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Analysis of the Nexus between Structural and Climate Changes in EU Pig Farming

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Abstract: The EU's ambition to establish economy-wide climate neutrality by 2050 requires challenging transformations in many economic activities. This paper aims to investigate the nexus of structural changes and greenhouse gas emissions (GHGEs) in an important sector of the livestock system, namely pig farming, during the period of 2010–2020 and to discuss the main directions of GHGE reduction. The academic novelty of this contribution is characterised by a combination of the shift-share and cluster analysis that allows for the investigation of the evolution phenomenon, applying the sustainability prism in order to understand the nexus between pig farming and the livestock system, as well as combining the national and EU levels. Results suggest that the steep decline in the number of holdings and a moderate reduction in livestock units (LSUs) on farms do not bring tangible GHGE reduction results. The cluster analysis confirms that pig farming systems in pre-2004 member states, except for Finland and Greece, demonstrated positive developments or a lower decline in holdings with pigs and live swine LSUs compared to other countries, while in the dominant share of post-2003 member states, the GHGE reduction rate was higher. This research identifies a reduction in the pig population, improvement in feed production and the development of related supply chains, and changes in manure management and utilisation as the main directions of GHGE reduction; however, the identified clusters are related with different potentials of GHGE reduction when applying the aforementioned measures. Recommendations include the development and support of actions that focus on GHGE reduction from swine manure and contribute to the establishment of a circular economy in the EU.

Keywords: agriculture; cluster analysis; greenhouse gas emissions; pig farming; shift-share analysis; structural change

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1. Introduction

The environmental pressure of the European Union's (EU) agricultural system continues to grow due to population development dynamics and income improvement. According to the most recent projections by the United Nations [1], the global population could stand at 9.7 billion people in 2050 compared to 2.5 billion in 1950. In this context, the livestock sector is recognised as a key player in food security and climate change mitigation [2] because meat provides protein and vitamins that are vital for a healthy diet while also being the main agricultural contributor to greenhouse gas emissions (GHGEs). In 2021, the dominant type of consumed meat in the EU was pork, and the corresponding consumption accounted for 32.5 kg of the total meat consumption, i.e., 67.7 kg retail weight per capita [3]. Academic studies suggest that swine production generates significantly lower GHGEs compared to dairy and beef [2,4], but pork products are recognised as the third largest contributor of GHGEs in the livestock sector [5].

Although pork remains the first choice in many member states (MSs), changes in global markets and animal welfare standards, the enlargement of the EU post-2003, and recent crises have contributed to the evolution of the EU pig farming structure. This literature review allows the author to state that a substantial share of recent academic contributions on structural changes in pig farming covers socioeconomic aspects and comes from countries that joined the EU in 2004 and later. These MSs have faced the unprecedented evolution of the national livestock sector (for example, see [6–11]). The strong focus on environmental concerns and climate change mitigation arises from the pre-2004 MSs because most of these MSs have developed a highly concentrated production system and provide remarkable contributions to GHGEs due to EU pig farming. Over the past decade, researchers provided fundamental studies that investigated both the outcomes of climate change in pig farming [12–14] and the impact of pork production on climate change [15–17]; some researchers went beyond and analysed its impact on sustainability and introduced holistic approaches to investigate pig production systems [18–22]. Recent studies have mainly focused on individual MSs or groups of EU countries, while EU-wide research on changes in pig farming has attracted less academic attention.

Although this literature review identified numerous studies on the nexus of climate change and pork production, the selected research aspect has not been covered. The aim of this research is to investigate the nexus of structural changes and GHGEs in this important sector of the livestock system, namely pig farming, during the period of 2010–2020 and to discuss the main directions of GHGE reduction. The academic novelty of this contribution is characterised by a combination of shift-share and cluster analysis for the investigation of the nexus between structural and GHGE changes in livestock. The aforementioned literature review shows that the most recent studies do not employ this methodological framework; however, this method allows for the investigation of the evolution phenomenon by applying a sustainability prism, shows the nexus between pig farming and the livestock system, and combines the national and EU levels. First, the conducted research employs indicators that cover different aspects of sustainability and sheds light on the nexus between changes in pig farming and the livestock system. Second, the actual growth rates of the investigated indicators are applied in the cluster analysis to classify countries on the basis of the change patterns during the period of 2010–2020, and the progress of MS towards the establishment of the sustainable food systems is discussed.

2. Materials and Methods

2.1. Materials

This research covers EU countries (EU-27), excluding the United Kingdom, and relies on secondary data from Eurostat and the European Environment Agency for the period from 2010 to 2020. This database provides reliable and comparable data on EU pig farming. Although the Farm Accountancy Data Network database could also provide important indicators for this analysis, this database is focused on commercial farms and could be useful for the further improvement of knowledge in this important niche. The selected period is characterised by the accession of Croatia and multiple crises that have accelerated structural changes in EU pig farming.

The shift-share analysis is selected because it empowers the investigation of pig farming as a component of livestock system. This approach allows us to benchmark the development patterns of system components and to draw conclusions on the most important components that could be managed in order to improve the overall situation and obtain the desired changes in the livestock system. Cluster analysis is used to identify groups of countries with similar development patterns. This knowledge could be utilised by policy makers for the development of specific measures or to better understand the relevance of specific supports for the achievement of strategic EU objectives.

The sustainability prism in the shift-share analysis is represented by three indicators. The study by [23] suggests that the economic dimension could be covered by indicators that explain productivity factors or agricultural income. In this paper, the economic aspect is covered by the output-related indicator that reports on changes in pig and livestock populations in the EU. The research employs indicators of live swine (domestic species) and total livestock. As the shift-share analysis presumes that the pig population is an element of the livestock system, the benchmarking of different livestock types becomes a challenge.

This issue is addressed by utilising the methodological approach of the livestock unit (LSU), which allows us to estimate the changes in the structure of livestock.

According to [23], the social dimension is linked to rural areas and the quality of life there. Holdings with animals show places of residence and could be linked with employment or additional income generation in rural areas. Thus, the social aspect of pig farming evolution is captured by changes in holdings. A similar criterion is employed by [24] to investigate farm structural change. The number of holdings with livestock is selected as a criterion that describes the livestock system, while pig farming is represented by holdings with pigs.

The environmental dimension relies on the indicator of GHGEs and combines two indicators of paramount importance, namely enteric fermentation and manure management. Although the livestock sector is responsible for the consumption of one-third of cereals for feed production [2] and the related GHGEs, this research is limited to the specific focus of two main sources of GHGEs from pig and livestock production, because these sources could be directly linked to the environmental pressure on the EU agricultural system, while feed could be imported. The study by [17] argues that EU pig farming businesses often rely on imported soybeans, and this routine relocates GHGEs related to feed production.

It is important to note that some research limitations could be linked to the changes of Eurostat methodologies. For example, the unit coefficient of Equidae was removed, and some changes in the estimation of the poultry section were made in 2020 compared to 2010. However, these animals represented a negligible share in the main structure of livestock. Although the decline in the number of holdings was a distinct character of the investigated period, results are also affected by changes in the farm size threshold in some MSs. Nevertheless, the research results are indicative and explain the paramount directions in the evolution of EU agriculture.

