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**Sustainability of agricultural tractors usage
in open field and in specialized crops,
from the performance and environmental
standpoints**

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Extended Summary

In the current global context, environmental challenges are increasingly drawing attention to the impacts caused by fossil fuel-powered vehicles. Among these, self-propelled agricultural machines, which are predominantly equipped with diesel internal combustion engines, play a significant role. Diesel combustion produces various gaseous pollutants that are released into the atmosphere, including carbon monoxide (CO), unburnt hydrocarbons (HC) and, most notably, particulate matter (PM) and nitrogen oxides (NO_x).

To mitigate the impact of these emissions, regulatory frameworks similar to the Euro standards for on-road vehicles were introduced also for non-road vehicles, including agricultural machinery, starting in 1996 in both Europe and the United States. These regulations have progressively imposed stricter limits on emissions for newly introduced vehicles.

As a result, manufacturers of internal combustion engines fitted on self-propelled agricultural machines have been compelled to implement technical improvements and/or additional devices to minimize pollutant emissions and comply with regulatory thresholds.

The primary aim of this study is to assess the performance of a number of selected tractor models, representative of the Italian machinery fleet, in terms of energy efficiency and gaseous pollutant emissions.

Experimental data were compared against current emission regulations, including also comparative assessments with older tractors that are not subject to these standards due to their technical obsolescence.

The methodological approach involved analysing specific fuel consumption (i.e. energy efficiency) and the concentration of key pollutants in exhaust emissions, taking into account the actual operating conditions of the tractors within the agricultural sectors in which they are typically employed. This approach enabled the calculation of the true efficiency of the machines under investigation, providing a comprehensive overview of their sustainability in use.

The experimental framework of this study is built upon three key pillars.

First pillar

The first pillar of this study focused on the comparative assessment of the energy efficiency of four tractors employed in performing ten agricultural tasks within the viticulture sector. For each task, the nominal and under-load engine speeds, torque, and power output at the PTO were identified, along with hourly fuel consumption. These values were then normalized by specific power to calculate specific fuel consumption (Table 1).

To highlight the efficiency level of the tasks, the data obtained were classified using a "traffic light" system.

Table 1- The application of "traffic light" colour system to the SFC values, measured at different running points, enables a prompt and effective evaluation of efficiency.

Field operation	Specific fuel consumption, g/kWh			
	Kubota M5091	Same Frutteto II 85	Same Argon 70	Goldoni E100
P. R. shredding	264.36	250.61	246.39	256.76
PPP spraying	269.03	290.19	237.72	238.91
Fertilising (M/O)	264.58	313.81	238.05	235.18
Pre-pruning	n.d.	389.43	244.26	n.d.
Grass shredding	278.58	302.54	242.66	240.12
(C/M) weeding	342.17	341.24	247.84	232.59
Sucking	n.d.	389.43	244.26	n.d.
Topping	342.17	341.24	247.84	232.59
Defoliation	269.13	266.68	244.49	233.17
G. harvesting	258.36	262.21	255.60	239.63
<i>Weighted Avg.</i>	<i>267.91</i>	<i>303.18</i>	<i>241.17</i>	<i>226.43</i>
Colour class	E	G	C	A

The specific fuel consumption of the tractors varies depending on both the model analysed for a given task and the operating conditions of the same tractor.

To facilitate a more immediate comparison of the energy efficiency and environmental impact of the tested machines, colour labels, assigned based on defined ranges of specific fuel consumption (SFC) values, were further classified into categories (ranging from A to G), providing a standardized evaluation.

Second pillar

The second pillar involved the preliminary definition of operational scenarios for various agricultural sectors. Each sector was associated with a specific tractor model, with detailed specifications of its working conditions. This approach enabled a comprehensive and realistic assessment of the environmental impact of each tractor under investigation (Table 2).

Table 2 - Tractors utilized in the different production chains for the second pillar.

Make	Model	Tractor usage
Fiat	70-90	Open field
Deutz Fahr	Agrofarm 430	Open field
Kubota	M5101	Vineyard, mechanical harvesting
New Holland	TN70V	Vineyard, manual harvesting
New Holland	TN70V	Apple Orchard

Thanks to targeted simulations of real working conditions operated at fixed-point, pollutant gas emissions were measured and subsequently compared with the limits established by relevant regulations, adopting a colour code to evaluate the emissions impact at a glance. An example of these results is shown in **tab. 3**.

For each task, the duration and frequency of execution on an annual basis and for an average-sized farm were estimated to determine the overall impact of a specific tractor. An example of this assessment is provided in **tab. 4**.

The obtained values enabled the calculation of emissions for each agricultural sector throughout the entire growing season, allowing for a comparative assessment that considers the overall environmental impact.

Table 3 - Apple production chain (with New Holland TN 70V).

Field operation	CO	HC	NOX	PM
	g/kWh			
PPP spraying	0.69	7.35	3.71	0.03
Apple transport	1.95	7.78	10.67	0.27
Grass shredding	0.60	7.58	3.71	0.03
Pruning residues shredding	0.69	7.58	3.71	0.03
Organic fertilization	10.72	22.39	10.96	0.10
Chemical fertilization	5.89	15.15	7.41	0.07
Soil management	22.67	16.83	8.24	1.37

Table 4 – Forage production chain (with Fiat 70-90).

Field operation	Intensity of use	CO	HC	NOx	PM
	h/year	kg/year			
Seeding	80.0	27.3	13.3	23.2	0.02
Fertilization	160.0	83.7	85.6	41.5	0.03
Grass mowing	30.0	6.1	8.5	8.5	0.02
Grass conditioning	15.0	8.5	3.3	5.0	0.18
Pick-up carriage	5.00	262.0	2.7	1.3	0.00
Hay racking	56.0	18.4	24.8	14.1	0.02
Baling	30.0	4.4	5.6	11.9	0.29
Wrapping	12.0	6.8	2.7	4.0	0.14
Bale transportation (farm road)	24.3	5.4	14.7	8.8	0.01
Total		163.4	161.2	118.3	0.71

Third pillar

Gaseous pollutant emissions have long been recognized as harmful not only to the environment but also to human health. The third pillar of this study focused on analysing the acute and chronic effects of exposure to these emissions, drawing on evidence from medical literature, particularly regarding workers who are continuously exposed to exhaust fumes from internal combustion engines in a professional setting. The most commonly reported health issues include respiratory, pulmonary and cardiovascular diseases. Recent research, however, has suggested a possible link between exposure to certain pollutants and the onset of neurodegenerative disorders. The technical legislation in this area is at present significantly lacking, with no robust current regulations available to identify potentially harmful operating conditions.

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1. Introduction

1.1. Evolution of agricultural machinery up to the 1950s

The mechanization of agricultural production has been driven by a need that dates back several centuries. The first experimental concept of an agricultural vehicle not reliant on animal power was proposed in the late 18th century by Nicholas Joseph Cugnot, who designed the first steam-powered tractor prototype. Despite this pioneering effort, it was not until the final decade of the 19th century that tractors suitable for practical agricultural use were developed, marking the advent of industrial tractors. These early machines, characterized by significant mass and limited power, were not yet conceived as multifunctional vehicles adaptable to diverse agricultural conditions. In the early 20th century, the introduction of the Fordson model by the Ford Motor Company marked a significant development in global agriculture. In Italy, the prototype tractor was developed by the Cassani company (actually evolved in Same Deutz-Fahr group), and after 15 years of research, the first Italian agricultural tractor was introduced in 1942. During the interwar period, tractor productivity and distribution expanded nationally with the establishment of important manufacturers such as Fiat, Landini, Same, Lamborghini, Goldoni and Antonio Carraro.

1.2. The tractor in modern agriculture

Following World War II, a transition from steam engines to diesel engines in tractors was started. These diesel engines, based on a design by German engineer Rudolf Diesel in the late 19th century, provided enhanced efficiency, leading to significant technical and morphological advancements in tractors. By the late 1960s, nearly all tractors produced in Europe were powered by diesel engines, due to the widespread adoption of this technology. The availability of advanced machinery (included several implement types), alongside post-war economic growth, helped an exponential increase in agricultural productivity, contributing to what is known as the "Green Revolution" and the development of "Agriculture 2.0."

1.3. Agriculture 2.0

"Agriculture 2.0" and the "Green Revolution" refer to a period characterized by the increased adoption and dissemination of agricultural machinery aimed at maximizing crop yields while minimizing labour for various strenuous field tasks. During the development of Agriculture 2.0 from 1960 to 1990, the primary goal of mechanization was to enhance the work capacity and performance of agricultural machinery. The machinery developed during this period became increasingly large and powerful. However, the focus was predominantly on maximizing yield, with less attention paid to environmental considerations such as engine efficiency and gaseous pollutant emissions coming from diesel combustion. Concurrently, there was a significant increase in the use of plant protection products and modern technologies for crop protection. The integration of these technologies to the widespread use of agricultural machinery led to a substantial increase in agricultural output and a reduction in production costs, thereby lowering the cost of agricultural products.

1.4. Agriculture 3.0

Beginning in the mid-1990s, a series of technological advancements introduced innovative technologies into agricultural machinery. The worldwide diffusion of the internet helped the first development of technologies that evolved over the next decades, including variable rate application, prescription mapping, assisted guidance, and data management. Additionally, a growing focus was placed on the efficiency and emissions of non-road and heavy-duty vehicles, reflecting a previous similar trend in the automotive industry. The primary aim of technological advancements in Agriculture 3.0 was to maintain the performance of tractors while improving efficiency, specifically by reducing fuel consumption (both hourly and specific) without compromising performance. Simultaneously, the 1990s marked the beginning of regulatory efforts to address pollutant emissions, resulting in the issuing in 1996 of the first regulations for non-road and heavy-duty vehicles, which set specific emission standards based on power class criterion.

1.5. The modern tractor

The modern tractor is described as an extremely complex machine, making up over 20,000 components. It is designed to generate power under various forms and transfer it to the implements, thereby enabling a wide range of agricultural tasks. In more detail, the power generated by a tractor can be mechanical, pneumatic, hydraulic, or electric. Except for electric power—which, in some modern and innovative tractors, is provided by an autonomous generation system—all these forms of power are generated or supported by the internal combustion engine, which serves as the central unit for power generation.

1.6. The internal combustion engine

The internal combustion engine serves as the power plant of the tractor, for converting the potential chemical energy of fuel into thermal energy and then into mechanical energy. This energy conversion occurs through the combustion of diesel fuel within a confined space, in the presence of a gaseous oxidizer (the oxygen, a component of the air) and under high pressure. The mixing of liquid fuel and gaseous oxidizer at elevated temperatures and pressures creates the conditions necessary for a chemical process known as spontaneous ignition. The transformation of energy from chemical to thermal enables the transfer of part of this energy to the tractor's physical system, which then converts it into mechanical energy and later into work.

The group used for this energy transformation consists of a cylinder block, which houses the cylinders and the crankcase, pistons, a connecting rod-crank mechanism, and a crankshaft. Specifically, this system includes both fixed components, such as the cylinder, and movable components. The piston moves with a reciprocating linear motion within the cylinder, reducing the volume available for the fuel-oxidizer mixture. This reduction in volume, under high pressure, initiates combustion. The piston's reciprocating motion is then converted into rotational motion through a crank mechanism consisting of connecting rods and cranks, connected to the crankshaft. This energy transfer occurs at specific timing intervals, characteristic of diesel engines and their thermodynamic principles.

The operation of internal combustion engines varies between the Diesel cycle, typical of compression ignition engines (combustion started by temperature and pressure), and the Otto cycle, typical of spark-ignition engines, where the pressurized mixture requires an ignition source (spark plug) to start combustion. In agriculture, internal combustion engines used on self-propelled machinery are almost exclusively Diesel cycle engines, with some exceptions for vehicles powered by natural gas and smaller equipment, such as chainsaws, rotary tillers, and motorized wheelbarrows, which very often employ spark-ignition engines.

The engine components are made from different materials to match the specific durability and characteristics required for each component. For example, the cylinders in diesel engines are made from steel and alloys that are highly resistant to heat and pressure, while the pistons are typically made from lighter alloys to ease movement.

The piston, which has a circular section, features grooves on the upper part of its outer surface where the piston rings and oil scraper ring are located. The piston rings ensure the sealing of the combustion chamber, preventing exhaust gases from entering the lubrication oil, while the oil scraper ring removes the thin oil film from the cylinder walls, reducing friction between the moving piston and cylinder and preventing the combustion of oil, which would produce harmful gaseous pollutants.

The piston is connected to the crankshaft via a connecting rod and crank system and a robust piston pin. The crankshaft enables the transfer of mechanical energy in a rotary motion and contributes to the alternating movement of the pistons, especially during the passive phases of combustion.

The actual combustion, and thus the transformation of chemical energy into thermal energy, occurs in a confined volume, known as the combustion chamber, which is delimited by the cylinder at the top and the piston head (or "crown") at the bottom. The piston head forms the mobile lower part of the combustion chamber, where recesses of various shapes are often formed to intensify fluid turbulence, enhancing the mixing of fuel and oxidizer and thus their combustion. The most common design of the piston head includes a central cusp that induces a rapid rotational motion in the fluids introduced into the combustion chamber.

To enable combustion, a specific quantity of air (oxidizer) must be introduced into the combustion chamber before the fuel, as defined by the stoichiometric ratio. The

introduction of air and the subsequent expulsion of exhaust gases from the combustion chamber are controlled by two or more valves (one for air intake and one for exhaust gas expulsion), operated by lever systems driven by two camshafts. The correct calibration of the rotation speed of these camshafts ensures that the valves open and close just before and at once after combustion, preparing the engine for another operating cycle. The fuel is introduced into the combustion chamber by the injector. After diesel fuel is drawn from the tank and delivered to the injectors by the feeding pump and then by the injection pump, the injector's role is to atomize the fuel within the combustion chamber along with the oxidizer. In traditional diesel engines, the injector has a needle valve kept closed by a spring. When the fuel pressure (generated by the pump and its delivery system) exceeds the spring's resistance, the needle lifts, and the fuel is finely atomized through calibrated nozzles, entering the combustion chamber.

1.6.1. Operation of the diesel cycle internal combustion engine

Modern diesel engines installed in vehicles and heavy-duty machinery are predominantly four-stroke diesel engines. In four-stroke engines, a cycle is completed with two alternate piston strokes (down, up, down, up), resulting in two crankshaft rotations. A four-stroke diesel engine cycle consists of four phases: intake, compression and injection, combustion and expansion, and exhaust. Specifically:

1. Intake Phase: Air (oxidizer) is drawn into the cylinder's free volume as the piston moves downward (towards the bottom dead centre), creating a vacuum in the cylinder and drawing in air through the open intake valve.
2. Compression and Injection Phase: The air is compressed as the piston rises from the bottom dead centre to the top dead centre, compressing the entire volume of air into the combustion chamber. Near the top of the compression stroke, diesel fuel is atomized into the combustion chamber via an injector, where the compressed air has reached hot temperatures and pressures due to the reduced volume.
3. Combustion and Expansion Phase: This phase involves the spontaneous ignition of the fuel-air mixture due to high pressure and temperature, leading to a rapid increase in temperature and pressure that forcefully pushes the piston

downward. This is the only "active" phase of the diesel cycle, where piston movement is driven by energy transformation.

4. Exhaust Phase: The piston rises from the bottom dead centre towards the top dead centre, compressing the exhaust gases and directing them towards the open exhaust valve to help their expulsion. Once the exhaust gases are expelled, the cycle begins again with the intake phase.

1.7. Devices for enhancing performance and efficiency of diesel engines

To improve the efficiency of diesel engines, it is essential to ensure the correct combustion of the fuel, thereby achieving the complete conversion of chemical energy into thermal and mechanical energy. Ensuring proper combustion involves not only the correct amount of diesel in the combustion chamber but also, importantly, the oxidizer. The oxidizer, specifically the oxygen present in the air, is crucial for the proper combustion of diesel. In diesel engines, this ratio is typically 14:1, meaning 14 parts of oxygen to 1 part of diesel. To maximize the efficiency and combustion of the diesel, this ratio can be changed by increasing the amount of air while keeping the diesel constant; this is achievable using for example a turbocharger (Gümüş M., et al. 2012).

