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CHANGES IN THE EMISSION OF TOXIC COMPOUNDS FROM FARMING MACHINERY USED IN POLAND BETWEEN 2011 AND 2013

Summary

The article presents changes in the total annual emission of limited toxic compounds released into the atmosphere together with exhaust gases from farming machinery used in Poland between 2011 and 2013. The calculations were based on the amounts of the excise tax refund for 'farming' fuel, which were expended from the budget during the years under study. The methodology of calculations presented by the authors in the previous publication was also used in this study. It was based on emission limits included in Directive 97/68/EC and on exceeding of these limits during the operation of farming machinery under typical field conditions, which was presented by Lindgren. The fuel consumed by the whole population of farming machinery (including tractors, mobile and stationary machinery with diesel engines) has the greatest influence on the total emission of toxic compounds. This dependence was particularly noticeable when 2012 and 2013 were compared. In 2012 the lowest consumption of farming fuel was noted, i.e. 601.7 million tonnes. It resulted in the lowest total emission of toxic compounds, i.e. 88,188 tonnes. In 2013 the emission of toxic compounds was greater by 6.7% than in the previous year and reached 94,137 tonnes. It was caused by the highest fuel consumption during the years under study, i.e. 646.9 million tonnes.
***Key words**: emission, toxic compounds, farming machinery, fuel, Directive 97/68/EC*

ZMIANY EMISJI ZWIĄZKÓW TOKSYCZNYCH Z MASZYN ROLNICZYCH EKSPLOATOWANYCH W POLSCE W LATACH 2011-2013

Streszczenie

W pracy przedstawiono zmiany całkowitej rocznej emisji do atmosfery limitowanych związków toksycznych uwalnianych wraz ze spalinami przez maszyny rolnicze eksploatowane w polskim rolnictwie w latach 2011-2013. Jako podstawę do obliczeń przyjęto kwoty zwrotu podatku akcyzowego za tzw. paliwo rolnicze, które wydatkowano z budżetu w analizowanych latach. Do obliczeń zastosowano metodykę przedstawioną przez autorów we wcześniejszej publikacji, bazującą na limitach emisji zawartych w dyrektywie 97/68/WE oraz przedstawionych przez Lindgren'a przekroczeń tych limitów podczas pracy maszyny rolniczych w typowych warunkach polowych. Największy wpływ na całkowitą emisję związków toksycznych ma zużycie paliwa przez całą populację maszyn rolniczych (w tym ciągników, maszyn samobieżnych oraz stacjonarnych wyposażonych w silniki ZS). Zależność ta jest szczególnie widoczna pomiędzy latami 2012 oraz 2013. W 2012 r. zanotowano najniższe zużycie "paliwa rolniczego" wynoszące 601,7 mln t, co przełożyło się na najmniejszą sumaryczną emisję związków toksycznych wynoszącą 88 188 t. Natomiast w 2013 r. emisja związków toksycznych wzrosła do poziomu 94 137 t, co stanowi wzrost o 6,7% w stosunku do roku poprzedniego. Było to spowodowane najwyższym, w analizowanych latach, zużyciem paliwa równym 646,9 mln t.
***Słowa kluczowe**: emisja, związki toksyczne, maszyny rolnicze, paliwo, dyrektywa 97/68/WE*

1. Introduction

Agriculture is a branch of economy with the main task to provide food to humans and to manage natural resources with minimal burden to the natural environment. However, the rapid development of farming technology in the second half of the 20th century noticeably increased the consumption of fossil fuels. As a result, there was increased emission of toxic compounds which were released with exhaust fumes into the atmosphere. In view of the fact that the use of mobile machinery and tractors is an important part of the agricultural production technology, constructors of engines used in farming machinery tried to optimise the process of combustion so as to limit fuel consumption and maximise the power and torque generated by engines.

However, in the second half of the 1990s the European Commission gave priority to ecology and limitation of the emission of toxic compounds, which are hazard to health and life. Directive 97/68/EC [4] was issued and implemented. It limits the emission of gas and particulate pollution from combustion engines installed in non-road mobile machinery. This category comprises engines used in tractors, mobile farming machinery as well as stationary machinery, such as generator sets and pump units.

