Article

GHG and NH₃ Emissions vs. Energy Efficiency of Maize Production Technology: Evidence from Polish Farms; a Further Study

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Abstract: The paper determines the effect of selected cultivation technologies, including production chain energy inputs (growing, harvest, heap forming) on greenhouse gas emissions (GHGs) to the atmosphere. The data for the study was collected from 13 actually operating family farms ranging in size from 2 to 13 ha, located in the Podlaskie voivodship (Poland). GHG and ammonia (NH₃) emissions from natural and mineral fertilisation as well as GHGs from energy carriers in a form of fuels (ON) were estimated. The average GHG emissions from the sources analysed were 1848.030 kg·CO₂eq·ha^{−1} and 29.492 kg·CO₂eq·t^{−1} of the green forage yield. The average NH₃ emissions per hectare were 15,261.808 kg NH₃ and 248.871 kg NH₃·t^{−1} of yield. The strongest impact on the environment, due to the GHG emissions to the atmosphere, thus contributing to the greenhouse effect, is due nitrogen fertilisation, both mineral and natural. On average, in the technologies under study, 61% of the total GHG emissions came from fertilisation. The GHG emissions were correlated with the energy efficiency, calculated at the previous research stage, of the production technologies applied. There is a negative correlation ($r = -0.80$) between the features studied, which means that the higher the energy efficiency of the silage maize plantations, the lower the air pollution emissions in a form of the GHGs from the sources under study. It is so important to prevent environmental degradation to continue, conduct in-depth, interdisciplinary research on reducing the energy consumption of crop production technologies and striving to increase energy efficiency.

Keywords: GHG emission; NH₃ emission; crop production; fertilization; fuel consumption; climate change

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1. Introduction

Despite the different sites, as for the climate change, actions are being taken to decrease the greenhouse gas (GHG) emissions from agriculture and to stabilize their concentration in the atmosphere. To accomplish those goals, interdisciplinary research and the close cooperation of agronomists, soil scientists, ecologists and environmental authorities is indispensable. With the advancement of Poland's socioeconomic development, the importance of the energy economy is also increasing in agriculture. The march of civilisation, scientific and technological advancement as well as the resulting economic development have been responsible for an ongoing increase in the consumption of electricity and fuels transported globally. Increases in the pollution concentration ultimately degrade the environment (soil, air and water). To prevent the consequences of these climate change-related phenomena, it is necessary to quickly reduce global emissions of greenhouse gases, of which the world emits about 50 billion tons every year, measured in carbon dioxide equivalents (CO₂eq) [1]. The most onerous air pollutants which come from agriculture are ammonia, nitrous oxide,

nitrogen oxides, methane, carbon dioxide, odours and particulates [2]. As reported by the International Energy Agency (IEA) [3], the present energy system is mostly based on energy obtained from conventional sources. According to the report by the Energy Information Administration (EIA) [4], by 2040 the global energy consumption will have increased by 56%, which will result in a corresponding 46% increase in global CO₂ emissions. An increase in the energy intensity technology is correlated with a decrease in greenhouse gas emissions [5,6]. It was estimated that the agriculture sector in the European Union (EU) accounts for 10% of the total greenhouse gas emissions of the EU (Figure 1) [7].

Figure 1. Contribution of agriculture to total GHG emissions (%), EU-28, 2015 [7].

The Commission's Communication to the European Parliament presents GHG emission reductions under current policies (red line in the chart) and reduction options and forecasts of GHG emission reductions in the European Union by 2050, by sector, also from agriculture (Figure 2).

At the same time there are considered threats to the natural environment resulting from the application of conventional fuels and the issues of respecting the environment and the actions are taken to promote the production of energy from renewable sources. In fear of a competition between a production of energy crops and food crops [8], the biomass production effectiveness, the crops in the areas not covered by agricultural use [9], an increase in the use of by-products for energy purposes, e.g., to reduce the greenhouse gas emissions, are gaining importance [10].

Figure 2. The course of reducing greenhouse gas emissions in the EU by 2050 (1990 = 100%) [11].

Emissions reduction due to agricultural biogas production is not only an effect of limiting the emissions during storage and applying organic fertilisers but also of replacing some energy from conventional fuels by increasing recycling and reusing the resources contributes to “closing the cycle” in the product life cycle, which will be beneficial both for the environment and for the economy [12–16]. Maximising the use of materials, products and waste enhances energy saving and greenhouse gas emissions reduction [17].