1.7.1. Supercharging and turbocharging in diesel engines

Supercharging is a technique used in internal combustion engines to increase the amount of air introduced into the cylinders, allowing more fuel to be burned during each cycle, thus achieving higher performance or more power. Among the various methods of supercharging, the application of a turbocharger has proven particularly effective for diesel engines. A turbocharger is a system designed to harness the kinetic energy of exhaust gases to drive a turbine coupled to a compressor. The exhaust gases, exiting the cylinder, are characterized by elevated temperatures and pressures. These characteristics are used to power a turbine connected to the compressor, via a common shaft. (Bertinatto R., et al. 2021) The compressor draws air from the external environment and compresses it before sending it to the cylinders. By increasing the air

pressure, the amount entering through the intake valve, within the same unit of time, is higher, allowing more fuel to be burned and thereby improving engine performance. While turbocharging offers numerous benefits in terms of efficiency and performance, the same cannot be said for emissions. (Zhu G. et al. 2018) Proper combustion of diesel should reduce soot production but tends to increase the amount of nitrogen oxides produced due to the high combustion temperatures. Key advantages include:

- Supercharging allows for greater power output without increasing the engine displacement. This is particularly useful in diesel engines, where significant power increases can be achieved by adjusting the turbocharger's boost pressure.
- The turbocharger improves the engine's volumetric efficiency, enabling more complete combustion of the fuel. In diesel engines, this translates to better use of the diesel's calorific value, reducing specific fuel consumption.
- Due to more complete combustion, turbocharged diesel engines can produce, under optimal operating conditions, fewer carbon residues like particulates and soot but more nitrogen oxides.
- The use of a turbocharger allows for better engine response, especially during acceleration. This feature is particularly appreciated in automotive applications, where prompt power delivery is crucial.

Despite the significant value turbochargers add to engine efficiency and performance, they are often paired with an intercooler.

1.7.2. Intercooler in turbocharged diesel engines

The intercooler coupled to the turbocharger is a heat exchanger that reduces the temperature of the air before it enters the cylinder. The compression of air raises its temperature, and cooling it with an intercooler increases its density, allowing a greater mass of air (i.e. oxygen) to be introduced into the cylinders and further improving combustion efficiency. (Liu S. & Zhang Y., 2020) As a result, increasing combustion quality also increases its temperature. For this reason, turbocharged diesel engines must be designed with appropriately sized cooling and heat dissipation systems. The intercooler typically consists of a radiator, through which compressed air passes and is cooled by an external airflow (air-to-air intercooler) or a coolant (water-to-air intercooler). In air-to-air intercoolers, compressed air passes through a series of fins or

tubes, while external air passes through these fins to remove heat. In water-to-air intercoolers, the coolant absorbs the heat from the compressed air and transfers it to a separate radiator. (Sergienko S., et al. 2021)

In heavy-duty engines, such as those in agricultural and industrial vehicles, radiators are designed to manage high thermal loads and are often paired with enhanced fans to improve cooling. Supercharging can be classified as light or heavy, depending on the level of added pressure provided. In light supercharging, the boost pressures are moderate (0.3-0.4 bar), and the thermal and mechanical stresses on the engine do not increase significantly, avoiding the need for major structural modifications. In heavy supercharging, the pressures are much higher, requiring reinforced components and advanced cooling systems to manage the increased thermal and mechanical load.

1.7.3. Common rail in diesel engines

The Common Rail injection system, also known as "common rail injection," represents one of the most significant innovations in diesel engine technology of the last decades. In traditional diesel engines, each injector has a dedicated fuel supply line and run at a relatively high max pressure value (less than 180 bar). The advent of the common rail system revolutionized this concept. In fact, this system improved both engine performance and energy efficiency, while also reducing pollutant emissions. (Zhu G. et al. 2018; Agarwal A., et al. 2014)

In more detail, the Common Rail system uses a high-pressure injection pump to maintain the fuel in the rail at an extremely high-pressure value (also above 2000 bar) making it constantly available for all injectors and for the entire injection duration. From this rail, various branches distribute fuel to the injectors of each cylinder. The main advantage is that unlike traditional mechanical injection, where fuel pressure depends on the engine speed, the common rail system features an independent pressure pump. This ensures consistent injection pressure under all operating conditions, so improving efficiency even at low speeds. (Mao B., et al. 2018)

Like turbochargers and intercoolers, the application of the common rail has brought numerous performance benefits to the engine. Key advantages include:

- better atomization of fuel by the injectors, which work at higher pressures with better regulation of the amount of fuel to be injected.

- Improved combustion performance through better atomization and thus a more complete and efficient combustion process.
- Enhanced engine performance in terms of both power and torque.
- Improved combustion also reduces emissions of particulate matter.
- Electronic injection control enables smoother and quieter operation, with corresponding reductions in engine vibrations and noise.

Since its market introduction in the late 1990s, the common rail has been progressively improved, with even higher injection pressures and more precise fuel injection management, ensuring improvements in efficiency and emissions reduction. (El Shenawny E.A., et al.2019; Coskun G., et al.2018; Picayapat K., et al.2014) Today, the common rail is widely used not only in heavy-duty vehicles but also in many diesel-powered passenger vehicles, thanks to its ability to reduce pollutant emissions.

1.7.4. Performance of agricultural diesel engines

The performance of internal combustion engines is commonly evaluated through bench tests. For agricultural tractors, these tests are conducted both on the isolated engine, at the crankshaft output or, as an alternative, when installed on the tractor, via the power take-off. Generally, these tests are performed under fixed load conditions and aim to measure fundamental parameters such as torque, power and specific fuel consumption, versus engine speed.

The most common test involves running at "full throttle," i.e. with the accelerator fully depressed, to determine the maximum torque and power values and the absolute minimum specific consumption. For more detailed characterization, partial load tests may be conducted, with less than maximum fuel delivery, to analyse engine performance under more realistic operating conditions. (Mao B., et al. 2018)

Modernly, the engine load is developed using an electromagnetic brake, capable of applying a fine and adjustable resistance torque, accurately simulating the real loads to which the engine is subjected during agricultural operations. An increase in resisting torque corresponds to a corresponding increase in driving torque but also reduces engine speed until a certain limit is reached, beyond which the driving torque begins to decrease, leading the engine to an unstable running state.

During testing, the process starts from the condition of maximum no-load speed, and an increasing load is applied, recording the values of torque, power and specific fuel consumption at predetermined intervals of speed reduction (50 or 100 rpm). The results are then graphically represented in a two-dimensional system, illustrating the various interrelations among the measured parameters. Commonly:

- the horizontal axis shows the engine speed (ω), expressed in rpm.
- The left vertical axis shows the power (P) in kW.
- The right vertical axis, in the upper part, shows the driving torque (C) in Nm, while the lower part highlights the specific fuel consumption (Cs) in g/kWh. (Dash S.K., at all. 2022)

Specific fuel consumption represents the amount of fuel consumed (in grams) per unit of time (in hours) during the production of a constant power. It is important to note that specific fuel consumption is inversely proportional to engine efficiency under test conditions.

1.8. Anti-pollution devices

Air pollution caused by greenhouse gases is one of the major global environmental issues. Among the various sources of these emissions, internal combustion engines fuelled by petroleum derivatives contribute significantly. The first regulations aimed at reducing vehicle exhaust gas emissions were introduced in the United States, specifically in California, in the 1960s by the Environmental Protection Agency (EPA). However, these regulations initially only applied to on-road vehicle engines. (Bie P., at all. 2023)

About a decade later, Europe also adopted similar measures, but it was not until the mid-1990s that these restrictions were extended to non-road vehicles, including agricultural tractors and self-propelled machinery. The regulations, referred to as "Tier" by the EPA and structured into "Stages" under European legislation, are nearly equivalent and mandate a gradual reduction in pollutant gas emissions based on engine power and application sector.

For pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM), increasingly stringent limits have been established over time, also applying to diesel engines, divided into power classes.

Compliance with the various Stages has needed significant investment in the development and evolution of engines, with a particular focus on reducing NO_x and PM emissions in diesel engines. (Lovarelli D. & Bacenetti J., 2019; Leirião, L. et al. 2020)

To reduce gaseous pollutants emitted by engines, several strategies have been developed, with two achieving relative success: limiting the formation of pollutants in the combustion chamber and using filters and catalysts downstream of combustion. Actually, both strategies are often used in combination. The main solutions for reducing pollutant formation in the combustion chamber include partial exhaust gas recirculation (EGR) and increasing injection pressures (common rail). For the removal of pollutants after combustion, diesel particulate filters (DPF), catalytic filters, and urea-based catalysts (SCR) are used.

In diesel engines installed on agricultural machinery, solutions already successfully evaluated in the automotive sector, such as the transition from indirect to direct high-pressure common-rail injection, have been adopted. However, to meet stringent regulations about nitrogen oxides (NO_x) and particulate matter (PM), other interventions, particularly in exhaust gas after-treatment, have been necessary. (Ayodhya A. S. & Narayanappa K.G. 2018; Lopatin O., 2020; Rymaniak, Ł. Et al. 2020) The main and most widespread devices adopted include:

- EGR (Exhaust Gas Recirculation)
- SCR (Selective Catalytic Reduction)
- DPF (Diesel Particulate Filter)
- DOC (Diesel Oxidation Catalyst)

1.8.1. EGR (Exhaust Gas Recirculation)

The application of EGR (Exhaust Gas Recirculation) is a widely used technique in diesel engines to reduce nitrogen oxide (NO_x) emissions caused by high combustion temperatures. This solution involves reintroducing about 5-15% of the exhaust gases (by volume) back into the combustion chamber, lowering the combustion temperature and so reducing NO_x production.

The EGR process is typically carried out externally, intercepting a variable part of the exhaust gases through a dedicated, electronically controlled valve. The gases are then

cooled via a heat exchanger to reduce their temperature and increase their density before being reintroduced into the combustion chamber along with diesel and combustion air. While effective in reducing NO_x, this solution, which was the first in time adopted by manufacturers, inevitably increases particulate matter (PM) and unburned hydrocarbons (HC) production, as well as causing an efficiency loss, leading to higher specific fuel consumption. This happens because combustion occurs at lower temperatures and is therefore less complete. (Mao B., et al.2018)

This system also leads to faster degradation of the lubricating oil and can increase particulate matter due to the reintroduction of particles into the combustion chamber, which can form nuclei for agglomeration of other carbon residues, further promoting incomplete combustion. Incomplete combustion not only affects the effectiveness of the lubricating oil but also significantly increases combustion residues. Thus, although EGR is a widely used solution for reducing NO_x, the same cannot be said for PM and HC, which, conversely, increase due to lower combustion efficiency. Likewise, poorer combustion results in poorer engine efficiency, inevitably affecting the overall performance of the machine. (Jafarmadar S. & Nemati P., 2017; Tsolakis A., 2006)

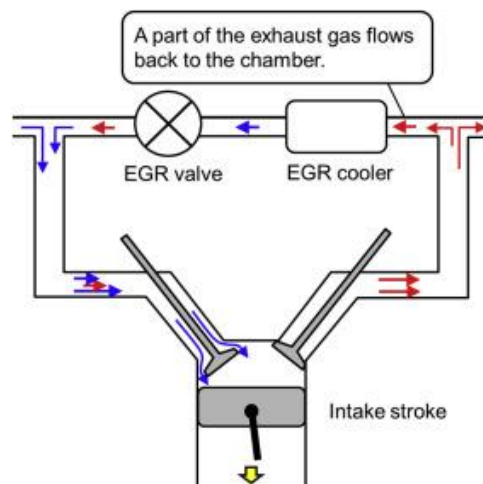


Figure 1 Operational diagram of an EGR system

1.8.2. SCR (Selective Catalytic Reduction)

The SCR (Selective Catalytic Reduction) system is an advanced technology used in diesel engines (both automotive and heavy-duty sectors) to significantly reduce nitrogen oxide (NO_x) emissions. This system effectively reduces NO_x levels through

an "ex-post" treatment of exhaust gases, that is, after they are generated, downstream of the combustion chamber. (Jiang Y. et al. 2018; Jung Y., 2022)

The operation of the SCR system can be described in the following steps:

- **Injection of AdBlue:** inside a catalyst, and controlled by a dedicated electronic control unit, a solution of pure urea (commonly known as "AdBlue") at 32.5% concentration in distilled water is sprayed into the exhaust gas stream. This solution is injected into the hot exhaust gases. (Xu Z. et al. 2018)
- **Urea decomposition:** at elevated temperatures, urea decomposes, releasing ammonia (NH_3) and carbon dioxide (CO_2). (Choi B. et al. 2013; Demir U. et al. 2022)
- **Catalytic reaction:** the exhaust gases and ammonia pass through an SCR catalyst. In the catalyst, ammonia reacts with the nitrogen oxides (NO_x) in the exhaust gases, converting them into atmospheric nitrogen (N_2 , which is non-toxic) and water (H_2O), in the form of vapour.
- **Control and modulation:** to minimize any NO_x escaping the SCR process, a sensor is placed downstream of the device to detect residual NO_x . This sensor sends information to the control unit, which continuously modulates the amount of AdBlue injected, ensuring the best system efficiency.

The SCR solution allows diesel engines to run under the best conditions in terms of efficiency, i.e., at high combustion temperatures and pressures, which promotes low specific fuel consumption and so lower particulate matter (PM) and unburned hydrocarbon (HC) emissions. However, the adoption of the SCR system involves practical and operational considerations, such as the need for periodic AdBlue refills, increased vehicle complexity and costs, and sensitivity to reagent quality. This issue is particularly relevant in vehicles with high engine compartment congestion (such as narrow-track tractors), which require careful study for the placement of instruments and devices. (Sari S. et al. 2016; Tadano Y. S. et al., 2014)

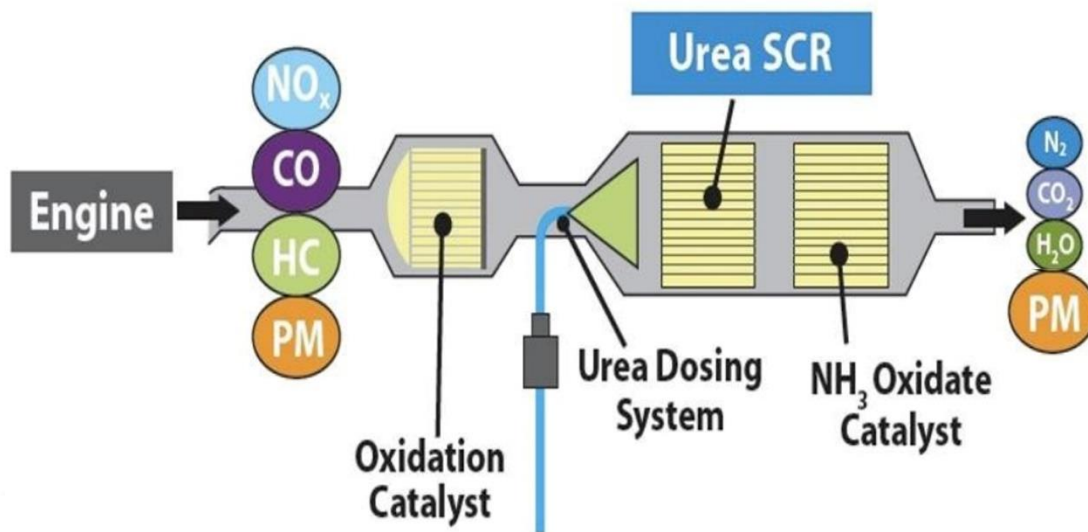


Figure 2 - Operational diagram of an SCR system

1.8.3. DPF (Diesel Particulate Filter)

The DPF (Diesel Particulate Filter) is a fundamental technology in diesel engines for reducing particulate matter (PM) emissions. This device acts as an extremely fine sieve made of refractory material, capable of trapping particles larger than the filter's passage section, preventing their release into the atmosphere. (Jiang Y. et al. 2018; Jung Y. et al. 2022)

The operation of the DPF system is detailed in the following steps:

- **Exhaust gas filtration:** Exhaust gases are directed through the particulate filter, which traps soot and other solid particles. However, like all physical filters, the DPF progressively clogs. Particulate accumulation reduces the filter channels' cross-section, increasing back pressure and obstructing the exhaust gas flow, leading to a gradual decline in engine performance. (Cano M. et al. 2019; Tartakovsky L. et al. 2015)
- **Monitoring sensors:** To avoid frequent filter replacement, which would be quite costly, two sensors are installed, one upstream and one downstream of the filter. These sensors measure the differential pressure across the filter and signal when a certain pressure threshold, indicating a degree of clogging, is exceeded. (Zhang Z.-H. & Balasubramanian R., 2018)

- **Filter regeneration:** When the filter reaches a certain level of clogging, regeneration is conducted to burn off the accumulated particles and restore filter efficiency. Regeneration can occur in two ways: (Zhang Z. et al. 2023; Meng Z. et al. 2020)
 - **Passive regeneration:** This happens automatically during normal vehicle operation when exhaust gas temperatures are high enough to burn off accumulated particles. This intervention does not compromise vehicle performance and simply activates a warning light showing exhaust gas temperatures above normal.
 - **Active regeneration:** Occurs when the vehicle's operating conditions are insufficient to reach the necessary temperatures. In this case, the engine's injection control unit sends more fuel post-injection, temporarily increasing consumption. This fuel increase raises exhaust gas temperatures, causing combustion of the trapped carbonaceous particles in the filter, reducing their size and allowing their expulsion.

