Exhaust gases emissions from agricultural tractors: State of the art and future perspectives for machinery operators

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Abstract

Due to the increased attention paid to environmental sustainability, the environmental concerns that come from agricultural operations are of increasing worldwide importance. For agricultural operations, one of the most important issues focuses on exhaust gases emissions released from tractors during fuel combustion. In particular, the increasing interest is in reducing the emissions of pollutants from exhaust gases to improve air quality. This review aims to analyse the recent scientific literature with respect to the solutions adopted to control exhaust gases emissions from agricultural tractors, and similar self-propelled machines, and to highlight the improvements about the possibilities of reducing these pollutants during field operations. Twenty-four studies were analysed. Of these, most researches focused on the more recent tractor engine designs (emission Stage 3A or Tier 3), and most of the instrumentation included power-take-off dynamometers, portable gas analysers, electronic control units for the monitoring of machinery parameters and fuel flowmeters. Some studies analysed the effects of different fuel blends (33.3%), while only few studies analysed the environmental burden of field operations considering the variation in exhaust gases (16.7%). The most important interventions that were

found in these studies regarded the need for increasing fuel efficiency, introducing technical solutions with respect to the recent emission limits and, consequently, to reduce pollutant emissions, as well as introducing biofuel blends. This latter area can be less effective than the other solutions because the composition of blends can also increase some exhaust gases, mainly CO_2 and NO_X.

Keywords

Exhaust gases emissions, pollutants, fuel consumption, biodiesel, environmental sustainability, normative restrictions

Nomenclature

Ammonia	NH_3
Carbon dioxide	CO_2
Carbon monoxide	CO
Diesel oxidation catalyst	DOC
Diesel particulate filtration	DPF
Electronic control unit	ECU
Exhaust gas recirculation	EGR
Hydrocarbons	HC
Life cycle assessment	LCA
Methane	CH_4
Nitrate	NO_3
Nitrogen oxides	NO_X
Particulate matter	PM
Portable exhaust gas analyser	PEMS
Selective catalytic reduction	SCR

1 Introduction

Emissions to air, water and soil are some of the most important causes of environmental burdens from agricultural processes (IPCC, 2006; Notarnicola, et al., 2015). Among these, emissions to air and water include methane (CH_4), ammonia (NH_3) and nitrate (NO_3) that are mainly caused by ruminant animals and the storage and spreading of slurry, but they also include pollutant exhaust gases such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM), and hydrocarbons (HC) released from agricultural tractors and self-propelled machines during the fuel combustion.

The agricultural sector has seen numerous improvements in terms of efficiency and technological progresses, but there is still a need for improvement (Lang et al., 2018) in both. Focusing on field operations for crop cultivation, fuel consumption and engine emissions can have a negative impact from the environmental perspective (Lovarelli & Bacenetti, 2017b). Over the years, the European Union as well as the US Environmental Protection Agency have introduced norms to regulate the exhaust gases that are released during the combustion of fuels in cars, trucks, ships and off-road vehicles, amongst which agricultural tractors are included. In the most recent years, more and more stringent limits have been introduced (97/68/EC, 2010/22/EU, 2010/26/EU) limiting the emission of NO_X, CO, PM and HC from engines. The European legislation refers to Emission Stages (i.e. I, II, IIIA, IIIB, IVfinal) whereas in the US legislation they are identified as Tiers (i.e. 1, 2, 3, 4, 5). Tractor producers can decide to respect the restrictions with any of the possible technologies available (e.g., exhaust gas recirculation, selective catalytic reduction, diesel oxidation catalyst and diesel particulate filtration) (Cavallo, Pampuro and Facello, 2011), but commonly the practical choices available to producers are similar since restrictions are harsh. The main characteristics of the technological solutions introduced on agricultural tractors and self-propelled machines are described hereafter.

The *Diesel Particulate Filter (DPF)* is a device used to remove particulate matter or soot from exhaust gases. Filter regeneration is made by means of a catalyst that burns off the accumulated particulate; alternatively, a fuel burner heats the filter to soot combustion temperatures.

The *Exhaust Gases Recirculation (EGR)* is a device introduced for limiting NO_X emissions. It is characterised by a combustion system with a dedicated valve located in the combustion chamber that allows recirculating a portion of the exhaust gases as intake air (~5 – 15% volume of the intake air). This system is adopted to reduce the production of NO_X (NO and NO_2) because the recirculation of exhaust gases avoids peak temperatures during combustion. As a drawback, the reduction of clean air available for the combustion results in decreased fuel efficiency, which means that a higher fuel consumption is needed to achieve the same engine performance of other cases.