2.2. Methods

The research adapts a standard shift-share analysis logic (for more details, see [25]) for each dimension of sustainability. This framework allows us to decompose the actual change of the investigated indicator into three components that help to consider possible change under different conditions (i.e., the growth rate of the EU livestock system or its components). The situation in the EU livestock sector is recognised as a system, while pig farming is a structural component of a particular research interest. The nexus between the growth rates in the livestock system is described in Equation (1):

$$GS_j = GL + (GS - GL) + \left(GS_j - GS\right), \quad (1)$$

where GS_j refers to the growth rate of the investigated pig farming indicator (live swine LSUs, holdings with pigs or GHGEs from live swine) in the jth MS, GL is the growth rate of the indicator that describes the EU livestock system (livestock LSUs, number of holdings with livestock or GHGEs from livestock), and GS denotes the growth rate of the EU pig farming indicator (live swine LSUs, holdings with pigs or GHGEs from live swine).

The actual change of the investigated indicator (ΔSCI_j) for the selected MS could be broken down into three effects (Equation (2)):

$$\Delta SCI_j = GS_j \times SCI_{j,2010} = SCI_{j,2020} - SCI_{j,2010} = LS_j + PF_j + PFM_j, \quad (2)$$

where SCI_j is the investigated indicator (live swine LSUs, holdings with pigs or GHGEs from live swine) in the jth MS for the indicated year; LS_j shows the effect of the livestock growth rate GL application for pig farming of the jth MS; PF_j is linked to the growth rate (GS-GL) and shows the effect of MS specialisation in pig farming, which compares the growth rates of EU pig farming (GS) to the EU livestock system (GL); and PFM_j estimates the growth rate (GS_j-GS) and shows the effect of pig farming for the jth MS, i.e., the possible evolution of pig farming in the MS if the growth rate considers the pig farming growth rate that shows the difference between the growth rate in individual MSs (GS_j) and EU pig farming (GS).

The decomposition of three main effects, namely, LS_j, PF_j, and PFM_j (see Equation (2)), is specified in Equations (3)–(5):

$$LS_j = SCI_{j,2010} \times GL = SCI_{j,2010} \times \left(\frac{SCI_{2020} - SCI_{2010}}{SCI_{2010}} \right), \tag{3}$$

$$PF_j = SCI_{j,2010} \times (GS - GL) = SCI_{j,2010} \times \left(\frac{SCI_{s,2020} - SCI_{s,2010}}{SCI_{s,2010}} - \frac{SCI_{2020} - SCI_{2010}}{SCI_{2010}} \right), \tag{4}$$

$$PFM_j = SCI_{j,2010} \times (GS_j - GS) = SCI_{j,2010} \times \left(\frac{SCI_{j,2020} - SCI_{j,2010}}{SCI_{j,2010}} - \frac{SCI_{s,2020} - SCI_{s,2010}}{SCI_{s,2010}} \right), \tag{5}$$

where *SCI* is the selected indicator of the EU livestock system (livestock LSUs, holdings with livestock or GHGEs from livestock) for the indicated year, and SCI_s is the selected indicator of EU pig farming (live swine LSUs, holdings with pigs or GHGEs from live swine) for the indicated year.

The shift-share analysis allows us to benchmark the actual change of LSUs, the number of holdings, and the GHGEs against the hypothetical changes. The real situation is compared to the growth rates of the whole system or pig farming components. Although these results shed light on the situation in MSs, the shift-share approach relies on individual indicators, and this fact impedes the understanding of the progress towards the establishment of sustainable food systems. Thus, this research employs indicators of the actual growth rates (GS_j) in MSs to cluster EU countries in accordance with the similarities of the evolution patterns during the period of 2010–2020.

This research relies on a hierarchical agglomerative cluster analysis, which employs a connectivity model that allows relatively homogeneous groups of MSs to be identified, and the clustering results to be benchmarked step-by-step without preconception. The analysis of the step-by-step clustering process starts from the individual MSs and uses characteristics of three growth rates to merge countries into homogeneous groups until one cluster is left. Clustering applies the between-groups linkage method based on the squared Euclidean distance interval (for more details, see [26]).

First, the squared Euclidean distance interval assists in building a proximity matrix that estimates the distances or dissimilarities for the investigated MSs, employing actual growth rates. The adapted squared Euclidean formula is provided in Equation (6):

$$SED_{ab} = \sum\nolimits_{j=1}^{k} (GS_{aj} - GS_{bj})^2 \tag{6}$$

where GS_{aj} is the value of the *j*th growth rate for the *a*th MS, GS_{bj} is the value of the *j*th growth rate for the *b*th MS, and *k* is the number of growth rates included in the cluster analysis.

Second, the agglomeration schedule and dendrogram are employed to explore the (dis)similarities between the countries based on the growth rates of national pig farming systems. The agglomeration schedule provides a numerical summary and allows for the analysis of clustering stages, while the dendrogram illustrates the step-by-step arrangement of clusters and helps to assess the cohesiveness of clusters.

The agglomeration schedule and dendrogram reflect the following step-by-step clustering procedure. MSs or earlier identified clusters are joined in new clusters if they have the smallest squared Euclidean distance values, while each step updates the proximity matrix for decision making. It should be noted that the selected distance measure can estimate values only for a pair of MSs. Average linkage (between groups) method suggests that in case of clusters that include more than one MS, the distance between clusters is calculated as the average of all distances between the pairs that belong to different clusters.

For example, in the case of cluster A (a, d) and cluster B (b, c), the distance would be the average of distances between (a, b), (a, c), (d, b), and (d, c).

The analysis of agglomeration stages provides more information about countries with significant differences in evolution patterns and creates knowledge for academic discussion.

3. Results

3.1. Changes in the Socioeconomic Dimension

With the exception of Spain, Portugal, and Luxembourg, the indicator of live swine LSUs in MSs decreased during the period of 2010–2020. In Greece, Croatia, Lithuania, Malta, Slovenia, Romania, and Finland, live swine LSUs declined by more than a quarter, while other MSs demonstrated less dramatic changes over the same period. The analysis of the livestock LSU structure suggests that the share of live swine was highest in Denmark (68.46%), Spain (49.14%), and Belgium (40.81%) (Table 1). Thus, the nexus between the role of MSs in EU swine production and the share of live swine LSUs in the livestock LSU structure could assist in decision making on climate change mitigation potential in individual MSs.

Table 1. Changes in the structure of live swine LSUs and results of the shift-share analysis.

