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Greenhouse gas and ammonia emissions in modelled cereal crop production under Polish agricultural conditions: An example spring barley

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Abstract: Based on the analysis of statistical data, the average area under cultivation and average yields of barley in Poland in 2010–2020 were calculated. Barley is one of the most important cereals grown in Poland. Its cultivation area occupied an average of 920,595 ha in these years, with average yields of 3.66 $Mg \cdot ha^{-1}$. Barley is a cereal grown mainly as a spring cereal. The average area under spring species in these years accounted for 95% (875,771 ha) of the total area under this cereal, and the average yield of spring varieties was 3.60 $Mg \cdot ha^{-1}$. In order to estimate emissions of greenhouse gases (GHG) and ammonia (NH_3), the sources of emissions – inorganic fertilisers, fuel consumption – were analysed for selected barley cultivation technologies, differentiated by yield level, and variant model production technologies were developed to obtain projected yields. Emissions were calculated for individual greenhouse gases (N_2O, CH_4 and CO_2) and they were recalculated according to the greenhouse potential of each gas (GWP – global warming potential) to be able to compare the total amount of greenhouse gas emissions for the analysed variants. Greenhouse gas emissions for cultivation technology ranged from 134.53 to 136.48 kg CO_2eq for 1 Mg yield. A more accurate Tier 2 method was used to estimate NH_3 emissions, taking into account soil conditions and climate zone. The estimated ammonia emissions from the application of mineral fertilisers were from 0.99 kg to 2.35 kg for 1 Mg yield.

Keywords: agriculture, air pollution, barley crop, crop technology, GHG emission, NH_3 emission

INTRODUCTION

Despite differing view on the causes of climate change, measures are being taken to reduce greenhouse gas (GHG) emissions and stabilise their concentrations in the atmosphere. For reporting purposes, national inventories of emissions of pollutants entering the atmosphere are prepared, which, in international terms, are a set of data providing information on the annual emissions of individual substances in a country. In Poland, the institution for calculating and reporting emissions for international conventions, European obligations and for national purposes is the Emission Inventory Team at the National Center for Balancing and Emission Management (Pol. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami – KOBiZE) at the Institute of Environmental Protection – State Research Institute (Pol. Instytut Ochrony Środowiska – Państwowy Instytut Badawczy), supervised by the minister of the climate (Ustawa, 2009; Obwieszczenie, 2022). Among the many fields of human activity, agriculture has a large share of GHG emissions, especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In this sector, we distinguish GHG emission streams from crop and livestock production. The main sources of GHG emissions in the agricultural sector are: enteric fermentation (CH_4 emissions), animal manure (CH_4, N_2O emissions), direct emissions from soils (N_2O emissions), including but not limited to: application of mineral fertilisers, organic fertilisers, crop residues, N_2O emissions from animal faeces on pastures and rangelands, indirect N_2O emissions from soils; from deposition of nitrogen compounds (NH_3, NO_x) from the atmosphere into the ground and from nitrogen leaching from the ground, combustion of plant waste (CH_4 and N_2O emissions).

In order to estimate GHG and NH_3 emissions and also in the search for opportunities for reduction, it is necessary to analyse the sources of emissions in individual agricultural production technologies, including crops. In Poland, the crops of greatest importance in crop production are root crops, cereals and oilseeds. Among cereals, the largest areas under cultivation are wheat, triticale, rye and barley. The cereal that is predominantly grown as a spring crop is barley – the area under spring barley accounts for 95% of the total area under this cereal (GUS, 2021).

According to the GUS (2021), based on KOBiZE data, Poland's national CO_2 emissions from agriculture in 2020 amounted to about 1.5 mln Mg CO_2eq. It was mainly associated with the intensification of crop production, particularly soil liming (about 57%), the application of urea fertilisers (about 30%) and the release of CO_2 during ploughing after fertiliser application, accompanied by the decomposition of organic matter (about 13%).

