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Exhaust emissions from agricultural tractors in West Pomerania, Poland

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Abstract: The intensification of agricultural production is increasing environmental pollution in rural areas. A significant contribution to air pollution in this respect comes from the combustion of fuel by tractor engines that drive agricultural machinery and equipment. The most important pollutants from this source, which have a negative impact on the atmosphere as well as on human health, include diazotium oxide (N_2O), carbon dioxide (CO_2), and carbon monoxide (CO). Determining emissions is not an easy matter, if only because of their great diversity in terms of age, operating time, technical condition, as well as the type of operations performed, agrotechnical procedures. The paper attempts to estimate the emission of pollutants from fuel combustion by agricultural tractor engines in West Pomeranian Voivodeship. The basic source of energy on farms is the energy from the combustion of conventional fuels – mainly diesel – by engines of tractors and machines enabling the majority of field work to be carried out. The most common engines used in these tractors are diesel engines, mainly turbocharged with direct injection (DI). On the basis of the developed load cycle, data from the Central Register of Vehicles and Drivers database and laboratory tests, spatial maps of emissions of individual toxic components of exhaust gases were obtained in all the districts of the region. Analysis of the results showed, among other things, that the Gryfice district is the most heavily burdened with these pollutants and the Police district the least.

Keywords: agriculture, engine, exhaust gases, greenhouse gases (GHG) emission, tractors

INTRODUCTION

The growth of the world's human population is forcing an increasing need for food production. The significant intensification of agriculture results in a continuous increase in the emission of pollutants into the environment, including greenhouse gases (GHG). Mainly GHG emitted from agriculture are: methane (CH_4), diazotium oxide (N_2O), carbon dioxide (CO_2). The emission sources are: livestock enteric fermentation (CH_4), livestock manure (CH_4 and N_2O), agricultural soils (N_2O), crop residue combustion (CH_4 and N_2O) and a separate sector attributed to land use, land use change and forestry (Kolasa-Więcek, 2012; EC, 2025).

According to World Health Organisation (WHO, 2016) air pollution is the largest environmental health risk in the European Union (EU). Air pollution results in ~400,000 premature deaths in the EU each year and large financial expenditures related to the effects of treatment (EEA, 2017).

The state of the air in the areas of rural municipalities is influenced by emissions from various sources. One of them, although not directly related to agricultural activities, is emission from linear sources, located along transport routes running through the areas of these municipalities (Konieczna, Roman and Rzodkiewicz, 2023).

The primary source of energy on farms has been, and continues to be, energy from the combustion of conventional fuels – mainly diesel – by engines in tractors and machinery enabling most field work to be carried out (Singh, 2006; Kowalski, 2012). These typically use diesel engines mainly turbocharged with direct injection (DI). Low fuel consumption and low emissions are characteristics of the diesel engine, where the exhaust gas composition is only slightly affected even after "heavy duty". The problem with diesel engines is the significant NO_x and particulate matter (PM) emissions, which are 5–8 times higher than in spark engines (Merkisz, 1999).

For non-road vehicles like agricultural tractors, in the EU, there are emission standards (Regulation, 2016). Non-road vehicles are subject to the limits for the standard designated Stage V (EU 2015/96 and 2000/25/EC) (Antosik, 2018).

In order to meet increasingly stringent exhaust emission standards, it is no longer sufficient to change the regulation of the parameters of the injection system (Wasilewski *et al.*, 2020), but it is necessary to introduce changes in the construction of the diesel engines. Although the reduction in exhaust PM between new and old engines is significant, the rate of tractors replacement on farms plays a decisive role. It is estimated that there are currently around 10 mln tractors in use in EU countries (as of 2014), of which around 3 mln units are tractors up to 15 years old in continuous use on farms. However, the remainder, aged between 15 and even 70 years, operate sporadically for about 5–10% of the time of what is newer. Studies show that tractors up to 15 years old are responsible for as much as around 70% of total PM emissions and it is their replacement that should be encouraged. With estimated annual tractor sales in the EU of up to 200,000 units, it could take at least 15 years to make a significant reduction in exhaust emissions (Staniszewski, 2014).

There is limited information in the available literature on the scale of environmental pollution resulting from the combustion of fossil fuels during the use of agricultural tractors. The value of the total emissions of harmful exhaust compounds from agricultural vehicles from across the country cannot be determined directly. Currently, measuring exhaust emissions during field work is not difficult but require specialised and expensive measuring equipment (Lovarelli and Bacenetti, 2019; Saetti *et al.*, 2021) or use of engine data in the Controller Area Network (CAN) system (Mattetti *et al.*, 2021; Götz *et al.*, 2025). In this aspect, it is much easier to equip and create a power profile for an electric tractor (Angelucci and Mattetti, 2024). Besides, for the results of such tests to be reliable, each tractor would have to be equipped with an exhaust gas analyser.

Some estimations can be made on the basis of energy consumption in agriculture, especially of fuels. Already in 2000, energy consumption in Polish agriculture was $5.561 \cdot 10^{10}$ kWh (7.1% of national consumption). At the same time, the share of agriculture was the highest in diesel consumption (27% of the national direct consumption) (Pawlak, 2002).

The study "Carbon-neutral Poland 2050" (Engel *et al.*, 2020) estimated that in 2017, agriculture was responsible for 11% of the country's CO_2 emissions (44,000 Mg). Methane and nitrous oxide accounted for 75% of this total, mainly as a result of the use of inorganic fertilisers in crops, the cultivation of organic soils and the enteric fermentation of dairy and meat cattle. Carbon dioxide from fuel combustion by agricultural equipment accounted for the remaining 25%.