MS	Results of the Shift-Share Analysis, LSUs				Share of MS Live Swine LSUs in the EU Structure in 2010, %	Share of MS Live Swine LSUs in the EU Structure in 2020, %	Share of Live Swine LSUs in Livestock LSUs in 2020, %
	LS_j	PF_j	PFM_j	Live Swine Actual Change from 2010 to 2020 (ΔSCI_j)			
BE	−110,753.17	21,751.99	5341.18	−83,660	4.39	4.41	40.81
BG	−12,445.92	2444.39	−10,908.47	−20,910	0.49	0.46	15.62
CZ	−32,078.46	6300.23	−84,301.77	−110,080	1.27	1.02	21.69
DK	−246,685.84	48,449.25	−467,213.41	−665,450	9.78	8.40	68.46
DE	−448,324.60	88,051.23	−128,766.63	−489,040	17.77	17.39	36.30
EE	−6250.67	1227.64	−10,316.96	−15,340	0.25	0.22	25.22
IE	−26,622.02	5228.58	21,043.44	−350	1.06	1.12	6.00
EL	−17,098.32	3358.12	−49,859.80	−63,600	0.68	0.53	9.18
ES	−431,820.55	84,809.83	2,331,940.72	1,984,930	17.11	23.99	49.14
FR	−226,318.71	44,449.14	−170,080.43	−351,950	8.97	8.47	15.11
HR	−26,760.94	5255.86	−108,694.93	−130,200	1.06	0.74	33.37
IT	−172,253.09	33,830.61	−73,137.53	−211,560	6.83	6.61	24.24
CY	−5374.36	1055.53	−1041.17	−5360	0.21	0.21	30.98
LV	−6774.08	1330.43	−306.36	−5750	0.27	0.27	19.14
LT	−14,110.15	2771.24	−79,361.10	−90,700	0.56	0.33	15.37
LU	−1274.13	250.24	2113.89	1090	0.05	0.06	11.79
HU	−55,654.77	10,930.63	−42,885.86	−87,610	2.21	2.08	37.26
MT	−1224.32	240.46	−6286.14	−7270	0.05	0.03	31.96
NL	−175,152.85	34,400.13	−48,387.28	−189,140	6.94	6.80	36.84
AT	−55,576.19	10,915.20	−69,919.00	−114,580	2.20	2.00	30.33
PL	−256,574.38	50,391.37	−583,766.99	−789,950	10.17	8.45	28.63
PT	−32,190.72	6322.28	87,818.44	61,950	1.28	1.53	21.46
RO	−96,292.22	18,911.85	−343,929.63	−421,310	3.82	2.80	21.69
SI	−6478.70	1272.42	−32,533.72	−37,740	0.26	0.16	12.01
SK	−10,073.76	1978.49	−25,354.73	−33,450	0.40	0.32	18.17
FI	−23,043.79	4525.81	−97,912.03	−116,430	0.91	0.62	22.32
SE	−25,968.11	5100.15	−13,312.04	−34,180	1.03	0.99	20.33

Source: author's own calculations based on Eurostat data.

The benchmarking of the live swine structure in 2010 with the situation in 2020 shows the growing role of Spain in EU pig farming. Countries that joined the EU in 2004 and later demonstrate negative dynamics of pig population development and a corresponding decline in the overall structure of live swine LSUs, while in other MSs the decline in live swine LSUs is not necessarily linked to the loss of the position in the EU structure. In fact, Belgium, Ireland, Spain, Luxembourg, and Portugal managed to increase their share over the period of 2010–2020.

The analysis of LS_j values and the comparison with the actual live swine LSUs change from 2010 to 2020 allow us to draw conclusions of a different nature. First, the LS_j values are negative, i.e., the EU livestock system demonstrates negative development during the period of 2010–2020. However, the benchmarking of LS_j and ΔSCI_j values shows differences between overall changes in the EU livestock system and the actual evolution of pig farming in individual MSs. In Belgium, Cyprus, Ireland, Spain, Latvia, Luxembourg, and Portugal, the negative growth rate of the livestock system is stronger than unfavourable developments in pig farming, while other countries demonstrate the shrinking of live swine LSUs at a higher rate than the EU livestock system.

PF_j values shed some light on the impact of pig farming specialisation and show the possible development of the indicator in the individual country if the growth rate is the difference between the EU pig farming and EU livestock system growth rates. In the dominant share of EU countries, the decline rate in LSUs is lower than in the cases of live swine LSUs, and PF_j values show the positive development for the investigated period. However, the effect of pig farming PFM_j for individual MSs differs remarkably. According to Table 1, Belgium, Luxembourg, Spain, Ireland, and Portugal have positive PFM_j values; however, some MS also demonstrate a lower decline in live swine LSUs than the indicator of the actual change.

According to Eurostat, in 2020, 72.87% of EU holdings with pigs were in Romania and Poland. However, the benchmarking of 2010 and 2020 shows a dramatic change in redistribution of holdings with pigs in the EU. All MSs except Ireland and Italy demonstrated a decline in the number of holdings with pigs. In Belgium, the Czech Republic, Malta, and Sweeden, the number of holdings with pigs dropped by less than a third, while other MSs survived a more dramatic decline in the number of holdings during the period of 2010–2020. EU pig farming faced the exit of small pig farms, while the consequences of African Swine Fever (ASF) and the reaction of MSs that joined the EU post-2003 to the high market concentration, new support schemes, and growing price volatility of agricultural commodities exacerbated the situation.

The LS_j effect shows the possible change of holdings with pigs at a growth rate of the EU holdings with livestock (Table 2). Results imply that in Belgium, the Czech Republic, Ireland, Italy, Malta, Austria, and Sweden, the decline in the number of holdings with pigs is slower than the possible change if the growth rate of the EU livestock system were applied. The effect PF_j demonstrates that the application of growth rate (*GS-GL*) exacerbates the situation compared to the actual growth rate only in two MSs. Indeed, the effect PFM_j shows that the growth rates of holdings with pigs in MSs demonstrate different patterns. In fact, only ten countries demonstrated negative PFM_j values.

Figure 1 reports on the nexus of GS_j indicators for live swine LSUs and the number of holdings with pigs. The positive growth rates are reported only for some pre-2004 MSs, while the dominant share of countries belongs to the space with both negative GS_j values. It is worth noting that countries that joined the EU during and after the main enlargement demonstrate more fundamental structural changes.

Eurostat statistics suggest that all MSs except the Czech Republic demonstrated a decline in the number of holdings with livestock during the period of 2010–2020. The Eurostat livestock population index, based on head of animals, reports on the decline in bovine animals, sheep, and goat populations in the EU. In many MSs, the shrinking of livestock populations was accompanied by a fall in the number of small farms. The steep decline in the number of holdings with pigs could be partially explained by the growth of the average farm size in countries that joined the EU post-2003. Bellini [27] explains that the evolution of pig farming in new MSs is due to low technical efficiency and an unfavourable position compared to large farms that benefit from economies of scale. According to [28], EU pig farming spatial concentration is growing, and this process contributes to the gradual disappearance of small farms. Growing animal welfare standards, changes in manure management and disposal demanded additional investments [6,11] and exacerbated the situation of smaller farms after the EU accession. The Common Agricultural Policy (CAP) support schemes; increased volatility of agricultural commodities' prices, including feed; trade deterioration with the Russian Federation; and animal disease outbreaks also played an important role in transformations of national agricultural systems. In some countries, traditional pig farming activity on small farms became less attractive due to more profitable business alternatives and improved food availability. It should be noted that the aforementioned factors were among the main explanatory variables; however, this list is not exhaustive. The EU market merges MSs with unique histories of agricultural development, and this fact introduces specific development patterns in national pig farming systems.

Table 2. Changes in the structure of holdings with pigs and results of the shift-share analysis.