Later the directive was revised a few times. Each time more rigorous limits of permissible emission were introduced. The priority of the directive was to limit the emission of carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbons (HC) and particulate matter (PM) from diesel engines. Tables 1-3 show applicable limits at individual stages of limitation of emission and dates when the stages were introduced.

What needs to be explained is the fact that when a new stage of limitation of the emission of toxic compounds becomes applicable, for one year engine and machinery manufacturers can still release products made before the date of introduction of the new stage.

However, although the European Commission introduced limits on the emission of toxic compounds, in reality tractors cannot meet the requirements of Directive 97/68/EC.

Table 1. Emission limits introduced at stages I and II of Directive 97/68/EC [4]
Tab. 1. Limity emisji wprowadzone w etapach I i II dyrektywy 97/68/WE [4]

Engine category	Net power [kW]	Date of introduction	CO [g·(kWh)$^{-1}$]	HC	NO_x	PM
Stage I						
A	130 ≤ P ≤ 560	1999.01	5.0	1.3	9.2	0.54
B	75 ≤ P < 130	1999.01	5.0	1.3	9.2	0.70
C	37 ≤ P < 75	1999.04	6.5	1.3	9.2	0.85
Stage II						
E	130 ≤ P ≤ 560	2002.01	3.5	1.0	6.0	0.2
F	75 ≤ P < 130	2003.01	5.0	1.0	6.0	0.3
G	37 ≤ P < 75	2004.01	5.0	1.3	7.0	0.4
D	18 ≤ P < 37	2001.01	5.5	1.5	8.0	0.8

Table 2. Emission limits introduced at stages IIIA and IIIB of Directive 97/68 EC [4]
Tab. 2. Limity emisji wprowadzone w etapach IIIA i IIIB Dyrektywy 97/68/WE [4]

Engine category	Net power [kW]	Date of introduction	CO [g·(kWh)$^{-1}$]	HC	HC+NO_x	NO_x	PM
Stage IIIA							
H	130 ≤ P ≤ 560	2006.01	3.5	-	4.0	-	0.2
I	75 ≤ P < 130	2007.01	5.0	-	4.0	-	0.3
J	37 ≤ P < 75	2008.01	5.0	-	4.7	-	0.4
K	19 ≤ P < 37	2007.01	5.5	-	7.5	-	0.6
Stage IIIB							
L	130 ≤ P ≤ 560	2011.01	3.5	0.19	-	2.0	0.025
M	75 ≤ P < 130	2012.01	5.0	0.19	-	3.3	0.025
N	56 ≤ P < 75	2012.01	5.0	0.19	-	3.3	0.025
P	37 ≤ P < 56	2013.01	5.0	-	4.7	-	0.025

Table 3. Emission limits introduced at stage IV of Directive 97/68/EC [4]
Tab. 3. Limity emisji wprowadzone w etapie IV Dyrektywy 97/68/WE [4]

Engine category	Net power [kW]	Date of introduction	CO [g·(kWh)$^{-1}$]	HC	NOx	PM
Stage IV						
Q	130 ≤ P ≤ 560	2014.01	3.5	0.19	0.4	0.025
R	56 ≤ P < 130	2014.10	5.0	0.19	0.4	0.025

This fact is proved by the results of studies conducted at a few centres [6, 7, 9, 12]. Lindgren [7] gave the most vivid presentation by comparing the results of emission measurements for medium and high-power tractors. In comparison with the values of specific emissions achieved under homologation conditions following Directive 97/68/EC (test C1 according to ISO 8178), which are marked as 100% in Figure 1, the specific emissions of carbon monoxide and hydrocarbons are even a few dozen per cent greater when the machines are used for typical farming operation in the field.

This information was used to develop a method of estimation of the actual total emission of toxic compounds by combustion engines used in Polish agriculture [3].

The aim of the study was to estimate the total emission of toxic compounds, i.e. carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter from engines installed in tractors and farming machinery used in Polish agriculture between 2011 and 2013. This analysis will enable assessment how the progressing modernisation of tractors and farming machinery used on farms influences the scale of environment pollution with toxic gases.