The *Selective Catalytic Reduction (SCR)* device is a post-combustion treatment that converts the NO_X into molecular nitrogen (N_2) and water vapour by using NH_3 as reducing agent. Ammonia is introduced in the process through a urea solution (32% concentration) in water and converts the NO_X through thermolysis and hydrolysis. Differing from the EGR, the SCR is more effective, and it reaches higher fuel efficiency (+4 to +5% with respect to EGR) (Maiboom, Tauzia, Shah and Hétet, 2009; Volvo, 2010). It also promotes a higher engine lifespan because the engine normally works with clean air involving less maintenance. Another difference from EGR-equipped tractors is that in EGR there is a valve that controls the recirculation, whereas the SCR is a more complex system that requires devoted parts such as a urea solution tank, a nozzle for its distribution and a chamber for the chemical reaction. Although a high fuel efficiency is achieved with the SCR, the consumption of the urea solution needs to be considered when analysing the environmental benefits of its production, use, maintenance and disposal as well as the farmer's additional attention to the preservation and use of the urea solution (Bacenetti, Lovarelli, Facchinetti, Pessina, 2018).

Specifically, the environmental concerns about exhaust gases emissions have increased in recent decades in correspondence with the increase in worries about global warming, acidification and air pollution. In this context, environmental sustainability assessments have increased, among which the life cycle assessment (LCA) approach (ISO 14040 and 14044 Series, 2006) has been the most widespread method for the quantification of the environmental impact of products and services. For its application it is vital to collect reliable data about all inputs and outputs included within the life cycle of the process to be studied. In literature are present few studies that analyse the environmental impact of field operations and that pay attention on the exhaust gases emissions released from engines. This lack is partially caused by the variability of machinery (tractors and self-propelled machines) in terms of engine power, age and emission control technology, and of site-specific information about their working conditions. Models and instrumentation for primary data collection about engine variables (e.g., CANbus) can be essential to solve these problems (Lovarelli &

Bacenetti, 2017b; Pitla, Luck, Werner, Lin, Shearer, 2016), as well as help with the undefined number of outdated tractors present on farms (average lifespans can equal to 25 years) (Bietresato, Calcante, Mazzetto, 2015).

Along with the technological improvements, the use of biodiesel blends can help respect the limits in the release of exhaust gases; however, blends must be identified properly to avoid drawbacks. More in detail, biodiesel blends obtained from different biomasses and adopted with different ratios have different chemical characteristics that influence the energetic composition, efficiency and combustion in the engine (Simikic at al., 2018) with respect to diesel fuel and to other different possible fuel blends. Additionally, farmers do not normally have control of the different blends because the market is seen as the main driver.

The aim of this study is to review the scientific literature that has researched on exhaust gases emissions released from agricultural tractors and their evolution over time. The specific goals are to:

- Identify the state of the art about exhaust gases emissions released from agricultural tractors and the proposed solutions for their reduction,
- Obtain information about which technological solutions have been investigated in relation with the legislation for pollutants reduction,
- Discuss the achieved results and draw conclusions about the current knowledge on the environmental impacts associated with fuel consumption and exhaust gases emissions of agricultural tractors.

The review is organised as follows: firstly, details are provided on the methods for the search of literature information; then, the results are analysed and discussed.

2 Literature review

Literature was analysed by searching on the database Web of Science™ and performing a search from the year 1944 to 2018. The keywords selected to perform the review were "tractors emissions", "agricultural tractors", "exhaust gases", "environmental impact" and "pollution" since they allowed the widest number of relevant scientific studies to be obtained. In any case, from this search emerged that there is a limited number of studies focusing on the topic of exhaust gases emitted from agricultural tractor engines. In particular, 117 studies were found. Although they emerged from the matching of some of the keywords, 57% of them were excluded after examining the title and abstract because they were not within the searched topic: some of the studies dealt with CO_2 emissions from heavy-duty engines or with physic-chemical features related to biodiesel blends, heat recovery and biomethane-fuelled or electric or robotic tractors. Of the 50 selected studies, 52% were excluded during a second step, from which it was found that some studies focused on fuel consumption and fuel efficiency without researching specifically pollutant emissions from fuel combustion. Also, other studies focused on comparing different fuels and/or biofuels and on seeking the optimal blend of biofuel without specifying combustion emissions. Finally, 24 studies were included in this literature review as being within the effective scope of analysing exhaust gases emissions released during the normal use of agricultural tractors. Figure 1 shows a scheme of these steps in the literature screening process.