In addition to continuously updated air quality information (GIOŚ, 2025a), data on emissions: PM10 and PM2.5 from agricultural tractors also appear in the form of overview maps (Fig. 1). They only describe the location of these emissions, without detailing their values. Agriculture was responsible for 43,919.7 Mg NO_x and 482.9 Mg CO emissions from the Polish area. This compares with 231,150.7 Mg NO_x and 502,358.9 Mg CO from road transport (Wahlig, 2019).

The soils of the West Pomeranian Voivodship are characterised by great typological diversity, different soil quality classes and agricultural suitability complexes. It is the compactness of the soil that has the greatest influence on the energy intensity of soil cultivation and the correct choice of tractor power. Differences in ploughing efficiency of different soil types (heavy, light) can be as much as 50% (Muzalewski, 2015).

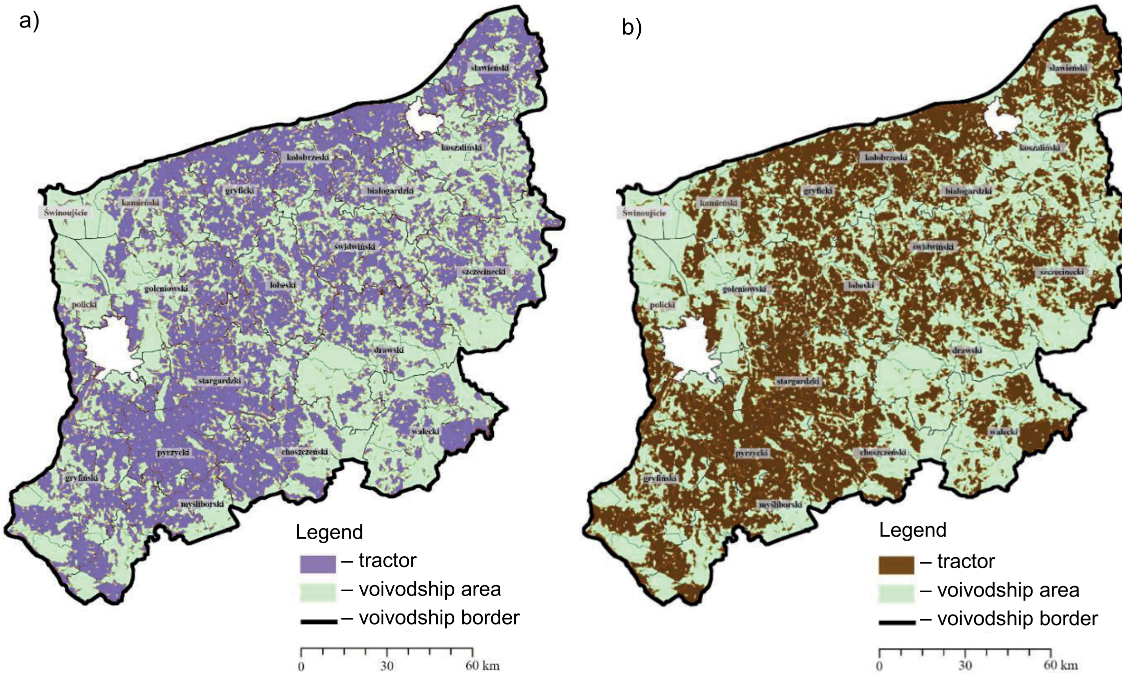

Fig. 1. Location of particulate matter (PM) emissions from agricultural tractors in the West Pomeranian Voivodeship: a) PM10, b) PM2.5; source: own elaboration based on Wahlig (2019)

Within the area of the West Pomeranian Voivodeship with an area of 22,902 km^2 (7.3% of the country's area) there are 114 communes in 18 rural and 3 urban districts (Koszalin, Szczecin, Świnoujście). Agricultural land makes up 48.7% of the total area of the region (arable land – 38.5%, meadows – 6.6%, pastures – 3.4%, orchards – 0.2%) (GIOŚ, 2025b).

Based on literature review and own research, it was concluded that the information on the number, power and age of tractors in use, their operating time per year, and the area and type of land used for agriculture in a given region is sufficient to determine exhaust emissions from the agricultural sector, together with the precise location of their sources.

In this paper, the spatial distribution of emissions of selected components of exhaust gases (CO, CO_2, NO_x) from agricultural tractors was determined and presented on a map of the West Pomeranian Voivodship. The quantitative distribution of exhaust emissions between individual districts of the province was also indicated. An innovative method was used to calculate these emissions on the basis of a proprietary load cycle.

MATERIALS AND METHODS

The first stage of the research consisted in determining a regionally appropriate model of agricultural tractor operation. A ten-phase test tractor was selected, which was developed on the basis of a faithful time simulation of the load states of a tractor engine operating under the conditions of the studied region (Koniuszy and Nadolny, 2007; Koniuszy, 2010). Similar methods were used in other countries (Ettl *et al.*, 2018; Kim and Kim, 2023).

The second stage was the implementation of tests on a dynamometer bench, according to the proposed load cycle (Fig. 2), allowing the ecological properties of the tractor engine to be accurately determined. In doing so, it was recognised that the large variation in loads during the dynamometer tests must be reflected in the level of exhaust emissions and fuel consumption.