The EU Renewable Energy Directive (RED) provides guidelines for sustainable development criteria systems and increasing the use of biofuels through sustainable production [18–20]. One of the requirements for biofuels to be considered sustainable is that they must also reduce the greenhouse gas emissions at least by 50%, as compared with fossil fuels [17]. For reporting purposes, there are national inventories of pollution emissions introduced to the atmosphere which, in international terms, are a set of data on the annual emissions of respective substances in the country. As for CO₂, the inventory, next to emissions, also considers carbon absorption by forest biomass. The process of emissions inventory development and reporting is specified by international agreements. One of the essential features of the inventory development methodology is the principle of calculating data for the entire time series if new information is acquired or if new emissions inventory methodology is applied; emissions inventories are subject to regular updating. Direct emissions of N₂O direct-N are calculated with the use of the coefficients recommended by the IPCC provided for in “Guidelines for National Greenhouse Gas Inventories” [21–23]. In Poland, the National Centre for Emissions Management (KOBiZE) of the Institute of Environmental Protection—the National Research Institute is a body responsible for annual emissions calculations, a national greenhouse gas inventory development and for reporting for the international climate convention, to perform the obligations to the European Union, compliant with the Greenhouse Gas and Other Substance Emissions Management System Act of 17 July 2009 (Journal of Law No 130, item 1070 with further amendments) [24]. Greenhouse gases, CO₂, CH₄, N₂O, HFCs, PFCs, SF₆, the annual reporting, as Poland’s obligations under the United Nations Framework Convention on Climate Changes (UNFCCC), and for the purpose of the domestic statistics and to satisfy the requirements of the European Union [25].

The pollution emissions are related to various areas and forms of human activity, mostly industrial activity. The chemical compounds reaching the atmosphere undergo many changes, react with other compounds, which sometimes leads to a production of new chemical compounds the negative impact of which on the environment is sometimes greater than the harmfulness of the initial pollution.

CO_2 , CH_4 and N_2O are gases contributing to the greenhouse effect by absorbing infrared radiation, and basically retaining heat in the atmosphere. A growing concentration of those gases in the atmosphere is mostly due to fossil fuel burning, the processes of industrialization and to land use changes. This is due to more and more intensive arable land cultivation and deforestation; over 90% of emissions resulting from a change in land use. Of the nitrogen oxides which occur at various levels of oxidation— N_2O , NO , N_2O_3 , NO_2 —the most-and-the-longest-persisting-in-the-atmosphere is N_2O . All those factors result in an increase in the GHGs concentration and they are some of the more considerable causes of anthropogenic climate changes. Just like in other sectors of the economy, also in agriculture, especially in plant production, new technological solutions are searched for to limit the greenhouse gas and ammonia (NH_3) emissions without limiting the amount and deteriorating the quality of the yields [26]. Economic losses and nitrogen pollution of common water resources and the atmospheric air due to nitrates leaching below the root zone of crops and gas emissions, NH_3 and N_2O , can be prevented, e.g., by applying slow-release fertilisers and inhibitors [27,28].

Since 2016 reporting on the pollution emissions produced in the chain of production of substrates of agricultural origin (biomass) for energy use has been also an obligation of the agricultural sector [29]. All the entities which take part in a biocomponent or biofuel production chain are obliged to present an estimate of emissions, and the entity introducing the biofuel on the end market—the estimate of emissions and their reduction. Each successive agricultural material processing entity, next to the estimates of the emissions produced during their technological processes, must consider the emissions produced in agricultural production. The European Union requirements in terms of the level of reducing GHGs thanks to the use of biofuels and the conditions to be met by the source of materials for biofuel production as well as promoting the use of energy from renewable sources while, at the same time, ensuring environmental-friendliness, are provided for in, e.g., Directives 2009/28/EC [17] and 2009/30/EC [30].

A partial demand for biomass for energy purposes can be met by growing maize, a crop which is especially applicable for the use in the biogas plant. It shows, e.g., high green mass yields per area unit, a high yield of biogas and good ensiling properties [31,32]. In Poland, in the field harvest structure of fodder crops, maize accounts for the biggest planted acreage, representing more than 60% of the total fodder crops acreage [33]. Maize cultivation requires, however, high energy inputs; hence a need of studies on how to enhance the production energy efficiency and how to reduce the resulting GHG emissions. Through the adequate, optimal and adapted-to-the-requirements-of-the-farm selection of machinery and tools, a selection of machinery and tools can affect the energy intensity of respective processes in the production chain and enhancing the agrotechnical practices can affect GHG emissions to the atmosphere [34,35]. The climate change forecasts have and will still have a high impact on plant growing conditions [36,37]. Maize must be considered a species which, thanks to its physiology, can easily adapt to unfavourable climate changes and which will use the effects of those transformations well [38]. It is expected that in Central Europe, also in Poland, an increase in maize yields will account for 14% [39]. Faber et al. [40] report on climate changes being capable of increasing the maize yields in Poland from 6 to 43% and on nitrogen efficiency in maize increasing from 2 to 17%. Nitrogen efficiency enhancement can limit unproductive nitrogen losses from the fertilisers applied, which can make the climate changes even greater due to nitrous oxide (N_2O) and ammonia (NH_3) emissions to the atmosphere and pollution of waters with nitrates [41,42]. The aim of the research was to identify the optimal technological variant in terms of greenhouse gas emissions, the amount of which is closely correlated with energy efficiency.