MS	Results of the Shift-Share Analysis				Share of MS Holdings with Pigs in the EU Structure in 2010, %	Share of MS Holdings with Pigs in the EU Structure in 2020, %
	LS_j	PF_j	PFM_j	Actual Change in Number of Holdings with Pigs (ΔSCI_j), 2010–2020		
BE	−2316.73	−1151.71	1808.44	−1660	0.54	0.36
BG	−32,359.45	−16,086.85	−30,453.69	−78,900	1.52	0.29
CZ	−1573.33	−782.15	1455.48	−900	0.40	0.26
DK	−1994.20	−991.37	885.57	−2100	0.42	0.25
DE	−23,639.27	−11,751.79	7141.07	−28,250	3.79	2.70
EE	−609.67	−303.08	−567.25	−1480	0.10	0.01
IR	−475.93	−236.60	882.53	170	2.92	0.12
EL	−7603.11	−3779.74	−2037.15	−13,420	3.05	0.50
ES	−27,442.80	−13,642.64	5685.44	−35,400	4.16	2.91
FR	−9616.98	−4780.89	4347.86	−10,050	4.74	1.22
HR	−50,370.14	−25,040.51	−6839.35	−82,250	1.95	3.88
IT	−10,305.31	−5123.08	27,378.39	11,950	4.70	3.23
CY	−247.80	−123.19	−99.01	−470	0.20	0.01
LV	−7146.85	−3552.91	−3820.24	−14,520	0.64	0.31
LT	−24,665.87	−12,262.14	−17,401.98	−54,330	1.75	0.71
LU	−55.07	−27.38	12.44	−70	0.03	0.01
HU	−72,019.16	−35,802.88	−26,827.96	−134,650	2.71	4.10
MT	−51.13	−25.42	36.55	−40	0.04	0.01
NL	−2765.13	−1374.63	669.75	−3470	0.77	0.30
AT	−14,852.23	−7383.49	9205.72	−13,030	1.93	2.09
PL	−152,793.89	−75,958.42	−74,697.69	−303,450	13.56	7.20
PT	−19,698.08	−9792.51	7770.59	−21,720	3.53	2.40
RO	−651,193.19	−323,727.65	94,910.84	−880,010	44.31	65.67
SI	−10,399.71	−5170.01	1439.71	−14,130	1.08	1.04
SK	−4240.12	−2107.89	−1401.99	−7750	0.26	0.26
FI	−818.13	−406.72	64.85	−1160	0.29	0.08
SE	−668.67	−332.41	451.08	−550	0.55	0.10

Source: author's own calculations based on Eurostat data.

ASF had a devastating impact on the EU pig farming structure and contributed to the disappearance of smallholdings with pigs. Although small farms do not play an important role in international trade, these farms contribute to ASF transmission and change the status of the country [29]. For example, in Poland and Lithuania, ASF was highly prevalent in smallholdings [30,31], while the dominant share of small farms with pigs in Romania became an obstacle to overcome the ASF crisis. According to [32], in 2021, the accumulated number of ASF outbreaks in Romania exceeded EU cases, while the pig population declined by a quarter, and the volumes of imported pork increased. During the ASF crisis, the main challenge on small farms was the implementation of biosecurity measures. Thus, national policies included measures to overcome financial and knowledge gaps, control the population of wild boars, etc. In some MSs, the decline in the number of smallholdings with pigs was supported by special measures that encouraged small farms to refuse pig rearing and switch to other animals. This type of support was aiming to reduce the number of small farms that often failed to ensure biosafety measures and were treated as a threat to large-scale farming. As a result, national pig farming structures evolved.

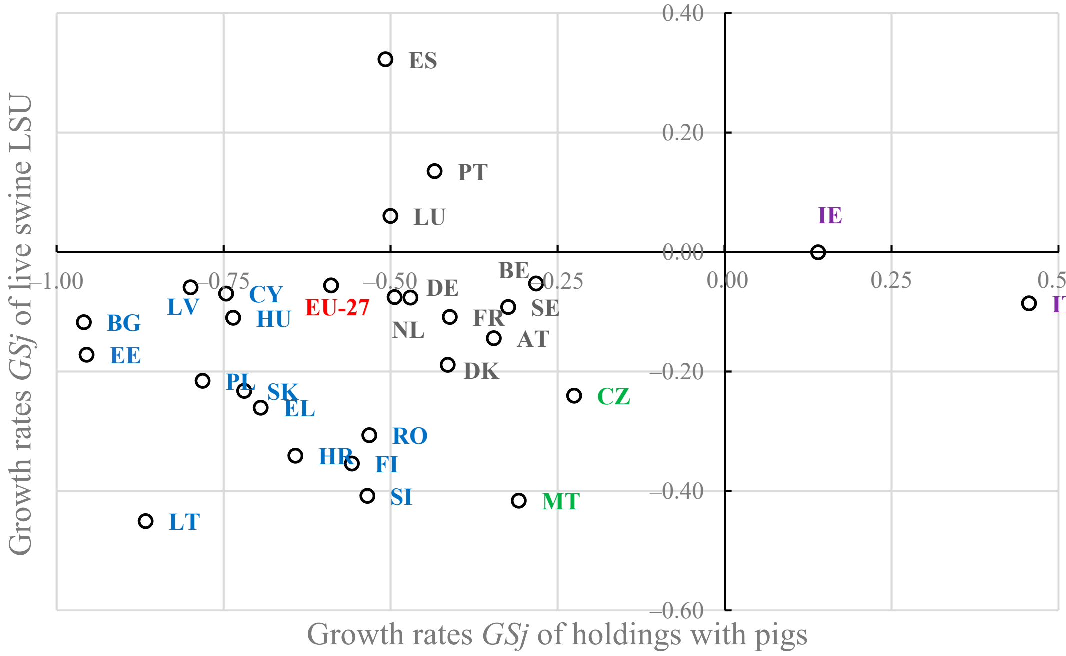

Figure 1. Growth rates of the socioeconomic dimension in MS. Note: The label colour reports on the cluster (Cluster 1, Cluster 2, Cluster 3, and Cluster 4), while red shows the EU-27 situation. Source: author's own calculations based on Eurostat data.

3.2. Changes in the Environmental Dimension

During the period of 2010–2020, GHGEs from enteric fermentation and manure management from live swine declined in all countries except Estonia, Germany, Ireland, Spain, Luxembourg, and Portugal. Over the same period, a decline in GHGEs by more than a quarter was observed in the Czech Republic, Croatia, Cyprus, Latvia, Lithuania, Malta, Poland, Romania, Slovenia, and Slovakia. Table 3 shows that the main contributors of GHGEs in pig farming were Spain, Germany, France, The Netherlands, Italy, and Denmark. In 2020, these MSs were responsible for more than 3/4 of the EU GHGEs from live swine. Most of the countries that joined the EU in 2004 demonstrated a significant reduction in GHGEs due to shrinking of the pig population. The analysis of the overall MS livestock GHGEs from the enteric fermentation and manure management nexus with swine GHGE components shows that the main mitigation attempts must be directed to manure management practices, while swine GHGEs represent an important contribution to the overall structure in only a few countries.

Results of the shift-share analysis suggest that the pace of GHGE reduction in the EU livestock sector was slower than that in EU pig farming. The comparison of LS_j and the actual change columns show that Germany, Estonia, Ireland, Spain, Luxembourg, and Portugal did not demonstrate progress towards the reduction in GHGEs from live swine, but the introduction of the growth rate of the EU livestock system shows a higher rate of GHGE decline. The effect PF_j shows negative values, but in many MSs the actual progress in the pig farming sector shows better achievements than the hypothetical growth rate. The PFM_j effect reflects the differences between countries that have national pig farming development below or above the level of the EU pig farming growth rate. In fact, if the hypothetical growth rates of PFM_j effect were applied, six countries would demonstrate higher levels of GHGEs than the actual change.