Estimating emissions from agricultural crops for reporting purposes and for seeking solutions aimed at reducing the adverse environmental impact of plant crops is quite difficult. There is a large discrepancy in results even for the same crop which depends on the scope of the study, the methodology used, as well as the accuracy of the data adopted for the calculations. In the paper by Clune, Crossin and Verghese (2017), authors compared the results of different authors. The carbon footprint of cereal cultivation ranged from 0.11 to 1.38 kg CO_2eq·kg^{-1}. The results of Rajaniemi, Mikkola and Ahokas (2011) showed GHG emissions of 1.93 kg CO_2eq·ha^{-1} and 570 g CO_2eq·kg^{-1} from barley cultivation. In a study by Żyłowski (2019), the estimated carbon footprint ranged from 568 to 8,435 kg CO_2eq·ha^{-1} (average 2,484 kg CO_2eq·ha^{-1}) and for 1 kg of grain was 0.60 kg CO_2eq·kg^{-1} (0.11–2.94 kg CO_2eq·kg^{-1}). However, calculations were performed for GWP 298 for N_2O.

Detailed analyses of the types of pollutants emitted into the atmosphere, their amount, depending on the technology of crop production (Tworkowski *et al.*, 2015), regional variation of cultivated areas and yields, are an essential element in the selection of measures to reduce their formation and to carry out considerations on the possibilities of reducing GHG and NH_3 emissions into the atmosphere (Communication, 2011; Li *et al.*, 2016; Żyłowski, 2019; Lovarelli *et al.*, 2020).

STUDY MATERIALS AND METHODS

STUDY MATERIALS

The study Central Statistical Office data (GUS, 2021) showed that barley is one of the dominant cereals grown in Poland. In 2010–2020, barley crops occupied an average of 920,595 ha, and average yields in these years were 3.66 Mg·ha^{-1}. Average barley yields by voivodship ranged from 2.98 Mg·ha^{-1} (Podlaskie voivodship) to 4.73 Mg·ha^{-1} (Opolskie voivodship) – Figure 1.

As many as 12 voivodships (Podlaskie, Świętokrzyskie, Mazowieckie, Łódzkie, Podkarpackie, Warmińsko-Mazurskie, Lubuskie, Małopolskie, Lubelskie, Śląskie, Kujawsko-Pomorskie, and Pomorskie) had average yields below the national average, which was – 3.66 Mg·ha^{-1} (Fig. 1). The average of yields

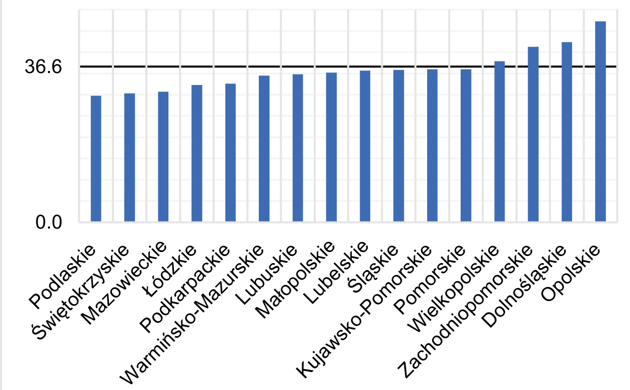

Fig. 1. Variation of barley yields in voivodships in relation to the national average in Poland in 2010–2020; source: own study based on GUS (2012a; 2012b; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021)

from voivodships with values below the national average, was 3.36 Mg·ha^{-1}. Only in four voivodships (Wielkopolskie, Zachodniopomorskie, Dolnośląskie, Opolskie) the average yields from 2010–2020 exceed the average yield for the country. Average yields for these voivodships amounted to 4.22 Mg·ha^{-1}.

Barley is a cereal that is predominantly grown as a spring crop. In 2010–2020, the cultivation of spring species occupied 875,771 ha, and the average yield of spring varieties was 3.60 Mg·ha^{-1} (Tab. 1).

Table 1. Average area and average yield of barley crops in Poland from 2010 to 2020

Crop	Average crop area 2010–2020		Average yield 2010–2020 (Mg·ha^{-1})
	ha	%	
Barley	920,595	100	3.66
Winter barley	44,824	5	4.17
Spring barley	875,771	95	3.60

Source: own study based on GUS (2012a; 2012b; 2013; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021).