2. Methods

Table 1 provides information on the sources of emissions and the kinds of pollution, emitted to the atmosphere, covered by the analyses.

Table 1. Sources of emissions and types of pollutants emitted to the atmosphere.

Source of the Emission	Type of Contamination Greenhouse Gases GHG			NH ₃
	N ₂ O	CO ₂	CH ₄	
Natural fertilizers	+			+
Inorganic fertilizers, including urea	+	+		+
Fuel consumption	+	+	+	

With the IPCC guidelines [21], the reports by KOBIZE [25,43,44] and EMEP/EEA 2016 [45], a pollution estimation methodology has been developed.

2.1. Emissions of N₂O and CO₂ from the Use of Natural and Inorganic Fertilisers

The calculations of N₂O direct emissions from the application of natural fertilisers of animal origin, cattle and swine manure and slurry, as well as artificial nitrogen fertilisers were performed using the IPCC methodology [21]:

$$EN_{2O\text{Direct-N}} = E_{SN} + E_{NN}$$

where $EN_{2O\text{Direct-N}}$ —direct emissions from soil, from fertilisers [$\text{kg}\cdot\text{ha}^{-1}$, $\text{kg}\cdot\text{t}^{-1}$ yield], E_{SN} —emissions from the artificial nitrogen fertilisers applied [$\text{kg}\cdot\text{ha}^{-1}$, $\text{kg}\cdot\text{t}^{-1}$ yield],

E_{NN} —emissions from the natural fertilisers of animal origin provided to soil [$\text{kg}\cdot\text{ha}^{-1}$, $\text{kg}\cdot\text{t}^{-1}$ yield].

The amount ($\text{kg N}_2\text{O-N/kg}$) of N supplied with fertilisers was multiplied by 44/28 to estimate the emissions of N₂O from the nitrogen supplied with the fertilisers applied [45].

Drawing on the IPCC methodology [21], a formula has been developed from which the CO₂ emissions were estimated from the application of urea:

$$CO_2 - C_{\text{Emission}} = U \cdot EF_U$$

where $CO_2 - C_{\text{Emission}}$ —emissions of C from urea application [$\text{kg}\cdot\text{ha}^{-1}$, $\text{kg}\cdot\text{t}^{-1}$ yield], U —amount of urea [$\text{kg}\cdot\text{ha}^{-1}$] and EF_U —emissions factor for urea = 0.2 [21].

To convert $CO_2 - C$ emissions into CO₂ emissions, the result must be multiplied by 44/12.

2.2. Emissions of N₂O, CO₂ and CH₄ from the Fuel Consumption

In the technologies analysed, GHG (CO₂, CH₄ and N₂O) emissions produced from diesel oil consumption in tractor and agricultural machinery engines were estimated. The real time of tractor or machinery engagement, next to the productive operation time, also consists of the time required to perform the actions related to their operation, e.g., returns, adjustments, as well as the time not directly allocated to the performance of the treatment, e.g., technical operation, the time of passes; a drive from the tractor, machinery or combined cultivator garaging place to the field [46,47].

The calculations were made based on the following formulae which applied the values of emissions factor of the gases [48]:

$$\text{Emissions } CO_2P = Zp \cdot EF_{ON}CO_2P$$

$$\text{Emissions } CH_4 = Zp \cdot EF_{ON}CH_4$$

$$\text{Emissions } N_2O = Zp \cdot EF_{ON}N_2O$$

where Zp —fuel consumption [kg], $EF_{ON}CO_2P$ —potential emissions factor for CO₂ = 3.170 [$\text{g}\cdot\text{kg}^{-1}\text{ON}$], $EF_{ON}CH_4$ —emissions factor for CH₄ = 0.19 [$\text{g}\cdot\text{kg}^{-1}\text{ON}$] and $EF_{ON}N_2O$ —emissions factor for N₂O = 0.16 [$\text{g}\cdot\text{kg}^{-1}\text{ON}$].

To convert the amount of the fuel consumed in dm³ into kg, compliant with Journal of Law 2018 Item 2527 [49], the following conversion factor was used: 1 dm³ ON = 0.84 kg.

The emissions of respective GHGs (N₂O, CO₂, CH₄) from the sources under study were converted, compliant with the global warming potential (Table 2), into equivalent unit CO₂eq, created to facilitate a comparison of the emissions of those gases [50]. The global warming potential expresses the number of kilograms of coal which, over 100 years, gives the same effect of global warming as 1 kg of the greenhouse gas analysed.