Benefits and practical considerations: The DPF can reduce particulate emissions by up to 90%, improving air quality and helping diesel vehicles follow environmental regulations. However, the system also presents challenges, including installation and maintenance costs, increased fuel consumption during active regeneration, and the need for periodic maintenance to ensure long-term effectiveness. Excessive particulate accumulation can cause clogging, requiring filter cleaning or replacement.

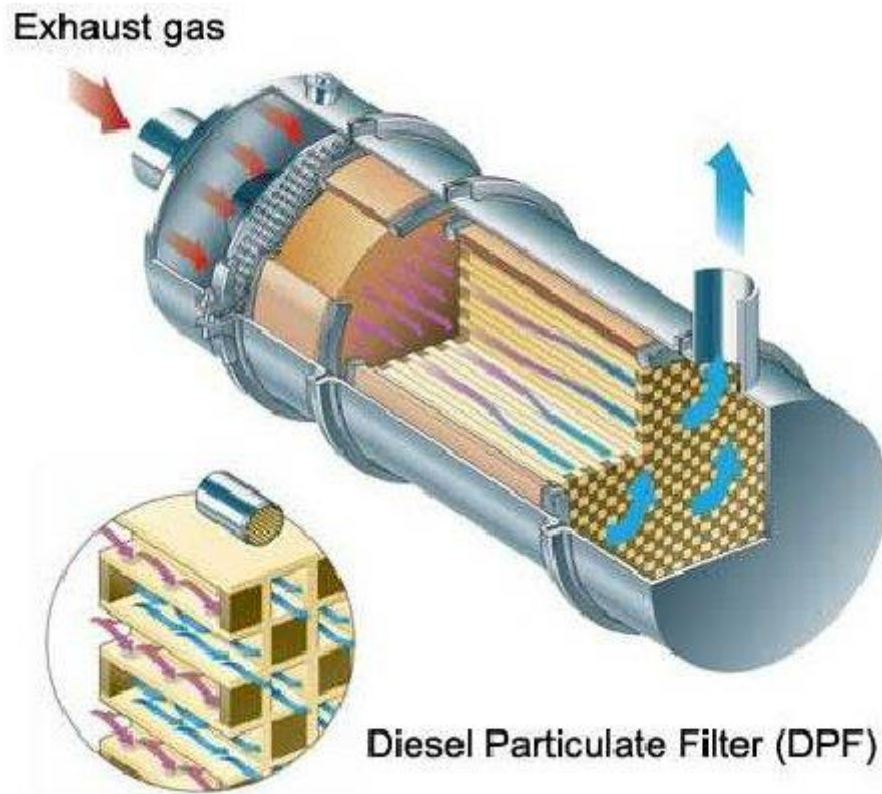


Figure 3 - Operational diagram of an DPF system

1.8.4. DOC (Diesel Oxidation Catalyst)

The DOC (Diesel Oxidation Catalyst) is an essential component designed to reduce emissions of unburned hydrocarbons (HC) and carbon monoxide (CO) in exhaust gases, converting them into carbon dioxide (CO₂) and water vapour. This device is particularly effective in removing the soluble organic fraction of particulate matter (PM) derived from hydrocarbons and accidental contamination of unburned lubricating oil.

In addition, the DOC shows a high ability in reducing polycyclic aromatic hydrocarbons, compounds known for their high toxicity. Its structure consists of a honeycomb ceramic matrix coated with thin layers of noble metals such as platinum, palladium and rhodium. These noble metals function as catalysts, accelerating the chemical reactions necessary for the oxidation of pollutant gases. (Caliskan H. &Mori K. 2017; Yu X. et all. 2024)

However, the DOC can pose a potential issue by releasing ultrafine particles when used on exhaust gases generated from diesel with suboptimal sulphur content (<15

ppm). This problem is particularly relevant in agricultural settings, where operational conditions may favour such a scenario.

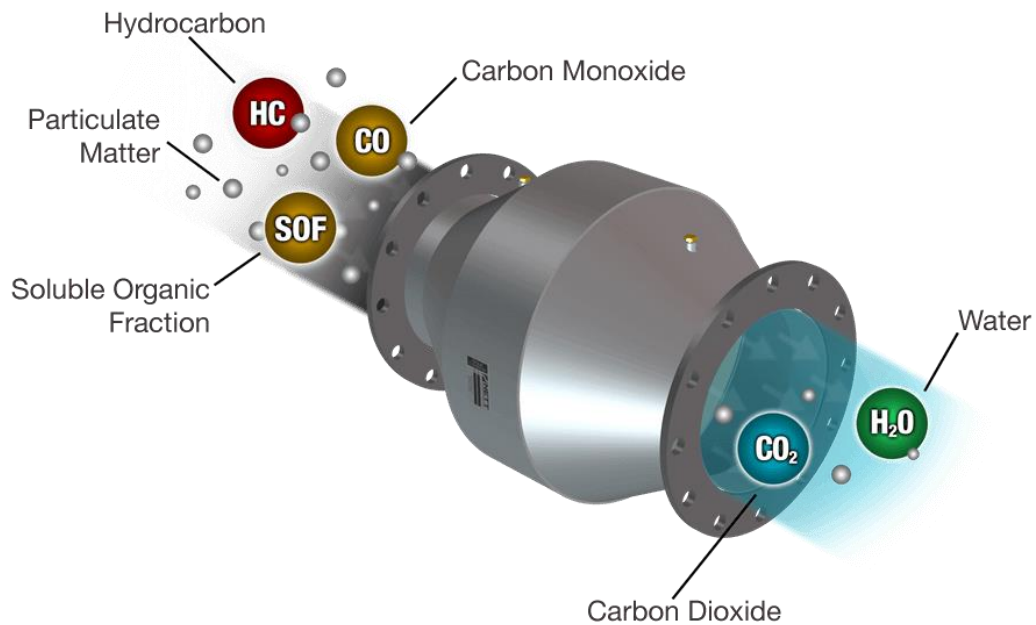


Figure 4 - Operational diagram of an EGR system

The DOC is a crucial element within the exhaust gas treatment system of diesel engines, working in synergy with other devices like the diesel particulate filter (DPF) and selective catalytic reduction (SCR) system. The goal is to ensure a significant reduction in pollutant emissions and compliance with current environmental standards, thereby improving air quality and mitigating the environmental impact of diesel vehicles. (Jung Y. et al. 2022)

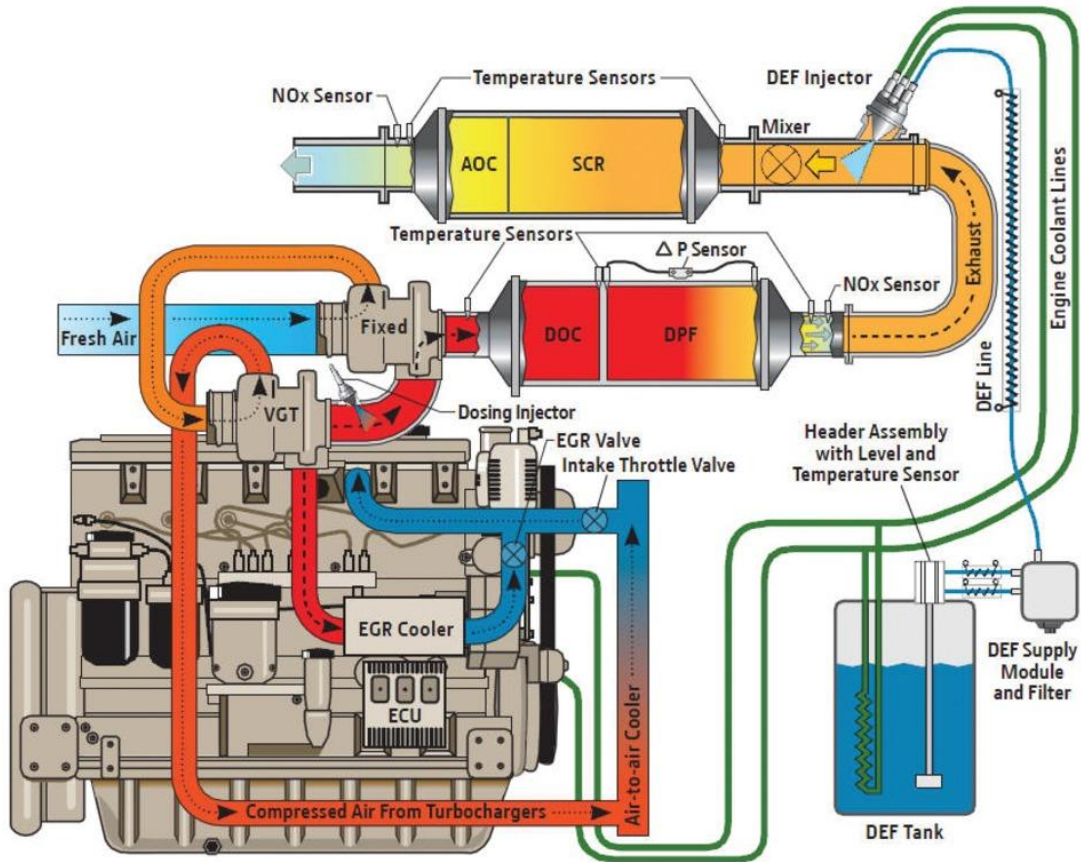


Figure 5 - Diagram of an engine equipped with multiple anti-pollution devices

Technical improvements and the application of anti-pollution technologies have traditionally been implemented to reduce gaseous emissions from fossil fuels. To achieve greater environmental efficiency and further decrease gaseous emissions, alternative solutions have been explored. Over the past 20 to 30 years, biofuels, derived from vegetable sources or by-products and waste materials, have emerged as prominent alternatives. These biofuels are more sustainable while keeping operational efficiency.

1.9. Alternative (renewable) fuels

To further mitigate the production of pollutant emissions generated by internal combustion engines, beyond the design of more efficient and high-performance engines and the application of anti-pollution devices (which limit the emission of

exhaust gases post-combustion), interventions can also be made at the energy source level. Typically, for heavy-duty agricultural engines, the primary fuel is fossil-derived diesel. However, in recent decades, advancements in technology have led to the discovery and development of alternative fuels, specifically biofuels. (Ithnin A. & Yahya W., 2017; Butcher M.G., et al. 2018)

The emergence of biofuels dates to the early 2000s, and since the initial studies, significant technological progress has been achieved. Conventionally, the evolution of biofuels can be categorized into three generations based on the feedstock (and the corresponding production process) utilized for biofuel synthesis. (Agarwal A. et al. 2015; Dash S.K. et al. 2022)

The first generation involved the conversion of food crops such as corn, sugarcane, rapeseed oil, soybeans, palm oil, and wheat into biofuels, which raised significant concerns regarding land use competition (food-feed-fuel conflict). Starchy and sugar crops were primarily used for bioethanol production, while oilseeds were processed into vegetable oils and biodiesel. (Mancio A.A. et al. 2018)

To address the issue of competition for agricultural land, the second generation of biofuels focused on non-food biomass, such as agricultural residues (straw, corn husks), forest residues, non-food crops (e.g., *Jatropha* and *Miscanthus*), and organic waste. Second-generation biofuels, including bioethanol and biobutanol, are produced through the fermentation of sugars extracted from lignocellulosic materials via pretreatment and hydrolysis processes. Second-generation biodiesel is derived from oils extracted from non-food plants or by processing waste oils. The primary advantage of second-generation biofuels is their non-competitive stance with food production, as they utilize agricultural and industrial by-products of low economic value. This approach reduces environmental impact and improves waste management. However, the production technologies are more complex and costly compared to first-generation biofuels, necessitating significant technological and infrastructural advancements to become economically viable.

The third generation of biofuels, the most recent, utilizes photosynthetic organisms such as algae and genetically modified microorganisms. Algae, cultivated in photobioreactors or open ponds, can be converted into biofuels through various processes, including oil extraction, fermentation, and gasification. Engineered

microorganisms can directly produce biofuels such as ethanol, butanol, or hydrocarbons through advanced fermentation processes. This generation of biofuels offers several advantages, including high yield in feedstock production (algae can produce significantly more biofuel per hectare compared to terrestrial crops). (Butcher M.G., et al. 2018)

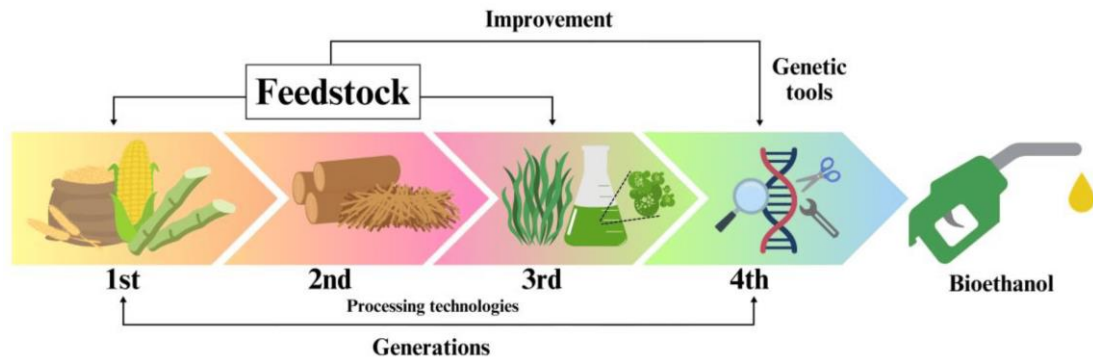


Figure 6 - The sustainability of biofuels depends on the energy sources used. The goal is to optimize the utilization of animal and plant by-products that are not suitable for human or animal consumption.

Additionally, these biofuels do not compete with food production and can be cultivated in areas unsuitable for traditional agriculture, offering substantial potential for greenhouse gas emission reductions. However, third-generation biofuel production technologies are still in the development stage and not yet commercially mature. Production costs remain high, and further research is required to improve efficiency and reduce costs.

Among the primary biofuels available on the market are biodiesel, hydrotreated vegetable oil (HVO), biomethane, vegetable oil, and bioethanol.