Similarly, the average yields of spring barley in each voivodship were calculated. Average yields of spring barley varieties in 2010–2020 from voivodships ranged from 2.97 Mg·ha^{-1} in Podlaskie voivodship to 4.65 Mg·ha^{-1} in Opolskie voivodship. The average yields from the voivodships were divided into two groups. The average yield of spring varieties of this species for Poland in 2010–2020, which amounted to 3.60 Mg·ha^{-1}, was used as a criterion for division (Tab. 2, Fig. 2). In one group, voivodships with yields below the national average were placed, in the other higher than the national average. The average yield of spring barley from voivodships from 2010–2020 with an average below the national average was 3.32 Mg·ha^{-1}, and the average yield of voivodships above the Polish average was 4.12 Mg·ha^{-1} (Tab. 2).

STUDY METHODS

On the basis of the results obtained from the analysis of statistical data on the area of cultivation and yield of spring barley, and after calculating average yield values, cultivation technologies were

Table 2. Average yields of spring barley ($Mg \cdot ha^{-1}$) in Poland by voivodship

Country/Voivodship	Average yield 2010–2020
Poland	**3.60**
Voivodships with average yields below the national average	
Podlaskie	2.97
Świętokrzyskie	3.02
Mazowieckie	3.06
Łódzkie	3.19
Podkarpackie	3.25
Lubuskie	3.30
Warmińsko-mazurskie	3.43
Małopolskie	3.50
Śląskie	3.51
Lubelskie	3.54
Pomorskie	3.54
Kujawsko-pomorskie	3.57
Average for group of voivodships	**3.32**
Voivodships with average yields above the national average	
Wielkopolskie	3.69
Zachodniopomorskie	3.97
Dolnośląskie	4.18
Opolskie	4.65
Average for group of voivodships	4.12

Source: own study based on GUS (2012a; 2012b; 2013; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021).

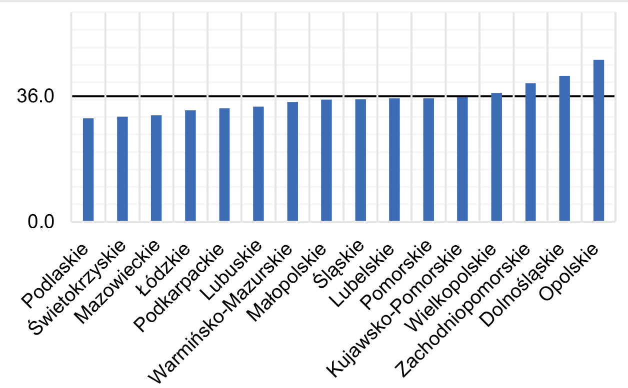

Fig. 2. Yield variation of spring barley varieties in voivodships in relation to the national average in Poland in 2010–2020; source: own study based on GUS (2012a; 2012b; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021)

developed for average, lower, higher than the national average. The yield of a given crop depends, among other things, on the natural conditions of the region and the amount of nitrogen fertilisers applied, the amount of agrotechnical treatments applied (the amount of fuel used), which are a source of GHG emissions (CO_2, N_2O, CH_4) and NH_3.

The study looked at the stage of barley cultivation, from soil preparation to seeding, fertilisation, sowing, tillage treatments, and harvesting. Emissions of GHG were estimated from the application of mineral fertilisers and from fuel consumption during commuting from the habitat to the field and during agrotechnical operations (Muzalewski, 2020). The following assumptions were made: the size of the farm 20–30 ha, the acreage of barley cultivation 5 ha, the distance of the field from the farm 1 km – relevant to the amount of fuel consumed. In the estimation of GHG emissions from fuel, the power of tractors and self-propelled machinery was taken into account, which, in accordance with the principles of machinery selection (Muzalewski, 2015), were adjusted to the assumed size of the farm, the work efficiency of individual machines and working sets was calculated for the agrotechnical procedures performed, taking into account access from the habitat to the field, loading of plant protection products, seeds, necessary adjustments, harvesting.

In order to determine the amount of fertiliser doses, based on IUNG (Jadczyszyn, Kowalczyk and Lipiński, 2010) fertiliser recommendations, the amounts of individual nutrients necessary to provide for obtaining the projected yield were determined in four model variants of spring barley cultivation technology, which were given the symbols JN, JS, JW, and J7 (Tab. 3).