Table 2. Global warming potential ¹.

	Counter for CO ₂ Equivalent
CO ₂	1
N ₂ O	298
CH ₄	25

¹ IPCC 2007 [50].

2.3. Emission of NH₃

According to the current EMEP/EEA guidelines (2016) [45], to estimate the emissions of NH₃, one can apply the Tier 1 method or a more accurate one, Tier 2. Tier 1 is the simplest method for estimating the emissions of ammonia from inorganic fertilisers, where the emissions factor for EF(NH₃) has a fixed value of 0.05 kg NH₃ per kilogram of N in the inorganic fertiliser applied, irrespective of the kind of the fertiliser. The study involved the use of a more accurate methodology, Tier 2, where the values of the emissions factor depend on the fertiliser type, soil pH, and on specific climate conditions. The analyses use the factor (Table 3) compliant with the EMEP/EEA guidelines (2016) [45] for the soils with pH below 7, found for about 80% of the soils of Poland, for the temperate climate zone.

Table 3. N content and emissions factor for NH₃ for selected inorganic fertilisers ¹.

Type/Name of the Fertilizer	N Content [%]	The Emission Factor EF		
		N ₂ O-N	CO ₂ -C	NH ₃ [g NH ₃ ·kg N ⁻¹]
Ammonium sulphate	34	0.01		16
Ammonium phosphate	18	0.01		51
Ammonium sulfate	21	0.01		92
Calcium nitrate	15	0.01		8
Urea	46	0.01	0.2	159
Compound fertilizers (NPK)		0.01		67

¹ Own study based on EMEP/EEA 2016, 3.D Crop production and agricultural soils [45]; Intergovernmental Panel on Climate Change 2006 [21], data of fertilizer manufacturers.

To convert NH₃-N emissions into NH₃ emissions, the result must be multiplied by 17/14. Drawing on the assumptions made from the data reported in literature and the data declared by the manufacturers with the nitrogen content in the fertilisers applied, a formula has been developed for the estimate of NH₃ emissions from the application of mineral nitrogen fertilisers:

$$\text{Emissions NH}_3 = A_N \cdot \text{EF} \cdot 17/14$$

where A_N—nitrogen rate (N) in the fertiliser applied [kg]; compliant with the percentage composition of the fertilisers provided by the manufacturer (Table 3) and EF—emissions factor for respective fertilisers containing nitrogen [g NH₃·kg N⁻¹ in fertiliser] (Table 3).

To convert NH₃-N emissions into NH₃ emissions, the result must be multiplied by 17/14.

The emissions of ammonia (NH_3) were estimated from the application of natural fertilisers: cattle and swine slurry and manure.

The calculations of the emissions of NH_3 from slurry were made with the formula:

$$\text{NH}_3 \text{ emission} = A_G \cdot kN_G \cdot EF_G \cdot 17/14$$

where A_G —slurry rate [kg], kN_G —content of N in slurry [%] (Table 4), EF_G —emissions factor [$\text{g NH}_3 \cdot \text{kg N}^{-1}$] (Table 4). To convert $\text{NH}_3\text{-N}$ emissions into NH_3 emissions, the result must be multiplied by 17/14.

Table 4. N content in respective kinds of natural fertilisers ¹.

Type/Name of the Fertilizer	N Content [%]	The Emission Factor EF [$\text{g NH}_3 \cdot \text{kg N}^{-1}$]
Cattle manure	0.318	0.2500
Manure-pigs	0.352	0.7000
Cattle slurry	0.383	0.1892
Slurry-pigs	0.373	0.5355

¹ Own study based on Journal of Laws, Journal Of Laws, item 1339 of 12 July 2018 [51].

NH_3 emissions produced as a result of cattle and swine manure application were estimated from the formula:

$$\text{NH}_3 \text{ emissions} = A_O \cdot kN_O \cdot EF_O \cdot 17/14$$

where A_O —manure rate [kg], kN_O —content of N in manure [%] (Table 4), and EF_O —emissions factor [$\text{g NH}_3 \cdot \text{kg N}^{-1}$] (Table 4).

To convert $\text{NH}_3\text{-N}$ emissions into NH_3 emissions, the result must be multiplied by 17/14.

2.4. Scope of Research

The study was performed using the data from the farms located in the Podlaskie voivodship, in the south-eastern part of Poland (Figure 3). The region's climate is temperate with a clear continental climate impact. In the Podlaskie voivodship, the average annual temperature is about +7 °C. The warmest month is July; the average daily temperature is +18 °C, and the coldest one—January; the average daily temperature −4.5 °C. The annual precipitation ranges from 550 to 580 mm.