Table 3. Changes in the structure of GHGEs from live swine and results of the shift-share analysis.

MS	Results of the Shift-Share Analysis, Thou t				Share of MS GHGEs in EU Structure in 2010, %	Share of MS GHGEs in EU Structure in 2020, %	Swine EF/MM in MS Livestock GHGE (EF + MM) Structure in 2020, %
	LS_j	PF_j	PFM_j	Actual Change in GHGEs from 2010 to 2020 (ΔSCI_j)			
BE	−5.10	−20.88	−49.75	−75.73	4.22	4.04	4.12/13.03
BG	−0.52	−2.12	−26.01	−28.65	0.43	0.33	1.00/3.01
CZ	−1.31	−5.36	−129.77	−136.44	1.08	0.61	1.43/2.34
DK	−10.50	−42.99	−21.97	−75.45	8.69	8.61	5.20/24.63
DE	−16.54	−67.75	153.62	69.33	13.69	14.26	1.96/8.74
EE	−0.26	−1.08	5.05	3.71	0.22	0.24	1.15/6.20
IR	−1.76	−7.23	38.84	29.85	1.46	1.60	0.33/2.28
EL	−2.02	−8.27	−68.08	−78.37	1.67	1.42	0.58/7.13
ES	−25.40	−104.00	1506.99	1377.59	21.02	26.54	2.65/23.93
FR	−13.32	−54.55	−151.23	−219.10	11.03	10.47	0.59/5.55
HR	−1.38	−5.67	−82.38	−89.44	1.15	0.84	2.67/11.51
IT	−11.53	−47.19	−74.35	−133.07	9.54	9.27	1.67/10.11
CY	−0.50	−2.07	−55.55	−58.12	0.42	0.21	3.16/9.08
LV	−0.24	−1.00	−20.19	−21.44	0.20	0.13	1.15/1.98
LT	−0.66	−2.70	−83.73	−87.09	0.55	0.24	1.05/2.04
LU	−0.06	−0.23	0.57	0.28	0.05	0.05	0.54/1.84
HU	−2.20	−9.00	−57.63	−68.83	1.82	1.61	3.44/9.27
MT	−0.02	−0.08	−1.96	−2.06	0.02	0.01	2.85/1.73
NL	−11.61	−47.56	−159.02	−218.19	9.61	9.03	3.56/14.06
AT	−1.03	−4.21	−19.37	−24.60	0.85	0.78	1.29/2.74
PL	−6.95	−28.47	−389.88	−425.30	5.75	4.33	2.60/3.79
PT	−2.16	−8.85	54.71	43.69	1.79	1.99	1.42/9.26
RO	−3.59	−14.71	−276.38	−294.68	2.97	1.96	1.35/3.75
SI	−0.27	−1.10	−24.59	−25.96	0.22	0.13	0.69/1.91
SK	−0.45	−1.84	−30.31	−32.60	0.37	0.26	1.72/3.72
FI	−0.76	−3.09	−26.98	−30.83	0.63	0.53	1.01/3.65
SE	−0.66	−2.72	−10.69	−14.07	0.55	0.51	1.55/2.05

EF—enteric fermentation, MM—manure management. Source: author's own calculations based on European Environment Agency data.

Figure 2 breaks down the growth rates GS_j of GHGEs from live swine into the growth rates of swine enteric fermentation and manure management for the period of 2010–2020. These growth rates (GS_j) allow us to benchmark the progress of two important niches that determine the main GHGEs from swine. According to results, Spain, Portugal, Ireland, and Germany have exacerbated the situation and increased the amount of GHGEs from enteric fermentation and manure management. Estonia and Luxembourg had higher manure management emissions, while Denmark increased the amount of enteric fermentation. Other countries demonstrated a decline in both types of GHGEs from live swine over the investigated period.

3.3. Pig Farming Development Clusters in the EU

In order to understand main patterns of EU pig farming structural changes during the period of 2010–2020, hierarchical cluster analysis is applied. Although the dendrogram suggests that further merging of clusters could be considered, this paper identifies four clusters with differences in the MS development patterns. The main characteristics of clusters are presented in Figure 3.

Cluster 1 (Austria, Belgium, Denmark, Germany, Spain, France, Luxembourg, The Netherlands, Portugal, and Sweden) only covers MSs that joined the EU before 2004. The dominant share of these countries developed competitive production and contributed to the functioning of the highly concentrated EU pork market. These countries demonstrate less dramatic changes in the socioeconomic dimension compared to Cluster 2 and often benefit from economies of scale. Cluster 1 includes polluters that are responsible for more than 3/4 of the GHGEs in the EU pig farming structure.

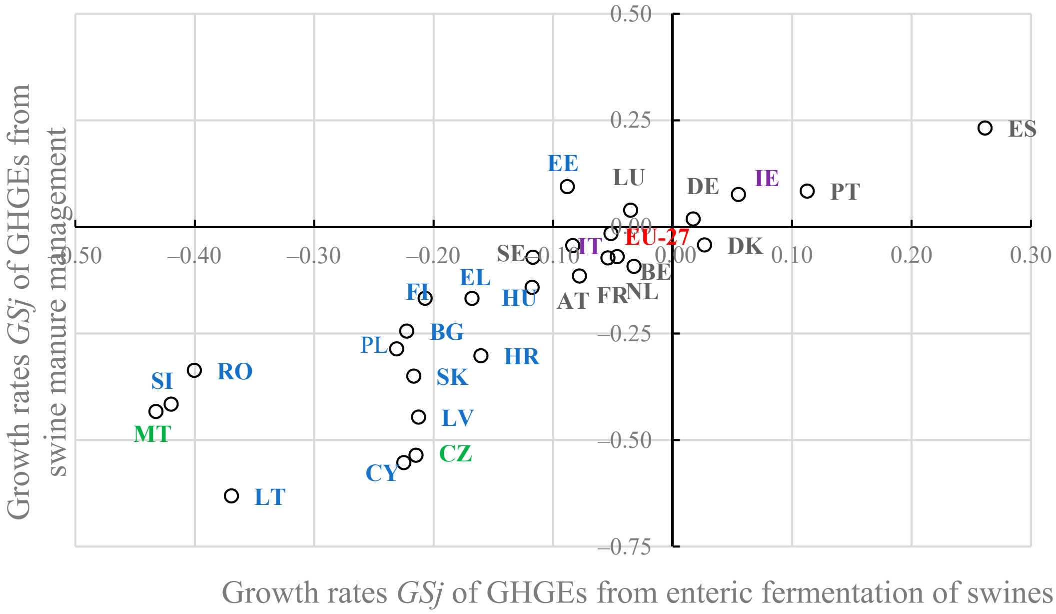

Figure 2. Growth rates of environmental dimension in MS. Note: The label colour reports on the cluster (Cluster 1, Cluster 2, Cluster 3, and Cluster 4), while red shows EU-27 situation. Source: author's own calculations based on European Environment Agency data.