Figure 1 around here

The parameters that were investigated in the literature review examined:

- *Fuel consumption*: this involves identifying whether in the articles the fuel consumption of the agricultural operations was studied or not, either with direct measurements and instrumentation or by modelling;
- *Biodiesel blends*: it was investigated whether the study was carried out on diesel fuelled tractors (i.e. no biodiesel blends were declared) or if different blends were tested to identify the blend(s) that provided a greater engine efficiency, lower fuel consumption and/or lower exhaust gases emissions;
- *Exhaust gases emissions*: since the goal of this review is to consider studies where pollutant emissions are dealt with, in all studies where one or more gases were evaluated a list of all of them is reported;
- *Life Cycle Assessment* (LCA): scientific studies where this approach is adopted were identified;

- *Field/bench testing*: tests on agricultural tractor engines can be made directly in the field while carrying out operations or during bench tests where the engine is tested in stationary conditions and simulating field operation;
- *Instrumentation*: the instrumentation adopted for the tests was explored. For example, a PTO dynamometer was used during bench tests, while other instrumentation such as a fuel flowmeter and a gas analyser can be used during field tests,
- *Agricultural tractors* adopted and their main features: in all studies, where one or more tractors were used, for each of them the following were reported:
    - engine power (kW),
    - field operation (list),
    - Tier/stage to which every tractor or self-propelled machine belonged in accordance to its construction. Every tractor was equipped with different instrumentation or had defined characteristics to respect the legislation for limiting exhaust gases emissions (European Directives 97/68/EC, 2010/22/EU, 2010/26/EU). Depending on this parameter and on the solutions adopted for regulating emissions, the exhaust gases produced were studied.

3 Results and discussion

Figure 2 shows the timeline of the reviewed studies. From 2010, a trend of increasing research focus can be seen on exhaust gas emissions from agricultural tractors, confirming that the topic has achieved wide interest on the scientific research.

Figure 2 around here

Table 1 reports on information collected within the literature search. Among the studies, the "quantification of emissions" was approached in different ways: some researchers (Lindgren, Larsson, Hansson, 2010; Janulevičius et al., 2013; Juostas & Janulevičius, 2014; Bacenetti, Lovarelli, Facchinetti, Pessina, 2018) quantified the pollutant emissions considering only some specific working conditions of the engine (e.g., full load, 50% of full load), while others (Janulevičius et al., 2017; Janulevičius et al., 2018; Lovarelli, Fiala, Larsson, 2018) mapped the emissions during real field conditions.

In Table 1, 24 studies are reported. The majority of studies examined operations in European countries, in particular Italy, Lithuania and Sweden. Only 5 studies reported research in North and South America and Australia. In 21 of the scientific papers, fuel consumption was analysed, of which 8 also evaluate different blends for biofuels and their related effect on exhaust gases emissions.

Fuel consumption and exhausts emissions are recognised to be the main environmental concerns for agricultural field operations, as shown by the research on annual crops (Lovarelli & Bacenetti, 2017a; Engström, Nilsson and Finnveden, 2018; Noya, González-García, Bacenetti, Fiala, & Moreira, 2018) and arboreal crops (Avraamides & Fatta, 2008; Bernardi et al., 2018). Only in 4 studies (16.7%) was LCA performed to evaluate environmental performance of field operations. Moreover, not all studies declared if the experiment was only carried out in the field (5 studies) or only carried out in a bench test (10 of studies) in accordance with C1 tests from OECD ISO 8178. In the remaining studies it was declared that both field and bench tests were used (9 studies) or not declared at all.

With regard to tractors, in almost all studies was given information about engine power, field operation performed, main engine data and legislative limits for exhaust gases. The most investigated tractors are those responding to EU Stage IIIA (EU Directive) and to Tier 3 (US EPA Agency).

Table 2 reports the frequency of studies in which every exhaust gas was reported.

The wide majority of studies investigated gases such as CO_2, CO and NO_X, followed by HC and PM. Legislation has strictly forced the introduction of limits to their emission, whereas other gases are not directly regulated. Additionally, the most extensively used instrumentation for the measurement of exhaust gases is basically equipped with the physic-chemical systems needed to measure these gases. The most widely declared to be used were portable exhaust gas analysers (PEMS) because, being portable instrumentation, they permit the analysis of different tractor engines during their life span in different locations and under different working conditions.