It is a region dominated by agriculture, the key economic sector. The analyses were made for 13 silage maize cultivation technologies, referred to as MS1-MS13. The variety (FAO to 240) was adapted to the climate of the Podlaskie voivodship. The data for the research was taken from the technological charts. The plantation acreage ranged from 2 (MS2, MS7) to 13 (MS3) ha. The fields were 0.05 (MS2) to 2.5 (MS7, MS8) km away from the farm. The amount of the diesel oil consumed on agricultural plantations is also affected by the working conditions, especially the soil type and condition, the landform, field acreage and shape [52]. The yields fell within the range from 45 (MS13) to 80 (MS6) $\text{t} \cdot \text{ha}^{-1}$.

The variants selected differed in terms of the type and the amount of the fertilisation applied; natural (cattle and swine manure and cattle and swine slurry) and mineral (POLIFOSKA® 8-24-24, 6-20-30, 4-12-32, ammonium nitrate, ammonium phosphate, urea). With the amount of nitrogen and carbon supplied with fertilisers calculated, there were estimated the emissions of respective greenhouse gases (N_2O and CO_2) and ammonia (NH_3) as well as the emissions of GHGs (N_2O , CO_2 , CH_4) from fuel (diesel oil) consumed by tractor and machinery engines.

Figure 3. Podlaskie voivodship [53].

3. Results

With the assumptions made, the information on the yield, the amount of fuel consumed and the calculation results for the amount of nitrogen supplied with fertilisers, calculated for the respective fertilisers, the amount of GHG and NH_3 emissions for the silage maize production technologies were estimated. The silage maize production variants differed in terms of the type and the amount of the fertilisation applied. In 12 out of 13 cultivation variants, natural fertilisation was applied; in seven cases it was cattle manure and/or slurry (MS1–5, MS12–13), in five variants—pig manure and/or slurry (MS6, MS8–11). Technology MS7 involved the use of mineral fertilisation, while in MS13—natural fertilisation only. Together with the manure and slurry fertilisers, the plantations were supplied with 0.0 (MS7) to 207.6 $\text{kg N}\cdot\text{ha}^{-1}$ (MS1). The mineral fertilisation provided 0 (MS13) to 181.0 $\text{kg N}\cdot\text{ha}^{-1}$ (MS3) (Table 5). As converted into a pure component, the average N rate from natural fertilisers was 115.5 $\text{kg N}\cdot\text{ha}^{-1}$, and from mineral fertilisers—104.0 $\text{kg N}\cdot\text{ha}^{-1}$. The average total N rate per hectare was 219.4 $\text{kg N}\cdot\text{ha}^{-1}$.

Table 5. Selected technology-specific elements.

Technology No.	Cultivation Area [ha]	Distance from the Farm [km]	Yield [$\text{t}\cdot\text{ha}^{-1}$]	N Content [%]	The Amount of N from Fertilizers [$\text{kg}\cdot\text{ha}^{-1}$]		
					Natural	Mineral	Total
MS1	3.4	0.8	72	323.5	207.6	173.0	380.6
MS2	2	0.05	60	184.5	174.0	131.4	305.4
MS3	13	1.5	50	152.9	112.0	181.0	293.0
MS4	5.07	0.5	55	147.5	132.5	79.5	212.1
MS5	3.25	0.6	65	255.0	94.6	114.6	209.2
MS6	4.5	1	80	116.2	76.0	148.4	224.4
MS7	2	2.5	50	120.0	0	138.0	138.0
MS8	3.5	2.5	70	414.9	156.8	75.6	232.4
MS9	10	2.2	67	388.5	140.0	78.2	218.2
MS10	5	1.6	75	425.6	122.5	75.4	197.9
MS11	8	2.2	75	369.0	122.5	75.4	197.9
MS12	5	1	50	379.4	122.9	81.0	203.9
MS13	3.21	1.5	45	128.9	39.9	0	39.9

The GHG and NH₃ emissions for respective silage maize production technologies were referred to an area unit; hectare (Table 6) and to the yield unit; tonne (Table 7).

Table 8 provided the estimates of GHG and NH₃ emissions [kg] released to the atmosphere as a result of the application of inorganic and organic fertilisers and fuel consumption per area unit [ha]. The amounts of pollution released in a form of GHGs ranged from 535.677 (technology MS13) to 2657.868 kg·CO₂eq·ha^{−1} (technology MS1). The average emissions of those gases per hectare for the 13 technologies was 1848.030 kg·CO₂eq·ha^{−1}. As for the emissions of ammonia (NH₃), the lowest amount was released in technology MS13—0.012 kg NH₃·ha^{−1}, where nitrogen is supplied only in a form of natural fertilisers. The highest amount of ammonia (NH₃) per hectare was emitted in technology MS3—32,711.677 kg NH₃. The average NH₃ emissions per hectare for all the 13 technologies was 15,261.808 kg NH₃·ha^{−1} (Table 6).