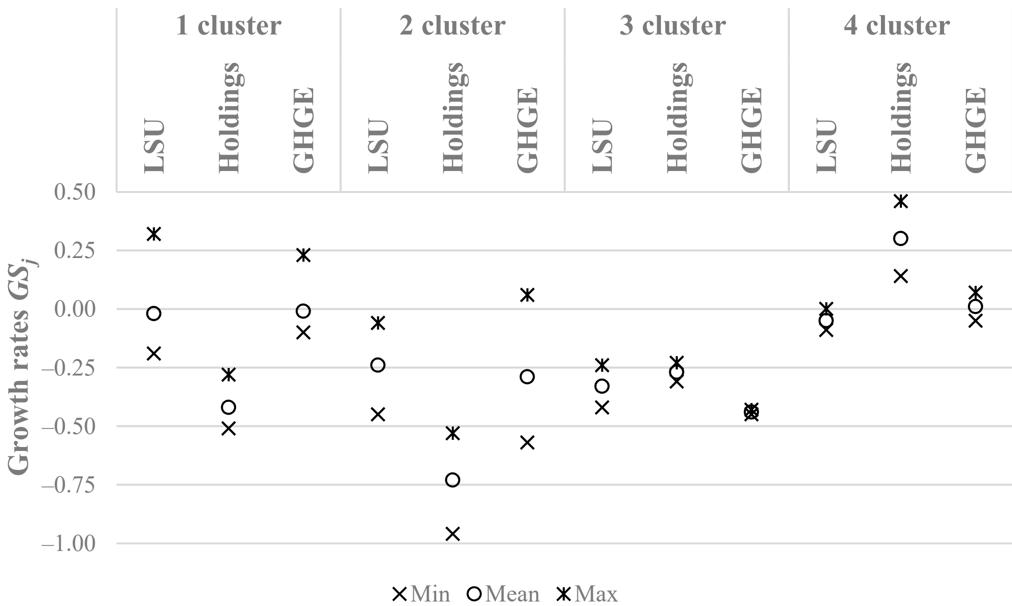

Figure 3. Main characteristics of pig farming development clusters. Source: author's own calculations based on Eurostat and European Environment Agency data.

Cluster 2 (Bulgaria, Cyprus, Croatia, Greece, Hungary, Latvia, Lithuania, Poland, Romania, Slovenia, Slovakia, Finland, and Estonia) has the most extensive representation and covers mainly MSs that joined the EU in 2004 and later, with the exception of Greece and Finland. Cluster 2 includes MSs that survived substantial structural changes during the period of 2010–2020 compared to Cluster 1. Although Cluster 2 represents pig producers that experience market power from the main producing countries, the case of Poland is unique. This country managed to join the main producing MSs [8] despite significant changes in the socioeconomic dimension.

On the one hand, the disappearance of small farms from national pig farming systems is an important characteristic of Cluster 2. The sharp decline in the number of holdings with pigs is accompanied by the shrinking of the pig population and the growth of the average farm size. On the other hand, these changes reduce GHGEs from pig farming. Indeed, the environmental benefits are received at the cost of new socioeconomic challenges. The situation in Finland differs from other pre-2004 MSs because this country demands higher animal welfare, pig health, and biosecurity standards from pig farmers than is required by EU legislation, while local prices are less sensitive to changes on the EU pork market. This pig farming development direction contributed to the transformation of the socioeconomic dimension. During the investigated period, the steepest decline is reported for farms that combine piglet production and pig rearing for meat, while this group of farms represents the dominant share of pig farms in 2010 [33]. In Greece, the average pig farm size was growing because small farms did not compensate production costs.

Cluster 3 (the Czech Republic and Malta) demonstrates patterns that are similar to the evolution of pig farming in Cluster 2. However, the social indicator has slower negative growth rate, while the average value of live swine LSUs per holding is higher than in most MSs from Cluster 2. Nevertheless, the decline in live swine LSUs has a higher negative growth rate compared to the dominant share of MSs in Cluster 2. As a result, the Czech Republic and Malta are among the top five MSs with the highest GHGE reduction rate from manure management.

Cluster 4 (Italy and Ireland) includes pre-2004 MS. During the period of 2010–2020, Cluster 4 demonstrated an increase in the number of holdings with pigs and declining average live swine LSUs per holding ratios, while the development patterns of the economic and environmental indicators were in line with the situation in Cluster 1. The negative growth rate of live swine LSUs is negligible. Italy shows a moderate contribution to the reduction in GHGEs; however, in Ireland, the environmental indicator reports on the growing GHGEs. In Italy, the environmental impact is related to the specialisation in production of heavy pigs, which requires a longer fattening period and restricted feeding compared to production in other European countries [34]. Over the investigated period, competitive large-scale export-orientated pig farming in Ireland benefitted from new Asian markets [35] but ASF-induced benefits have an undesired impact on the environmental dimension.

4. Discussion

The research suggests that the number of EU holdings with pigs fell by more than half, while the corresponding decline in live swine LSUs was 5.64%. GHGEs from the enteric fermentation of swine and manure management decreased by 2.21%. Thus, dramatic structural changes in the social dimension of the EU pig farming system did not bring evident environmental benefits during the period 2010–2020. Research results are in line with the findings of the special report on Common Agricultural Policy and Climate [36] that show almost stable GHGEs from livestock during the investigated period. Our results show that pig farming only slightly exceeds a tenth of livestock GHGEs from enteric fermentation and manure management. For this reason, the main actions to mitigate GHGEs must be focused on cattle and dairy farms. Nevertheless, changes in the pig farming system could also provide a modest contribution to the establishment of more sustainable EU agriculture, and knowledge about this area is critical.

4.1. The Role of Legislation

EU Climate Law provides an intermediate target to reduce net GHGEs by 55.0% by 2030 with relation to 1990 levels, while economy-wide climate neutrality in the EU is projected to be accomplished by 2050. Ambitious strategic goals on climate change mitigation in the European Green Deal and a lack of evident progress in GHGE reduction after the remarkable CAP support (over 100.0 billion euro) for climate mitigation measures in agriculture during the period of 2014–2020 [36] explain the changes in legislation and progress monitoring. Regulation (EU) 2021/1119 sets intermediate climate targets and highlights the role of agriculture in achieving those targets, while Regulations (EU) 2018/841 and (EU) 2018/1999 increase the visibility of livestock-related GHGE mitigation efforts in MSs and encourage further improvements in this area.

The most recent strategies include livestock as an important direction of climate change mitigation. For example, the Farm to Fork Strategy aims to accelerate the transition to a sustainable food system and contributes to the implementation of the EU strategy to reduce methane emissions. The Farm to Fork Strategy also highlights the importance of organic farming and introduces new "eco-schemes", allowing the CAP to encourage sustainable practices. However, recent academic studies criticise organic farming as a single solution to achieve the goal of sustainable EU agriculture [18,36] because the carbon footprint, emissions from manure management and enteric fermentation on organic farms are higher than on conventional farms [37]. Another concern is the utilisation of resources for the production of organic pork compared to conventional farming [36]. In fact, the EU sustainable pig farming system should find trade-offs between different farming practices and provide the best balance of contributions to human diets, energy issues, soil fertility management, climate change mitigation, etc.