Additionally, as regard to the tractors available in the reviewed studies, the rated engine power differed widely. In particular, as shown in Table 3, when the limits to pollutants emissions were more stringent, the engine power of tractors in the studies were higher (on average, 141 kW for tractors in which SCR was present compared to 88 kW for tractors introduced previously). This is mostly due to the fact that technologies such as the SCR can, at this time, only be fitted on powerful tractors. By contrast, older tractors responding to limits to exhaust gases before the introduction of SCR were usually less powerful, and for even older tractors, no emission control solution was available. The presence of old but less powerful tractors can be motivated also by reduced need for powerful tractors that characterised the agricultural system of some decades ago (Bietresato, Calcante, Mazzetto, 2015).

3.1 Effect of field conditions on exhaust gas emissions

From the results of experimental tests performed on field, it emerges that field conditions deeply influence the production of exhaust gases, as well as the selected biofuel blend used. In particular, as reported in Lovarelli, Fiala and Larsson (2018) and in Lindgren & Hansson (2002), variability of engine characteristics during on-field activity, together with transient effects showed that during field activity emissions were not always within limits. This variability was found to differ depending on the field operation but was not found during bench tests or during field operations where there were little or no variations in engine characteristics (e.g., engine load) and no transient effects. Also different biofuel blends showed very different results about concerning energy and environmental efficiencies and sustainability. It is recommended that knowledge about the possibility of introducing limits to exhaust gases considering the effective fieldwork conditions (Lovarelli, Fiala, Larsson, 2018) and/or by taking into account the not-to-exceed zones (Janulevičius, Juostas, Čipliene 2016; Janulevičius, Juostas, Čipliene, 2017) for optimal engine efficiency is required. This opportunity allows the identification of the best combinations of torque and engine speed (Grisso, Perumpral, Roberson Pitman, 2014) to make the engine work as much as possible under optimal conditions (Lovarelli, Fiala, Larsson, 2018). Several studies highlighted the ideal combinations to achieve efficient engine work conditions (Janulevičius, Juostas, Pupinis, 2013; Lovarelli, Bacenetti, Fiala, 2017; Perozzi, Mattetti, Molari, Sereni, 2016; Pitla, Luck, Werner, Lin, Shearer, 2016). This requires the coupling of suitable tractors and implements in order to carry out an operation using a proper engine load (i.e. the engine power is close to that required by the machinery). This option, together with adequate driving schemes and drivers skills need to bring to good compromises in terms of engine performances (as defined by the engine curves that relate torque and engine speed) as well as of brake specific fuel consumption. With both of these, optimised fuel consumption can be reached, and pollutant exhaust gases are produced during a more complete combustion, hence in reduced amounts. The effect of such conditions can bring both economic and environmental benefits. Economic benefits come from consuming less fuel when a high fuel efficiency and a low brake specific fuel consumption is achieved with respect to the same operation performed with a less efficient engine. Benefits from an environmental point of view involve a lower fuel consumption and reduced emission of exhaust gases into the atmosphere, providing positive effects on human health as shown by Krahl, Munack, Shröder, Bünger and Bahadir (2002) and on the environmental impacts that contribute to global warming, acidification, formation of particulate aerosols, depletion of the ozone layer and of the mineral and fossil resources (Lovarelli & Bacenetti, 2017; Bacenetti, Lovarelli, Facchinetti, Pessina, 2018). These environmental impact categories can be quantified by means of LCA, which shows that exhaust gases emissions are a major environmental concern for processes involving agricultural machinery operations.

3.2 Biodiesel effect on exhaust gas emissions

Biodiesel blends have been widely investigated as possibly contributing towards reducing the release of harmful exhaust gases. In particular, Simikic et al. (2018) showed that the use of biodiesel and blends of biodiesel and fossil diesel have a negative effect on emissions, reducing engine power and drawbar power and increasing specific fuel consumption. However, this result is not constant for all blends and all work cases according to Tomić, Savin, Micic, Simikic and Furman (2013), Al-lawayzy, Yusaf and Jensen (2012), and Li & McLaughlin (2005). These studies showed that depending on the vegetable biomass used, at medium engine load, tested biodiesel had a similar performance to diesel fuelled engines but that a worsening of fuel efficiency was achieved by increasing the biodiesel proportion in the blend. The thermal efficiency slightly improved with biodiesel blends, and all these differences were greater when a larger proportion of biodiesel was present in the blend.

