

Article

Comparative Assessment of Greenhouse Gas Emissions in Pig Farming Using Tier Inventories

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Abstract: Although pig meat accounts for nearly half of total meat production in Europe, less attention has been focused on the greenhouse gas (GHG) emissions of pig farming. The aim of this study was to assess and compare the impact of pig livestock on GHG emissions during the period 2015–2020 in major European countries, including Greece, using different computational approaches (Tier 1, Tier 2, Gleam-i software v. 2.0 developed by FAO, Rome, Italy). A semi-extensive pig farm was also used as a small-scale scenario. The ranking of the countries related to GHG emissions was not affected by the applied methodology. Spain had the highest emissions due to the higher number of farming animals. The noted numeric differences in the estimations can be attributed to the elaborated and different equational approach that Tier 2 methodology and Gleam-i followed, considering many livestock parameters. Additionally, the semi-extensive farm had lower emissions/fewer animal compared to the average intensive pig farm in the Greek territory. The Tier 1 approach revealed that breeding animals produces more to the emissions, contrary to Tier 2, which showed that fattening pigs is responsible for the majority of GHG emissions. Therefore, specific animal categories could be targeted (i.e., fattening gilts) in a more specialized manner apart from general strategies (i.e., animal improvement).

Keywords: GHG emissions; carbon footprint; pig; tier methodology; Gleam-i; environmental impact



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1. Introduction

Climate change has been reported to have a direct impact on agriculture and livestock [1], as their production depends on weather conditions. On the other hand, the agriculture–food sector is considered one of the most important sectors of the European economy, contributing a high proportion of total greenhouse gas emissions [2–4]. The types of food with the highest environmental burdens are meat (beef, pork, chicken) and dairy (cheese, milk, butter) products [5]. The impact of livestock production on climate change has been of great concern in recent decades, mainly due to the increase in human population. It is estimated that the sector is responsible for 14.5% of total anthropogenic greenhouse gas (GHG) emissions, which means that more than nine million CO₂ equivalents (eq.) are emitted every year due to livestock activity. GHG emissions from the livestock sector include CO₂, CH₄ and NO₂. Enteric fermentation, feed production and processing, manure, transportation and further processing of animal products are the main contributors of these emissions [1,3]. Therefore, a wide range of mitigation strategies have been proposed to eliminate these emissions, such as changes in diet content, manure management and herd management [1]. Further to these strategies, novel techniques to capture methane or carbon dioxide emissions have been developed, including, for example, antimethanogenic strategies (chemical inhibitors, electron acceptors and ionophores) or carbon capture and utilization strategies (CCU) using microalgae for enhanced carbon sequestration [1,6–9].

On the other hand, the human population is expected to reach 9.7 billion by 2050 [10]. This population growth, together with the increase in the urbanization rate and the amelioration of humans' social status, is expected to lead in an increase in future need for

livestock products, which is estimated to double by 2050 [1,11]. Therefore, the livestock sector will require more natural resources to meet these demands, resulting in a larger environmental footprint.

Until now, ruminants have mainly been of interest due to the considerable methane (CH_4) emissions derived from enteric fermentation, whereas less attention has been paid to other non-ruminant species. Indeed, the ruminant sector, especially beef cattle, followed by dairy cattle and buffaloes, is considered to be among the main contributors of GHG emissions, participating in the “tank” of global warming potential, with more than 74% of total CO_2 -eq produced by the livestock sector [3]. However, in the light of the high consumption of many other livestock commodities, attention should also be paid to other livestock categories in the European Union, such as pig farming.

The European pig farming sector accounts for nearly half of total meat production. Germany, Spain and France are the main contributors of pig meat, producing more than half of all pig meat produced in the EU. In addition, pig meat ranks in first position in terms of consumer preference [12]. The sector is highly diverse, with considerable differences in rearing methods and farm size across the member states, ranging from backyard farming to industrial systems. Pig farming in Greece is considered one of the most dynamic sectors of intensive farming systems, after poultry production. It accounts for 25% of domestic meat production, with a self-sufficiency rate of approximately 35% [13]. Within common agricultural policy (CAP), the sector is enhanced by the common organization of markets, regulating trade and providing support in the event of a sectoral crisis. The new framework of CAP sets as a priority a more environmental approach, reflecting a lower contribution of the sector to livestock’s environmental impact.

Livestock’s carbon footprint is mainly based on the assessment of the respective GHG emissions. According to the Intergovernmental Panel on Climate Change guidelines [14], the estimation of GHG emissions can be achieved following different tier methodologies (Tier 1, 2 or 3) according to the available data. These approaches are based on using specific equations of elevated computational power according to the available data (i.e., population number, animal categories, feed parameters, etc.). According to Tier 1 methodologies, GHG emission estimations per head of livestock are responsive only to changes in animal numbers and populations. On the contrary, Tier 2 methodologies intend to better capture the management of GHG emissions and offer higher precision, as these methodologies are based on more elaborate data, such as classification of different types of livestock categories, as well as data regarding livestock weight, weight gain, feed digestibility, level of production, etc. Tier 3 methodologies refer to the most sophisticated approach, including models and inventory measurement systems tailored to national circumstances, repeated over time and driven by high-resolution activity data and disaggregated at the subnational level. However, as the carbon footprint is emerging among the various human activities, a number of promising software applications have been developed to facilitate the estimation of GHG emissions based on the aforementioned approaches. A promising software that utilizes a Tier 2 approach is the “Global Livestock Environmental Assessment Model” (GLEAM), a web-based tool that was recently developed by the Food and Agriculture Organization to estimate GHG emissions in the livestock sector [15].

The environmental impact of GHG emissions has been well studied, especially in ruminant species. Most studies refer to a set of examined farms under the same or different farming systems (i.e., intensive, semi-intensive, organic) using specific boundaries in each study, although results are not comparable between the majority of studies due to different functional units and/or different computational approaches (model equations, IPCC equations, LCA software approaches, etc.). When referring to the country level, they use only either Tier 1 or Tier 2 approaches [14,16]. However, scarce information exists about the assessment of GHG emissions, especially in the pig sector, using different inventories in the same dataset. Therefore, the aim of the present study is to depict the impact of pig livestock on climate change in terms of GHG emissions, particularly methane (CH_4) and direct (N_2O) and indirect (NO_x , NH_3 , NO_3^-) nitrogen emissions, during the last six

consecutive years in the territory of Greece, as well as in major European countries, using comparatively different methodological approaches (Tier 1 and Tier 2 using IPCC equations as well Tier 2 using GLeam-i software developed by FAO, Rome, Italy). In addition, a case study of a typical semi-extensive pig farm in Northern Greece in terms of GHG is considered as a small-scale scenario. To the best of our knowledge, this is the first comprehensive and differentiated assessment regarding the emissions of pig farming, especially in Greece, and may serve as a fundamental step to evaluate estimated GHG emissions in order to identify gaps and limitations in the used methodologies, as well as to highlight potential mitigation strategies that could be applied to eliminate GHG emissions in pig livestock production.