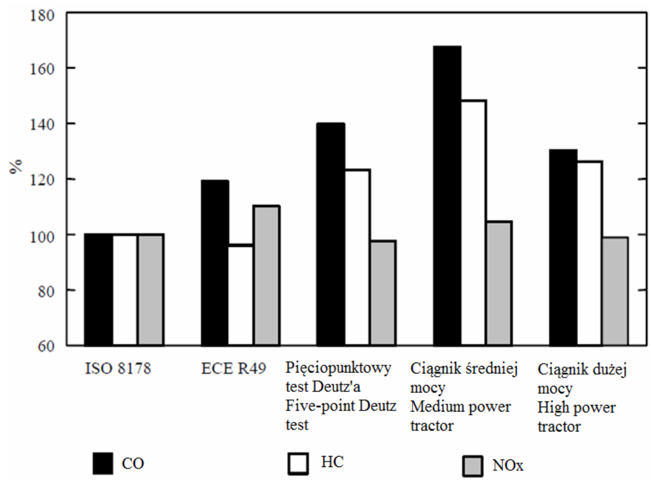

Fig. 1. Relative values of real specific emission compared with the results of C1 test in accordance with ISO 8175 for medium and high-power tractors [7]
Rys. 1. Względne wartości rzeczywistej emisji jednostkowej w stosunku do wyników testu C1 wg ISO 8175 dla ciągników średniej i dużej mocy [7]

Table 4. The amount of the annual excise tax refund, the weight of consumed ‘farming’ fuel and the mechanical energy produced by consumption of this fuel during the years under analysis
Tab. 4. Kwoty rocznego zwrotu podatku akcyzowego, masy zużytego "paliwa rolniczego" oraz energia mechaniczna wytworzona w wyniku zużycia tego paliwa w analizowanych latach

Budget year	Amount of excise tax refund	Amount of excise tax refund per litre of fuel	Weight of "farming" fuel subject to excise tax refund	Mechanical energy generated by engines in farming machinery
	[PLN]	[PLN · dm^{-3}]	[kg]	[kWh]
2011	635.0m [11]	0.85 [11]	620.1m	$2.20 \cdot 10^9$
2012	688.7m [2]	0.95 [2]	601.7m	$2.13 \cdot 10^9$
2013	756.0m [10]	0.97 [2]	646.9m	$2.29 \cdot 10^9$

Source: own work / Źródło: opracowanie własne

2. Material and methods

The amount of the global emission of toxic compounds was estimated on the basis of the annual ‘farming’ fuel consumption in Poland. It was determined by means of the amounts spent from the budget on excise tax refund during the years under analysis (Table 4).

The annual fuel consumption (expressed as dm^3) was used to calculate the weight of consumed fuel, where a diesel density of 0.830 $kg \cdot dm^{-3}$ was assumed. When the weight of fuel consumed by tractors and farming machinery and the average specific fuel consumption (it was estimated at 282 $g \cdot (kWh)^{-1}$ in an earlier study) were known [3], it was possible to calculate the amount of energy generated by engines installed in tractors and farming machinery working in Polish agriculture during the years under analysis.

In order to estimate the global emission of toxic compounds it is necessary to know the age structure of tractors and farming machinery used in Poland between 2011 and 2013. There are some problems with obtaining data about the age of farming machinery, because there are no databases with this information in Poland. Neither mobile farming machinery (combine harvesters, forage harvesters, sprayers, etc.) nor stationary machinery (pump units and generator sets) needs to be registered. The only source of information about the age structure of machinery used in Polish agriculture is the Central Register of Vehicles, as it provides information about tractors, which need to be registered. However, according to press reports, there are also errors in the database of the Central Register of Vehicles, but they usually provide wrong information about the oldest vehicles [1, 5]. Due to the lack of more credible sources of information and in view of the fact that the National Agricultural Census of 2010 [8] showed that the number of tractors used on Polish farms (1,466,334) was nearly ten times greater than the number of combine harvesters (152,140), which was the second most numerous category of machinery, we assumed that the age structure of tractors could represent the whole population of farming machinery (including tractors, mobile and stationary machinery with diesel engines) used in Polish agriculture. The data obtained from the Central Register of Vehicles (Table 5) were used to estimate the percentage of tractors meeting the requirements of individual stages of emission limitation under Directive 97/68/EC among the population of tractors registered in Poland during the years under study. Table 6 shows the results. Column ‘0’ shows the number of tractors manufactured before the Directive became applicable.