1.9.1. Biodiesel and HVO

Among biofuels chemically closest to fossil-derived diesel are biodiesel and HVO. Both biofuels possess high calorific values and chemical-physical properties similar to diesel, enabling their use in diesel engines without requiring any structural modifications to the engine or the fuel supply system.

1.9.1.1. Biodiesel

Biodiesel is a renewable fuel with a history that began at the start of the 20th century. The first prototype of an internal combustion engine, presented by Rudolf Diesel, was powered by vegetable oils, thus anticipating the use of renewable energy sources. (Agarwal A. K. et al. 2014) In the 1930s, experiments with vegetable oils began, but it was not until the 1970s, in response to the energy crisis, that biodiesel gained attention as an alternative to fossil fuels. (Karpanai Selvan B. et al. 2022; Emaish H. et al. 2021) During the 1990s, the commercialization of biodiesel increased in various countries, and from 2000 onwards, due to rising environmental concerns and oil prices, its production and use saw significant growth.

Biodiesel appears as an oily fluid, primarily composed of fatty acid methyl esters (FAME), obtained through the transesterification process of vegetable oils or animal fats. (Evcil A. et al. 2018; Krahl J. et al. 2007; Lešnik, L., & Biluš, I. 2016)

One of the main advantages of biodiesel, compared to other biofuels, is its ability to be used as-is in diesel cycle engines, thanks to its chemical-physical properties that are particularly like traditional diesel.

Table 5 - Chemical-physical properties of Diesel and Biodiesel

Typical Characteristics of Fuels	Diesel	Biodiesel (RME)
Molecular Mass	120-320	296
Viscosity (20°C) mm ² /s	4-5.5	6-8
Cetane Number	50	54
Calorific Value (MJ/dm ³)	35.7	32.6
Density (15°C) kg/dm ³	0.84	0.88

Biodiesel is often used, even in the automotive and transport sectors, blended with fossil-origin diesel in various proportions. The use of diesel engines powered by biodiesel allows for a significant reduction in atmospheric pollutant emissions, particularly particulate matter. Biodiesel can be produced, using various technologies, from different raw materials including food crops such as soybean, rapeseed and palm,

as well as waste oils and animal residues. (Yoon S.K. et al. 2019; Ayhan V. et al. 2020; Shahir V.K. 2015; Abdollihi M. et al. 2020)

Its widespread use in various transport sectors and heavy-duty applications makes it a potential solution for decarbonizing the transport sector without giving up the internal combustion engine. In the agricultural sector, it can be used for the locomotion and movement of tractors and self-propelled equipment, or as a power generator where it finds application in cogeneration plants and power plants. (Mofijur M. et al. 2016; Carmona-Cabello M. et al. 2018; Richter S. et al. 2018; Karthickeyan V. et al. 2019) Currently, the applicability of biodiesel is also being evaluated in the maritime transport sector, where it can be used to reduce the environmental impact of maritime operations.

1.9.1.2. HVO (Hydrotreated Vegetable Oil)

HVO, or hydrotreated vegetable oil, is a second-generation biofuel produced through the hydrotreatment process of vegetable oils and animal fats. This chemical process, which involves the removal of oxygen using hydrogen under elevated temperature and pressure conditions, allows the conversion of lipid feedstocks into saturated aliphatic hydrocarbons, analogous to fossil fuels.

HVO presents several technical advantages. (d’Ambrosio S. et al. 2022; Bohl T. et al. 2018) Its chemical composition, like conventional diesel, ensures excellent compatibility with existing diesel engines and distribution infrastructure, facilitating its adoption. Moreover, HVO is characterized by a high cetane number, which contributes to improved combustion performance and reduced emissions of unburned particulates.

Table 6 - Chemical-physical properties of Diesel and HVO

Typical Characteristics of Fuels	Diesel	HVO
Molecular Mass	120-320	200-300
Viscosity (20°C) mm ² /s	4-5.5	2-4
Cetane Number	50	70-90
Calorific Value (MJ/dm ³)	35.7	34-36
Density (15°C) kg/dm ³	0.84	0.77-0.79

From an environmental perspective, HVO allows for a significant reduction in greenhouse gas emissions, with values that can vary from 60% to 85% compared to fossil fuels, depending on the feedstock used. The use of waste oils and animal fats reduces competition with food production, thus contributing to more sustainable resource management. (Enweremadu C.C. & Rutto H.L.2010; Carmona-Cabello M. et al. 2018) To ensure proper resource utilization, it is crucial to guarantee the sustainability of the feedstocks used for HVO production. HVO production can also be combined with other advanced technologies, such as gasification and chemical synthesis, to further optimize yield and overall process efficiency.

1.9.2. Biomethane

Biomethane is a renewable gas obtained by purifying biogas, produced through the anaerobic digestion of organic materials. The first research on biomethane took place around the 1970s, when pilot-scale experiments were conducted in Europe to exploit the energy potential of organic waste. In the 1990s, with growing interest in renewable energy sources, the production of biogas and consequently biomethane expanded significantly. The introduction of stricter regulations aimed at reducing greenhouse gas emissions further increased the importance of biomethane in the European energy landscape.

The characteristics of biomethane make it a sustainable alternative to fossil fuels. This biofuel is characterized by a methane content of over 95%. Biomethane has a high energy capacity, and the absence of impurities such as carbon dioxide and sulphur ensure its quality and compatibility with existing natural gas infrastructure, while also reducing its harmful environmental impact (sulphur dioxide). (Wiemann S. et al. 2018)

Biomethane is used in various sectors. It is employed in the production of electricity and heat through cogeneration plants, enhancing the overall energy efficiency of the system. Finally, biomethane can be injected into the natural gas distribution network, supporting energy security and diversification of supply sources. Additionally, in the transport sector, it is used as a fuel for gas-powered vehicles, contributing to the reduction of pollutant emissions.

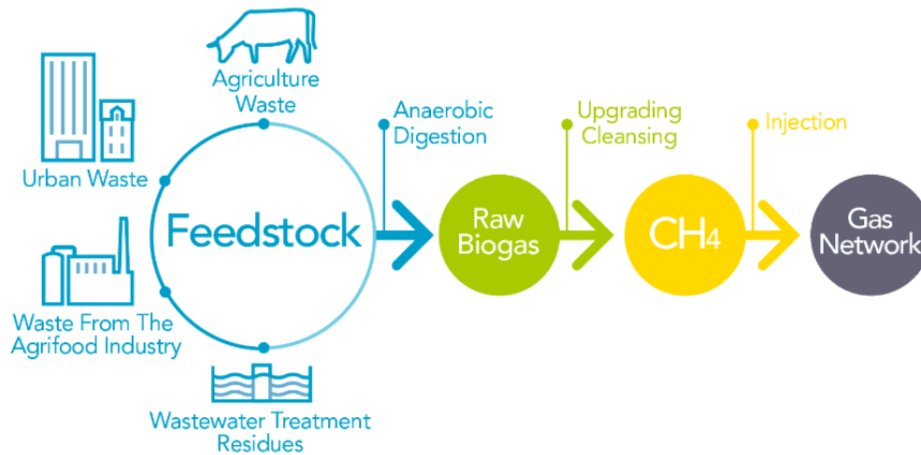


Figure 7 - Biogas production occurs through the anaerobic digestion of various by-products, which, after refining, can yield biomethane for self-consumption or injection into the grid.

In recent years, the use of biomethane-powered heavy-duty vehicles (such as tractors, e.g., New Holland T6 Methane Power) has been studied, providing a useful solution for operations with anaerobic digesters that can directly utilize the biofuel.

1.9.2.1. New Holland T6 Methane Power

New Holland has recently launched a new version of the T6 tractor model. This recent version is equipped with an FPT Industrial NEF 6-cylinder engine specifically designed for agricultural use. Unlike previous models, the New Holland T6 Methane Power is powered by compressed methane or biomethane while ensuring the same performance as the diesel model. Thanks to the new fuel system, CO₂ emissions have been reduced by up to 80%, while generating the same power and torque. Methane combustion is cleaner than diesel, allowing for a significant reduction in particulate and nitrogen oxide (NO_x) emissions. Besides environmental sustainability advantages, the new model developed by New Holland offers reduced operating costs due to the lower fuel cost and independence from fossil fuels. Additionally, in some countries, the use of biomethane is supported by incentives promoting its adoption in various sectors.



Figure 8 – The New Holland T6 Methan Power tractor

1.9.3. Vegetable oil

The initial fuels utilized for powering diesel cycle internal combustion engines in the early 20th century were vegetable oils. (Evcil A. et al. 2018) Derived from crops such as rapeseed, sunflower, and soybean, vegetable oils can be used in their pure form (Straight Vegetable Oil, SVO) or blended with conventional diesel, providing a viable alternative to fossil fuels. The employment of vegetable oil in diesel engines is considered a sustainable strategy for the energy transition, due to its renewable origin and potential for reducing greenhouse gas emissions. Nevertheless, the use of food crops for biofuel production is ethically contentious, prompting the investigation into new production avenues (second and third-generation biofuels). (Krahl J. et al. 2007) From a technical standpoint, the combustion of vegetable oils offers significant benefits, including a higher energy density and superior biodegradability compared to fossil fuels. (Atmanli A. et al. 2014; Burciu S.M. et al. 2019; Phoungthong K. et al. 2013) However, the physicochemical properties of vegetable oils, such as high viscosity and the presence of certain compounds, can result in operational issues, such as injector clogging and the accumulation of carbon deposits within the engine. To mitigate these challenges, pretreatment processes like transesterification, which converts oils into biodiesel (Fatty Acid Methyl Esters, FAME), or the use of oil heating systems to reduce viscosity during injection, are often required.

The utilization of vegetable oils and biodiesel facilitates a notable reduction in nitrogen oxides (NO_x) and volatile organic compounds (VOCs), promoting more sustainable mobility. The integration of vegetable oil into diesel engines is particularly advantageous in agricultural contexts, where vehicle fleets can benefit from a local and sustainable supply of raw materials. Some tractor models manufactured by John Deere, Deutz Fahr, and Fendt are designed to operate with pure vegetable oil (Thunke, K et al. 2014). These tractors can either run on a blend of vegetable oil and diesel or by using the two fuels separately. In the latter case, the tractors are equipped with two separate fuel tanks: one for diesel, used for engine start-up and shutdown, and one for vegetable oil, utilized during regular operation.

These vehicles can be used for transporting agricultural products or performing daily farm operations, thereby contributing to increased energy autonomy.

Table 7 Chemical-physical properties of Diesel and Rapeseed oil

Typical Characteristics of Fuels	Diesel	Rapeseed oil
Molecular Mass	120-320	883
Viscosity (20°C) mm ² /s	4-5.5	75
Cetane Number	50	44
Calorific Value (MJ/dm ³)	35.7	33.7
Density (15°C) kg/dm ³	0.84	0.91

The application of vegetable oil can also extend to corporate fleets and public transportation systems, where sustainability policies can be implemented to diminish environmental impact. The compatibility of vegetable oils with existing infrastructure and the potential for gradual integration makes this solution particularly appealing for the energy transition.

1.9.4. Bioethanol

Bioethanol is a plant-based biofuel produced primarily through the fermentation of sugars present in biomass. Like other oil-based biofuels, interest in bioethanol emerged in the 20th century. However, its significant adoption and distribution began in the

1970s, following energy crises that spurred technical advancements and research towards alternative energy sources distinct from fossil fuels. (Mofijur M. et al. 2016) Between the late 1990s and early 2000s, substantial programs for the production and distribution of bioethanol were developed in regions such as Latin America and the USA, supported by policies and incentives aimed at energy diversification.

Bioethanol possesses several characteristics that render it an attractive option in the contemporary energy landscape. As an ethyl alcohol, it has high purity, a lower energy content compared to gasoline, but a higher-octane number, enhancing engine performance. The production of bioethanol involves fermentation processes using raw materials such as sugarcane, corn, and wheat (in the case of first-generation biofuels). Recently, lignocellulosic biomass sources are being explored to enhance sustainability. (Yang F. et al. 2018) The major advantage of bioethanol, compared to gasoline, is its biodegradability, significantly contributing to the reduction of greenhouse gas emissions, making it a sustainable solution (if properly produced) in the context of increasing environmental concerns.

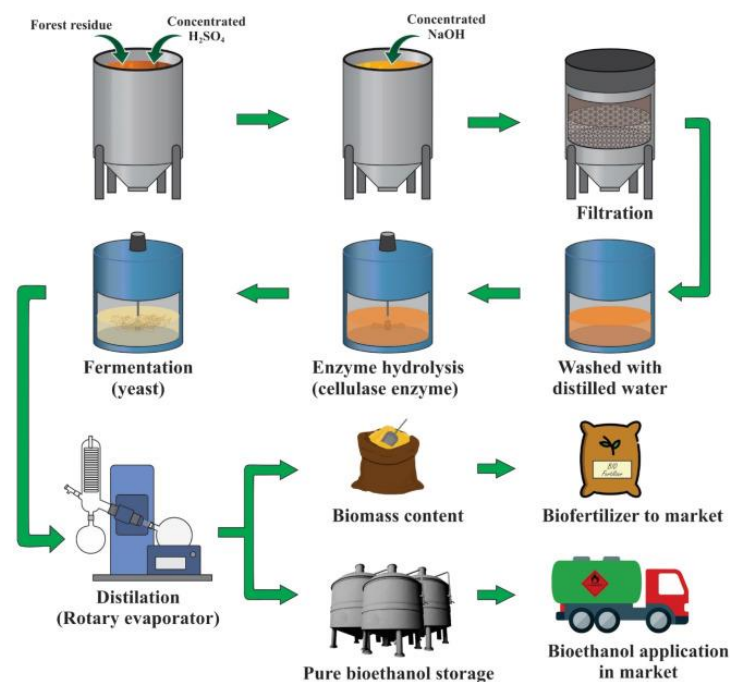


Figure 9 - Bioethanol production diagram

Bioethanol is utilized in various sectors, predominantly in transportation, where it is used both as a pure fuel (E100) and blended with gasoline (e.g., E10 or E85). This

application helps reduce dependence on fossil fuels and decrease pollutant emissions. Additionally, bioethanol is employed in the industrial sector as a solvent and a raw material for producing chemicals, facilitating the transition towards more sustainable production processes.

1.9.5. Electric power

Another viable option today for further reducing emissions from internal combustion engines involves not only modifying the energy source but also the engine itself. Like advancements in the automotive sector, several models of tractors with dual fuel systems (diesel + electric) or purely electric powertrains have been developed. There is a progressive electrification of the global tractor fleet. The first models of hybrid tractors (dual fuel diesel + electric) emerged in the early 2000s. (Dhond R. et al. 2021; Farzaneh F. & Jung S. 2023) The initial partially electrified tractor models featured an onboard generator of varying sizes, responsible for secondary operations, such as powering the tractor's air conditioning compressor, among others. Thanks to technical advancements, it is now possible to observe hybrid tractor models where the electric component not only handles the secondary functions of the tractor but also contributes to locomotion and power distribution.

1.9.5.1. Hybrid engines: dual engine

Already widely used in the automotive sector, the use of hybrid engines for automotive traction is considered an innovative solution in terms of environmental sustainability. The combination of an internal combustion engine with an electric motor allows, if meticulously designed and used, the sum of the advantages of both systems.

Pairing two engines to create a hybrid system optimizes energy efficiency, reduces greenhouse gas emissions, and improves overall vehicle performance. Hybrid engines are primarily classified into two categories: parallel hybrids and series hybrids.

In parallel hybrid engines, both units (electric motor and internal combustion engine) can provide power to the vehicle simultaneously or alternately. In series hybrid engines, the combustion engine acts as a generator to recharge the batteries and power the electric motor, which is responsible for traction.