Table 3. Recommended doses of N, P_2O_5 and K_2O in model technological variants of spring barley cultivation

Technology variant	Dose of ($kg \cdot ha^{-1}$)			Yield ($Mg \cdot ha^{-1}$)
	N	P_2O_5	K_2O	
JN	26	33	38	below average – 3.32 $Mg \cdot ha^{-1}$
JS	32	35	41	average – 3.6 $Mg \cdot ha^{-1}$
JW	42	39	46	above average – 4.12 $Mg \cdot ha^{-1}$
J7	100	60	75	7.00
Fertiliser recommendation[1)]	80	55	65	6.00
	100	60	75	7.00
	120	70	85	8.00

[1)] Jadczyszyn *et al.* (2010).
Source: own elaboration and literature data.

To deepen the analyses due to the projected yield, the technology with the potential yield possible under intensive cultivation (7.0 $Mg \cdot ha^{-1}$) was also selected.

Depending on the percentage composition of individual substances (N, P_2O_5 and K_2O) in mineral fertilisers (according to the manufacturer's information – Tab. 4), an assortment was proposed and fertiliser doses were calculated. Cultivation technologies included variants with only mineral fertilisation.

The amounts of individual nutrients (N, P_2O_5, K_2O) for obtaining the predicted yield in the model variants of cultivation technology were adjusted to obtain the correct amounts of macronutrients for spring barley crops (JN, JS, JW, J7) – Table 5.

In order to deepen the analysis in view of the projected yield, which depends, among other things, on the level of

Table 4. Nitrogen, phosphorus and potassium content (%) in mineral fertilisers proposed for use

Fertiliser	Fertiliser content		
	nitrogen (N)	phosphorus (P_2O_5)	potassium (K_2O)
Urea	46		
Ammonium phosphate	18	46	
Potassium salt			60

Source: own elaboration based on manufacturer's information.

fertilisation, the number of agrotechnical treatments carried out, with which fuel consumption is associated, technologies with potential yields that can be obtained in excess of the average figures calculated on the basis of analyses of yields obtained in provinces in Poland – based on fertiliser recommendations of IUNG (Jadczyszyn *et al.* 2010) were also selected; spring barley – 7 Mg·ha^{-1} (J7 variant) – Tables 5 and 6.

Analyses were carried out using data on the amount of inorganic fertiliser, limestone fertiliser applied, as well as the amount of fuel consumed. The types of pollutants considered from the studied sources are listed in Table 7.

The calculation of the amount of direct emissions of CO_2 and N_2O from fertiliser application was based on the methodology presented by Buendia *et al.* (eds.) (2019). In estimating greenhouse gas (GHG) emissions: N_2O and CO_2, the obtained results of individual GHG emissions were converted according to their greenhouse potential to show the total amount of GHG emissions in the equivalent unit – which takes into account the greenhouse potential of individual gases (GWP – global warming potential). This unit was created to allow comparison of gas emissions (Eggleston *et al.* (eds.), 2006). The greenhouse gas potential expresses the amount of kilograms of carbon that, over a 100-year period, produces the same global warming effect as 1 kg of the greenhouse gas under analysis. IPCC (2014) guidelines were used to calculate emissions expressed in CO_2 equivalent. The global warming potential values, for CO_2, N_2O and also CH_4 are shown in Table 8.

Analysed were four variants of spring barley cultivation that varied in terms of yields received. The analysis considered variants with sole application of mineral fertilisers. For the purpose of estimating GHG, and NH_3 emissions, each variant was characterised in terms of the amount of inorganic (including urea) and calcium fertilisers applied. The amount of nitrogen and carbon delivered by each source was calculated. The estimation of GHG from mineral fertiliser application was based on guidelines by Buendia *et al.* (eds.) (2019).

Emission of N_2O from mineral fertilisation was calculated based on Equation (1):

$$N_2O_{\mathrm{Direct}}\text{–N Emission} = F_m \cdot EF_{fm} \quad (1)$$

where: N_2O_{Direct}-N Emission = emission from mineral fertiliser application (kg·ha^{-1} or kg·Mg yield^{-1}), F_m = amount of mineral fertiliser (kg·ha^{-1} or kg·Mg yield^{-1}), EF_{fm} = ammonia fertiliser emission factor, EF_{fm} = 0.01 (Buendia *et al.* (eds.), 2019).