For the silage maize production technology variants, there was specified a percentage value of emissions from respective sources (Table 7). The analyses were made separately for GHGs and NH₃. Assuming the emissions of GHGs from fertilisation and diesel oil consumption as 100%, the emissions from fertilisers accounted for 34.9% (MS13) to 79.8% (MS6). On average, the emissions from that source accounted for 61.1% of the total GHG emissions.

Table 6. GHG and NH₃ emissions for the technologies under study per area unit (ha).

Technology No.	Emissions							
	GHG [kg CO ₂ eq·ha ^{−1}]					NH ₃ [kg NH ₃ ·ha ^{−1}]		
	Fertilizers			ON Combustion	Total	The Amount of N from Fertilizers [kg·ha ^{−1}]		
	Natural	Mineral	Total			Natural	Mineral	Total
MS1	972.106	810.134	1782.240	875.627	2657.868	0.059	3856.571	3856.630
MS2	814.817	725.327	1540.145	499.412	2039.557	0.048	15,741.879	15,741.926
MS3	524.480	1104.264	1628.744	413.930	2042.674	0.034	32,711.643	32,711.677
MS4	620.686	372.412	993.098	399.353	1392.451	0.040	6470.059	6470.099
MS5	442.782	719.641	1162.423	690.245	1852.667	0.025	22,134.897	22,134.921
MS6	355.897	885.603	1241.500	314.595	1556.095	0.049	25,434.429	25,434.478
MS7	0	866.234	866.234	324.821	1191.055	0	26,643.857	26,643.857
MS8	734.272	474.366	1208.638	1122.952	2331.591	0.123	14,590.684	14,590.807
MS9	655.600	490.866	1146.466	1051.518	2197.985	0.119	15,098.186	15,098.305
MS10	573.650	473.541	1047.191	1152.032	2199.223	0.104	14,565.309	14,565.413
MS11	573.650	473.541	1047.191	998.824	2046.016	0.104	14,565.309	14,565.413
MS12	575.322	379.311	954.634	1026.898	1981.532	0.033	6589.929	6589.962
MS13	186.731	0	186.731	348.946	535.677	0.012	0	0.012
Min	0	0	186.731	314.595	535.677	0	0	0.012
Max	972.106	1104.264	182.240	1152.032	2657.868	0.123	32,711.643	32,711.677
Mean	540.769	598.096	1138.864	709.166	1848.030	0.058	15,261.750	15,261.808
Standard deviation	555.344	572.851	1128.196	372.420	1500.615	0.033	2727.008	2727.041

Table 7. Percentage share of GHG and NH₃ emissions from the sources studied in the total emissions.

Technology No.	Emissions [%]								
	GHG						NH3		
	Fertilizers			Fertilizers	ON Combustion	Total	Fertilizers		
	Natural	Mineral	Total				Natural	Mineral	Total
MS1	54.5	45.5	100	67.1	32.9	100	0.002	99.998	100
MS2	52.9	47.1	100	75.5	24.5	100	0	100	100
MS3	32.2	67.8	100	79.7	20.3	100	0	100	100
MS4	62.5	37.5	100	71.3	28.7	100	0.001	99.999	100
MS5	38.1	61.9	100	62.7	37.3	100	0	100	100
MS6	28.7	71.3	100	79.8	20.2	100	0	100	100
MS7	0	100	100	72.7	27.3	100	0	100	100
MS8	60.8	39.2	100	51.8	48.2	100	0.001	99.999	100
MS9	57.2	42.8	100	52.2	47.8	100	0.001	99.999	100
MS10	54.8	45.2	100	47.6	52.4	100	0.001	99.999	100
MS11	54.8	45.2	100	51.2	48.8	100	0.001	99.999	100
MS12	60.3	39.7	100	48.2	51.8	100	0.001	99.999	100
MS13	100	0	100	34.9	65.1	100	100	0	100
Min	0	0		34.9	20.2		0	0	
Max	100	100		79.8	65.1		100	100	
Mean	50.5	49.5		61.1	38.9		7.693	92.307	

Table 8. GHG and NH₃ emissions for respective technologies per yield unit (t).