The areas presented in the diagram are proportional to the share of the individual phases, and the obtained values of the emission of selected components of the exhaust gases of the tested engines served as representative values for the two sets, into which the agricultural tractors registered in the voivodship were classified in the following part of this study.

The tests were carried out on a dynamometer bench in the laboratory of the Vehicle Operation Department – Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology in Szczecin (Pol.: Katedra Eksploatacji Pojazdów – Wydział Inżynierii Mechanicznej i Mechatroniki, Zachodniopomorski Uniwersytet Technologiczny w Szczecinie).

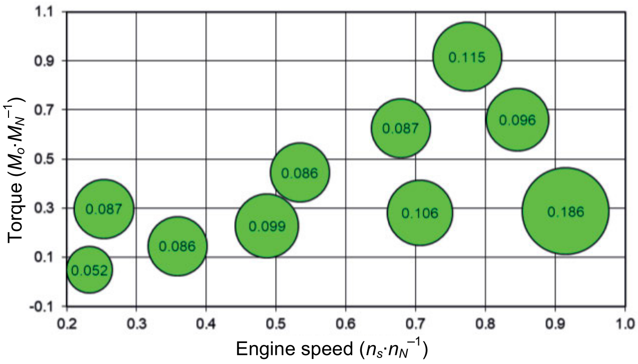

Fig. 2. 10-phase tractor load cycle; M_o = engine torque, M_N = engine torque at rated power, n_s = engine speed, n_N = engine speed at rated power; source: own study

Due to the wide variety of tractor engines found in agriculture in terms of age, it was considered that the research would be carried out on two representative engines. The test subjects were therefore two diesel engines (Photo 1):

a) Andoria 4CTi90-1BE6 (engine A) – an older generation engine with a traditional fuel injection system (Andoria-Mot, 2005),
b) Fiat 1.3 JTD MultiJet (engine B) – a high-tech engine with a common rail (CR) injection system (Fiat, 2025).

The basic technical parameters of the engines are shown in Table 1.

Ekodiesel Ultra, a diesel produced by Orlen S.A. with the addition of 7% fatty acid methyl esters (FAME), was used in the experimental tests. The fuel contained the following additives: detergents, lubricity additives, anticorrosive additives, additives improving oxidation resistance, increasing the cetane number, deemulsifiers, depressants, anti-foaming, biocidal additives and a fuel tracer.

Exhaust gas analysis was carried out using a Capelec CAP 3201 multi-component analyser on a dynamometer bench according to a fixed load cycle. The analyser is capable of measuring carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC) converted to hexane equivalent (C_6H_{14}) and oxygen (O_2) concentration in the exhaust gas. It is also equipped with a kit for measuring NO_x levels.

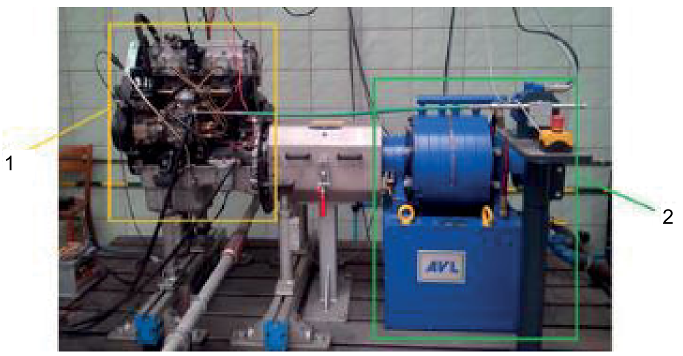

Photo 1. View of test bench; *1* = Andoria 4CTi90-1BE6, *2* = AVL Dynoperform 160 brake, *3* = Fiat 1.3 JTD Multijet, *4* = Elektromex EMX-100 electromechanical brake (phot.: *J. Wojciech*)

Table 1. Technical data of tested diesel engines (4CTi90-1BE6, 4CTi90-1BE engine manual, Fiat MultiJet 1.3 engine manual)

Specification	Characteristics depending on the engine type	
	A	B
Engine type description	four-stroke turbodiesel	four-stroke turbodiesel with fixed geometry turbo-charger, no DPF
Fuel injection	indirect, into the vortex chamber	direct, common rail
Cylinder number and arrangement	4, vertical	4, vertical
Engine volume (dm^3)	2,417	1,248
Compression ratio	20.6	18.1
Rated power (kW)	66	51
Rotational speed at rated power (rpm)	4,100	4,000
Maximum torque (Nm)	205	145
Speed at maximum torque (rpm)	2,000–2,500	1,500
Specific fuel consumption at maximum torque ($g \cdot kWh^{-1}$)	~270	nd

Explanations: DPF = diesel particulate filter, nd = no data.
Source: own study.

Prior to measurement on the dynamometer bench, the engine warmed up to nominal operating temperature (oil temperature of at least 80°C). Then, after placing the analyser's measuring probe in the engine's exhaust system, the aspirated exhaust gas flowed through a tube to the measuring chambers (CO, NO_x, HC, CO_2) or sensor (O_2).

The values of engine speed, usable torque and hourly fuel consumption were recorded at the individual measuring points.

The third stage of the research consisted in calculating and assigning annual emissions to the individual districts of the province on the basis of data obtained from Central Register of Vehicles and Drivers (Pol.: Centralna Ewidencja Pojazdów i Kierowców).

The following tractor parameters were analysed: make, type and model, year of manufacture, engine capacity and power. Assignment of the tractor to the appropriate engine category (A or B) was carried out on the basis of the power and year of manufacture of the registered vehicle.