2. Materials and Methods

2.1. Area of Study

The study included the estimation of GHG emissions of (a) a semi-extensive pig farm rearing an autochthonous breed pig in the territory of northern Greece, (b) the Greek pig sector and (c) the major European pig-farming countries (France, Germany, Denmark, Spain, Italy, the Netherlands, Portugal, Bulgaria, Croatia) using Tier 1 and 2 approaches according to IPCC guidelines [14,17], as well as GLEAM-i software [15]. Regarding Tier 1 and 2 approaches, all on-farm activities related to pig production were considered to estimate methane (CH₄) emissions through intestinal fermentation and manure management, as well as direct (N₂O) and indirect (NO_x, NH₃, NO₃[−]) nitrogen emissions. GLeam-i software was used to indirectly consider emissions related to transportation at the territory level. GHG emissions in each European country level were estimated for the last six consecutive years (2015–2020). Estimations for the case study of the semi-extensive pig farm were made only for 2019 due to inadequate available data from previous years (especially for feed parameters). Results are presented in Gg equivalents of carbon dioxide (Gg CO₂-eq), considering the 100-year global warming potential of non-CO₂ GHG emissions and that of CH₄ and N₂O as 25 and 298 times CO₂, respectively.

2.2. Population Number

2.2.1. Semi-Extensive Pig Farm

The studied pig farm followed a semi-extensive system for breeding sows, replacement gilts, boars and weaned piglets and an intensive system for fattening pigs (pre-fattening and fattening piglets). The typical characteristics of the examined farm, as well as the recorded number of each animal category, are depicted in Table 1. All data concerning farming system characteristics (population, reproductive and productive characteristics, diets, etc.) were collected using a specially designed questionnaire, on-site visits to the farm and personal interviews with the owner.

For the correct computation of GHG emissions in the animals living less than one calendar year (i.e., fattening gilts), the exact population number was estimated using the following Equation (1) [14,17]:

$$N = Days_{alive} \times \left(\frac{NAPA}{365} \right) \quad (1)$$

where N = the number of head of livestock species/animal category in the country (equivalent to annual average population), and $NAPA$ = number of animals produced annually.

2.2.2. Pig Population of European Countries

The total pig population, as well as the population of each animal category (i.e., sows, boars), was retrieved from the European Statistical Office (EUROSTAT) [18] for each targeted case for the studied years (Table 2). In animal categories in which populations live less than one calendar year (i.e., fattening gilts), the exact population number was estimated as previously described (Equation (1)).

Table 1. Characteristics of the studied semi-extensive pig farm.

Parameter	Value
Number of adult females	122
Number of adult males	9
Weight at birth (Kg)	1.5
Weight of weaned piglets (Kg)	9
Daily weight gain of fattening animals (g)	0.215
Live weight of adult females (Kg)	70
Live weight of adult males (Kg)	110
Live weight of slaughtered animals (fattening pigs; Kg)	60
Duration of gestation period (days)	115
Duration of lactation period (days)	55
Days between parturition and next pregnancy (days)	180
Weaning age (days)	55
Mortality rate of weaned piglets	0.02
Mortality rate of fattening animals	0.02
Replacement rate of males	10
Litter size (number of animals)	8
Replacement rate of adult females	10
Fertility of adult females	1.5
Death rate of young females	0.02
Death rate of adult animals	0.02
Used Feeds for animal diets %	
Grazing	55%
Leguminous beans	5%
Crop residue from leguminous plant cultivation	10%
Grains from wheat	5%
Grains from maize	15%
Grains from rice	10%

2.3. Emissions Estimation Using Tier Methodologies

The estimation of GHG emissions (methane and nitrous oxide) using Tier 1 and Tier 2 methodologies was based on the equations and guidelines proposed by the IPCC [14,17] for each specific gas category. As IPCC recommendations are publicly available, hereafter, the number of each used equation is highlighted following the nomenclature of IPCC guidelines.

2.3.1. Methane (CH₄) Emissions

Equations (10.19) and (10.20) were used for the estimation of the total annual methane emissions derived from porcine intestinal fermentation [14]. According to IPCC guidelines [17], for this type of emissions, only a Tier 1 approach was followed because these emissions contribute a very low percentage of the total derived emissions compared to other productive animals, such as cattle. Therefore, country-specific emissions factors (EFs) were used to estimate intestinal fermentation methane emissions.

CH₄ emissions derived from manure management were estimated using Equation (10.22) [17]. In the Tier 1 approach, a fixed emission factor per country was used based on the guidelines of the IPCC [17]. In the case of the examined semi-extensive pig farm, the applied manure management system consisted of 60% in daily spread of manure and 40% in a manure storage system for the categories of grazing animals. For the animal category of fattening pigs (intensively reared), manure management was based only on a storage system. The latter was also assumed for the case of European farms, as they implement an intensive farming system. For estimation of methane emissions derived from manure using the Tier 2 methodology, a more elaborated approach was implemented, estimating

the respective emission factor (EF) using Equation (10.23) [17]. For the above estimations, the climate region of each examined case was considered, as proposed by the IPCC [17].

Table 2. Pig population per animal category in the studied European countries.

Country	Animal Category	2015	2016	2017	2018	2019	2020
Bulgaria	Sows	58,150	64,510	62,160	69,990	50,860	65,770
	Boars	2220	1080	1000	1120	750	930
	Replacement gilts	4690	8060	6850	8130	9410	6750
Croatia	Sows	118,000	120,000	125,000	122,000	125,000	110,000
	Boars	4000	3000	3000	3000	3000	3000
	Replacement gilts	19,000	11,000	15,000	15,000	15,000	13,000
Denmark	Sows	1,237,000	1,236,000	1,260,000	1,243,000	1,244,000	1,273,000
	Boars	11,000	11,000	10,000	11,000	10,000	13,000
	Replacement gilts	221,000	234,000	225,000	223,000	216,000	239,000
France	Sows	1,011,000	986,000	998,000	1,018,000	984,000	965,000
	Boars	10,000	9000	9000	8000	8000	13,000
	Replacement gilts	106,000	108,000	112,000	112,000	108,000	86,000
Germany	Sows	1,973,240	1,908,360	1,905,360	1,837,000	1,787,900	1,694,700
	Boars	25,350	24,990	24,240	17,900	18,500	19,600
	Replacement gilts	224,950	216,790	226,000	226,100	210,300	197,000
Greece	Sows	137,000	106,000	100,000	91,000	94,000	93,000
	Boars	11,000	8000	7000	5000	5000	5000
	Replacement gilts	22,000	11,000	13,000	9,000	10,000	10,000
Italy	Sows	582,450	558,070	561,640	556,810	556,010	568,550
	Boars	28,350	28,680	29,020	23,100	23,440	22,460
	Replacement gilts	52,310	55,780	56,940	53,550	42,470	46,500
Netherlands	Sows	1,053,000	1,022,000	1,066,000	967,000	1,047,000	923,000
	Boars	4000	3000	9000	7000	5000	5000
	Replacement gilts	137,000	157,000	165,000	134,000	160,000	152,000
Portugal	Sows	240,140	233,250	235,640	236,060	237,280	230,910
	Boars	5450	4880	5780	5060	5220	5010
	Replacement gilts	21,980	22,050	24,250	24,540	23,530	25,940
Spain	Sows	2,466,270	2,415,170	2,454,330	2,500,520	2,576,990	2,635,250
	Boars	38,250	33,230	31,420	28,900	26,830	31,240
	Replacement gilts	261,660	246,570	302,010	288,820	308,850	317,770