From a performance perspective, hybrid engines offer significant advantages. The combination of the two energy sources allows for smooth and responsive acceleration, thanks to the immediate torque provided by the electric motor. Superior performance during start-up and manoeuvres is documented, with the overall system efficiency potentially exceeding 50%, compared to the typical 20-30% of internal combustion engines (it should be noted that the electric motor has an efficiency of 90% compared to the diesel-powered internal combustion engine, which reaches just over 40% under the best conditions).

Since 2020, Weichai has introduced several heavy-duty engines to the market with efficiencies exceeding 50% (52-53%). While these advancements are groundbreaking and have the potential to significantly enhance the performance of heavy-duty engines, they cannot yet serve as a reference standard due to their current limited market penetration. (<https://www.prnewswire.com/apac/news-releases/four-world-records-set-weichai-power-unveils-worlds-first-diesel-engine-with-53-09-thermal-efficiency-302122681.html>; <https://dieselnet.com/news/2024/04weichai.php>)

A particularly relevant aspect of electric motors (paired with internal combustion engines in hybrid vehicles) is energy recovery capability. During braking or deceleration phases, the hybrid system can recover part of the kinetic energy, converting it into electrical energy to recharge the batteries and increase the vehicle's range. This process contributes to greater efficiency and, consequently, to a reduction in pollutant emissions. (Mocera F. et al. 2022; Mocera F. & Martini V. 2022)

The implementation of hybrid engines is particularly advantageous in urban environments and heavy vehicles, where stop-and-go traffic conditions can benefit from using the electric motor, reducing fuel consumption. Additionally, in heavy-duty vehicles, the operational flexibility offered by hybrid engines allows for handling various load and terrain conditions, improving operational reliability. Not least, the presence of an electric motor could improve the ergonomics of some operations, reducing vibrations and noise.

1.9.5.1.1. John Deere 7530E

Examining market offerings, it is evident that solutions for tractors and agricultural machinery at various levels of electrification have been available for years. Over 15

years ago, in 2007 (at Agritechnica), John Deere introduced two versions of the same tractor model: the 7530 Premium and the 7530 E-Premium. The first version featured a traditional 150-180HP tractor powered by an internal combustion engine, while the 7530 E-Premium version included a small electric motor to manage certain utilities.

Both models shared the following basic features:

The tractor is equipped with a John Deere PowerTech Plus engine with a displacement of 6800 cm³. It utilizes an electronically controlled common rail system with 4 valves per cylinder. It is equipped with a VGT turbo intercooler with external EGR. The cooling system is managed by a Vistronic, which electronically regulates the fan. The transmission is a John Deere Infinitely Variable Transmission (IVT) characterized by continuous variation. The speed management system allows for a range of speeds from 0.05 to 42 km/h. The PTO is independent with electrohydraulic braking and engagement. The PTO shaft has a diameter of 45 mm with 20 splines, capable of operating at both 540 and 1000 min⁻¹. The hydraulic system is equipped with load sensing and a dedicated pump with variable flow and pressure of 120 l/min. The hydraulic lift has an electrohydraulic operation with a lifting capacity of up to 90 kN. (Pessina D. & Facchinetti D., 2009)

Additionally, the 7530 E-Premium model is equipped with an electric generator capable of providing up to 20 kW of auxiliary electrical power. The generator allowed for the operation of certain engine components, increasing efficiency and simultaneously powering some electrical equipment at 230/400V. The generator, applied to the crankshaft, powered some accessories that were traditionally mechanically driven, such as the reversible cooling fan, air conditioning compressor, and all compressed air equipment. This not only decoupled the operation of these accessories from the engine speed but also reduced the power absorption from the engine (which was transferred to the electric generator), ultimately benefiting fuel consumption and efficiency.

1.9.5.1.2. Landini REX 4-Hybrid

In 2020, the Landini brand launched the new REX4 Electra model, a hybrid-powered tractor for specialized crops. This tractor is equipped with a 110 CV diesel internal combustion engine. This engine, through the generator and battery, powers the two

front electric motors that drive the front axle. This 4WD tractor features electric traction for the front axle, improving fuel consumption, efficiency, and emission levels. The electric front axle is also particularly effective in manoeuvres, reducing the turning radius and allowing operations between rows.

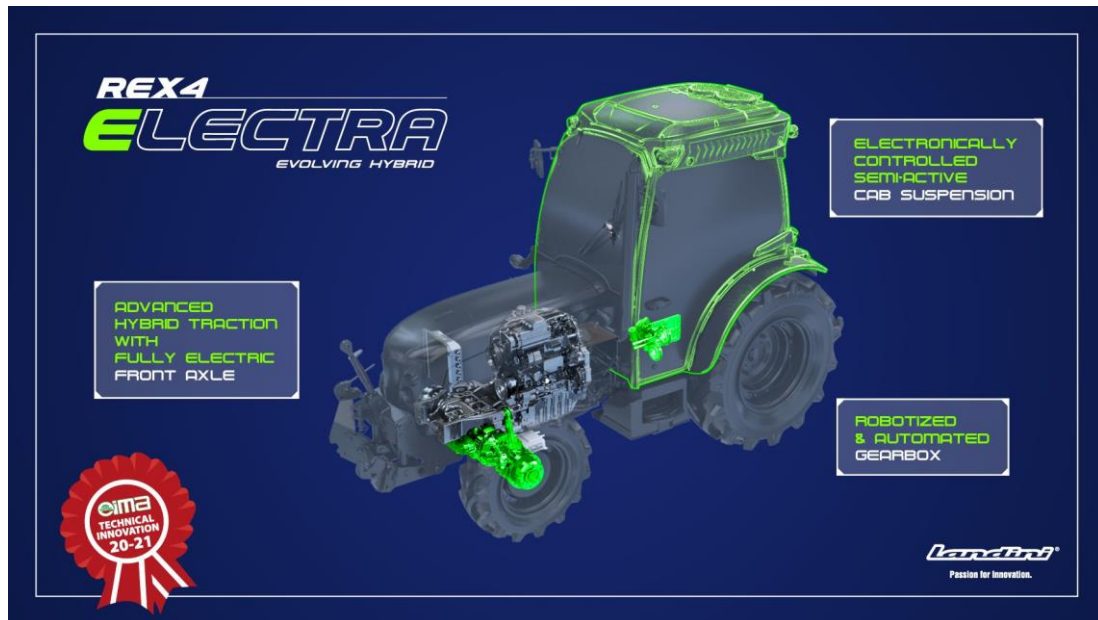


Figure 10 - Landini REX 4-Hybrid

While hybrid power has achieved significant milestones in the past 20 years thanks to technical progress and research, it is still a choice far from operational reality (like full electric power). These power systems are limited by battery packs, which unfortunately have not yet reached sufficient energy density levels to guarantee a full day's work (approximately 8 hours).

1.9.6. Batteries for hybrid and full electric motors: critical issues

1.9.6.1. Full electric

The advent of hybrid powertrains in heavy-duty vehicles 15 years ago led to increased efficiency and reduced emissions. A further step was taken with the introduction of full electric powertrains. The application of electric motors for traction purposes represents

one of the most advanced and sustainable solutions in the mobility sector. (Kubik A. et al. 2023; Melo R. et al. 2019) These motors are characterized by high efficiency (approximately 90%) and a reduced environmental impact, thanks to the absence of combustion, offering often superior performance compared to internal combustion engines.

Electric motors use various configurations, including direct current (DC) and alternating current (AC) motors, with the latter frequently employed in traction applications. Among AC motors, synchronous and asynchronous motors are distinguished, each with specific advantages in terms of efficiency and torque control. Synchronous motors are valued for their ability to provide high torque at low speeds, making them ideal for vehicle traction.

A key advantage of electric motors is the immediate torque delivery, allowing for rapid acceleration and speed adjustments. While this characteristic is not essential in the heavy-duty sector, electric motors also offer greater construction simplicity, resulting in higher reliability and lower maintenance costs. The performance of electric motors can vary significantly depending on their design and intended use. (Ueka Y et al. 2013; Malik A. & Kohli S. 2020) The nominal power of these motors can range from a few kW for light vehicles (such as electric motorcycles) to over 1,000 kW for heavy-duty vehicles (such as buses and trucks).

Constructively simpler, the electric motor features reduced power losses, resulting in particularly high efficiency of about 90%. Although the electric motor's market penetration is still marginal compared to internal combustion engines, it is available in a multitude of vehicles, from light ones in the automotive sector to heavy-duty ones. Currently, this seems to be the best choice for reducing pollutant emissions and improving traction motor efficiency.

However, the limited charging network and battery energy density do not allow for usage comparable to that of internal combustion engines. For instance, while a tractor powered by an internal combustion engine can work continuously for 8 hours, the same is not possible with an electric tractor. The current battery capacity does not support comparable operational autonomy, and there are also the downtimes required for recharging the battery pack. While a diesel vehicle can resume work immediately after

refuelling (taking only a few minutes), electric vehicles require several hours of downtime for recharging, even if partial. (Cecchini M. et al. 2024)

Despite these critical issues, research and technical progress are working to improve battery efficiency to offer electric vehicles with the same performance and operational autonomy as internal combustion vehicles.

1.9.6.1.1. Fendt Vario E100: a specialized full electric tractor

The Fendt Vario E100 is one of the first full-electric tractors introduced to the international market. It is a compact tractor, ideal for working in enclosed environments such as greenhouses, due to the absence of pollutant gas emissions from combustion. The tractor is equipped with a 100-kWh battery, providing sufficient energy for several hours of fieldwork. The electric motor can deliver continuous power of 55 kW up to a peak of 66 kW, ensuring high and consistent performance.

The Fendt Vario E100's charging system supports 22 kW AC for standard charges and 80 kW DC for fast charges, reducing downtime and maximizing operational efficiency. The tractor features the Vario transmission, offering continuous speed variation for precise control and optimal traction in all conditions. It is equipped with a high-efficiency hydraulic system, providing high flow rates for operating various agricultural implements. Being fully electric, the Fendt Vario E100 reduces carbon emissions and environmental impact, promoting more sustainable agricultural practices.

In terms of sustainability and reducing pollutant emissions during operations, full-electric tractors seem to be an excellent compromise. However, the current low energy density of batteries does not allow for a full day's work on a single charge. Consequently, replacing the entire fleet of machines (from fossil-fuel-powered to full-electric) will not be a near-future occurrence, at least until batteries capable of supporting heavy-duty work and high-power demands for more than 8 consecutive hours are available.

1.9.6.2. Electric motor power supply

Electric motors today are mostly powered by batteries. Batteries for electric motors, commonly known as electric vehicle (EV) batteries, are crucial components that store the energy needed to power the motor.

Several types of batteries are available on the market, each with different performances and characteristics depending on their intended use. Key parameters for evaluating and categorizing batteries include energy density and the number of charge cycles. Energy density is divided into volumetric energy density and gravimetric energy density. The former, expressed in Wh/l, represents the amount of energy storable per unit volume of the battery, while the latter, expressed in Wh/kg, indicates the amount of energy storable per unit weight of the battery.

The number of charge cycles is an indicative value that represents the number of charge/discharge cycles the battery can provide before reaching the end of its life, i.e., losing its original performance. In addition to these performance parameters, evaluations on safety (issues of overheating and combustion) and cost are also important, as several types of batteries will have varying costs.

Among the main types of batteries for vehicles are:

- **Lithium-Ion Batteries (Li-ion):** The most common in modern electric vehicles. They are valued for their high energy density, meaning they can store a lot of energy per unit of weight. They are also relatively lightweight and have a long lifespan. Li-ion batteries are widely used due to their balance between performance, cost, and safety.
- **Lithium Iron Phosphate Batteries (LiFePO₄):** A variant of lithium-ion batteries characterized by greater thermal and chemical stability. They are less prone to fires or explosions, making them a safer choice in some applications. However, they have a lower energy density compared to standard Li-ion batteries.
- **Solid-State Batteries:** An emerging technology that uses a solid electrolyte instead of a liquid one. These batteries promise higher energy density, faster charging times, and greater safety. However, they are still in development and not yet widely available on the market.

- Nickel-Metal Hydride Batteries (NiMH): Widely used in early electric and hybrid vehicles. Although they have a lower energy density compared to lithium-ion batteries, they are more robust and have a longer lifespan. They are now less common in modern electric vehicles, having been largely replaced by Li-ion batteries.
- Lead-Acid Batteries: One of the oldest rechargeable battery technologies. They are heavy and have low energy density but are cheap and robust. Currently, their use in electric vehicles is limited, generally reserved for vehicles with very low energy requirements or as auxiliary batteries.

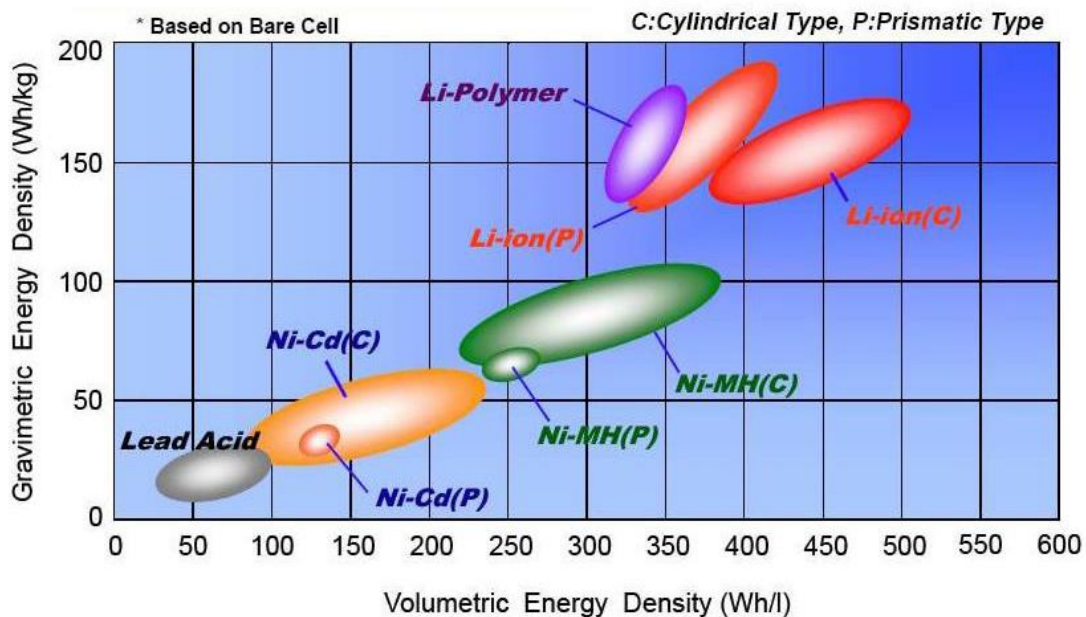


Figure 11 – Energy density of different types of batteries

The ongoing critical issues with electric motors, due to battery energy density and long current charging times, are driving research and technical progress toward new prospects. The goal is to improve battery performance to reduce charging times, thus promoting the adoption of electric vehicles with all the associated benefits (higher efficiency and drastic reduction of emissions).

In recent years, alongside battery-powered electric propulsion, hydrogen power has also started to appear.

1.9.7. Hydrogen power supply

1.9.7.1. Hydrogen-powered fuel cells

In recent years, alongside electric motors, hydrogen power has been studied as an added resource for vehicle power. Hydrogen can be used either as a fuel for hydrogen fuel cells to power an electric motor or as a combustible for internal combustion engines.

Hydrogen fuel cell power is based on using fuel cells that convert hydrogen into electricity to power the vehicle's electric motor. Fuel cells produce electricity through a chemical reaction between hydrogen (H_2) and oxygen (O_2) naturally present in the air. This process generates electricity, which powers the electric motor, heat, and water as the only byproduct. Thus, the entire process is particularly eco-friendly. Hydrogen is stored in specially designed high-pressure gas tanks to withstand various operating conditions. (Hacking M. et al. 2019; Haseli Y. 2018)

This technology offers several advantages:

- **Massive Emission Reduction:** The only byproduct of electricity generation is water vapor, making this power source particularly ecological, especially if hydrogen production is derived from renewable sources.
- **Comparable Autonomy:** Hydrogen-powered vehicles offer autonomy like internal combustion engine vehicles, with refuelling times also potentially short.