Table 5. Farm tractors registered in Poland between 1999 and 2013
Tab. 5. Ciągniki rolnicze zarejestrowane w Polsce w latach 1999-2013

Year	Total number of tractors registered	Number of new tractors registered
	[pieces]	[pieces]
1999	1,333,371	7,373
2000	1,341,666	8,295
2001	1,352,197	10,531
2002	1,364,579	12,382
2003	1,378,875	14,296
2004	1,391,117	12,242
2005	1,399,163	8,046
2006	1,410,697	11,534
2007	1,424,575	13,878
2008	1,438,117	13,542
2009	1,451,827	13,710
2010	1,466,334	14,507
2011	1,483,108	16,774
2012	1,502,245	19,137
2013	1,517,283	15,038

Source: own work / Źródło: opracowanie własne

Table 6. The percentage of individual groups of tractors in the total population of tractors registered in Poland between 2011 and 2013
Tab. 6. Udziały poszczególnych grup ciągników rolniczych w ogólnej populacji ciągników zarejestrowanych na terenie Polski w latach 2011-2013

Stage under 67/68/EC	2011		2012		2013	
	Tractors meeting requirements of stage	Population percentage	Tractors meeting requirements of stage	Population percentage	Tractors meeting requirements of stage	Population percentage
	[pieces]	[%]	[pieces]	[%]	[pieces]	[%]
IIIB	16,774	1.13	35,911	2.39	50,949	3.36
IIIA	67,171	4.53	67,171	4.47	67,171	4.43
II	57,497	3.88	57,497	3.83	57,497	3.79
I	15,668	1.06	15,668	1.04	15,668	1.03
0	1,325,998	89.41	1,325,998	88.27	1,325,998	87.39
Total	1,483,108	100.00	1,502,245	100.00	1,517,283	100.00

Source: own work / Źródło: opracowanie własne

In order to simplify further calculations we decided not to consider individual engine categories specified at consecutive stages of emission limitation. We assumed mean values of permissible emission limits for each stage (Table 7).

Table 7. Averaged toxic emission limits according to Directive 97/68/EC [4]
Tab. 7. Uśrednione limity emisji związków toksycznych wg Dyrektywy 97/68/WE [4]

Stage	CO $[g\cdot(kWh)^{-1}]$	HC $[g\cdot(kWh)^{-1}]$	NO_x $[g\cdot(kWh)^{-1}]$	PM $[g\cdot(kWh)^{-1}]$
0	11.00	2.60	18.40	1.36
I	5.50	1.30	9.20	0.68
II	4.75	1.20	6.75	0.43
IIIA	4.75	0.19	4.86	0.38
IIIB	4.63	0.19	3.28	0.03

Simultaneously, we assumed that the tractors manufactured before Directive 97/68/EC became applicable may have emitted twice as much toxic compounds as the engines meeting the requirements of stage I. This assumption was assumed by analogy to differences in permissible values of specific emissions between consecutive stages of emission limitation, where the average value was close to 50%.

In view of the aforementioned results of the study by Lindgren [7], we assumed that the emission values should be increased by relative growths of specific emission listed in Table 8.

Table 8. The assumed values of relative growth of specific emissions during actual field operation
Tab. 8. Przyjęte względne przyrosty emisji jednostkowej w warunkach rzeczywistej eksploatacji polowej

CO [%]	HC [%]	NO_x [%]	PM [%]
170.00	150.00	110.00	140.00

Source: own work / Źródło: opracowanie własne

The data shown above were used to determine the actual specific emission of individual toxic substances at consecutive stages of emission limitation. The following dependence was used:

$$E_i = \overline{E}_i \cdot \frac{P_{iw}}{100\%} \ [\text{g (kWh)}^{-1}], \quad (1)$$

where:
E_{ir} – the actual specific emission of individual toxic compounds,
$\overline{E_i}$ – averaged limits of emission of individual toxic compounds,
P_{iw} – the relative growth of specific emission.