2.3.2. Estimations of Nitrous Oxide (N₂O) Emissions Derived from Manure Management

Direct Estimations

Direct nitrogen gases (N₂O) derived from the management of pig manure were estimated with Equation (10.25) according to the guidelines of the IPCC (2019). The application of the equation requires the estimation of the excreted nitrogen per animal (N_{ex}), whereas the emission factor (EF) is provided by the IPCC guidelines [14,17]. For the Tier 1 approach, the calculation of the excreted nitrogen (N_{ex}) is based on Equation (10.30) [17].

Tier 2 methodology utilizes a more specialized approach that concerns productive characteristics and special nutritional traits. Therefore, N_{ex} factor is estimated using Equation (10.31A), which considers the nitrogen taken in and retained by an animal according

to its productive stage [17]. The intake of nitrogen was computed following Equation (10.32A), whereas the nitrous retained by an animal was estimated with Equations (10.33A) and (10.33C) based on the IPCC guidelines [17].

Indirect Estimations

The estimation of indirect nitrogen gases (N_2O) takes into account the respective emissions that are volatilized and leached using Equations (10.28) and (10.29), respectively [17].

2.4. GHG Emissions Estimation Using GLEAM-i Software

GLEAM-i software v.2.0 [15] was used for a more comprehensive assessment of GHG emissions in the examined cases. GLEAM uses a Tier 2 methodology approach. The number of pig populations used in each examined case was based on the data retrieved from EUROSTAT (country cases) or on data collected from an in-situ survey in the case of the examined pig farm. The default values were used for the rest of the required data because these parameters reflect the respective country's average values [19].

3. Results

Analysis of pig populations in the examined cases is depicted in Tables 1 and 2. Throughout the studied period the population remained relatively stable for the majority of studied countries, apart from Spain, where an increase was noted, in contrast to Germany and Greece.

3.1. Tier 1 Approach

3.1.1. Methane Emissions

Table 3 presents total methane emissions derived from animals' intestinal fermentation using Tier 1 methodology in the examined countries. The highest methane emissions were observed in Spain and Germany for the entire examined period (2015–2020). The other major pig meat-producing countries (Denmark, the Netherlands, France) ranked in the middle of the list, whereas Greece, together, with the two other Balkan countries (Croatia and Bulgaria) occupied the lowest positions. It is also noted that during the examined period, the majority of the countries had stable methane emissions, apart from Spain, where methane emissions increased in the final years of the examined period (2019–2020). On the contrary, Germany and, to a lesser extent, France exhibited decreased methane emissions. Similar results were noted for methane emissions derived from manure (Table 4).

Table 3. Results of CH_4 emissions from enteric fermentation using Tier 1 methodology (Gg CO_2 -eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	953.43	933.15	950.12	967.18	997.07	1,019.83	970.13
2	GERMANY	763.22	738.11	737.28	710.93	691.61	655.54	716.12
3	DENMARK	481.27	481.37	490.17	483.64	483.72	495.77	485.99
4	NETHERLANDS	407.56	396.43	413.77	374.71	406.17	358.50	392.86
5	FRANCE	390.58	381.07	385.80	393.40	380.26	372.37	383.91
6	ITALY	225.54	216.37	217.79	215.59	214.88	219.79	218.32
7	PORTUGAL	92.77	90.12	91.15	91.29	91.73	89.37	91.07
8	CROATIA	45.94	46.37	48.43	47.28	48.43	42.62	46.51
9	GREECE	51.87	39.95	37.75	34.24	35.38	34.97	39.03
10	BULGARIA	22.47	24.99	24.04	27.08	19.81	25.41	23.97

* Based on the mean value of the studied period (2015–2020).

3.1.2. Nitrogen Oxide Emissions

Table 5 presents an estimate of nitrogen oxide emissions in the studied cases. The two European countries with the highest emissions were Spain and Germany, while Greece ranked in eighth position. Almost all countries showed relatively stable emissions during

the studied period, except Bulgaria and Greece, where a decrease in the respective emissions was observed.

Table 4. Results of CH₄ emissions from manure management using Tier 1 methodology (Gg CO₂-eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	13,363,290.91	13,077,740.47	13,317,149.06	13,554,735.0	13,973,372.63	14,293,249.35	13,596,589.57
2	GERMANY	10,696,714.01	10,344,931.82	10,333,542.25	9,963,316.21	9,692,301.19	9,187,294.12	10,036,349.93
3	DENMARK	6,747,247.69	6,749,264.48	6,871,730.27	6,780,460.21	6,781,086.69	6,951,431.75	6,813,536.85
4	NETHERLANDS	5,710,605.09	5,555,433.14	5,799,746.84	5,251,362.65	5,692,308.20	5,024,796.65	5,505,708.76
5	FRANCE	5,473,019.71	5,339,731.95	5,406,156.99	5,512,334.06	5,328,283.50	5,218,012.78	5,379,589.83
6	ITALY	3,165,175.44	3,037,039.67	3,057,040.90	3,024,825.69	3,014,529.28	3,083,118.37	3,063,621.56
7	PORTUGAL	1,300,501.82	1,263,272.82	1,277,977.04	1,279,843.12	1,285,914.75	1,253,063.28	1,276,762.14
8	CROATIA	644,683.32	650,090.00	679,088.73	663,048.89	679,088.73	597,756.68	652,292.73
9	GREECE	753,254.79	579,013.50	547,311.42	495,415.78	512,022.04	506,675.43	565,615.50
10	BULGARIA	315,238.72	350,291.06	36,980.74	379,660.37	277,825.21	356,172.51	336,028.10

* Based on the mean value of the studied period (2015–2020).