The Central Register of Vehicles and Drivers database contains 22,764 tractors registered in the province. However, due to the occurrence of formal deficiencies preventing the identification of the agricultural vehicle, 22,056 items, or 96.88% of the population, were finally accepted for further elaboration.

RESULTS AND DISCUSSION

After determining a regionally appropriate equivalent load cycle and performing tests on a dynamometer bench, the energy and environmental parameters of the tested engines were obtained (Tabs. 2, 3). The determined weighted averages over the 10-phase cycle enabled the subsequent test stages to be carried out.

After analysis of the data (second stage of the study), the proportion of tractors older than 20 years was found to be over 70%. This environmentally unfavourable share does not only apply to the study area. For Poland as a whole, the average tractor replacement rate is 3–4% per year, which means that most tractors are in use for more than 20 years (avg. age 25 years) (Lorencowicz and Uziak, 2020). Similar insights were obtained by Osuch *et al.* (2017) after analysing a random selection of 30 farms in the Krotoszyn district. Majority of the tractors tested there (more than 63%) did not meet exhaust emission standards.

It is generally accepted that it makes economic sense to purchase an agricultural tractor for those farms where the annual operation will be a minimum of 500 h, up to almost 800 h. With such use, the expected use time of the tractor is 15–20 years or 10.000–12.000 operating hours. The annual use of tractors depends on the amount of work carried out on farms and increases with increasing farm area and engine power (Maciulewski and Pawlak, 2014). According to Parafiniuk, Kocira and Sawa (2012), tractors are used annually between ~350 h and 400 h. Similar values are described by Maciulewski and Pawlak (2014) – the average annual use of tractors on the farms they studied ranged from 199 h to 582 h (avg. 422 h). Similarly, Koniuszy (2010) claims, defining the length of tractor operating time per year as no more than 500 h, mostly 300 h, with an average tractor load of 60–70% of rated power.

In comparison, in north-western Turkey, annual tractor is used on farms with an area of 10 ha or less averaged 384 h, while on farms with an area of 40 ha or more – avg. 551 h (Saglam and Akdemir, 2002). In China, the annual use of agricultural tractors was put at 276 h (Ai *et al.*, 2021) and 430 h (Fu *et al.*, 2013).

Analysis of the data has shown that Pyrzyce district stands out both in terms of the highest number of agricultural tractors in relation to a given area (5.6 units per 100 ha agricultural land) and the actual power of agricultural tractors (300 kW). This may be mainly due to the higher power demand required to cultivate compact soils. On the other hand, the smallest number of such vehicles is in the Szczecinek district, with an average of 2.5 units per 100 ha agricultural land.

The realisation of the third stage of the research made it possible to obtain the final values of emission of selected components of exhaust gases from agricultural tractors from the area of particular districts. The annual exhaust emissions from agricultural tractors were: 1,062 Mg NO_x, 563 Mg CO and 341,486 Mg CO_2. The variation in NO_x and CO emissions

Table 2. Exhaust gas content and specific fuel consumption (g_e) determined over a 10-phase cycle for engine A (n_N = 4,100 rpm, M_N = 154 Nm)

Parameter	Phase number									
	1	2	3	4	5	6	7	8	9	10
n_s (rpm)	3,772	3,485	3,157	2,911	2,788	2,214	2,009	1,476	1,025	943
M_o (Nm)	52.2	118.8	165.6	50.4	113.4	81.0	41.4	27.0	54.0	9.0
Weight factor	0.19	0.1	0.11	0.11	0.09	0.08	0.1	0.08	0.09	0.05
NO_x (g·kWh^{-1})	4.77	2.97	1.38	2.81	2.14	1.95	2.78	3.32	2.96	11.50
– min.	1.38									
– max.	11.50									
– median	2.89									
– *SD*	2.75									
– average	3.40									
CO_2 (g·kWh^{-1})	1,086	767	475	921	671	756	1,091	1,439	974	4,359
– min.	475.00									
– max.	4,359.00									
– median	947.50									
– *SD*	1,065.42									
– average	1,087.00									
O_2 (g·kWh^{-1})	3,147	1,061	829	3,473	1,253	1,945	4,566	7,387	3,184	34,121
– min.	829.00									
– max.	34,121.00									
– median	3,165.50									
– *SD*	9,524.93									
– average	4,486.00									
CO (g·kWh^{-1})	0.4	0.0	0.0	0.0	0.0	0.0	2.4	6.1	0.1	26.1
– min.	0.00									
– max.	26.10									
– median	0.05									
– *SD*	7.75									
– average	2.11									
g_e (g·kWh^{-1})	437	289	270	381	276	279	377	463	315	1,440
– min.	270.00									
– max.	1,440.00									
– median	346.00									
– *SD*	335.64									
– average	406.00									

Explanations: n_N, M_N, n_s, and M_o as in Fig. 2, *SD* = standard deviation.
Source: own study.

between counties is shown in Figure 3a, while CO_2 emissions are shown in Figure 3b. The Gryfino district emits the most pollutants, which may be related to its largest area of agricultural land of all the counties in question. From the agricultural area (95,370 ha) of this most emitting county, agricultural tractors produced annually: 104.5 Mg NO_x, 55.8 Mg CO and 33,600 Mg CO_2. The Police district (21,945 ha agricultural land) has by far the smallest share of environmental pollution from exhaust gases. Annual emissions are: 15.9 Mg NO_x, 8.79 Mg CO and 5,100 Mg CO_2. In relation to the average annual NO_x emissions (15,000 Mg) from industrial plants located in the voivodship, emissions from agricultural tractors account for only 7.1% of this value. However, compared to CO emissions (2,500–5,000 Mg·year^{-1}) from industry, emissions from tractors account for 11.3–22.5%.