However, several challenges must be addressed to enable the success and widespread adoption of this technology:

- **Low Efficiency:** Analysing the overall efficiency of fuel cells highlights several significant limitations, primarily due to the complexity of the hydrogen production process. Water electrolysis, one of the most considered green options, has a relatively low efficiency of approximately 60%. Additionally, the subsequent use of hydrogen in fuel cells maintains a similar efficiency. Consequently, the combined efficiency of these two processes is reduced to around 36%. This value must be further reduced by the efficiency of the electric motor, which converts energy into mechanical power with an efficiency of

90%. In the end, the overall efficiency is approximately 32%, comparable to that of an internal combustion engine in good condition.

- Infrastructure: Hydrogen refuelling infrastructure is still limited and uneven, with few stations compared to traditional fuel or electric charging stations.
- Production and Storage: Hydrogen production can be energy-intensive and not always sustainable, especially if derived from fossil fuels. Additionally, storing and transporting hydrogen require special precautions to ensure safety.
- Cost: Currently, hydrogen vehicles and fuel cells are expensive to produce, though costs are expected to decrease with increased production and technological development.

1.9.7.2. Hydrogen internal combustion engines

Alternatively, hydrogen can be used as a fuel for internal combustion engines. This requires modifications to internal combustion engines to allow hydrogen combustion instead of gasoline or diesel. The operation of a hydrogen internal combustion engine is like that of a gasoline engine, following the Otto cycle. (Banerjee R. et al. 2015) Combustion occurs through a mixture of air and hydrogen injected into the combustion chamber, where it burns at elevated temperatures and pressures due to the ignition from an electrically powered spark plug. This generates energy that drives the pistons, producing motion. Conventional engines require modifications to enable hydrogen combustion, including adjustments to the fuel system, fuel storage, combustion chamber shape, and electronic engine management (injection, ignition, etc.). (Yadav V.S. et al. 2012; Karagoz, Y. et al. 2015)

Hydrogen combustion primarily produces water vapor as waste. However, the hot temperatures reached during combustion can generate nitrogen oxides (NO_x), which are pollutants. Techniques such as water injection or low-temperature combustion are used to reduce these emissions. (Jhang S.-R. et al. 2016)

Advantages and Limitations

Advantages of hydrogen internal combustion engines:

- CO₂ emission reduction: significant reduction in CO₂ emissions.
- use of existing engines: existing engines can be adapted, making hydrogen power economically sustainable.

- comparable autonomy and refuelling time: like traditional internal combustion engines.

Limitations of hydrogen internal combustion engines:

- hydrogen production and storage: requires ambient temperature and high-pressure storage.
- renewable hydrogen production: needs to be derived from renewable sources.
- NO_x production: high-temperature combustion generates NO_x, contributing to air pollution.
- lower efficiency: less efficient than fuel cells.

Despite these challenges, hydrogen-powered internal combustion engines and fuel cells could be a winning choice, especially for heavy transport, where current electrification technologies are difficult to apply.

Hydrogen has the potential to become a significant part of the future energy mix, especially in sectors difficult to electrify, such as heavy transport, aviation, and shipping. Investments in research and development, along with supportive policies, are fostering the growth of this technology.

The adoption of hydrogen vehicles will depend on factors such as reducing the cost of green hydrogen production (hydrogen produced from renewable sources) and expanding refuelling infrastructure. Some tractor manufacturers, like Fendt, New Holland, Kubota, and John Deere, are developing prototypes with alternative power sources to improve market offerings, aiming to maximize efficiency and reduce emissions.

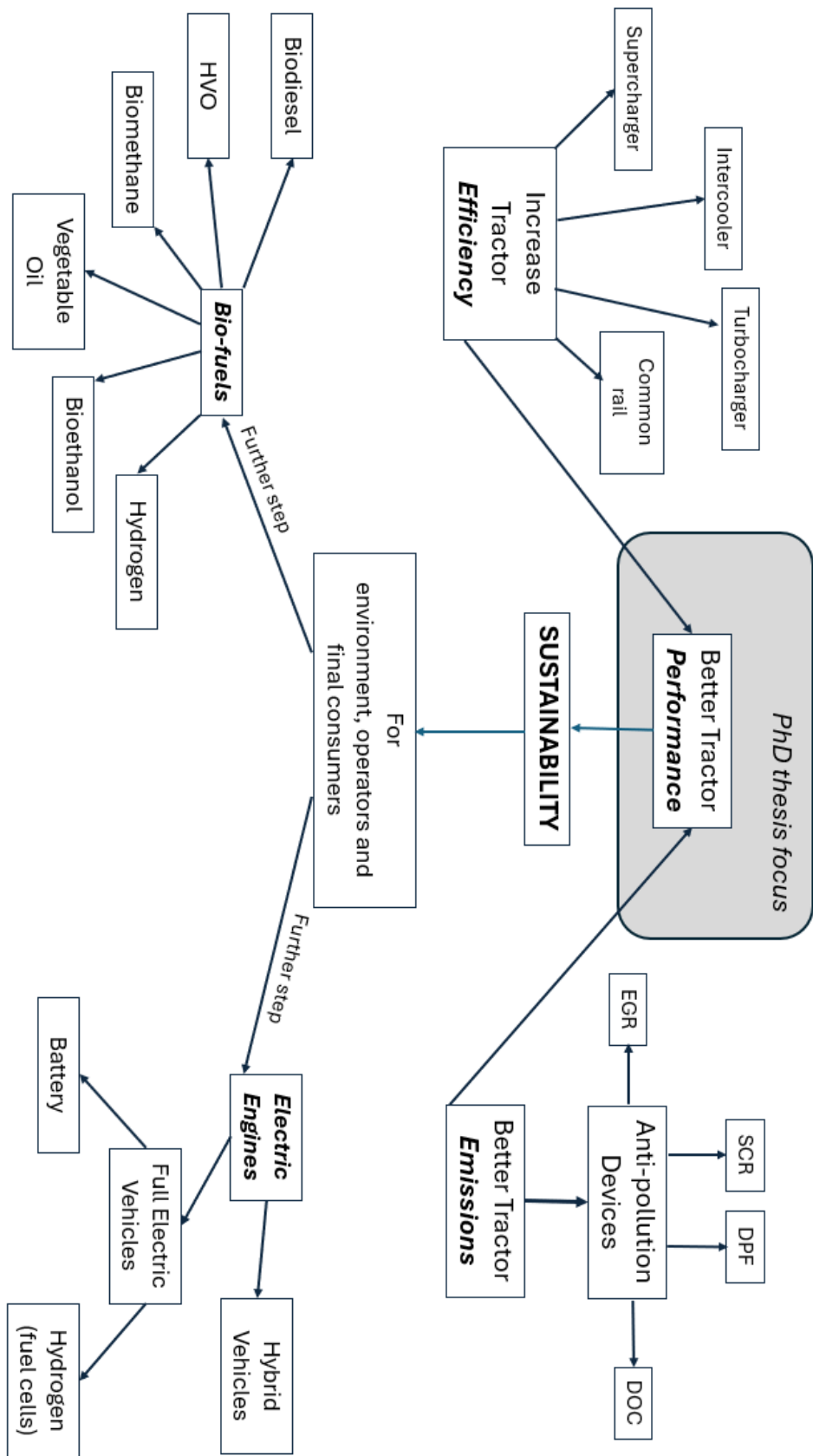


Figure 12 – Diagram outlining the objectives of the thesis in terms of energy sustainability and tractor performance.

2. Aim of the thesis

The thesis focuses on the analysis of sustainability in a general context within certain agricultural supply chains. Sustainability is defined based on the specific sector being examined. In the context of agricultural mechanization, sustainability is categorized into environmental sustainability, operator sustainability, and sustainability for end consumers.

Environmental sustainability involves the analysis of aspects of a given activity that may be harmful to the environment and ecosystems. Operator sustainability is concerned with ensuring that the execution of certain practices aligns with the well-being of the operator, such as when handling vibrating equipment or machinery that emits high levels of pollutants. Sustainability for end consumers involves the analysis of residues (pollutants, pesticides, harmful substances, etc.) that may remain on products due to processing, which could potentially harm consumers despite their lack of direct contact with the pollutant source. (Galli L.E. et al. 2023; Galli L.E. et al. 2024)

The performance of several tractor models, representative of the Italian machinery fleet, was evaluated in terms of energy efficiency and pollutant emissions. These analyses were conducted through direct comparison with technical data and the relevant anti-pollution regulations, where applicable. In cases where tractors were exempt from anti-pollution regulations due to their age, comparative evaluations were made with subsequent regulations, leading to several general observations. (Galli L.E. et al. 2024; Galli L.E. et al. 2023)

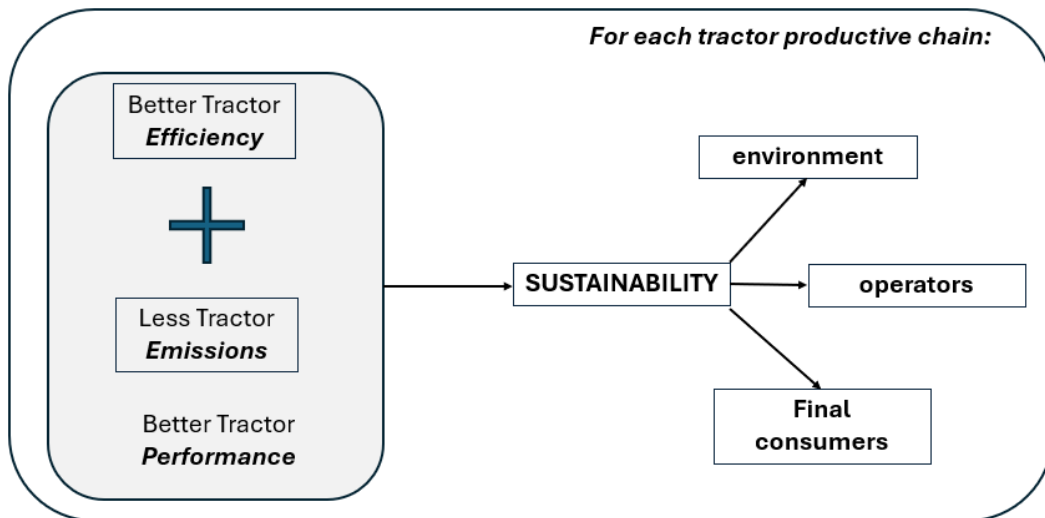


Figure 13 – Diagram outlining the objectives of the thesis in terms of energy sustainability and tractor performance.

Specifically, the analysis of tractor efficiency, based on specific fuel consumption values, and the concentration of major pollutants in exhaust emissions was conducted by examining various work chains. Certain tractors possess specific characteristics tailored to particular applications, which define the type of agricultural operations and the intended usage. For this reason, differentiated and specific production scenarios were developed for each tractor to analyse their performance under varied working conditions, considering typical uses and simulating real operating conditions across different work chains.

3. Background

This study, adopting a bottom-up approach, seeks to examine the operational contexts within which agricultural tractors work, to gain a detailed understanding of their performance. The study is devoted to classify the agricultural sector as divided into different production chains, which have undergone a considerable mechanization level across a large part of the globe. The implementation of the farming operations involves specific processes, to be executed with dedicated equipment.

Self-propelled agricultural machinery, including tractors and similar self-propelled machines, share certain features like the power generation system (internal combustion engine) but vary in architecture, size, mass and, importantly, performance. These variations render the single machine more suitable than another for use in a particular supply chain (for example, vineyards often employ tractors with narrower tracks to travel between rows).

To assess the performance of tractors accurately in their real environment, it is essential to study their behaviour in the field to confirm their actual performance. The broad array of supply chains in agriculture (such as open fields, vineyards, orchards, urban greenery management, nursery sector, etc.) and the diversity of operations within each chain represent a complex challenge in estimating tractor performance in real-world settings.

The methodology underpinning this research involved observing, analysing and collecting data from tractors operating across different supply chains, documenting details such as the operations performed, operation frequency, engine speed and load, etc. The objective of these analyses and measurements is to secure an accurate representation of tractors' real-world performance across diverse conditions.

The operations and data gathered in the field were then analysed and replicated in the laboratory, aiming to mimic as closely as possible the performance observed in the field. Reproducing the operational conditions and performance of the tractors in a controlled setting has allowed for the expansion of the study into several parallel research directions. These "three pillars" are:

- The study of the energy efficiency of tractor engines and the examination of potential over-mechanization,

- The measurement and analysis of pollutant emissions with reference to the homologation limits set by European (and US) regulations and their consequent environmental impact,
- The evaluation of the potential impacts of gaseous pollutants on operators' health.

3.1. Tractor Performance Tests Already in Use

Tractors, as well as all non-road machinery, are equipped with internal combustion engines capable of delivering high torque and power values. Despite the high-performance capabilities of these machines, they are rarely utilized at 100% of their potential. Indeed, due to their design characteristics, the engine together with the transmission, can offer a wide range of torque and power values, both to the PTO (Power Take-Off) and the wheels, to meet at the best grade the demands of the production environment.

In fact, the tractor, in addition to operating in very different environments, can perform multiple operations thanks to the variety of agricultural implements that can be coupled. Thanks to its versatility and multifunctionality, the tractor can perform a wide variety of operations, adapting it to the different agricultural and sometime non-agricultural needs.

Although the versatility of these vehicles is widely recognized, very often their performance is evaluated exclusively at full power, that is, at the maximum performance.

To verify the performance and characteristics of tractors (as well as all vehicles equipped with an engine) there can be two approaches.

The first, widely used in the automotive field, consists of bench testing. This involves performance tests of the engine alone, carried out in special facilities. In this case, the engine's performance is tested under optimal conditions, without considering the power transfer chain, but only its generation.

The purpose of these tests is to ascertain the engine's peak performance capabilities when functioning as a power source. The engine tests carried out on the bench require

specific protocols that define the operational conditions of the test. The engines are housed on specific supports and connected through special pipes to the fuel supply.

The second way to test the performance of an engine fitted on a tractor is to carry out the tests on the complete vehicle. These more comprehensive tests take into account the tractor's functionalities by subjecting it to performance tests, which include all the functionalities of the tractor, such as PTO performance and traction pull.

The performance tests carried out on the complete tractor are widely spread and recognized internationally for their effectiveness, so much so that they have become a prerequisite for marketing in many countries (e.g. the European Union). These performance tests must be carried out by independent third parties (recognized and certified) that impartially certify the characteristics of the tractor. Among the most widespread and recognized certifications are the standards issued by ISO and OECD. Some of the most commonly recognized test protocols for the performance check of tractors are represented by the OECD test Codes. Over the last 70 years, the OECD has developed and applied 10 test Codes devoted to the homologation of agricultural and forestry tractors and some of their parts. Of the 10 OECD test codes regarding the verification of performance and safety of agricultural machinery, two of them are dedicated exclusively to the performance of tractors: specifically, Code 1 (now dismissed) and Code 2.

3.1.1. OECD CODE 1

Originating in 1959, Code 1 marks its inception at a time when the Organisation for Economic Co-operation and Development (OECD) had not yet emerged as a global entity but functioned as the Organisation for European Economic Co-operation (OEEC). Distinguished as the inaugural testing protocol tailored for tractors, Code 1 aimed to rigorously assess the performance capabilities of diesel-powered, self-propelled agricultural machinery. This protocol mandated a comprehensive suite of evaluations, encompassing traction tests, assessments of maximum power output at the Power Take-Off (PTO), and examinations of the hydraulic system's operational efficiency and the hydraulic lift's functionality.