Table 5. Results of N₂O emissions from manure management using Tier 1 methodology (Gg CO₂-eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	44,313.46	43,365.76	44,158.41	44,945.79	46,333.14	47,394.60	45,085.19
2	GERMANY	35,469.56	34,303.19	34,265.13	33,036.17	32,137.92	30,463.90	33,279.31
3	DENMARK	22,371.22	22,377.73	22,783.69	22,481.31	22,483.27	23,048.42	22,590.94
4	NETHERLANDS	18,933.63	18,418.63	19,229.92	17,411.63	18,872.87	17,303.03	17,837.73
5	FRANCE	18,147.62	17,705.43	17,925.62	18,277.45	17,667.25	16,659.72	18,254.40
6	ITALY	10,500.30	10,075.47	10,141.84	10,033.77	9,999.85	10,227.00	10,163.04
7	PORTUGAL	4312.97	4189.40	4238.33	4244.35	4264.53	4155.53	4234.18
8	GREECE	2814.10	2417.56	2316.59	2138.59	2181.19	1982.46	2163.30
9	CROATIA	2138.20	2156.01	2252.11	2198.92	2252.11	1815.25	2280.55
10	BULGARIA	1045.66	1161.59	1117.45	1258.97	921.22	1181.07	1114.33

* Based on the mean value of the studied period (2015–2020).

3.2. Tier 2 Approach

3.2.1. Manure Methane Emissions

Methane emissions derived from manure management are depicted in Table 6. Similarly, to the results of the Tier approach 1, Spain and Germany occupied the first two positions, whereas Greece and Bulgaria had lower emissions compared to the other countries.

Table 6. Results of CH₄ emissions from manure management using Tier 2 methodology (Gg CO₂-eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	311,047.21	304,586.85	309,580.6	315,382.16	325,036.33	332,391.12	316,337.38
2	GERMANY	248,877.64	240,694.23	240,325.78	231,706.51	225,503.63	213,748.23	33,476.00
3	DENMARK	156,102.67	155,991.29	159,003.67	156,860.82	156,977.82	160,660.55	57,599.47
4	NETHERLANDS	132,819.43	128,935.27	134,494.28	121,984.81	132,090.48	116,459.49	27,797.29
5	FRANCE	127,500.03	124,351.56	125,867.86	128,386.41	124,098.47	121,685.68	25,315.00
6	ITALY	73,469.93	70,402.71	70,854.15	70,235.20	70,122.35	71,705.61	71,131.66
7	PORTUGAL	30,284.59	29,416.00	29,720.58	29,773.01	29,925.76	29,125.71	29,707.61
8	CROATIA	14,891.93	15,133.79	15,768.21	15,390.25	15,768.21	13,876.20	15,138.10
9	GREECE	17,296.86	13,375.63	12,620.85	11,480.26	11,859.34	11,733.35	13,061.05
10	BULGARIA	7333.73	8137.49	7839.98	8828.00	6418.95	8294.59	7808.79

* Based on the mean value of the studied period (2015–2020).

Figure 1 shows a comparison between average methane emissions for each examined case during the studied period estimated by Tier 1 and 2 methodologies. It is observed that in all cases, the Tier 1 approach estimated higher emissions results compared to that of Tier 2 approach.

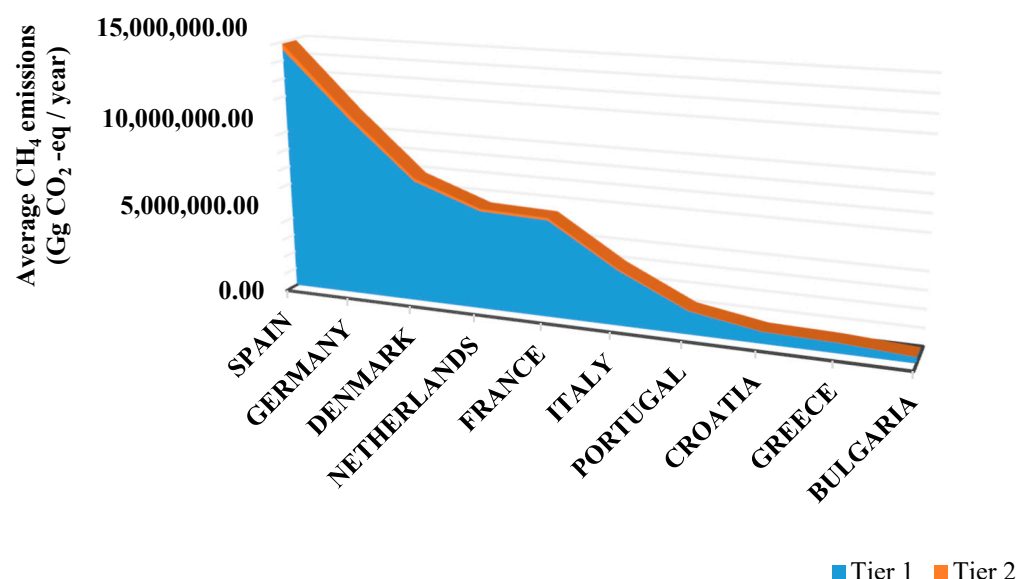


Figure 1. Comparison of mean CH₄ emissions from manure management using Tier 1 and 2 methodologies (Gg CO₂-eq/year). The different thickness of each graph (blue or red) represents the estimated emission by the two methodologies.

3.2.2. Nitrogen Oxide Emissions

The computed nitrogen oxide emissions are shown in Table 7. Accordingly, Spain and Germany were ranked in the first two places. Greece had a low gas concentration, occupying the eighth position. Bulgaria had the lowest emissions. Generally, all countries showed relatively stable emissions during the studied period. However, Germany and Greece showed a decrease in emissions between 2015 and 2020, whereas in Spain an increase in emissions was noted.

Table 7. Results of N₂O emissions from manure management using Tier 2 methodology (Gg CO₂-eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	27,087.99	26,497.09	27,028.04	27,490.50	28,347.71	29,001.25	27,575.43
2	GERMANY	21,693.26	20,979.48	20,964.69	17,964.75	19,658.96	18,634.02	19,982.53
3	DENMARK	13,753.96	13,770.19	14,006.73	13,822.48	13,816.42	14,182.04	13,891.97
4	FRANCE	11,088.68	10,822.35	10,959.38	11,171.67	10,798.62	10,560.53	10,900.21
5	NETHERLANDS	11,589.91	11,296.53	11,798.79	10,667.88	11,575.50	10,228.62	11,192.87
6	ITALY	6421.48	6167.88	6209.35	6137.06	6106.28	6246.94	6214.83
7	PORTUGAL	2634.22	2559.15	2591.40	2594.87	2606.23	2542.41	2588.04
8	CROATIA	1314.41	1317.00	1378.94	1346.75	1378.94	1213.87	1324.98
9	GREECE	1944.68	1559.68	1115.67	1006.28	1040.54	1029.81	1282.78
10	BULGARIA	638.61	711.27	683.34	770.27	566.85	721.70	682.01

* Based on the mean value of the studied period (2015–2020).