Table 5. Proposed mineral fertilisers and rates in model spring barley crop technologies

Techno-logy variant	Nutritional requirement			Yield	Urea		Polifoska 8 NPK 8-24-24				Potassium salt		Ammonium phosphate		
	N	P_2O_5	K_2O		N 46%	fertiliser dose	N 8%	P_2O_5 24%	K_2O 24%	fertiliser dose	K_2O 60%	fertiliser dose	N 18%	P_2O_5 46%	fertiliser dose
	kg·ha^{-1}														
JN	26	33	38	3,320	12.88	28	0	0	0	0	37.80	63	12.96	33.12	72
JS	32	35	41	3,600	18.40	40	0	0	0	0	40.80	68	13.50	34.50	75
JW	42	39	46	4,120	26.22	57	0	0	0	0	45.60	76	15.30	39.10	85
J7	100	60	75	7,000	77.28	168	6.40	19.20	19.20	80	55.80	93	15.84	40.48	88

Explanations: JN, JS, JW, and J7 as in Tab. 3.
Source: own elaboration.

Table 6. Summary of the different variants of spring barley cultivation

Technology variant	Yield		Mineral and lime fertilisers				Fuel (diesel oil – ON) consumption ($dm^3 \cdot ha^{-1}$)
	main	side	N	P (P_2O_5)	K (K_2O)	CaO[1)]	
	$Mg \cdot ha^{-1}$		$kg \cdot ha^{-1}$				
JN	3.32	4.15	26	33	38	119	79.62
JS	3.60	4.50	32	35	41	119	83.52
JW	4.12	5.15	42	39	46	119	84.00
J7	7.00	8.75	100	60	75	119	110.79

[1)] Dolomite lime 55% CaO dose for a ha per year.
Explanations: JN, JS, JW, J7 as in Tab. 3.
Source: own elaboration.

Table 7. Emission sources and estimated types of pollutant emitted into the atmosphere

Emission source	Estimated type of pollution			
	GHG			NH_3
	N_2O	CO_2	CH_4	
Mineral fertilisers	+	+		+
Limestone fertilisers		+		
Fuel consumption	+	+	+	

Source: own elaboration.

Table 8. Greenhouse gas potential

Gas	Counter for CO_2 equivalent
CO_2	1
N_2O	265
CH_4	28

Source: own elaboration according to IPCC (2014).

For liming, the formula used was:

$$\mathrm{CO_2{-}C\ Emission} = L_{\mathrm{Dolomite}} \cdot EF_{\mathrm{Dolomite}} \tag{2}$$

where: CO_2-C Emission = emission from lime fertiliser application ($kg \cdot ha^{-1}$ or $kg \cdot Mg$ yield^{-1}), $L_{Dolomite}$ = amount of dolomite lime ($CaMg(CO_3)_2$) ($kg \cdot ha^{-1}$ or $kg \cdot Mg$ yield^{-1}), $EF_{Dolomite}$ = dolomite lime emission factor, $EF_{Dolomite}$ = 0.13 (Buendia *et al.* (eds.), 2019).

In the analysed model technologies, CO_2 emissions from urea application were estimated based on the Equation (3):

$$\mathrm{CO_2{-}C\ Emission} = U \cdot EF_u \tag{3}$$

where: CO_2-C Emission = C emission from urea application ($kg \cdot ha^{-1}$ or $kg \cdot Mg \cdot$yield^{-1}), U = amount of urea ($kg \cdot ha^{-1}$ or $kg \cdot Mg$ yield^{-1}), EF_u = urea emission factor, EF_u = 0.2 (IPCC, 2019).

Based on assumptions made from literature data and data declared by manufacturers on the type of fertilisers used, a formula was formulated to estimate NH_3 emissions from nitrogen mineral fertiliser applications:

$$\mathrm{NH_3\ Emission} = F_N \cdot EF_N \tag{4}$$

where: F_N = the dose of nitrogen (N) in the applied fertiliser (kg), according to the percentage composition of the fertiliser range provided by the manufacturer, EF_N = emission factor for nitrogen-containing fertilisers (g NH3)$\cdot$(kg N)$^{-1}$ in fertiliser) – Table 9.

According to current EEA (2019) guidelines, a more accurate Tier 2 method can be used to estimate NH_3 emissions. In this method, $EF(NH_3)$ emission factors from applied mineral nitrogen fertilisers have a value depending on the type of fertiliser, soil reaction (pH) and climatic conditions (temperature). For Polish conditions, the analyses used indicator values (Tab. 9) in accordance with EFA (2019) guidelines for soils with pH below 7, which characterise 89% of Poland's soils (GUS, 2018) and that Poland falls into the temperate climate zone.