Biodiesels are characterised by different features among which are viscosity, density, flash points, sulphur and water content and heating value. They depend on what biomass material is used to produce the fuel (e.g., sunflower, soybean, rape, cotton, palm, etc.) and on the composition of the blend itself (% of blend). Regarding emissions, biodiesel and biodiesel blends were found to record a reduction in CO, HC and PM emission and in the temperature of exhaust gases, while they tended to produce an increase in CO_2 and NO_X. The reduction in CO is relevant and is mostly linked to the higher oxygen content and lower carbon and hydrogen content found in biodiesel and biodiesel blends. The increase in CO_2 and NO_X, was mostly related to the slightly higher fuel consumption with biodiesel and biodiesel blends, and to the higher oxygen content and engine temperature that affected NO_X production. From the findings of Lovarelli, Fiala and Larsson (2018) and Janulevičius, Juostas and Pupinis (2013), at lower engine loads fuel efficiency is reduced and both the specific fuel consumption and the specific exhaust gas emissions increase. Nevertheless, the benefit of adopting biodiesel fuels is linked to the reduction in the use of fossil fuels and to a reduced effect on engine durability and performance, although a higher frequency in the substitution of lubricant oil has been found (Bietresato & Friso, 2014; Thuneke, Gassner and Emberger, 2009).

Future research should evaluate the environmental benefits or drawbacks of using biodiesel fuel blends by means of LCA, in order to identify with a complete assessment the practical effect of such blends. With this regard, there are very few studies in the literature concerning this aspect and most of them regard the environmental aspects of biodiesel use without comparison to diesel fuel (Bacenetti, Restuccia, Schillaci, Failla, 2017).

3.3 Discussion and future research

Although significant progress has been achieved, the legislation that regulates exhaust gas emissions from off-road engines to further reduce pollutants released in the atmosphere, is still under development. Continuous research is required on the technical solutions to reduce emissions and their application to agricultural tractors. The measurement of fuel consumption and pollutant emissions in the field is an important step. This will surely be helpful for environmental assessments of agricultural production carried out using the LCA approach, which is more and more being adopted for the evaluation of the environmental sustainability of products and services in agriculture. Currently, the database most frequently used for LCA studies (Ecoinvent v.3.5) proposes an average value for fuel consumption and for each exhaust gas. This data was originally quantified as an average by a multitude of tractors in accordance with ISO 8178 C1 test, field measurements and literature, but has not been updated with the latest technology (i.e. fuel consumption and exhaust emissions are inventoried with data from the newest models of tractors set into operation from 1999 to 2001). The outcomes of the literature review highlighted that, as expected, fuel consumption and emissions of various pollutants in the exhaust gases are influenced by the site-specific factors (soil texture and moisture content, slope etc.) and operating conditions (working depth, field shape etc.) as well as by the technical aspects (type and age of machines and engines, presence of systems for the reduction of pollutant emissions etc.). In this context, the inventory data in the LCA databases are representative for "average" conditions (e.g., medium texture soil, rectangular field shape – 200 m x 50 m, slope < 5%, conventional soil tillage depth, and equipment with an average age of 10 years) while they are less representative for field operations performed in different contexts. Thus, updating databases will be fundamental for establishing reliable inventories and impact assessments in the future. An interesting improvement could be to make the user able to select the tractor model with which to perform the field operation, so that the inventoried emissions are representative of the tractor considered in the study. Furthermore, in-field measurements will also make available a large amount of primary data that can be used for specific case studies related to mechanisation, to efficiency improvements and to the analysis of the best compromises available among the mechanical characteristics. In fact, the results of this study also show that lot of research has been done in accordance with ISO 8178-C1 tests. These standard tests define a list of work conditions to be respected during bench tests in order to obtain comparable results among different engines without the effect of real field conditions. However, since it is recognised that exhaust gases emissions are subject to wide variations when measured directly during the field activities (Zavala et al., 2017; Lovarelli, Fiala, Larsson, 2018), in many studies, authors investigated these measurements and achieved accurate results but they were less applicable and not frequently comparable with other studies because the specific work conditions strongly affected the results (e.g., soil texture, soil conditions, air temperature). A future application of such accurate measurement systems could be to build tractors equipped with portable instrumentation, eventually simplified with respect to current designs in order to limit costs. In addition to monitor and collect data, this instrumentation could help regulate engine parameters in real time, which would effectively allow the normed emissions limits to be respected. In other words, adjusting engine parameters and technical systems that control emissions to limit exhaust gases that are harmful to human health and the environment below their normative limits while working in the field.