Figure 2 shows a comparison between average nitrogen oxide emissions for each examined case during the studied period estimated by Tier 1 and 2 methodologies. Like methane emissions, Tier 1 estimations were noted to be higher when compared to the corresponding Tier 2 values.

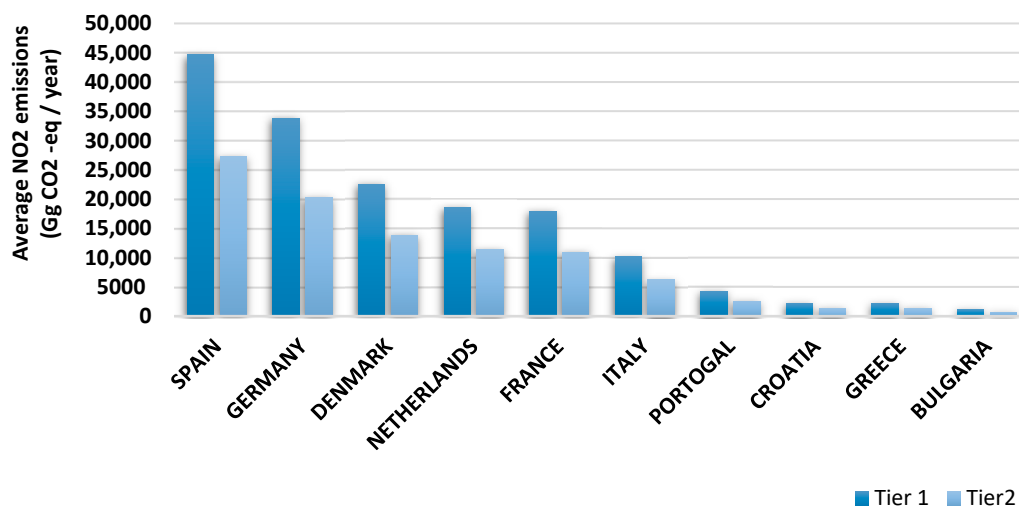


Figure 2. Comparison of mean N₂O emissions (Gg CO₂-eq) from manure management using Tier 1 and 2 methodologies.

3.3. GHG Estimation using GLEAM-i Software

Tables 8 and 9 show the GHG estimations (CH₄ and N₂O) using GLEAM-i software. It is noted that the European countries with the highest concentrations of methane gases were Spain and Germany, whereas Greece was in the penultimate position.

Table 8. Results of CH₄ emissions from manure management using GLEAM-i software (FAO, Rome, Italy) (Gg CO₂-eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	1183.60	1158.76	1177.37	1199.29	1235.75	1263.97	1203.12
2	GERMANY	572.70	553.89	552.99	532.93	518.73	491.77	537.17
3	DENMARK	297.39	297.15	302.88	298.83	299.04	306.11	300.23
4	NETHERLANDS	282.45	274.10	286.10	259.49	280.87	247.63	271.78
5	FRANCE	257.80	251.40	254.46	259.52	250.86	246.19	253.37
6	ITALY	191.08	183.12	184.29	182.56	182.30	186.38	184.95
7	PORTUGAL	106.52	103.44	104.56	104.69	105.24	102.41	104.48
8	GREECE	58.26	45.04	42.45	38.54	39.79	39.38	43.91
9	CROATIA	24.90	25.28	26.33	25.70	26.33	23.18	25.29
10	BULGARIA	15.06	16.65	16.04	18.06	13.12	16.97	15.98

* Based on the mean value of the studied period (2015–2020).

Table 9. Results of N₂O emissions from manure management using GLEAM-i software (FAO, Rome, Italy) (Gg CO₂-eq/year).

Position *	Country	2015	2016	2017	2018	2019	2020	Mean
1	SPAIN	3346.59	3276.19	3328.72	3390.59	3493.54	3573.48	3401.52
2	GERMANY	2560.46	2476.37	2472.32	2382.46	2319.01	2198.56	2401.53
3	NETHERLANDS	1129.31	1095.91	1144.10	1037.65	1123.05	990.15	1086.70
4	FRANCE	1027.26	1001.73	1013.91	1034.03	999.54	981.11	1009.60
5	ITALY	808.40	774.78	779.76	772.23	771.18	788.35	782.45
6	DENMARK	690.00	689.45	702.68	693.34	693.78	710.30	696.59
7	PORTUGAL	260.31	252.75	255.53	255.82	257.18	250.26	255.31
8	CROATIA	139.86	141.97	147.86	144.33	147.86	130.20	142.01
9	GREECE	163.88	126.67	119.38	108.31	111.84	110.66	123.46
10	BULGARIA	56.96	62.91	60.61	68.25	49.58	64.11	60.41

* Based on the mean value of the studied period (2015–2020).

In regard to the emissions of nitrous oxide gases, a similar trend was observed, with the exception of Denmark. Specifically, Denmark was ranked lower than with respect to methane emissions derived from manure management.

Figure 3 shows a comparison between the sum of methane and nitrogen oxide emissions for each country in the studied period. It is observed that the estimations based on IPCC equations (Tier 2) were higher than those estimated by GLEAM-i software.

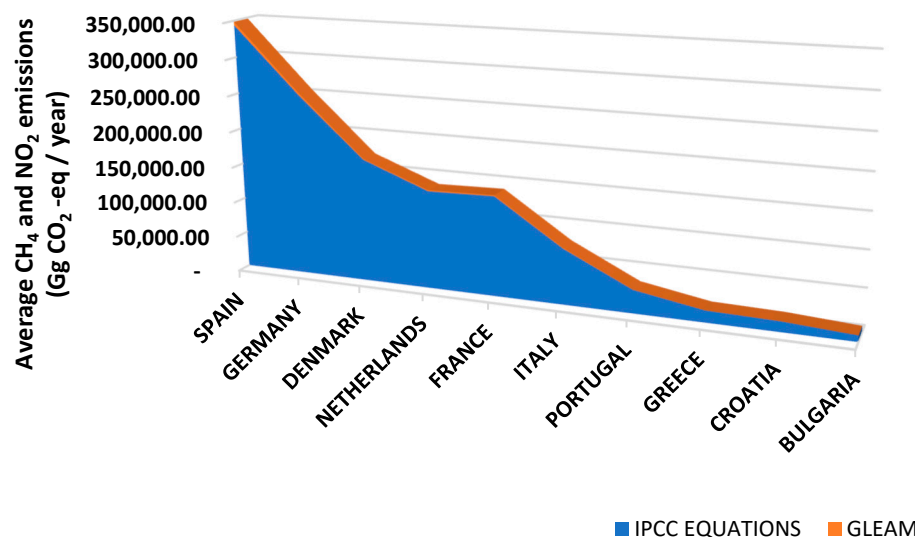


Figure 3. Comparison of mean CH_4 and N_2O emissions from manure management using Tier 2 IPCC equations) and GLEAM-i software (FAO, Rome, Italy) ($\text{Gg CO}_2\text{-eq/year}$). The different thickness of each graph (blue or red) represents the different estimated emissions by the two methodologies.