Furthermore, the protocol stipulated obligatory assessments beyond these foundational tests, including braking efficiency analyses, noise level measurements, steering

capability evaluations, and determinations of the machinery's centre of mass location. Additionally, it permitted the incorporation of optional tests tailored to specific operational conditions, such as low-temperature ignition capability, performance under ballasted conditions, and water resistance.

Despite its comprehensive nature, Code 1, over time, was accompanied and subsequently supplanted by Code 2—a streamlined version focused on tractor performance testing. This evolution reflected a shift towards protocols that, while retaining a focus on thorough assessment, sought to reduce the temporal and logistical demands associated with testing. By the dawn of the 2000s, this transition culminated in the complete obsolescence of Code 1 in favour of Code 2.

The discontinuation of Code 1 was necessitated by the operational difficulties associated with conducting traction tests, which required execution outdoors on a dry track. In regions with adverse climates, such as those typical of Northern Europe, unfavourable weather conditions often led to significant delays in test procedures.

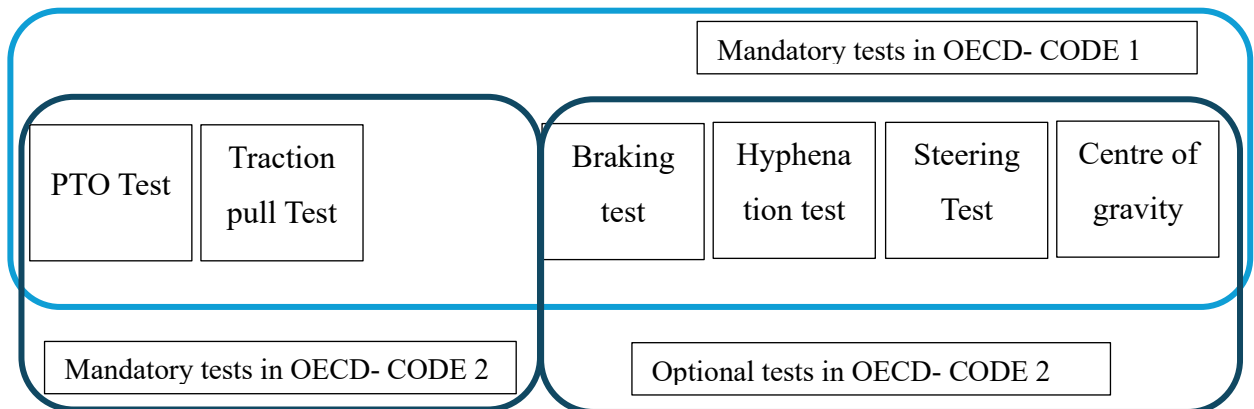


Figure 14 – Differences between OCED CODE1 and OECD CODE 2

3.1.2. OECD CODE 2

Code 2, at present the sole testing protocol delineated by the OECD for the validation of performance in agricultural tractors powered by diesel-fuelled internal combustion engines, originates from a condensed iteration of Code 1. This protocol mandates merely three compulsory assessments to evaluate the performance of agricultural tractors: the Power Take-Off (PTO) performance test, a simplified traction assessment, and the evaluation of the hydraulic circuit and hydraulic lift's performance. (Keller J.

et al. 2015; Rebrov O. et al. 2020) These obligatory examinations compiled within Code 2 aim to ascertain the tractors' performance capabilities across diverse operational scenarios:

3.1.2.1. PTO Performance Evaluation Protocol

The PTO testing framework aims to assess the engine's power output alongside its hourly and specific fuel consumption (SFC) metrics. For tractors that incorporate Selective Catalytic Reduction (SCR) systems for gaseous pollution control, utilizing AdBlue to mitigate NO_x emissions, an evaluation of these consumptions becomes imperative. The testing protocol mandates that, to ensure validity and representativeness, all tests must be conducted under stable temperature conditions ($23^{\circ}\text{C}\pm 7^{\circ}\text{C}$), scrutinizing performance metrics such as engine and PTO rotational speeds, torque, power output and fuel consumption.

This protocol's primary intent is to quantify the power delivered by the PTO across varied operational scenarios, in addition to examining other specific parameters throughout the distinct stages of the testing process:

- a. **Maximum Load Assessment:** This entails the evaluation of the peak power output by the engine at its convenient rotational speed. According to Code 2, this measurement necessitates a minimum of 6 readings within a one-hour time interval, with a prerequisite for consistent engine operational conditions throughout the period.
- b. **Rated Speed Evaluation:** This segment involves setting the engine to its maximum speed and subsequently adjusting it by applying a specific torque to the PTO until it reaches the manufacturer's declared rated speed. This approach facilitates the measurement of power at the nominal speed setting. (Roeber J. et al. 2017) Like the subsequent stage (c), this part of the test introduces additional power part-load conditions to mimic some of the operational modes frequently encountered during work cycles. (Refer to Figure 15)

Power	Speed			Fuel consumption		Specific energy	Reagent consumption ⁶			
	Engine	P. T.O.	Fan	Hourly	Specific		Hourly		Specific	
kW	min ⁻¹ (rev/min)			kg/h	l/h	g/kWh	kWh/l	kg/h	l/h	g/kWh
3.1.1	MAXIMUM POWER - ONE-HOUR TEST									
3.1.2	POWER AT RATED ENGINE SPEED									
3.1.3	POWER AT STANDARD PTO SPEED [1000 ± 25 or 540 ± 10 min ⁻¹ (rev/min)]									
3.1.4	PART LOADS									
3.1.4.1	the torque corresponding to maximum power at rated engine speed									
3.1.4.2	85% of torque obtained in 3.1.4.1									
3.1.4.3	75% of torque defined in 3.1.4.2									
3.1.4.4	50 % of torque defined in 3.1.4.2									
3.1.4.5	25 % of torque defined in 3.1.4.2									
3.1.4.6	unloaded									
3.1.5	PART LOADS AT STANDARD POWER TAKE-OFF SPEED [1000 ± 25 or 540 ± 10 min ⁻¹ (rev/min)]									
3.1.5.1	the torque corresponding to maximum power									
3.1.5.2	85 % of torque obtained in 3.1.5.1									
3.1.5.3	75 % of torque obtained in 3.1.5.2									
3.1.5.4	50 % of torque obtained in 3.1.5.2									
3.1.5.5	25 % of torque obtained in 3.1.5.2									
3.1.5.6	unloaded									

Figure 15 - Excerpt from the official module for data collection of OECD Code 2 tests at different running points.

c. PTO Rotational Speed Testing: For this assessment, the engine's maximal rotational speed must be established and then reduced to achieve the optimal PTO rotational speed, which, depending on the tractor's specifications and the standardizations of the PTO it is outfitted with, will be either 540 min⁻¹ or 1000 min⁻¹. Similar to the prior stage (b), this test applies further power part-load conditions to replicate commonly used operational modes during work cycles. (Refer to figure 15)

d. Part-Load Regime Examination: The objective of this concluding test is to investigate the engine's performance under varying load conditions. Therefore, measurements are taken with the rotational speed set at the nominal level (as declared by the manufacturer) and adjusted according to specific points outlined in the protocol's guidelines. (Refer to figure 16)

3.1.6 PART LOADS AT DIFFERENT ENGINE SPEEDS	Fuel Consumption						Reagent Consumption ⁷		
	Hourly		Specific		Specific energy		Hourly		Specific
	Kg/h	l/h	g/kWh		kWh/l		Kg/h	l/h	g/kWh
3.1.6.1 maximum power at rated engine speed									
3.1.6.2 80 % of power obtained in 3.1.6.1 at max. speed setting									
3.1.6.3 80 % of power obtained in 3.1.6.1 with governor control set to 90 % of rated engine speed									
3.1.6.4 40 % of power obtained in 3.1.6.1 with governor control set to 90 % of rated engine speed									
3.1.6.5 60 % of power obtained in 3.1.6.1 with governor control set to 60 % of rated engine speed									
3.1.6.6 40 % of power obtained in 3.1.6.1 with governor control set to 60 % of rated engine speed									

Figure 16 - Excerpt from the official module for data collection of OECD Code 2 tests at different running points.

3.1.2.2. Drawbar Performance Evaluation:

The drawbar performance evaluation serves to systematically assess and quantify the tractor’s traction capabilities. This assessment is conducted under predetermined, standardized conditions delineated within the test protocol. The evaluation entails the use of specially prepared tracks, which are standardized in aspects such as surface texture features, to ensure consistency in the outcomes across various globally distributed, authorized testing facilities. The methodology involves attaching the tractor to a dynamometer truck (or one or more alternative tractor(s) of suitable mass and power), which is characterized by specific attributes to ensure that, throughout the evaluation, it imposes a resistance force against the tractor’s forward motion, maintaining a maximum tire slippage threshold of 15%. The protocol dictates that both machines, interconnected via a towing bar fitted with load cells for precise data capture, initiate movement at the same speed. (Cutini M. et al. 2020) Following the stabilization of this speed, the procedure calls for a gradual reduction in the trailer’s speed, adhering to specified standards, until achieving the desired braking effect stipulated by the test parameters.

3.1.2.3. Hydraulic System Evaluation

The concluding obligatory examination delineated in Code 2 pertains to the performance assessment of the hydraulic circuit. This evaluation entails scrutinizing the operation of the hydraulic circuit and the lifting abilities of the hydraulic lift, with reference to ISO standards 789-10, 2006. The Code establishes the reference temperature for the hydraulic fluid during these evaluations, which is stipulated to be maintained between 60 and 70 °C to avoid any alterations in the viscosity of the hydraulic oil.

The evaluations comprise:

- a. Assessments of the hydraulic circuit, where the circuit's performance is gauged and appraised based on hydraulic power, pressure, engine speed, and flow rate.
- b. Validation of the lifting capabilities of the hydraulic lift. This is conducted through two distinct tests: the first is limited to the lifting capacity of the lift's two lower arms, interconnected by a bar equipped with a load cell. The second test simulates the lifting of a mounted implement, connecting all three points of the lift and maintaining hydraulic pressure at 90% of its maximum capacity.

3.2 Performance Verification Testing

Concurrently with the OECD-defined testing and certification protocols, alternative non-official test protocols have been devised for the assessment and validation of tractor performance. Noteworthy among these are the PowerMix tests (DLG, Germany), the efficiency classification tests conducted by Spain, as well as those carried out in Turkey, Korea and the USA. (Janulevičius, A. et al. 2013)

3.2.1. Efficiency Related to Specific Fuel Consumption (SFC):

In the early 2000s, Germany's DLG introduced the so-called “PowerMix” test, to gauge tractor efficiency in terms of energy consumption during the operation of power take-off (PTO), hydraulic lift, and towing hitch. This procedure involves a series of tests under varied workload conditions to accurately determine fuel consumption and

energy efficiency in simulated environments. Primarily conducted on testing tracks, with the exception of the transport test, which is performed on designated roads, these tests focus on the engine's power output and its influence on fuel consumption (and also AdBlue consumption, for engines equipped with SCR system). (Farias M. et al. 2019) This is done without delving into the specifics of individual tractor models. By measuring power output under specific scenarios, including full-load operations and subsequent load reductions, the PowerMix test evaluates energy efficiency and power modulation. Efficiency is quantified in grams per kilowatt-hour (g/kWh), facilitating comparisons across different tractor models to identify those with superior consumption metrics. (Jevtic J. et al, 2006; Lee J.W. et al. 2016; Kim S Kim K.U. 2010; Shafaei S.M. et al. 2018) A significant advantage of the PowerMix test is its repeatability under standardized conditions, unlike field tests that are susceptible to environmental variables and inconsistencies. Nonetheless, the test is critiqued for the high costs associated with the required instrumentation and for its testing limitations, which may not fully translate to the specialized agricultural practices prevalent in Southern Europe.

In the United States, extensive research has been conducted focusing on tractor energy efficiency, especially regarding specific fuel consumption in relation to power use at the PTO or towing capacity. The University of Lincoln, Nebraska, has conducted a broad spectrum of tests to evaluate the energy efficiency of agricultural machinery, taking into account both power generation and the employment of various transmission types. Virginia State University has furthered research to quantify energy consumption based on power output at the PTO and towing capacity. Other research institutions across the US, including those in Iowa and Kentucky, have pursued energy efficiency studies, broadening the scope and diversity of field analyses and studies, aided by data from the OECD.

3.2.2. Energetic Efficiency Index

Utilizing the data from OECD Code 2 reports, Spain, Turkey and South Korea have devised methodologies to compute the Energy Efficiency Index (EEI) and specific fuel

consumptions of agricultural vehicles. These methodologies assess the power needed by the agricultural machinery at both the PTO and towing hitch, correlating this power to fuel consumption to yield a value in litres per kilowatt-hour (l/kWh), indicative of the energy efficiency index. Additionally, these evaluations take into account consumption due to pollution control systems, including urea consumption for SCR-equipped devices.

In Spain, the Polytechnic University of Madrid, in partnership with IDAE and the Ministry of the Environment, has implemented an energy rating for select tractor models based on their consumption relative to power output. This system categorizes tractors into five groups, from A to E, based on their efficiency levels. Initiated in 2007, this classification is annually updated with newly tested models. From 2012, the scheme was expanded to include seven categories, from A to G, to enhance the granularity of emission level distinctions.

Turkey, via TAMTEST, the Agricultural Mechanization Testing Center under the Ministry of Agriculture, has adopted a parallel classification system that organizes tractors into categories based on power at the PTO and pulling force, with seven levels from A to G, determined by 5% power range increments. Contrary to Spain's approach, which concentrates on a restricted number of comparable models, Turkey's evaluation also encompasses tractors with continuously variable transmissions (CVT).

South Korea has unveiled its proprietary energy rating system, arranged into five tiers from I to V. This system incorporates data on the energy efficiency and consumption of tractors available in the Korean market, thus offering a comparative perspective on the energy performance of diverse models. (Jevtic J. et al, 2006; Lee J.W. et all. 2016; Kim S Kim K.U. 2010)

3.3. Issues with Full Power Testing

These examinations aim to identify the tractor's maximum capabilities by assessing its performance under conditions where the engine operates at full power. This test condition is established when the engine is capable of delivering its maximum output.

Although focusing on different aspects, the measurement of maximum power or torque serves to delineate the tractor's peak performance.

To examine the performance of engines, and consequently the tractors themselves, and to acquire a more comprehensive insight into their functioning, engine curves can be employed. Engine curves are graphical representations compiling discrete data points of torque, power, and often also specific fuel consumption, illustrating the performance trajectories over a range of tractor engine speeds.

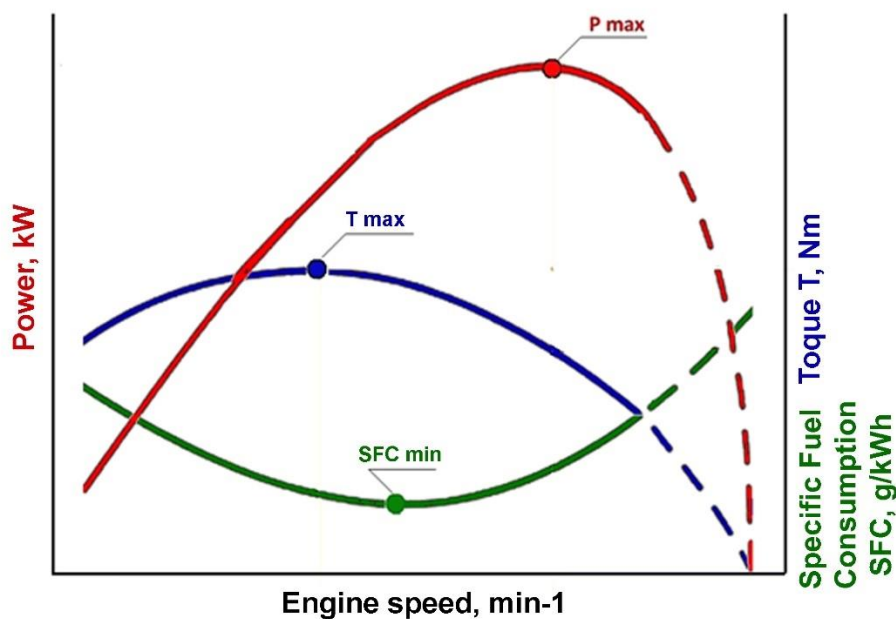


Figure 17 – Engine curves at maximum load

This measurement process involves setting the tractor's engine to its maximal operational speed (full throttle) and applying a resistance torque (usually via the Power Take-Off (PTO) or towing) to burden the engine with a load. Besides offering insights into the power and torque outputs at full load, these curves graphically elucidate the engine's behavioural patterns in terms of power and torque delivery.

