gift of periods of sunshine year-round; thus, we should maximize the use of solar power to cover farms' needs. Nevertheless, the proposals mentioned in the previous sections address important technical elements that need to be implemented to achieve the goal of reduced GHG emissions. However, for all these techniques to be effective, they need to be carried out based on overall central planning, in agreement with all stakeholders, including but not limited to organizations and business entities. These agreements will concern new "green development" plans as formulated by the Paris and Kyoto agreements. One such example is the EU's "Green Agreement 2050", an agreement for achieving a sustainable economy with zero net GHG emissions by 2050. Livestock and food production should be developed with the least impact to the environment and at the same time should be safe, nutritional, and of high quality. In addition, further research is needed to quantify the economic aspects of mitigation, as well as mitigation practices that may have an impact on other environmental and broader development goals, such as food security and animal welfare.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15031941/s1, Table S1: Emissions from agriculture as a total, enteric fermentation, and synthetic fertilizer use in 2019, in EU Mediterranean countries [32].

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