Due to the amount of atmospheric emissions generated at the stage of field production, it is also important to estimate the

Table 9. Nitrogen content and emission factors of N_2O, CO_2, NH_3 for selected inorganic fertilisers

Fertiliser type	N content (%)	Emission factor		
		N_2O-N	CO_2-C	NH_3 ((g NH_3)$\cdot$(kg N)$^{-1}$)
Ammonium phosphate	18	0.01		51
Urea	46	0.01	0.2	159
Compound fertilisers (NPK)		0.01		67
Dolomite lime			0.13	

Source: own elaboration according to EFA (2019) – 3.D Crop production and agricultural soils.

amount of fuel consumed, which depends on the number of treatments carried out, the size of the crop and the supply of the necessary amounts of nutrients for its obtaining, the plant protection products used.

Included in the calculations were the time of transport trips, the effective working time depending on the working width of the machines and tools and the working speed appropriately adapted to the work performed, the time to turn around, the time for loading and unloading (fertilisers, crop protection products, harvesting) and the time for removing potential defects and making adjustments.

Based on amount of fuel – diesel oil (ON) consumed in the analysed model variants the amount of GHG emissions: CO_2, N_2O, and CH_4 resulting from the combustion of diesel fuel by engines of tractors and agricultural machinery was estimated. Calculations were made based on the following formulas, which used the values of emission factors of the mentioned gases (Radzimirski and Taubert, 2009; Muzalewski, 2018).

$$\mathrm{CO_2P\ Emission} = Fc \cdot EF_{\mathrm{ON}}\mathrm{CO_2P} \tag{5}$$

$$\mathrm{CH_4\ Emission} = Fc \cdot EF_{\mathrm{ON}}\mathrm{CH_4} \tag{6}$$

$$\mathrm{N_2O\ Emission} = Fc \cdot EF_{\mathrm{ON}}\mathrm{N_2O} \tag{7}$$

where: Fc = fuel (ON) consumption (kg), $EF_{ON}CO_2P$ = CO_2 potential emission factor, $EF_{ON}CO_2P$ = 3,170 $g \cdot kg^{-1}$ ON, $EF_{ON}CH_4$ = CH_4 emission factor, $EF_{ON}CH_4$ = 0.19 ($g \cdot kg^{-1}$ ON), $EF_{ON}N_2O$ = N_2O emission factor = 0.16 ($g \cdot kg^{-1}$ ON).

In order to convert the amount of fuel consumed from dm^3 to kg, according to Rozporządzenie (2018), a conversion factor was used: 1 dm^3 ON = 0.84 kg.

RESULTS AND DISCUSSION

According to the adopted methodology of the study, the amounts of GHG emissions (CO_2, N_2O, CH_4), and NH_3 from the analysed sources, per 1 ha of cultivation and per 1 Mg of yield (Tab. 10) were estimated, which, for the purpose of comparison, were converted and expressed in the equivalent unit – ECO_2eq.

Greenhouse gases emissions of spring barley cultivation technologies ranged from 446.64 kg $CO_2eq \cdot ha^{-1}$ for an assumed yield of 3.32 $Mg \cdot ha^{-1}$ to 940.04 kg $CO_2eq \cdot ha^{-1}$ for a yield of 7.00 $Mg \cdot ha^{-1}$ (Tab. 10) – average 606.12 kg $CO_2eq \cdot ha^{-1}$, standard deviation 196.01 kg $CO_2eq \cdot ha^{-1}$).

The application of fertiliser and the consumption of ON to produce 1 Mg of yield resulted in emissions of 134.53 kg $CO_2eq \cdot Mg^{-1}$ for a yield of 3.32 $Mg \cdot ha^{-1}$. For yield of 3.60 $Mg \cdot ha^{-1}$, the production of a unit of yield (1 Mg) of spring barley resulted in the emission of 136.48 kg CO_2eq of greenhouse gases into the atmosphere (Tab. 10) – average 134.48 kg $CO_2eq \cdot Mg^{-1}$, standard deviation 1.36 kg $CO_2eq \cdot Mg^{-1}$).