The values of the actual specific emission of individual toxic compounds and the percentage of tractors meeting the requirements of individual stages of emission limitation among the total population of tractors operated in a particular year were used to calculate the averaged specific emission generated by the population of tractors. A weighted mean expressed with the following formula was used:

$$\overline{E_{iP}} = \left(\frac{U_0 \cdot E_{ir0} + U_I \cdot E_{irI} + U_{II} \cdot E_{irII}}{100\%}\right) + \left(\frac{U_{IIIA} \cdot E_{irIIIA} + U_{IIIB} \cdot E_{irIIIB}}{100\%}\right) \ [\text{g (kWh)}^{-1}], \quad (2)$$

where:
$\overline{E}_{iP}$ – the averaged actual emission of individual toxic compounds from the total population of machinery,
$U_0 \ldots U_{IIIB}$ – the shares of individual groups of machinery in the population.

The values above were used to calculate the global emission of each toxic compound in each year under study. It was the product of the average specific emission generated by the total population of machinery used in a particular year and the amount of mechanical energy generated by engines in the same year.

3. Results

The assumptions and calculations presented in this article resulted in the values of total emission of the toxic compounds under study from tractors and farming machinery used in Polish agriculture between 2011 and 2013. Table 9 shows the results.

Table 9. Total annual emissions of CO_2, CO, HC, NO_x and PM from agricultural machinery operated in Poland between 2011 and 2013
Tab. 9. Całkowita roczna emisja CO_2, CO, HC, NO_x oraz PM z maszyn rolniczych eksploatowanych w Polsce w latach 2011-2013

Year	CO [t]	HC [t]	NO_x [t]	PM [t]
2011	38,667	7,901	41,279	3,869
2012	37,258	7,577	39,645	3,708
2013	39,837	8,072	42,281	3,947

Source: own work / Źródło: opracowanie własne

Table 10. Total annual emissions of CO_2, CO, HC, NO_x and PM from agricultural machinery operated in Poland between 2011 and 2013, assuming that Directive 97/68/EC has not been implemented
Tab. 10. Całkowita roczna emisja CO_2, CO, HC, NO_x oraz PM z maszyn rolniczych eksploatowanych w Polsce w latach 2011-2013, przy założeniu, że Dyrektywa 97/68/WE nie została wdrożona

Year	CO [t]	HC [t]	NO_x [t]	PM [t]
2011	41,117	8,575	44,504	4,186
2012	39,900	8,321	43,186	4,063
2013	42,896	8,946	46,429	4,368

Source: own work / Źródło: opracowanie własne

In order to assess the influence of modernisation of tractors and farming machinery used in Polish agriculture on the scale of the environment pollution with toxic gases emitted into the atmosphere we made identical calculations, assuming that the emission from the whole population of tractors and farming machinery was at the level preceding the introduction of Directive 97/68/EC (Level '0', Table 7). Table 10 lists the results.

4. Conclusions

1. The amount of fuel consumed by farming machinery has the greatest influence on the estimated total emission of toxic compounds. This dependence is particularly noticeable when 2012 and 2013 are compared.

2. In 2012 the lowest farming fuel consumption was noted, i.e. 601.7 million tonnes. It resulted in the lowest total emission of toxic compounds, i.e. 88,188 tonnes. In 2013 the total toxic emission increased to 94,137 tonnes due to the highest fuel consumption in the years under study, i.e. 646.9 million tonnes.

3. The comparison of the total emission values in Tables 9 and 10 reveals that the modernisation of tractors and farming machinery used in Polish agriculture results in reduced toxic emission into the atmosphere. If we assume that the values from Table 10 are 100% emission, the most rapid favourable changes can be observed in the reduction of HC emission. Under Directive 97/68/EC the emission was reduced to 92.1% in 2011, whereas in 2013 it was reduced to 90.2%.

4. The reduction of PM emission was only slightly smaller (by about 0.2%). NO_x emission was limited more slowly by nearly 1%. CO emission was least reduced – in 2011 it amounted to 94.0% of the reference value (Table 10), whereas in 2013 it reached 92.9%.

5. The values of reduced toxic emissions are much slower than the decrease in the percentage of tractors which do not meet the requirements of Directive 97/68/EC. For example, in 2013 the share of those tractors amounted to 87.39%.

To sum up, we can suppose that the scale of using newer tractors and farming machinery is much greater than the scale of using older machinery, at least due to higher comfort and productivity. This situation should result in further reduction of the total toxic emission from tractors and farming machinery used in Poland. However, it is impossible to include this dependence in future emission estimates without surveying farm owners about the scale of using different generations of tractors and farming machinery.

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