The percentage share of the districts in the voivodship's CO_2 emissions is shown in Figure 4. The Gryfino district has a share of

Table 3. Exhaust gas content and specific fuel consumption (g_e) determined over a 10-phase cycle for engine B (n_N = 4,000 rpm, M_N = 122 Nm)

Parameter	Phase number									
	1	2	3	4	5	6	7	8	9	10
n_s (rpm)	3,680	3,400	3,080	2,840	2,720	2,160	1,960	1,440	1,000	920
M_o (Nm)	23.2	52.8	73.6	22.4	50.4	36.0	18.4	12.0	24.0	4.0
Weight factor	0.19	0.1	0.11	0.11	0.09	0.08	0.1	0.08	0.09	0.05
NO_x (g·kWh^{-1})	1.76	2.02	3.08	3.25	1.83	1.82	2.56	2.48	4.33	17.18
– min.	1.76									
– max.	17.18									
– median	2.52									
– *SD*	4.45									
– average	3.25									
CO_2 (g·kWh^{-1})	1,283	599	568	861	593	712	979	1,280	993	4,200
– min.	568.00									
– max.	4,200.00									
– median	920.00									
– *SD*	1,028.91									
– average	1,071.00									
O_2 (g·kWh^{-1})	1,392	544	314	2,148	648	978	2,507	3,445	1,596	28,450
– min.	314.00									
– max.	28,450									
– median	1,494.00									
– *SD*	8,135.36									
– average	2,819.00									
CO (g·kWh^{-1})	0	0	0	0	0	0	0	0	0	0
– min.	0									
– max.	0									
– median	0									
– *SD*	0									
– average	0									
g_e (g·kWh^{-1})	312	240	226	306	232	242	261	350	282	1,530
– min.	226.00									
– max.	1,530.00									
– median	271.50									
– *SD*	379.24									
– average	338.00									

Explanations: as in Tab. 2.
Source: own study.

almost 10%, in contrast to the Police district with 1.5% of emissions. The differentiation of CO_2 emissions between individual districts in the case of the two districts emitting the most, namely Gryfino and Stargard may be related to their largest area of agricultural area, which is further confirmed by the largest number of agricultural tractors used in their area, respectively: 4,056 units and 3,838 units.

The following counties, in terms of CO_2 emissions, no longer showed a close correlation with the area of agricultural land, so it must depend on other factors, such as locally different soil types and therefore different energy demand. The Pyrzyce district, which is twelfth in terms of the agricultural area in the study region, is fourth in terms of CO_2 emissions (7.2% share in the region). The juxtaposition of the number and power of tractors per 100 ha of agricultural area in the districts of the voivodship definitely confirms the greatest involvement of the number of tractors and their power in the Pyrzyce district.

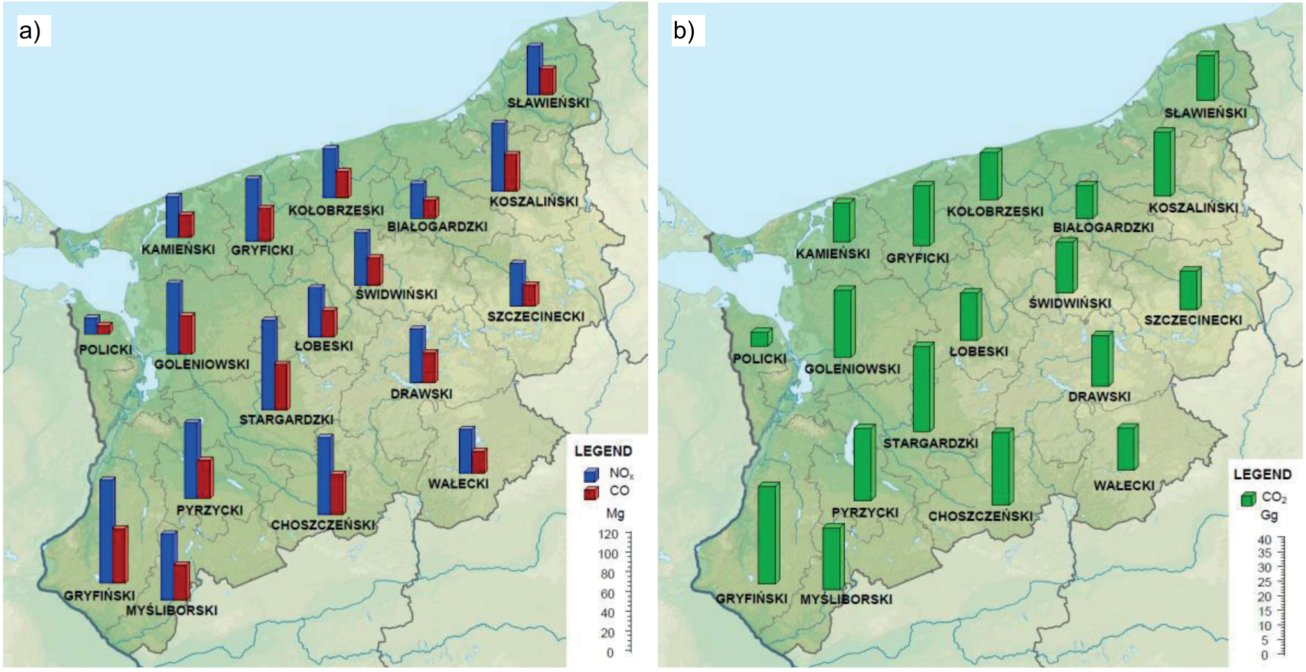

Fig. 3. Annual emissions of greenhouse gases from agricultural tractors in districts of the West Pomeranian Voivodship: a) nitrogen oxides (NO_x) and carbon monoxide (CO), b) carbon dioxide; source: own study