In the EU, the regulation of GHGEs mainly targets large intensive pig farms. The Industrial Emissions Directive 2010/75/EU provides EU-wide rules to prevent or reduce emissions from industrial activities and targets large intensive pig-rearing farms with more than 2000 places for pigs over 30.0 kg or more than 750 places for sows. This Directive empowers reference documents with the best available technique conclusions that are periodically updated by the European Commission. Another important source of GHGEs, manure and its management, is covered by [38], which provides a detailed review on the related EU legislation. In fact, the EU legislation is mainly focused on the regulation of large pig farms, and the further improvement of the GHGE situation on farms with a lower pig number threshold that are not covered by the legislation could be considered. However, these actions must be carefully evaluated because the growing burden could exacerbate the situation and result in further structural changes in the social dimension.

4.2. Structural Change Patterns in the EU Pig Farming System

The research suggests that the pig farming development situation in MSs is not homogeneous. The cluster analysis identifies significant differences in evolution patterns of MSs during the investigated period, and this knowledge could be a start for an academic discussion on different research areas and measures applied for the selected groups of countries in order to increase the sustainability of EU agriculture.

Many countries that joined the EU before 2004 contribute to the completion of a highly concentrated EU pork market with a higher investment potential for innovative and sophisticated GHGE reduction technologies compared to MSs that joined later. The clustering confirms similar development patterns in pre-2004 MSs and assigns the dominant share of those countries to Clusters 1 and 4. Over the investigated period, the growth rates of the socioeconomic dimension in these clusters demonstrate moderate negative changes or even positive developments. These MSs developed strategies that allowed them to stay competitive, while environmental benefits were often driven by the needs of policies and society.

The study by [8] reports on the pork market specialisation in main producing countries. In fact, GHGE potential is partly related to farm specialisation and animal density in MSs. For example, Italian farmers specialise in the fattening of heavy pigs and generate higher levels of GHGEs compared to farms that produce lighter pigs [34], the dominant share of French farms specialise in breeder-fattening and fattening activities [39], pig farms in Denmark specialise in piglet breeding and mixed production, and Spanish farms across borders occupy a fattening niche, while Germany, Belgium, and The Netherlands have mixed production [8]. The aforementioned countries from Clusters 1 and 4 represent the significant share in the EU pig population structure, while a more detailed analysis of

EU pig farming specialisation is provided in [27]. Results imply that Clusters 1 and 4 include the main EU pig farming polluters; the reduction in GHGEs in these target groups could be a priority to make a desired contribution to the establishment of more sustainable EU agriculture. However, the aforementioned MSs demonstrate a slight increase in total GHGEs over the investigated period, while country specialisations suggest that GHGE mitigation actions must address differences in specialisation.

Most small farms with pigs are located in MSs that joined the EU during or after the main enlargement in 2004 [27]. These farms contribute to rural income diversification and food security, i.e., poverty reduction and rural vitality. EU enlargement accelerated structural changes in the national pig farming systems of these MSs and had a severe impact on sustainability. The conducted research shows that the evolution of national pig farming systems is in progress, and that the higher negative growth rates of the investigated indicators allow us to identify Clusters 2 and 3 as an umbrella for MS with remarkable structural changes. Cluster 2 merges countries that joined the EU in 2004 or later, with the exception of Finland and Greece, and the investigated period is characterised by a steep decline in socioeconomic indicators. In these MSs, the positive contribution to the environmental dimension is mainly explained by a sharp decline in pig population and—to some extent—by the implementation of new pig farming practices (manure management and utilisation, feed production, etc.). In some MSs, the changes in pig population genetics and housing types also had an impact on GHGEs.

4.3. GHGE Reduction Alternatives

A decline in the pig population, the improvement of feed production and management of the related supply chains, and changes in manure management and manure utilisation are the main directions of GHGE reduction in EU pig farming. The identified clusters could be linked to differences in GHGE reduction potential to implement those directions.

An important direction of the academic discourse on GHGE mitigation is the ***reduction of the livestock population*** [36,40], which allows GHGEs related to enteric fermentation, manure management, feed production, etc. to be reduced. Although the EU cattle population is responsible for the largest share of GHGEs in the livestock sector, some researchers recognise that national GHGE reduction goals cannot be achieved without pig population reduction (for example, see [41]). However, our analysis suggests that this alternative could bring tangible results only in a few MSs (for example, in Denmark, Spain, etc.). Indeed, the role of national pig farming in the EU livestock system is an important criterion for decision making.

In pre-2004 MSs, which rear more than 4/5 of the EU pig population, the indicator of live swine LSUs is slightly reduced; however, GHGEs demonstrate a modest growth during the period of 2010–2020. In fact, dramatic transformations of the socioeconomic dimensions in Cluster 2 and 3 leave the GHGE situation at the EU pig farming level without remarkable changes. According to [40], the promising direction of GHGE reduction is improved productivity, which allows the pig population and GHGEs to be reduced without compromising food security goals. Thus, the pork production productivity research niche is important to address the climate change mitigation challenge.

However, the decline in the pig population remains the fastest solution that could mainly target MSs from Clusters 1 and 4, instead of MSs with self-sufficiency problems, lower pig density, and the potential to reduce GHGEs, improving pig farming practices. Indeed, the decline in the pig population must be accompanied by a corresponding shift in society, thereby facilitating the transition towards a lower consumption of meat and the funding of research on innovative products for plant-based diets. The switch to plant-based diets requires changes in society and the economy; however, academic research suggests that system transformations meet resistance. The study by [42] argues that the employment of a social tipping point could accelerate changes in the social system. Thus, the specific academic focus on social norms, social contagion potential for plant-based innovations, and the identification of groups in society with similar characteristics could improve understanding of pork consumption and facilitate changes in the EU social system.

On the other hand, academic research on the impact of dietary change on the EU economic system is another important topic, because this switch will influence many economic activities that benefit from swine production and utilise by-products (for example, energy and fuel, fertiliser, food, cosmetics, pharmacy, etc.). The knowledge about the functioning of the EU economic system and the challenges that follow after the intervention is critical for decision making. Another crucial question is whether the decline in the pig population is the best option for GHGE reduction compared to other livestock sectors in individual MSs.

The improvement of animal feed production and management of the related supply chains could influence the sustainability of the EU pig farming system. The study by [17] argues that the EU pig farming has a higher global warming potential (CO_2e) compared to US pig farming due to dependence on imported soybeans from Brazil and Argentina, as these countries change land use and destroy forests in order to benefit from the situation. As feed represents about 70.0% of production costs [35], the development of financially attractive short feed supply chains could solve two important problems, namely reduce the reliance on imported protein and reduce GHGEs. The most recent academic studies deal with the aforementioned research niche. For example, the study by [43] demonstrates that the switch to the local legume-supported rotations and the utilisation of legumes in pig feed could improve economic performance and bring environmental benefits, including contributing to climate change mitigation. The study by [44] compares local and imported protein sources and concludes that local feed can reduce the carbon footprint. This research niche requires additional attention at both national and EU levels because feed production is an important integral element of sustainable pig farming systems. Feed is a particularly sensitive survival matter in many MSs from Clusters 2 and 3, and feed supply chain failures strongly affect the socioeconomic dimension. However, changes of feed supply chains in Clusters 1 and 4 could result in tangible evidence of GHGE reductions and influence the global competitiveness of EU producers.