4 Conclusions

This literature review performed on the database Web of Science™ aims to analyse the state of the art of the scientific contributions about fuel consumption and exhaust gases emissions released from agricultural tractors. After a selection of studies adapt to the aim of this review, the following conclusions can be drawn:

- Not much is present in literature on the measurement of exhaust gas emissions and on the application of the Life Cycle Assessment approach which could lead to a holistic evaluation of the environmental performance of agricultural mechanisation;
- Research has increased with the introduction of emission limits and with the need to identify technical solutions to comply with these limits;
- Working at extremely low and extremely high engine loads is strongly discouraged for reasons of fuel consumption, exhaust gas emissions and for engine efficiency;
- Working in a defined medium range of torque and engine speed, and with the so called "gear up throttle down" allows engines to work under optimal engine conditions providing good results for field operations and satisfactory results in terms of fuel consumption and the release of exhaust gas emissions into air;
- Adopting biofuel blends with a low proportion of biofuel to fossil fuel is a suitable solution to achieve good environmental performance whilst maintaining useful engine performance compared to pure diesel, whereas at high percentages of biofuel in blends, engine performance, fuel consumption and exhaust gas emissions worsen;
- Since technology in this area has made huge progress, more studies should be carried out on identifying valid models for the reduction of exhaust gas emissions during field operation, and also focusing on a larger group of tractors with low, medium and high engine power, as well as on the self-propelled machines such as sprayers and harvesters.

Research on exhaust gas emissions is fundamental since it will lead not only to compliance with legislation, but also to direct effects on the environment and on human health. In this regard, the application of LCA to studies on exhaust gas emissions should be encouraged since it will be helpful to understand the effective role of legislation respect to the environmental impact of agricultural mechanisation and to disseminate knowledge to stakeholders, policy makers and farmers.

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FIGURES

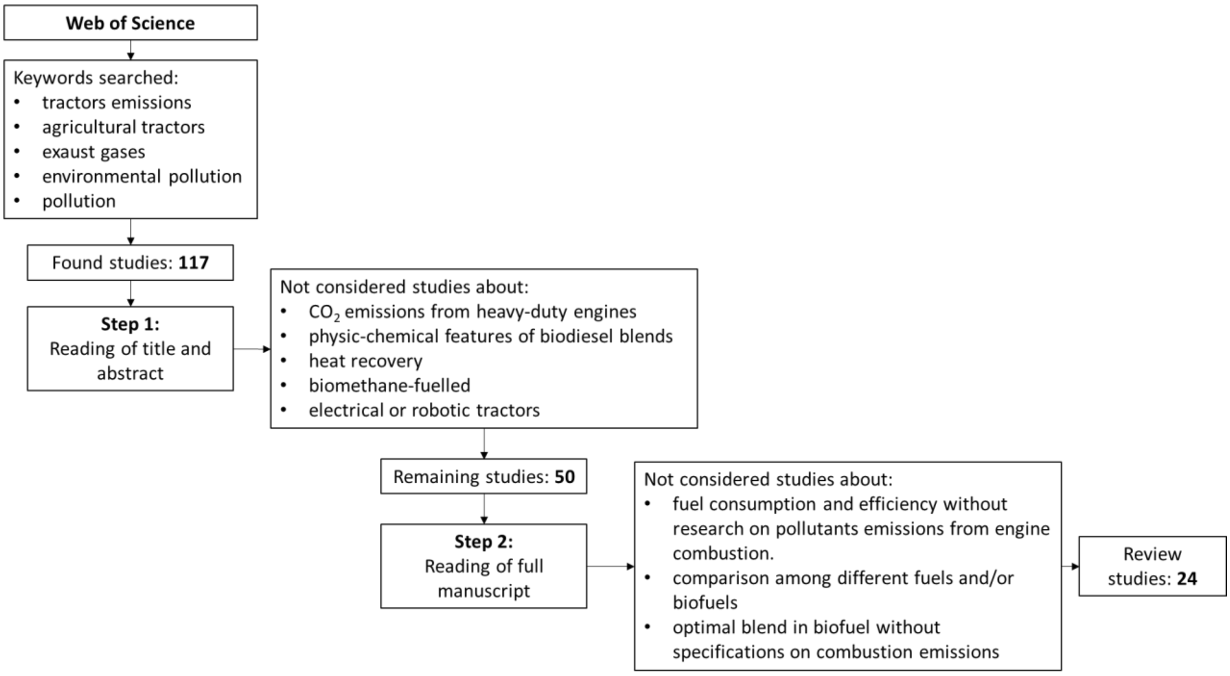

Figure 1. Logical steps for the research and selection of studies to include in the literature review.