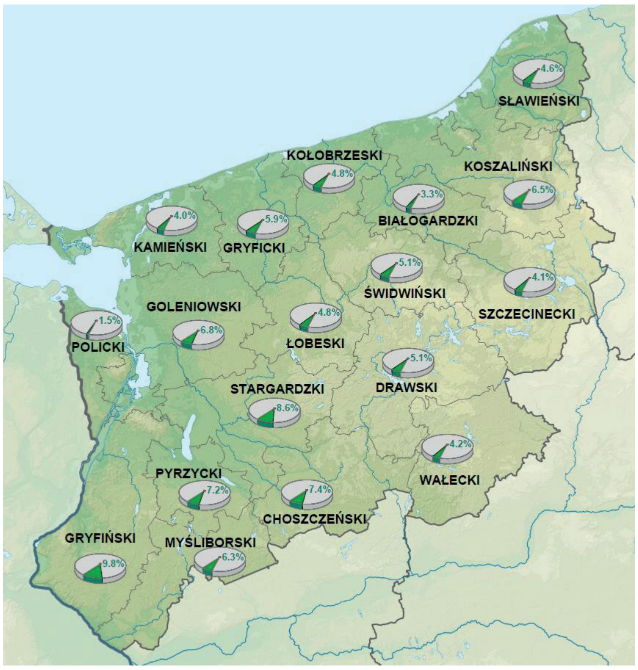

Fig. 4. Percentage of carbon dioxide (CO_2) emitted annually from agricultural tractors in relation to the area of the districts analysed; source: own study

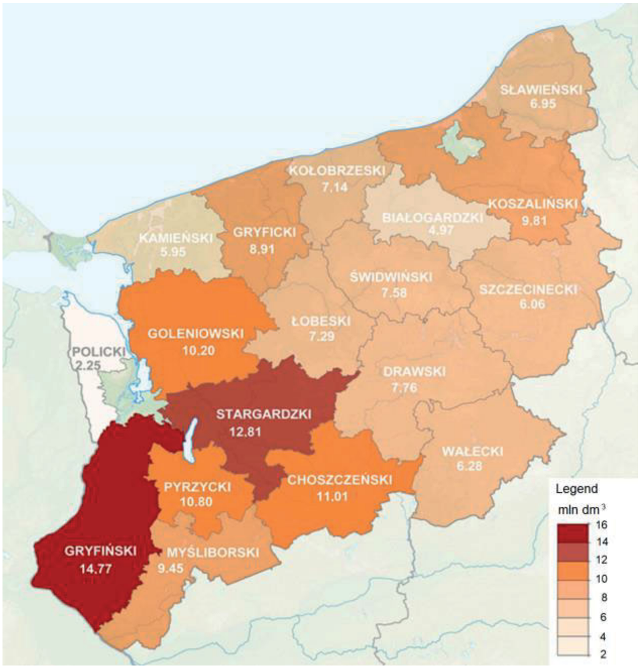

Fig. 5. Variation in annual demand for fuel used to power agricultural tractors performing work in a specific district; source: own study

The total amount of fuel burned per year by agricultural tractors engaged in work in the province is shown in Figure 5.

Analysing the share of agricultural tractors not subject to any emission standard, also in this aspect, the Pyrzyce district is dependent on the energy intensity of cultivating compacted soil, as the increased emissions are not due to the use of outdated and uneconomical tractors. Slightly higher emissions occur in the Choszczno district (7.4%), which is ranked sixth in terms of the agricultural area and has 84 more registered tractors than the Pyrzyce district. The compactness of the soil is the factor that most influences the performance of soil working machinery and the traction class of the tractor working with the machine, resulting in higher emissions of harmful compounds from exhaust gases into the atmosphere.

After analysis, it can be concluded that the amount of harmful exhaust compounds emitted is directly related to the amount of fuel used to drive internal combustion engines (Fig. 5). The highest demand for fuel to drive agricultural tractors is in the Gryfino district (~15 mln $dm^3 \cdot year^{-1}$) and the lowest in the Police district (~2 mln $dm^3 \cdot year^{-1}$). The highest fuel consumption occurs in the south-western area of the West Pomeranian Voivodship.

The differences in fuel consumption and exhaust emissions between individual districts are mainly due to agricultural production profiles. In districts located closer to large cities, agricultural production is much lower, as shown in the results.

Based on the results of the study, the following conclusions were drawn:

– the annual emission of exhaust compounds from agricultural tractors from the area of the West Pomeranian Voivodship is: 1,062 Mg NO_x, 563 Mg CO and 341,486 Mg CO_2;
– the highest amount of pollutants from fuel combustion by tractors engines engaged in agricultural work in the West Pomeranian Voivodship is emitted in the Gryfino district, while the smallest negative emissions were found in the Police district;
– tractors that have been in use for more than 20 years are responsible for the highest emissions of harmful compounds in exhaust gases.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Ai, Y. *et al.* (2021) "Quantifying air pollutant emission from agricultural machinery using surveys – A case study in Anhui, China," *Atmosphere*, 12(4), 440. Available at: https://doi.org/10.3390/atmos12040440.