Technology No.	Emissions							
	GHG [kg CO ₂ eq·t ⁻¹ of Yield]					NH ₃ [kg NH ₃ ·t ⁻¹ of Yield]		
	Fertilizers			ON Combustion	Total	Fertilizers		
	Natural	Mineral	Total			Natural	Mineral	Total
MS1	13.547	11.289	24.836	12.202	37.038	0.001	53.743	53.743
MS2	13.580	12.089	25.669	8.324	33.993	0.001	262.365	262.365
MS3	10.490	22.085	32.575	8.279	40.853	0.001	654.233	654.234
MS4	11.285	6.771	18.056	7.261	25.317	0.001	117.637	117.638
MS5	6.852	11.137	17.989	10.682	28.670	0	342.539	342.540
MS6	4.449	11.070	15.519	3.932	19.451	0.001	317.930	317.931
MS7	0	17.325	17.325	6.496	23.821	0	532.877	532.877
MS8	10.490	6.777	17.266	16.042	33.308	0.002	208.438	208.440
MS9	9.785	7.326	17.111	15.694	32.806	0.002	225.346	225.348
MS10	7.649	6.314	13.963	15.360	29.323	0.001	194.204	194.206
MS11	7.649	6.314	13.963	13.318	27.280	0.001	194.204	194.206
MS12	11.506	7.586	19.093	20.538	39.631	0.001	131.799	131.799
MS13	4.150	0	4.150	7.754	11.904	0	0	0
Min	0	0	4.150	3.932	11.904	0	0	0
Max	13.580	22.085	32.575	20.538	40.853	0.002	654.233	654.234
Mean	8.572	9.699	18.270	11.222	29.492	0.001	248.870	248.871
Standard deviation	6.645	7.983	14.628	3.145	17.773	0.000	38.002	38.002

In the technologies under study, the key source of ammonia emissions were mineral fertilisers, the emissions accounted for 92% of NH_3 emissions in total (Table 7).

The amounts of the GHG and NH_3 emissions were also referred 1 tonne of silage maize produced. Producing 1 tonne of the yield resulted in the GHG emissions from 11.904 (MS13) to 40.853 $\text{kg CO}_2\text{eq}$ (MS3). The fertiliser GHG emissions ranged from 4.150 (MS13) to 32.575 $\text{kg CO}_2\text{eq}\cdot\text{t}^{-1}$ (MS3), and the average value for the 13 technologies was 18.270 $\text{kg CO}_2\text{eq}\cdot\text{t}^{-1}$ of the yield. ON burning produced 3.932 (MS6) to 20.538 (MS12) $\text{kg CO}_2\text{eq}\cdot\text{t}^{-1}$ of the yield; on average fuel consumption for the production of 1 t of the yield resulted in 11.222 $\text{kg CO}_2\text{eq}\cdot\text{t}^{-1}$. The average emissions of ammonia (NH_3) per tonne of the yield amounted to 248.871 $\text{kg NH}_3\cdot\text{t}^{-1}$ (Table 8).

Correlation between Energy Efficiency and the Amount of GHG Emissions across the Silage Maize Cultivation Technologies

Technologies were ranked according to increasing energy efficiency and Figure 4 shows energy efficiency and GHG emissions of the technologies studied.

Figure 4. Energy efficiency and GHG emissions in silage maize production technologies.

The energy efficiency values estimated in the early research period for the respective silage maize production technologies [54] were correlated with the results of the GHG emissions for those technologies.

To describe the correlation between the energy efficiency factor value calculated and the GHG emissions expressed in an equivalent unit per hectare of silage maize plantation, the value of Pearson's correlation coefficient was calculated for those two traits. The calculations were made with the use of Microsoft Office 365 version 1807365 Excel spreadsheets (Figure 5). A negative correlation ($r = -0.80$) was found; the value ranged from -1 to 1 .

This means that the higher the energy efficiency of silage maize plantations, the lower the air pollution emissions in a form of GHGs from the sources considered.

Figure 5. Relationship between the energy efficiency and GHG emissions in silage maize production technologies.

4. Discussion

The estimation methods for GHG (N₂O, CO₂ and CH₄ and NH₃) emissions to the atmosphere from the production of silage maize facilitated determining the effect of different variants of cultivation technology on the emissions produced throughout the cultivation period. The most favourable variant due to GHG emissions per area unit (ha) and the unit of the yield (t) was technology MS13. In that technology, the silage maize production chain (from fertilisation and ON burning) per ha resulted in the emissions of 535.677 kg CO₂eq, while producing 1 tonne of the yield resulted in the emissions of 11.904 kg CO₂eq. The variant with most GHG emissions to the atmosphere per ha was variant MS1—2657.868 kg CO₂eq·ha⁻¹, while, due to the unit of the yield (t) it was technology MS3—40.853 kg CO₂eq·t⁻¹. Assuming the emissions in technology MS1 as 100%, in technology MS3 the estimate of GHG emissions per hectare was 23% lower, whereas the MS3 yield was 30% lower than the MS1 yield, which affected the result. The GHG emissions from fertilisation resulting from the fertilisation rates applied in MS3 were 1628.744 kg CO₂eq·ha⁻¹. They were only 8.6% lower from the amounts in MS1. A lower yield in MS3 (50 t·ha⁻¹) was not proportionally lower than the fertilisation rates changed.