3.4. GHG Emission Estimations from a Case-Study Pig-Farm

Table 10 shows the results of the estimated CH_4 emissions from enteric fermentation and manure management, as well as N_2O emissions from manure management per animal in each animal category reared in the examined case study of a semi-extensive pig farm using both Tier 1 and 2 methodologies. Higher emissions were noted for the category of fattening pig according to both methodologies used, except CH_4 enteric fermentation emissions. For comparative purposes, we also estimated the respective emissions per animal of each animal category for the average pig farm in the year 2019 in the Greek territory (Tables 10 and 11, Figures 4 and 5), dividing the total estimated emissions by animal category (i.e., sow, boar, fattening) by the total number of animals within each animal category.

Table 10. Estimated CH_4 emissions derived from enteric fermentation and manure management and N_2O emissions from manure management using Tier 1 and 2 methodologies per animal within each animal category on a semi-extensive pig farm ($\text{Gg CO}_2\text{-eq}$).

Animal Category	Tier 1			Tier 2	
	CH_4 Enteric Fermentation	CH_4 Manure Management	N_2O Manure Management	CH_4 Manure Management	N_2O Manure Management
Sow	0.00004	0.16	0.0005	0.0002	0.0004
Boar	0.00004	0.16	0.0005	0.0002	0.0004
Replacing gilt	0.00004	0.12	0.0004	0.0002	0.0004
Fattening pig	0.00004	0.50	0.0016	0.0010	0.0010
Total	0.00016	0.94	0.003	0.0016	0.0022

Table 11. Estimated CH₄ emissions derived from enteric fermentation and manure management and N₂O emissions from manure management using Tier 1 and 2 methodologies per animal within each animal category for the average pig farm in 2019 (Gg CO₂-eq).

Animal Category	Tier 1			Tier 2	
	CH ₄ Enteric Fermentation	CH ₄ Manure Management	N ₂ O Manure Management	CH ₄ Manure Management	N ₂ O Manure Management
Sow	0.00004	0.76	0.0027	0.0011	0.0019
Boar	0.00004	0.76	0.0027	0.0011	0.0023
Replacing Gilt	0.00004	0.57	0.0039	0.0011	0.0021
Fattening pig	0.00004	0.50	0.0018	0.0136	0.0010
Total	0.00016	2.59	0.0111	0.0169	0.0073

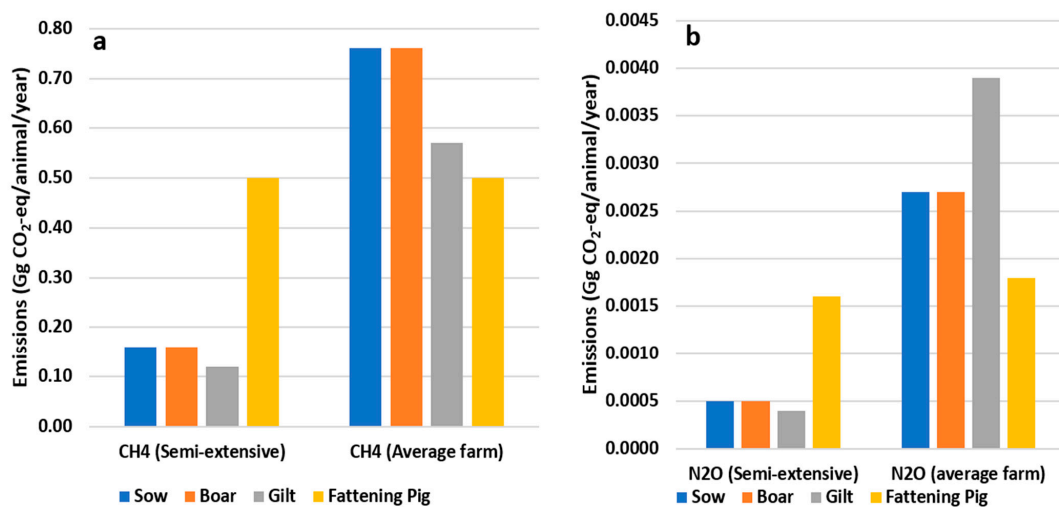


Figure 4. Comparison of computed CH₄ (a) and N₂O (b) emissions (Gg CO₂-eq/year) derived from manure management produced per pig on a semi-extensive Greek farm and an average Greek farm using Tier 1 methodology.

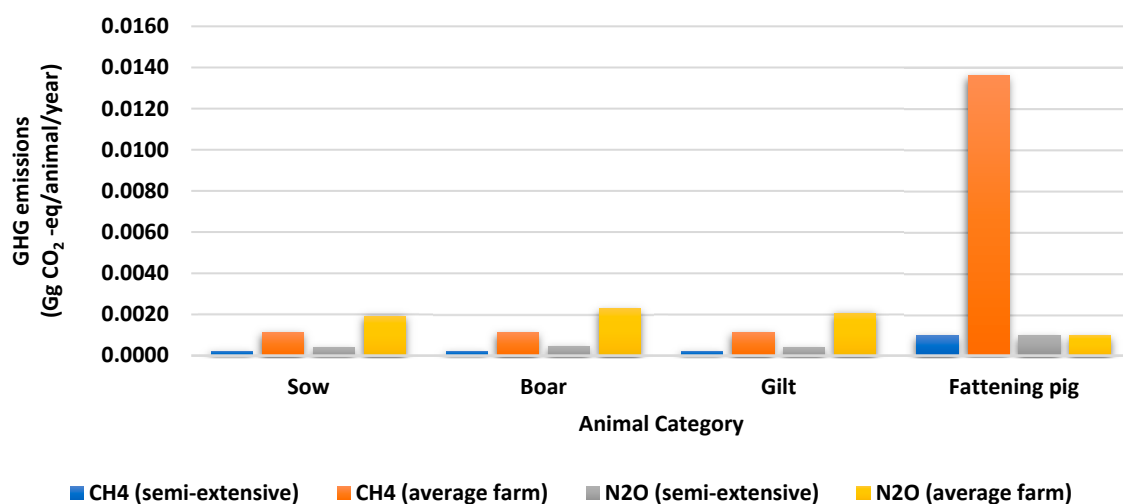


Figure 5. Comparison of computed CH₄ and N₂O emissions (Gg CO₂-eq/year) from manure management produced per pig on a semi-extensive Greek farm and an average Greek farm using Tier 2 methodology.