Andoria-Mot (2005) *Silnik wysokoprężny 4CTi90-1BE6 ... EURO 3 (66 kW), 4CTi90-1BE ... EURO 3 (75 kW). Instrukcja obsługi [Internal combustion-ignition engine 4CTi90-1BE6 ... EURO 3 (66 kW), 4CTi90-1BE ... EURO 3 (75 kW). Operating manual]*. Andrychów. Available at: https://honkerteam.pl/wp-content/uploads/2018/01/Instrukcja-obslugi-silnika-4CTi90-1BE6-Euro3.pdf (Accessed: June 10, 2025).

Angelucci, L. and Mattetti, M. (2024) "The development of reference working cycles for agricultural tractors," *Biosystems Engineering*, 242, pp. 29–37. Available at: https://doi.org/10.1016/j.biosystemseng.2024.04.004.

Antosik, G. (2018) "Technologie silnikowe – Czas na Stage V [Engine technologies – Time for Stage V]," *ATB Aktualności Techniki Budowlanej*, 06 September. Available at: https://atbudownictwo.pl/artykul/technologie-silnikowe-czas-na-stage-v (Accessed: June 10, 2025).

EC (2025) *Fit for 55*. Brussel: European Council. Available at: https://www.consilium.europa.eu/en/policies/fit-for-55/ (Accessed: June 25, 2025).

EEA (2017) "Air quality in Europe – 2017," *EEA Report*, 13/2017. Available at: https://www.eea.europa.eu/en/analysis/publications/air-quality-in-europe-2017 (Accessed: June 25, 2025).

Engel, H. *et al.* (2020) *Carbon-neutral Poland 2050. Turning a challenge into an opportunity*. McKinsey & Company. Available at: https://www.mckinsey.com/pl/~/media/mckinsey/locations/europe%20and%20middle%20east/polska/raporty/carbon%20neutral%20poland%202050/carbon%20neutral%20poland_mckinsey%20report.pdf (Accessed: June 10, 2025).

Ettl, J. *et al.* (2018) "Transfer of agricultural work operation profiles to a tractor test stand for exhaust emission evaluation," *Biosystems Engineering*, 176, pp. 185–197. Available at: https://doi.org/10.1016/j.biosystemseng.2018.10.016.

Fiat (2025) *Fiat Linea owner handbook*. Available at: https://aftersales.fiat.com/eLumData/EN/00/110_LINEA/00_110_LINEA_603.81.860_EN_01_12.10_L_LG/00_110_LINEA_603.81.860_EN_01_12.10_L_LG.pdf (Accessed: June 10, 2025).

Fu, M.L. *et al.* (2013) "Characteristics of agricultural tractors emissions under real-world operating cycle," *Transactions of the Chinese Society of Agricultural Engineering*, 29, 6, pp. 42–48. [In Chinese].

GIOŚ (2025a) *Bieżące dane pomiarowe [Current measurement data]*. Warszawa: Główny Inspektorat Ochrony Środowiska. Available at: https://powietrze.gios.gov.pl/pjp/current (Accessed: June 10, 2025).

GIOŚ (2025b) *Województwo zachodniopomorskie [West Pomeranian Voivodeship]*. Warszawa: Główny Inspektorat Ochrony Środowiska. Available at: http://www.gios.gov.pl/images/dokumenty/pms/raporty/ZACHODNIOPOMORSKIE.pdf (Accessed: June 10, 2025).

Götz, K. *et al.* (2025) "Agricultural load cycles: Tractor mission profiles from recorded GNSS and CAN bus data," *Data in Brief*, 60, 111494. Available at: https://doi.org/10.1016/j.dib.2025.111494.

Kim, M.H. and Kim, S.M. (2023) "Estimation of air pollutant emissions by tractor utilization in Korea," *Agriculture*, 13, 1811. Available at: https://doi.org/10.3390/agriculture13091811.

Kolasa-Więcek, A. (2012) "Analiza składowych głównych w ocenie zależności sposobu użytkowania gruntów z emisją gazów cieplarnianych z rolnictwa [Principal Component Analysis for evaluating the relationship between land use practices and agricultural greenhouse gas emissions]," *Inżynieria Rolnicza*, 2(137), pp. 105–112. Available at: https://ir.ptir.org/artykuly/pl/137/IR%28137%29_3200_pl.pdf (Accessed: June 25, 2025).

Konieczna, A., Roman, K. and Rzodkiewicz, W. (2023) "Fuel consumption, emissions of air pollutants and opportunities for reducing CO_2 emissions from linear sources in the model rural municipality," *Energies*, 16, 5553. Available at: https://doi.org/10.3390/en16145553.

Koniuszy, A. (2010) *Identyfikacja stanów obciążeń ciągnika rolniczego [Identification of load states of an agricultural tractor]*. Szczecin: Zachodniopomorski Uniwersytet Technologiczny w Szczecinie.

Koniuszy, A. and Nadolny, R. (2007) "*Układ do monitoringu pracy ciągnika [The manner of monitoring of tractor's operation and device for its performance]*. Urząd Patentowy Rzeczypospolitej Polskiej. Patent specification: Pat. 215773. Appl. no. P.381892. Date of filling 04.03.2007. Date of publ. 15.09.2008 (Biuletyn Urzędu Patentowego 19/2008). Available at: https://api-ewyszukiwarka.pue.uprp.gov.pl/api/collection/9c381e922be537047fb8ecbed6eb0de9#search=381892 (Accessed: June 10, 2025).