Another vital direction of action is pig diets. Research suggests that precision feeding has the potential for the development of more sustainable systems [28]. Optimal feed composition (especially nitrogen content), smart protein use, and special feed additives could improve the absorption of nutrients by animals and reduce GHGEs [16]. In this context, pig farm specialisation introduces important differences. For example, the longer fattening cycle of heavy pigs produced in accordance with Protected Designations of Origin and Protected Geographical Indications labels results in a decrease in feed conversion, growing excretions, and an increase in GHGEs during the last fattening stage. The authors of [34] argue that GHGE mitigation strategies for heavy pigs could be linked to the improvement of reproduction performance by sow, orientation towards local feed production, and the improvement of pig diets, as well as the revision of legislation that introduces limitations to environmental impact mitigation. The study by [40] examined the different effects of protein change in pig diets on GHGE reduction potential of pig breeding and fattening farms. Thus, the understanding of the impact of pig diets on GHGEs empowers a wide academic research niche. Although the GHGE reduction aspect is critical, pig diets in sustainable agricultural systems must take into consideration the challenge of manure quality, because this animal by-product becomes an important resource in the EU circular economy.

The third important direction of GHGE reduction is ***manure management and utilisation***. In 2020, GHGEs from the enteric fermentation of swine represented only 16.57%, while GHGEs from swine manure management exceeded 4/5 of the GHGE structure in the EU. This proportion suggests that academic research on GHGE reduction from manure management and circular climate neutral manure utilisation systems is critical because this niche targets the main source of GHGEs from live swine.

In many MSs, the GHGE reduction effect was driven by legislation that forced the renewal of housing and manure storage systems. This direction has the potential for the further improvement. Many academic studies review manure and slurry management practices, as well as the main technological and hygienic methods applied [16,36,45–47], and identify the list of appropriate alternatives. However, the identified list of best practices is not exhaustive, while the successful control and reduction in GHGEs depend on many factors. For example, academic research highlights the role of animal genetics [48], age and weight [16,34], activity and density [16,42], climate characteristics and season [16,45], building characteristics, including equipment, such as ventilation [16,49], frequency of manure/slurry removal from buildings [39,50], storage practices [46], emissions that depend on the particular manure utilisation techniques [15,46,51], etc. In fact, the GHGE potential in MSs depends on the multi-choice options on farms, and research that covers the aforementioned aspects and assists in the selection of the most effective and economically viable GHGE reduction alternatives remains critical for the development of sustainable pig farming systems.

The EU circular and biobased economy turns pig manure and slurry into a valuable raw material that could provide new products, while the process of utilization could ensure an even greater reduction in GHGEs. However, most of the manure management technologies are cost-ineffective and land-spreading often remains the selected alternative [35,39]. Indeed, current EU challenges imply two main manure utilisation directions for dealing with dependence on raw materials for the production of fertilisers and energy. The switch from mineral to organic fertilisers reduces the dependence of EU agriculture on imported phosphorous and has a positive impact on important soil characteristics in the long run. The deterioration of trade relations with the Russian Federation has become a strong stimulus for the development of renewable energy infrastructure to ensure energy security in the EU.

In fact, during recent decades, academic research benefited from EU funding, aiming to create and disseminate knowledge about technologically and economically viable multi-product circular systems for pig manure utilisation, allowing GHGEs to be reduced and resource availability problems to be solved. Framework Programmes, Horizon 2020, and Life Programme funded over 50 projects that deal with pig manure utilisation issues. The analysis of these projects shows that most of the projects were aiming at technology development and provided a contribution to demonstration goals. However, this funding was mainly absorbed by countries that joined the EU before 2004, while the Life Programme was dominated by coordinators from Spain. The most recent projects included Poland; however, the participation of other MSs that joined in 2004 and later was rather accidental and included only a few MSs.

Although this situation implies that funding was directed to the relevant target group and contributed to GHGE reduction in the main producing countries, our results suggest that the evolution of pig farming systems in Clusters 2 and 3 results in average farm size growth, and knowledge transfer from the main producing countries must be an important element of climate change mitigation actions. In fact, the most recent "MANEV" and "SYSTEMIC" projects could react to this challenge. For example, the "MANEV" project assists with the evaluation of the main pig manure treatment technologies and develops a decision support and planning tool, helping to design an efficient manure management system adapted to situations on farm [52]. The project "SYSTEMIC" offers the NUTRICAS tool for biogas plant owners that allows farmers to consider alternative technology cascades and nutrient recovery products, as well as estimate possible investment costs [53]. However, those projects limit result dissemination excluding partners from MSs that joined in 2004 and later, with the exception of Poland.

Another group of projects contributes to the development of particular technologies or circular systems that could be adapted on farms for pig manure utilisation. This research and experimental development niche could be illustrated by the following examples: the project "Pocket Power" investigates the challenges of the small-scale anaerobic digestion of pig manure [54,55]; the project "METHATRAC" combines the TRAC scraping process with anaerobic digestion to produce biogas and fertilizers from municipal sewage, pig manure, and slaughterhouse waste [56]; while the project "DEPURGEN" proposes an alternative to anaerobic digestion and introduces a system that produces fertiliser and pellets from manure and pine wood [57]. This group of projects also mainly targets the main polluters and covers the main producing countries from Clusters 1 and 4, including Poland. Therefore, MSs that face ongoing structural changes of pig farming systems could be a prospective research niche and a specific challenge that requires academic discussion on the role of pig farming in circular, resilient, and sustainable agriculture, as well as actions allowing changes to be directed towards the desired purpose.

5. Conclusions

During the period of 2010–2020, EU pig farming survived a significant decline in the number of holdings with pigs. This process went in line with the development patterns in the livestock sector; however, the shrinking of the holdings with pigs had a higher negative growth rate compared to the EU holdings with livestock. The shift-share analysis suggests that the pace of LSUs decline in the EU livestock system was higher than in EU farms with pigs. These changes did not cause the corresponding improvement in the GHGE situation. The GHGE structure of livestock implies that tangible results could be achieved focusing on cattle and dairy farms, while even the substantial GHGEs decline in pig farming results in a moderate change in the structure, as the contribution of enteric fermentation and the related manure management from live swine is slightly above a tenth of GHGEs from livestock.

The cluster analysis identifies differences in evolution patterns of pig farming in MSs. Clusters 1 and 4 cover pre-2004 MSs, with the exception of Finland and Greece, which demonstrate less dramatic changes in the socioeconomic dimension, as well as modest contributions to GHGE situation improvement or even growing GHGEs. These clusters include MSs that represent over 4/5 of the EU pig population and generate over 3/4 of EU's GHGEs from live swine. Although Clusters 2 and 3 survived major structural changes in national pig farming systems during the period of 2010–2020, the improvement of the GHGE situation in this group due to a shrinking pig population was compensated by the overall GHGE growth in MSs from Clusters 1 and 4.

The research identifies a reduction in pig population, an improvement in feed production and the development of related supply chains, and changes in manure management and utilisation as the main directions of GHGE reduction in the EU pig farming. The identified clusters could be related to different GHGE reduction potentials while applying the aforementioned measures and mapping important research niches to improve the situation. However, the focus on Clusters 1 and 4 allows the main polluters to be addressed. The ongoing transformation of MSs that joined the EU in 2004 and later introduces the target group with specific needs and a space for actions that could contribute to the emergence of more sustainable pig farming systems in the EU. It is recommended to develop and support actions that focus on GHGE reduction from swine manure and to contribute to the establishment of a circular economy in the EU.

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