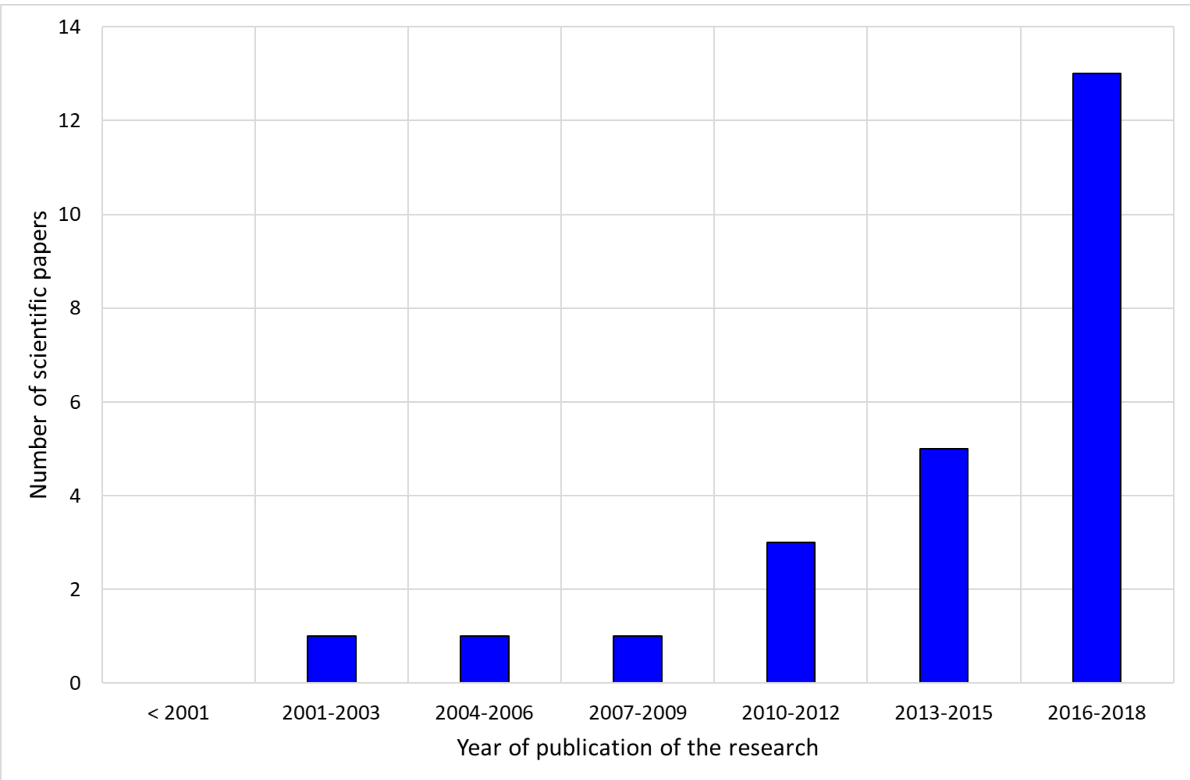

Figure 2. Timeline on the scientific literature evaluated in this review.

Table 1. Main results of the literature review.

Study	*Country*	*Fuel analysis*	*Biodiesel blends*	*Gases*	*LCA*	*Field/ bench test*	*Instrumentation*	*Engine power kW*	*Field operation*	*Tier/ stage*
Bacenetti et al. 2018	Italy	No	No	CO_2 CO NO_X PM HC	Yes	Bench	PTO dynamometer	179; 191	Ploughing	stage 3A, 3B
Dyer and Desjardins 2006	Canada	No	No	CO_2	No	n.a. (model)	n.a.	n.a	n.a.	n.a.
Emberger et al. 2016	Germany	Yes	Yes	CO_2 CO NO_X NO_2 HC PM	No	Bench	PTO dynamometer, gas analyser, partial flow dilution system, fuel balance and data logger	114; 94	n.a.	stage 3A,1
Janulevičius et al. 2013	Lithuania	Yes	No	CO_2 NO_X CO	No	Field	Fuel flowmeter; gas analyser	160.3	Ploughing	tier 3
Janulevičius et al. 2016	Lithuania	Yes	No	CO_2 CO	No	Bench	PTO dynamometer, ECU, fuel flow meter and gas analyser	160.3	n.a.	tier 3
Janulevičius et al. 2017	Lithuania	Yes	No	NO_X NO_2 NO	No	Bench	PTO dynamometer, ECU, fuel flowmeter and gas analyser	160.3	n.a.	tier 3
Janulevičius and Čipliene 2018	Lithuania	Yes	No	CO_2 NO_X	No	Field	PTO dynamometer, ECU, fuel flowmeter, gas analyser and penetrometer	160.3	Ploughing	tier 3
Lindgren et al. 2010	Sweden	Yes	No	CO_2 HC NO_X CO PM	No	Bench + Field	PTO dynamometer, ECU, gas analyser	160	Loading gravel dragging, transport, loading, wheel excavator	stage 2