Kowalski, J. (2012) "Stan i wykorzystanie parku maszynowego w gospodarstwach ekologicznych o zróżnicowanej powierzchni i strukturze użytków rolnych [Condition and use of a machinery park in ecological farms of a varied area and structure of arable lands]," *Inżynieria Rolnicza*, 4, pp. 171–180. Available at: https://ir.ptir.org/artykuly/pl/139/IR(139)_3271_pl.pdf (Accessed: June 25, 2025).

Lorencowicz, E. and Uziak, J. (2020) "Regional structure of tractor market in Poland," *Agricultural Engineering*, 24(3), pp. 51–62. Available at: https://doi.org/10.1515/agriceng-2020-0026.

Lovarelli, D. and Bacenetti, J. (2019) "Exhaust gases emissions from agricultural tractors: State of the art and future perspectives for machinery operators," *Biosystems Engineering*, 186, pp. 204–

213. Available at: https://doi.org/10.1016/j.biosystemseng.2019.07.011.

Maciulewski, B. and Pawlak, J. (2014) "Wykorzystanie ciągników w rolnictwie Polski Północno-Wschodniej [Tractor Utilization in the Agriculture of North-Eastern Poland]," *Problemy Inżynierii Rolniczej*, 1(83), pp. 21–30. Available at: https://bibliotekanauki.pl/articles/239424 (Accessed: June 25, 2025).

Mattetti, M. *et al.* (2021) "Outlining the mission profile of agricultural tractors through CAN-BUS data analytics," *Computers and Electronics in Agriculture*, 184, 106078. Available at: https://doi.org/10.1016/j.compag.2021.106078.

Merkisz, J. (1999) *Ekologiczne problemy silników spalinowych [Environmental concerns related to internal combustion engines]*. Poznań: Wyd. Politechnika Poznańska.

Muzalewski, A. (2015) *Zasady doboru maszyn rolniczych w ramach PROW na lata 2014–2020 [Criteria for selecting agricultural machinery within the RDP 2014–2020 Framework]*. Warszawa: Instytut Technologiczno-Przyrodniczy Oddział w Warszawie. Available at: https://www.gov.pl/web/arimr/vii-narzedzia-pomocnicze (Accessed: June 25, 2025).

Osuch, A. *et al.* (2017) "Ecologization of farms based on exhaust emission standards of agricultural machines used in Krotoszyn country," *Journal of Research and Applications in Agricultural Engineering*, 62(4), pp. 50–53. Available at: https://www.cabidigitallibrary.org/doi/pdf/10.5555/20183099295 (Accessed: June 25, 2025).

Parafiniuk, S., Kocira, S. and Sawa, J. (2012) "Teoretyczne i praktyczne wykorzystanie środków transportowych w gospodarstwach rodzinnych [Theoretical and practical use of the transport equipment in family farms]," *Logistyka*, 4, pp. 1160–1167.

Pawlak, J. (2002) "Zużycie energii w rolnictwie w Polsce i na świecie [Energy consumption in agriculture in Poland and worldwide]," in *VII Międzynarodowa Konferencja Naukowa Teoretyczne i aplikacyjne problemy inżynierii rolniczej w aspekcie przystosowania do programów badawczych w UE [7th International Scientific Conference: Theoretical and Applied Problems of Agricultural Engineering in the Context of Adaptation to EU Research Programmes]*, Polanica Zdrój 11–14 June, 2002, pp. 609–612.

Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC (Text with EEA relevance). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1628 (Accessed: October 23, 2025).

Saetti, M. *et al.* (2021) "On the power demands of accessories on an agricultural tractor," *Biosystems Engineering*, 206, pp. 109–122. Available at: https://doi.org/10.1016/j.biosystemseng.2021.03.015.

Saglam, C. and Akdemir, B. (2002) "Annual usage of tractors in North-West Turkey," *Biosystems Engineering*, 82, pp. 39–44. Available at: https://doi.org/10.1006/bioe.2002.0046.

Singh, G. (2006) "Estimation of a mechanization index and its impact on production and economic factors – a case study in India," *Biosystems Engineering* 93(1), pp. 99–106. Available at: https://doi.org/10.1016/j.biosystemseng.2005.08.003.

Staniszewski, P. (2014) "Kolejna norma na celowniku UE [Another standard targeted by the EU]," *Tygodnik Poradnik Rolniczy*, 25th August. Available at: https://www.tygodnik-rolniczy.pl/articles/technika/kolejna-norma-na-celowniku-ue/ (Accessed: June 10, 2025).

Wahlig, W. (2019) *Program ochrony powietrza wraz z planem działań krótkoterminowych dla strefy zachodniopomorskiej [Air protection programme including a short-term action plan for the West Pomeranian zone]*. Szczecin: ATMOTERM S.A. Available at: https://bip.rbip.wzp.pl/sites/bip.wzp.pl/files/articles/zalacznik-do206.pdf (Accessed: June 10, 2025).

Wasilewski, J. *et al.* (2020) "Assessment of CO_2 emission by tractor engine at varied control settings of fuel unit," *Agricultural Engineering*, 24(4), pp. 105–115. Available at: https://agriceng.ptir.org/index.php/AgricEng/article/view/265.

WHO (2016) *Ambient air pollution: A global assessment of exposure and burden of disease*. Geneva: World Health Organization.