The estimated methane emissions from enteric fermentation per animal were the same in both examined cases. On the other hand, the methane and nitrous oxide emissions derived from manure management per animal were different between the studied semi-extensive farm and the average pig farm, as well as per examined animal category. Specifically, the Tier 2 approach estimated lower emissions of CH₄ and N₂O than those estimated by the Tier 1 approach. According to the results of the average pig farm, a pig produces higher CH₄ and N₂O emissions derived from manure management; nevertheless, a Tier 1 or Tier 2 methodology was applied. It was also noted that in the case of the average pig farm, the animal category of “fattening pig” contributed more to the total CH₄ emissions derived from manure management when a Tier 2 methodology was applied. On the other hand, both boars and sows produced the majority of CH₄ and N₂O emissions derived from manure management when a Tier 1 methodology was used.

4. Discussion

Livestock is one of the fastest-developing subsectors of the agricultural sector. The projected increase in population between now and 2050 will multiply human needs for animal products, and this will undoubtedly lead to an increase in the natural resources used by the livestock sector to meet these needs and will negatively influence its environmental impact [20–22]. Emissions of GHG produced during livestock production are of great concern, as they significantly contribute to overall anthropogenic GHG emissions [3]. Although pig meat ranks in first position in terms of consumer consumption preferences, little attention has been given to the study of GHG emissions of the sector compared to other species (i.e., ruminants), especially on a country level. In the present study, we report, for the first, time the environmental impact of the Greek pig farming in terms of GHG emissions during six consecutive years, using both Tier 1 and 2 approaches, as recommended by the IPCC. In addition, the respective emissions were estimated for other European countries contributing to pig production for comparative purposes. The emissions derived from a typical semi-extensive pig farm in Greece were also reported as a small-scale approach. All reported emissions were calculated using different computation methods for comparison purposes between inventories.

For Tier 1 and 2 approaches, we first implemented the IPCC recommendation guidelines [14], using specific equations for the respective emission estimations with regard to methane and nitrous oxide gasses. According to the results, the countries were ranked accordingly to the reared populations, and Tier 2 emissions estimations were notably lower compared to those of Tier 1 in each country, reaching almost the half of those revealed through the Tier 1 approach in many of the examined cases. These results are in line with our expectations, as both methodologies utilize different parameters, which are responsible for the observed differentiation of the results for each gas category (i.e., CH₄, NO₂). The Tier 1 approach is one of the simplest and most common approaches for estimating GHG emissions, and it focuses on species populations and on the assessment factors (emission factors), which are specific to the examined animal species, regardless of age and/or production stage. In addition, the factors that are used depend on the generally characterization of the implemented productive system (high- or low-productivity systems) and not on country- or territory-level characteristics [17]. Population number was the key parameter in both approaches, according to the equations. Therefore, the general ranking of countries based on CH₄ and N₂O emissions is proportional to the changes in population per year; thus, the higher the number of animals within a certain production system, the higher estimated emissions. However, Tier 2 methodology, compared to Tier 1, considers animal population within each animal category and not only the total studied population. Because Tier 1 does not consider the number of animals within each animal category, as opposed to Tier 2 methodology, but only the total population, obviously, it may overestimate emissions compared to Tier 2. The latter methodology, apart from the animal number and herd structure, also considers many other specific parameters regarding animal husbandry, i.e., animal diet rations, animal performance, etc., which permits a more accurate approach. It should

be noted that in some developing countries, it has been reported that Tier 2 emission factors were higher than the corresponding factors of the Tier 1 inventory, leading to higher total emissions than those of estimated by a Tier 1 approach [23]. The choice of using one of the two approaches lies in the need to draw specific conclusions regarding the amount of greenhouse gas emissions or the need for qualitative conclusions concerning a general assessment of concentrations. In any case, IPCC guidelines recommends that all countries use higher-tier inventories for GHG estimations, as they are considered to lead to a more accurate result [14,17].

Another result emerging from the present study is that although the depth of analysis differs between Tier 1 and Tier 2 methodologies, in both cases, the ranking of the studied countries according to their emissions per gas type (CH_4 , N_2O) and per source (manure, enteric fermentation) did not change. Therefore, if only comparing approaches in terms of ranking regarding GHG emissions in the pig sector, then Tier 1 methodology could form an easy case scenario to draw up initial results, followed by a more elaborated approach (i.e., Tier 2) for further qualitative estimations and decisions.

We further proceeded to estimate GHG emissions using GLEAM-i, a software that provides emissions calculations with sufficient technical rigor [24]. GLEAM-i uses a herd model coupled with an IPCC (2006) Tier 2 approach, enabling characteristics of major importance in a livestock population to be considered in computations. The comparison of the results obtained by IPCC's Tier 2 equations and GLEAM-i showed some similarities with the results obtained from the comparison between Tier 1 and Tier 2 estimations. First, the ranking of the studied countries according to CH_4 and N_2O emissions remained the same. Secondly, the IPCC's Tier 2 and GLEAM-i outputs highlighted numerical differences in the estimations. The observed differences may be attributed to a different equational approach. IPCC equation parameters are based on default average approaches for each category (i.e., default values for nitrogen excretion rate or nitrogen gain by growth stage, live weight change of sows during gestation, etc.). In addition, GLEAM-i uses energy requirement parameters based on NRC equations for further swine GHG estimation, whereas IPCC guidelines lack such an approach [24]. There are also various parameters involved, the values of which are subject to some degree of uncertainty, which, in some cases, can impact the final results [24].

We, also, focused on estimating GHG emissions on a semi-extensive pig farm in northern Greece as a small-scale scenario. Tier 1 and Tier 2 approaches followed a similar trend as in the case of the examined countries, with Tier 2 estimations being lower compared to Tier 1 emissions due to the different equational approach that the methodologies follow. Based on the comparison of the estimated emissions per pig between the examined semi-extensive pig farm and the average pig farm, it was found that a semi-extensively reared pig contributes to the total emitted gasses to a lesser extent. A different manure management system and/or feed supply could have contributed to this difference. In the studied semi-extensive system, an autochthonous breed was used with low productivity compared to the hybrids that are used in intensive pig farming, which could contribute to the lower emissions per animal. Moreover, the larger amount of produced manure was directly spread in pastures due to grazing, compared to the average pig farm, where in the later, due to intensive farming, a deposit of manure was applied before any further treatment. Generally, grazing assists in lowering GHG emissions, as it eliminates the time that manure remains in a deposit site [25]. Depending on the methodology applied, different results in relation to the main source of GHGs were noted. When a Tier 1 methodology was applied, breeding animals (sows, boars) contributed to estimated GHGs in a greater extent. On the contrary, fattening pigs were noted to contribute more to the estimated emissions when a Tier 2 approach was followed. Tier 1 methodology is the simplest method, takes the least resources to capture emissions and it therefore not able to reflect the circumstances of countries compared to the Tier 2 inventory, which uses more detailed data, such as information on animals' energy requirements or dry matter within each examined animal category, to estimate their actual emissions. A profound reason that, the fattening pigs

were associated with the highest emissions under Tier 2 methodology, could be the ad libitum feeding and their intensive productive status (growth and fattening) [26], whereas under Tier 1 methodology, only population number is concerned. Therefore, if policy measures should be undertaken in terms of mitigation strategies, the methodology that is applied to estimate GHG emissions seems to be of utmost importance for evaluating which animal category contributes more to the estimations, especially when Tier 2 methodology is applied, that more accurately captures emissions. Furthermore, if policies intend to subsidize the category of breeding of animals (i.e., sows) as an attempt to strengthen pig husbandry, then it would be advisable that these measures be accompanied by GHG mitigation commitments, as the estimated environmental impact in terms of emissions is expected to increase with use of either a Tier 1 or Tier 2 methodology. In any case, specific categories could be targeted (i.e., breeding animals or fattening gilts) in a more specialized manner (i.e., improvement in diet digestibility, better utilization of manure) apart from more general strategies in livestock units (i.e., animal improvement).