Study	*Country*	*Fuel analysis*	*Biodiesel blends*	*Gases*	*LCA*	*Field/ bench test*	*Instrumentation*	*Engine power kW*	*Field operation*	*Tier/ stage*
Lovarelli et al. 2018	Sweden	Yes	No	CO_2 HC NO_X CO PM	No	Field	CANbus, data logger, GPS, gas analyser	82	Ploughing, rotary harrowing, spike harrowing, sowing, rolling	stage 3A
Larsson and Hansson 2011	Sweden	No	No	CO_2 CO NO_X PM HC	Yes	Bench + Field	n.a.	100	Ploughing, harrowing, rolling	stage 3A
Pirijola et al. 2017	Finland	Yes	Yes	NO_X CO_2 PM	No	Bench + Field	PTO dynamometer, ECU, gas analyser	99	n.a.	stage 3B
Schlosser et al. 2017	Brazil	Yes	No	O_2, CO_2 CO HC NO_X gas opacity	No	Bench	Dynamometer, fuel flowmeter, gas analyser, opacimeter and thermocouple and related software	57	n.a.	n.a.
Zavala et al. 2017	Mexico	Yes	No	PM NO_X CO_2 CO	No	Field	PEMS, GPS, CANbus and data logger	80	Soil preparation	tier 3
Sonntag et al. 2015	USA	Yes	No	CO CO_2 NO_X HC PM	No	Field (highway)	PEMS	40-90; 12 tractors	Mowing	11 tier 0; 1 tier 2
Perin et al. 2015	Portugal	Yes	Yes	O_2, CO_2, NO_2, NO, CO, HC	No	Bench	Dynamometer	77	Ploughing	2
Lovarelli and Bacenetti 2017b	Italy	Yes	No	CO_2, CO, NO_X	Yes	Field in part	In part CANbus, data logger, GPS, gas analyser	In part, 82	Rotary harrowing	stage 3A
Lovarelli et al. 2017	Italy	Yes	No	CO_2, HC, NO_X, CO, PM	Yes	n.a.	No	Several tractors	Ploughing	stage 3A

Study	***Country***	***Fuel analysis***	***Biodiesel blends***	***Gases***	***LCA***	***Field/ bench test***	***Instrumentation***	***Engine power kW***	***Field operation***	***Tier/ stage***
Juostas and Janulevičius 2014	Lithuania	Yes	n.a.	CO_2, CO, NO_X	No	Field	ECU, dynamometer	160.3	Drilling	tier 3
Ettl et al. 2017	Germany	Yes	Yes	NO_X, HC, CO, CO_2	No	Field	PEMS, PTO shaft with brake	133	Ploughing	stage iv
Tomić et al. 2013	Serbia	Yes	Yes	CO_2, CO, NO_X	No	Bench	Dynamometer, flowmeter, gas analyser, thermocouple	48	n.a.	tier 2
Al-Iwayzy et al. 2012	Australia	Yes	Yes	O_2, CO_2, CO, NO, HC	No	Bench	Dynamometer	25.8	n.a.	n.a.
Lindgren and Hansson 2002	Sweden	Yes	No	CO, HC, NO_X	No	Bench	In part CANbus GPS data logger gas analyser	81	Soil cultivation and heavy on-road transport	stage 3A
Thuneke and Erberger 2007	Germany	Yes	Yes	CO, HC, NO_X	No	Bench	n.a.	119; 94	n.a.	2; 1
Simikic et al. 2018	Serbia	Yes	Yes	CO, CO_2, NO_X	No	Bench + Field	Dynamometer, flow meter, gas analyser	99	Ploughing	stage 2

(§): Engine power (kW); n.a. = Not available information.

Table 2. Number of articles and frequency with which the listed exhaust gases were studied.

Exhaust gas	CO_2	CO	NO_X	PM	HC	NO_2	NO	O_2
Number	21	20	20	9	14	3	3	3
Frequency	87.5%	83.3%	83.3%	37.5%	58.3%	12.5%	12.5%	12.5%

Table 3. Mean values of tractor engine power per category of emission stage of belonging in the examined studies.

Emission stage	**Number of tractors**	**Tractor engine power**
Stage 0-2	8	63 ± 36 kW
Stage 3A – Tier 3	12	124 ± 40 kW
Stage 3B	2	145 ± 65 kW
Stage 4	1	n.a.(*)

Note: (*) Only one tractor belongs to this category.