The technology variant with the least unfavourable impact on the environment, due to NH₃ emissions to the atmosphere, was technology MS13, with natural fertilisation only. Most ammonia was emitted in technology MS3. Assuming the amount of N supplied with fertilisers to soil as 100%, natural fertilisers accounted for 38.2%, and mineral fertilisers—for 61.8%. The amount of NH₃ emissions was affected by a high share of mineral fertilisation and considerable differences in the value of the ammonia emissions factor in the fertilisers applied [45].

In the field silage maize production, the strongest impact on the environment, due to GHG emissions to the atmosphere and thus contributing to global warming, is found for nitrogen fertilisation, both mineral and natural, on average 61% of the total GHG emissions came in the technologies from that source, which is due to a high global warming potential of N₂O. In the structure of the share in GHG emissions across the fertilisers, the share is similar; 50.5% natural and 49.5% mineral fertilisers. A considerable share of GHG emissions from mineral nitrogen fertilisation was also found by Jacobs et al. [55]; 41–55% of the total GHG emissions from soil caused by N from mineral fertilisers and post-harvest residue. Similar results were reported by Camargo et al. [56], Meyer-Aurich et al. [57]. With the above in mind, mineral nitrogen fertilisation is considered the most promising N₂O emissions reducing practice. In the present research on family farms inconsiderable in

acreage, from 2 to 13 ha, the GHG emissions from ON burning accounted for 20.2 to 62.1% of the total emissions from the sources under study, while on high-performance farms they accounted for 10 to 19% of GHG emissions in total [55]. In this paper the post-harvest emissions were disregarded as the study covered silage maize and harvest was performed at the development stage, in terms of moisture and cutting height, optimal for ensilaging processes [58].

The correlation between the estimates of GHG emissions and the energy efficiency factor values calculated for the same technologies showed a negative value ($r = -80$). The higher the efficiency, the lower the impact of GHG emissions on the environment (atmosphere).

Globally, like other branches of the economy, in agricultural production, together with cost-cutting per ha, one aims at cutting on the energy inputs. Technological solutions are being sought to increase the efficiency and thus to decrease pollution emissions to the atmosphere [55,59]. One of the solutions can be, e.g., changing from traditional farming to simplified farming [60–62]. A change in the farming system from traditional, through simplified, all the way to direct sowing, decreases the amount of the fuel consumed due to a complete or partial elimination of some agrotechnical practices which, next to cutting down on energy intensity, affect the emissions and absorption of gases, mostly CO₂ and oxygen [63]. Limiting the CO₂ emissions from the plantations to the atmosphere is also a result of an increased carbon sequestration due to a change in the farming system introduced [64,65]. The treatment the elimination of which most considerably decreases the energy intensity is ploughing. According to Cudzik et al., plough elimination facilitates up to a 35% reduction in the total fuel consumption. Smagacz reported that shallow plough use consumed about 43% fuel less than deep plough cultivation.

Reducing nitrogen losses and emissions of those pollutions are possible by complying with guidelines of the Code of Good Agricultural Practice [26]. The key recommended methods of reducing GHG emissions to the atmosphere from agricultural sources, plant production, include a modification of the agrotechnical methods, especially a decreased use of nitrogen fertilisers by applying rational rates based on soil richness and nutrient requirements of a given crop species, applying improved nitrogen fertilisation technologies, obeying the fertilisation and plant protection agents dates, a selection of the assortment of fertilisers with lower emissions during production, adjusting the production systems to maximise the use of animal faeces for plant farming, a better post-harvest residue management, following the adequate crop rotation and applying undersown crops, which bind carbon and can limit the nitrogen fertilisation requirements, as well as supporting perennial crops [55,66].

In the literature studies, an important indicator of sustainable agriculture in the case of silage maize concerns energy balance. This can improve the quality and accuracy of biogas industry evaluation from the point of view of the agricultural substrate supply most often using average values of variable inputs in the cultivation of biomass. The notion of life cycle analysis (LCA) is also mainstream in the energy efficiency literature. There are not many, however there are published works on this topic for maize in Europe [67], like alternative tillage practices [68].

5. Conclusions

The results and their analysis have confirmed a negative correlation between the energy efficiency and GHG emissions to the atmosphere from the silage maize plantations.

The results of the comparative analysis of GHG and NH₃ emissions for respective silage maize technology variants, considering the production inputs as the sources of emissions: natural and mineral fertilisers as well as the use of fuel consumption per area unit and yielding, are planned to be used at successive stages of research involving a performance of analyses and considerations on the possibilities of cutting down on emissions from respective sources by introducing the agricultural production practices reducing the production of emissions.

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