A comparison of our findings with those reported in studies from the literature reflects some difficulties and limitations in a more general approach. Although previous studies reported the environmental impact of pig husbandry, each had set different boundaries and/or used different functional units to present the estimated GHG emissions. This was also recently depicted by Andretta et al. [16], who further stated that transformations in some cases did not lead to precise results. In addition, at country level, only Tier 1 or, in some cases, a combination of Tier 1 and Tier 2 equations, according to the availability of emission factors, have been used without any further separate comparison between the two approaches. Therefore, for informative scope, some examples of pig GHG assessment are further discussed below. A Swedish report [27] using country-specific emissions factors (Tier 2) estimated the environmental impact of pig production considering all the inputs at the farm level, as well as transport steps, but not emissions related to buildings, machinery and medicines. Total methane emissions from animals (enteric fermentation) and manure ranged from 16.66 to 29.21 kg/year, depending on the yearly amount of produced meat. The direct emissions of nitrous oxide from manure ranged from 34 to 120 kg N₂O/year, whereas the respective indirect emissions ranged from 21 to 55 kg N₂O/year. Losses of nitrous oxide from manure ranged from 0.0041 to 0.0059 kg N₂O per pig/year. The total emissions of GHGs varied between 3.6 and 4.4 kg CO₂-eq/kg of bone- and fat-free meat. Bava et al. [28] reported on the environmental impact of Italian pig production using a Tier 1 methodology to estimate methane emissions and a Tier 2 approach to estimate emissions derived from slurry management on six pig farms in northern Italy. The system boundaries included the on-farm processes and off-farm activities linked to the production of external inputs without considering slaughtering transfers and processes. Total emissions varied from 2.69 to 5.81 kg CO₂-eq/kg animal live weight. According to the same authors, fattening pigs (growing and finishing pigs) contributed more to the estimated emissions, similarly to the results of the present study. Dourmand et al. [29] revealed that conventional pig farms had lower emissions (2.25 Kg CO₂-eq/kg pig live weight) compared to organic (2.43 Kg CO₂-eq/kg pig live weight) or traditional systems (3.47 Kg CO₂-eq / kg pig live weight), which seems not to be in agreement with the noted results of the present study between a semi-extensive farm and average farms. Different functional units, feed supply and genetic material may have contributed to the observed differences. Another study [30] focusing on an Iberian traditional pig production system using a Tier 2 approach showed that growing stage contributed most to the emissions impact (75%), followed by the production of piglets (19%) per Kg of live pig at farm gate, which is similar to our observations. The same trend was also noted in intensive pig farming systems in Mexico, where fattening pigs produced the most emissions, followed by weaning piglets [31]. At country level, a previous study [32] reported that methane emissions of the Vietnam pig sector from manure management reached approximately 50 kt, and those of nitrous oxide and ammonia reached approximately 2 kt and 10 kt, respectively. Interestingly, Amon et al. [33] tried to capture changes in GHG emissions in Austria due to the shift from

the 1996 IPCC guidelines to the 2006 and 2019 IPCC refinements. The authors reported that moving from previous guidelines to the recent guidelines resulted in prominent changes in livestock GHG emissions from different source categories. Additionally, the importance of the used methodology and emissions factors was confirmed with respect to generate more accurate and transparent emission inventories. Therefore, the reported variability in functional units, as well as the implemented farming boundaries, is an important issue to be highlighted. The functional unit choice is certainly a challenging task because it directly impacts the estimated emissions and is also related to the aim of each study [34]. The same is true of the set of system boundaries. However, these parameters seem to be an utmost limitation when the comparison of results between studies is a main research scope, as further transformations are sometimes not possible or precise (e.g., results expressed in one ton of live pig are difficult to compare to those stated, i.e., in one kg of bone- and fat-free, meat because there are more processes included, and sometimes yield is based on country standards). Therefore, common agreed-upon guidelines for comparing the impact of GHG emissions between different pig farms would be a critical solution. Such guidelines for comparisons between studies assessing the environmental impact in the livestock sector could contribute to more precise, comprehensive and integrated assumptions.

5. Conclusions

Tier 1 and 2 methodologies did not affect the ranking in regard to the estimated GHG emissions among the studied countries. However, the noted differences in the numeric estimations between the applied computational methodologies are attributed to the more elaborated equational approach that Tier 2 methodology follows. Glead-i software, although it follows a Tier 2 approach, produced numeric differentiations compared to the results obtained by IPCC's Tier 2 equations, which can be attributed to a slightly different computational approach that the software follows in regard to animals' energy requirements. When a semi-extensive farming system and the average pig farm (intensive farming) in the Greek territory were compared, the former was noted to have lower emissions per animal. In addition, depending on the methodology applied, different results regarding which animal category contributes more to the GHG emissions were noted. Specifically, Tier 1 methodology revealed that breeding contributed more to these emissions, contrary to the Tier 2 approach, which showed that fattening pigs were responsible for the majority of GHG emissions. Generally, a strong relationship was noted between emissions and inventory methodology. Thus, depending on the methodology, specific categories could be targeted (i.e., breeding animals or fattening gilts) in a more specialized manner. Therefore, if mitigation policy measures should be undertaken, the methodology that is applied to estimate GHG emissions seems to be of utmost importance. In addition, if policies intend to subsidize a certain category of animals (i.e., sows) in an attempt to strengthen pig husbandry, it would be advisable that these measures be accompanied by GHG mitigation commitments, as emission estimations are expected to increase independently, depending which methodology is applied. Thus, it is important for pig sector to report detailed and transparent inventories, following periodic estimations of trends and new approaches in computational methods. Although many pig systems have been studied in terms of environmental impact assessments, results are not easily comparable due to different approaches applied in each study (different functional units, boundaries, statistical analyses, etc.). Common agreed-upon guidelines for comparison of studies should be introduced to contribute to the establishment of more precise, comprehensive and integrated interpretations.

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