Estimated amounts of NH_3 emissions, analogous to the results of GHG emissions, were related to a unit of area (ha) and a unit of yield (Mg) – Table 11.

The estimated ammonia emissions from the application of mineral fertilisers – per unit area – were 3.29 $kg \cdot ha^{-1}$ for a yield of 3.32 $Mg \cdot ha^{-1}$ and 16.42 $kg \cdot ha^{-1}$ for a yield of 7.00 $Mg \cdot ha^{-1}$ – average 7.53 $kg \cdot ha^{-1}$, standard deviation 5.23 $kg \cdot ha^{-1}$. To produce 1 Mg yield of spring barley, 0.99 kg NH_3 was emitted for a yield of 3.32 $Mg \cdot ha^{-1}$ and 2.35 kg NH_3 for a yield of 7.00 $Mg \cdot ha^{-1}$ (Tab. 11) – average 1.50 $kg \cdot Mg^{-1}$, standard deviation 0.51 $kg \cdot Mg^{-1}$).

Table 10. Greenhouse gases (GHG) emissions in spring barley cultivation

Yield	GHG			
	mineral fertiliser	fuel – diesel oil (ON) consumption		total
		CO_2	total	
GHG emission in relation to spring barley cultivation area (($kg\ CO_2eq) \cdot ha^{-1}$)				
3.32	231.10	212.35	215.54	**446.64**
3.60	265.13	222.85	226.20	**491.33**
4.12	317.66	225.40	228.79	**546.45**
7.00	640.59	295.01	299.45	**940.04**
GHG emission in relation to spring barley yield (($kg\ CO_2eq) \cdot Mg^{-1}$)				
3.32	69.61	63.96	64.92	**134.53**
3.60	73.65	61.90	62.83	**136.48**
4.12	77.10	54.71	55.53	**132.63**
7.00	91.51	42.14	42.78	**134.29**

Source: own study.

Table 11. Ammonia (NH_3) emission in relation to area under spring barley cultivation ($kg \cdot ha^{-1}$) and to yield ($kg \cdot Mg^{-1}$)

Yield ($Mg \cdot ha^{-1}$)	NH_3 emmission from mineral fertilisers	
	$kg \cdot ha^{-1}$	$kg \cdot Mg^{-1}$
3.32	3.29	0.99
3.60	4.39	1.22
4.12	6.01	1.46
7.00	16.42	2.35

Source: own study.

In the structure of the share of GHG emissions in crop production, a significant source of this pollution is the use of mineral fertilisers (Fabbri *et al.*, 2023). Emissions of GHG comes from N_2O – due to its high greenhouse potential – from nitrogen fertiliser application. A significant share of GHG emissions from mineral nitrogen fertilisation was also found by Jacobs *et al.* (2017), similar results were obtained by Meyer-Aurich *et al.* (2012), Camargo, Ryan and Richard (2013), Konieczna *et al.* (2019), Konieczna 2020 and Konieczna *et al.* (2021). With this in mind, modifications of cultivation technology, integrated nitrogen fertilisation is considered one of the most promising practices in reducing N_2O emissions (Malyan *et al.*, 2019; Żyłowski, 2019; Romashchenko *et al.*, 2023). The results of a study by Faber *et al.* (2023) showed that there is still a need to improve nitrogen use efficiency in Poland and its regions. Agriculture is the largest contributor to ammonia emissions, so measures to reduce ammonia emissions from agriculture have a large impact on total emissions, and any countermeasures play an important role in avoiding risks to human health and the environment (Wardal *et al.*, 2019).

CONCLUSIONS

Considering the threats to the environment, among other things, from agriculture, methods have been sought for many years, a lot of research has been carried out to increase the efficiency of production including crop production, as well as ways of managing waste biomass, e.g. for energy purposes, in order to reduce greenhouse gas emissions. The implementation of these tasks has been included in the scenarios of the EU's global projections aimed at reducing national emissions by 80% by 2050 compared to 1990. A set of projections was used to examine the global impact of climate action and its relationship to the energy sector and deforestation.

More detailed information on emissions from crops grown according to these technologies and in-depth research will allow for more knowledge and deeper analysis to seek ways to reduce them. The results will be used in the planned stages of research to estimate the possibility of reducing emissions from individual sources by modelling production technologies with methods and techniques for reducing GHG and NH_3 emissions.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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