Nonetheless, full-load curves fail to encapsulate the practical operational scenarios in which agricultural and forestry tractors are utilized. It is rare for tractors to employ continuously their full power capacity under real-world working conditions, though exceptions exist for certain field operations. While operations such as ploughing with multi-body ploughs or extensive harrowing might necessitate the tractor's full power,

envisioning such a scenario for tasks like spraying or mowing is challenging. Although operations in open fields could potentially exploit the engine's maximum power, this is not typically the case for specialized crops like orchards or for urban green space maintenance, which inherently involve tasks that are less demanding in terms of power. To avoid these limitations of data derived from full-load performance studies, an expansion of the investigation to include a variety of operational realities has proved essential. Acknowledging the distinct needs specific to each agricultural sector or even to each task, an exploration into the performance of various tractors under conditions of partial power has been pursued. This approach seeks to faithfully replicate, as closely as possible, the conditions experienced during field operations.

3.4. Operating Conditions and Customized Protocols

To assess at the maximum detail level the working conditions of tractor-implement combinations in the different operating condition, and therefore to reduce the inaccuracies to a minimum, it became imperative to design and implement specific testing protocols tailored to the most popular agricultural production chain developed in Italy. (Galli L.E. et al 2023; Farias M. et al. 2018; Kim Y.-S. et al. 2020) These protocols were formulated based on the various agricultural practices, taking into account the different scenarios, and envisaging a sequence of operations performed throughout the agricultural season, as well as the operating conditions of the used machinery. (Galli L.E. et al 2024; Janulevičius, A. et al 2013; Nekhoroshev, D. et al. 2020)

4. Materials and methods

4.1. Scenarios definition

The term "scenario" refers to a list of tasks characteristic of a given sector in agriculture. The scenarios were developed with reference to the real experience of farmers, who provided insights into the specific crop production cycle pertinent to their agricultural sector, the nature of tasks carried out throughout the growing season within a particular environmental context. Also, the usage and configuration settings of the tractor when coupled with their implements was obviously taken into account, including the frequency of operations throughout the entire growing season. The gathering of exhaustive information regarding the array of tasks involved in each sector facilitated the construction of realistic scenarios that have been precisely replicated in a laboratory setting.

Despite the advancements in technology that permit more straightforward data acquisition through CANBUS data directly from field operations, a deliberate decision was made to simulate these scenarios in a laboratory environment. This approach was chosen to mitigate potential inaccuracies arising from external variables, such as the impact of environmental debris on machinery that could lead to data distortion due to power spikes during certain agricultural tasks. A controlled laboratory simulation was chosen instead of CANBUS data reliance, using advanced instrumentation to mimic the operational conditions of tractors.

This approach takes into account the specific demands of each production sector, the agricultural tasks, and operating conditions, such as engine load and speed. The advantage of this laboratory-based replication lies in the ability to stabilize working conditions, significantly reducing variability in the parameters under investigation, such as load and speed engine instantaneous peaks or specific task performance, thereby offering a more consistent and representative snapshot of "standard" operational conditions.

In the present study, an analysis was conducted focusing exclusively on the operational phases performed directly in the field, while headland manoeuvres were deliberately

excluded. This decision was made because their impact on the overall efficiency of the tractor is considered marginal. As a result, individual phases involving turning, manoeuvring, and interruptions were not included.

Moreover, already OECD Code 2 (and other similar Standards) shows in a detailed mode the criteria of testing under designated operating conditions, often highlighting conditions of maximum tractor performance. The added value of this study resides in the study of the performance of the tractors in partial load conditions across different tasks in various production chains, each characterized by distinct needs and production peculiarities.

4.2. Scenarios and Conditions at Start-up and Under Load

For each operation within a given scenario, characteristic data regarding the execution of the individual task were collected. Each operation is defined by the nominal tractor engine speed and then the engine speed under load.

The definition "nominal engine speed" refers to the engine's rotational speed settled for carrying out a given operation at its beginning. Once the implement is engaged, a partial decrease of the engine speed will happen, caused by a given engine load, due to the power need of the implement.

Table 8 - Excerpt from the official module for data collection of OECD Code 2 tests at different running points.

Production chains	Field operations		Nominal engine speed	Underload engine speed
			<i>Min⁻¹</i>	
Open field	Operation 1			
	Operation 2			
	Operation ..			
	Operation n			

The scenarios envisioned in this study encompass a range of agricultural contexts, as follows:

- 1. open-field: haymaking and cereal production;**
- 2. vineyard;**
- 3. orchard: apple cultivation.**

Given the significant variability among Italian farms (in terms of size, soil types, and climate conditions) and their outputs, these scenarios were accurately customized to closely align with the diverse realities of the examined farms. For this reason, each scenario could be finely adjusted, to meet the peculiarity of each farm, modifying the operations condition, thereby assuring the best method's integrity and applicability.

4.3. Open Field Scenario

The open field scenario encapsulates agricultural practices very popular in Italy, focusing on the cultivation of the wide surface dedicated to cereal and herbaceous crops.

The study delineates this scenario into two main sectors: cereal and forage production. Cereal production primarily targets the cultivation of grains for human consumption, as well as animal feed (e.g., soybean cultivation for protein-rich animal nutrition). Conversely, forage production, chiefly concerned with zootechnical outputs like hay and also straw, typically involves less energy-intensive processes.

4.3.1. Cereal Production

Among the most energy-demanding sectors within the Italian agricultural landscape, cereal production encompasses a broad range of cultivation activities. Soil preparation and seedbed preparation require high power to ensure proper execution, as well as lower-energy demanding tasks, such as sowing and fertilization.

Moreover, cereal production includes both "dynamic" operations, where the tractor travelling is needed, but also "static" operations, like surface irrigation, when the tractor is coupled to a pump thanks to its PTO, to draw water for example from a canal or ditch. In this case, the tractor's full power output is drawn from the PTO itself.

Table 9 - Nominal engine speed and under-load engine speed for each defined agricultural operation within the cereal production chain.

Task	Nominal engine speed	Speed reduction	Engine speed under load	Power
	<i>min⁻¹</i>			<i>kW</i>
Ploughing	2000	400	1600	--
Harrowing	1600	150	1450	--
Seeding	1500	50	1450	--
Fertilization	1500	100	1400	--
Mechanical weeding	1600	100	1500	--
Irrigation	2000	500	1500	--
Grain transport (farm road)	1500	100	1400	--

4.3.2. Forage Production Chain

The forage production chain represents another significant activity within open-field systems. Unlike the cereal chain, the forage chain typically exhibits lower power requirements: the operations regarding this scenario are usually conducted with bulky machinery demanding minimal power, or as an alternative are “passive” operations not necessitating mechanical or hydraulic power to work. This scenario does not include soil cultivation, which is generally carried out only once in this chain, when the lawn must be prepared ex novo. The scenario focuses on seeding, plant protection treatments, mowing and pre-harvest hay management.

Among the most energy-intensive operations baling and wrapping of bales are included.

Table 10 - Nominal engine speed and under-load engine speed for each defined agricultural operation within the Forage production chain.

Task	Nominal engine speed	Speed reduction	Engine speed under load	Power
	<i>min⁻¹</i>			<i>kW</i>
Seeding	1300	100	1200	--
PPP Spraying (boom)	1300	50	1250	--
Fertilization	1400	50	1350	--
Grass mowing	1600	200	1400	--
Grass conditioning	1700	300	1400	--
Pick-up carriage	1400	50	1350	--
Hay racking	1250	50	1200	--
Baling	1700	250	1450	--
Wrapping	1700	300	1400	--
Shredding	1500	200	1300	--
Bale transportation (farm road)	1200	100	1100	--

4.4 Specialized Crops Scenario

Specialized cultivation encompasses a segment of agricultural production that is particularly notable for its focus on products that cater to specific market niches or that command a high added value.

This agricultural sector is distinguished by its diverse array of produce and the advanced technical expertise required of farmers, who must often adapt to unique growth conditions and engage in specialized cultivation practices. Among others, main areas of emphasis encompass viticulture, fruit cultivation, horticulture and ornamental plants cultivation. In more detail, the scenarios addressed in this study include viticulture and fruit cultivation.

4.4.1 Viticulture Scenario

Italy is among the world's leading wine producers. The cultivation of wine grapes is particularly widespread across the country, making it one of the country's most common agricultural practices.

Unlike open-field cultivation, which allows for the uniform utilization of agricultural land according to the farmer's needs, vineyard cultivation mandates adherence to specific planting layouts. Typically, wine grapes are grown in rows that run longitudinally across plots, with the spacing between rows being adjusted based on the vine spacing scheme. Vines, similar to other tree crops, are planted in configurations that persist in the cultivated plot for decades. The lifespan of a vineyard installation can extend up to 50 years before the vines are replaced due to low productivity.

The vine spacing varies depending on the production needs and geographical location. For example, rows designed for mechanical harvesting, which involves the use of tractor-towed or self-propelled harvesters, must maintain a minimum width of 1.8-2.2 m. Conversely, in Franciacorta, a region in the province of Brescia in northern Italy, the spacing between rows can be as narrow as 1.2 m, rendering mechanical harvesting impractical and necessitating manual labour for both harvesting and other several vineyard tasks. Due to the specific spacing requirements between vine rows, operating within vineyards necessitates the use of tractors with a specific narrow-track architecture. These specialized tractors differ from those utilized in open-field operations for their reduced overall width, enabling them to travel between the vineyard rows without damaging the vines or structural supports.

Furthermore, the range of operations within the viticulture sector can significantly vary, due to factors such as the vineyard's product final destination (wine or table grape), applicable regulatory standards, and the vineyard's surface area. These variables determine whether certain labour-intensive and costly operations can be mechanized, potentially through third-party services, or must necessarily be conducted manually.

In scenarios where the economic feasibility of mechanization is negated by constraints such as reduced vineyard surface or a reduced production output, the importance of manual labour emerges, consequently shaping the mechanization level adopted by the farm.

Table 11 - Nominal engine speed and under-load engine speed for each defined agricultural operation within the Vineyard production chain.

Task	Nominal engine speed	Speed reduction	Engine speed under load	Power
	min ⁻¹			kW
Harrowing	2350	250	2100	--
Shredding	2100	200	1900	--
Hoeing	1900	100	1800	--
Row management	1700	100	1600	--
PPP spraying	1700	150	1550	--
Fertilization	1500	100	1400	--
Pre-pruning	1200	50	1150	--
Pruning mowing	1800	150	1650	--
Grass mowing	1700	100	1600	--
Ridging	1100	100	1050	--
Mechanical weeding	1100	100	1000	--
Suckering	1200	50	1150	--
Topping	1300	50	1250	--
Defoliation	1400	100	1300	--
Fertilization	1200	150	1050	--
Chemical weeding	1200	200	1000	--
Grape harvesting	1800	200	1600	--

4.4.2. Apple Orchard Scenario

An exploration into fruit cultivation, specifically focusing on apple orchard management, is proposed in this study. Similar to vineyards, apple orchards are characterized by a fixed planting distance, remaining in place for at least a decade. The

inter-row spacing, typically between 3-5 m, facilitates the travelling of machinery within the orchard. In more detail, apple orchards utilize fruit collection wagons suitable to travel efficiently into the inter-row spaces.

Parallel to the vineyard scenario, apple orchards necessitate frequent applications of Plant Protection Products (PPPs), being them the most significant and frequent operations carried out in the orchard, often characterized by their regular application along the growing season, so demanding an important amount of annual labour time.

Table 12 - Nominal engine speed and under-load engine speed for each defined agricultural operation within the apple orchard production chain.

Task	Nominal engine speed	Speed reduction	Engine speed under load	Power
	min ⁻¹			kW
PPP spraying	1300	150	1150	--
Apple transport	2200	500	1700	--
Grass shredding	1500	150	1350	--
Pruning residues shredding	1500	200	1300	--
Chemical weeding	electric			--
Organic fertilization	1400	50	1350	--
Chemical fertilization	1300	50	1250	--
Soil management	1500	400	1100	--
Pruning	manual			--
Thinning wood cutting	electric			--

4.5 Materials

The general investigation was based on 3 main pillars:

- 1. tractors efficiency;**
- 2. pollutant gas emission;**
- 3. operators' health.**

To address the aspects outlined, an articulated measurement system was devised to quantify specific variables. Initially, a range of tractors, mainly provided by manufactures, dealerships was secured. Among other technical characteristics, the models taken into account varied in architecture, age and power class. This variety has to be profitable, enabling the application of the study's methodology across a wide spectrum of case studies.

The measurement system included various units, both for assessing tractor performance and fuel consumption, and to quantify the exhaust gaseous pollutants. Following data acquisition, analyses focused on efficiency, environmental pollution and operator well-being.

In more detail, for the assessment of tractor performance an electromagnetic dynamometer, enhanced with a module for measuring instantaneous fuel consumption was used. Data capture was facilitated through Bluetooth technology, with dedicated software used for analysis.

The measurement of exhaust gases introduced complexities due to the high temperatures and turbulent flow. To address this, exhaust gases were redirected through specialized piping to modify the flow from turbulent to laminar, enabling a correct measurement. The third phase focused on measuring pollutant levels, conducted post-flow modification to mitigate high temperature risks. The deployment of specific measuring devices allowed for the determination of pollutant concentrations (in terms of mass in volume), enabling a comprehensive assessment of the environmental impact, and the operator's health.

4.6 Research Tools

This investigation and all associated measurements were primarily conducted at the experimental farm Casina Baciocca, one of the farms of the University of Milan, located in Cornaredo (MI), Italy.

In an effort to diversify the range of tractors subjected to analysis and thereby construct a more comprehensive and uniform database, certain evaluations were undertaken at external facilities. These establishments included CREA-ING (Treviglio, BG – Italy) and the laboratory of the University of Bolzano (Italy) and facilitated the examination

of specific machinery through research partnerships, partly using, to some extent, their own instrumental resources.

Regardless of the specific locations where these evaluations and measurements took place, the instruments utilized at the experimental farm Cascina Baciocca are specified in the following.

4.6.1 Dynamometer

The electromagnetic dynamometer, provided by KL-Maschinenbau GmbH, EGGERS Dynamometer (Rendsburg, Germany), model PT 301 MES, is engineered to endure a maximum braking power of 600 kW. This apparatus measures torque and rotational velocity, which are the basic data for the calculation of power output. The methodology for conducting tests permits two approaches: maintaining either a constant speed or torque. Configuration via the control panel facilitates direct measurements through a computer interface, obviating the necessity for manual adjustment via the panel's regulator. The interfacing between the apparatus and computer employs Bluetooth technology, to assure rapid data transmission and to mitigate potential complications arising from connectivity issues and signal distortion. Control over the power assessment process, simplified via computer following meticulous instrumentation setup, is achieved through software that accommodates three modes of measurement: *Manual Measurement*: Enables the targeted collection of data upon the issuance of a specific signal by the computer.

Special Measurement: Requires the manual configuration of designated time intervals and rotational regimes via the computer to conduct observations.

Automatic Measurement: By establishing the initial rotational regime, the input speed for power, and determining the frequency of measurements based on time (seconds) and the decrement in rotational regime, it permits an exhaustive analysis of the tractor engine's characteristic curve.

4.6.2. Specific Fuel Consumption (SFC) Measurement Methodology

To investigate the specific hypotheses regarding the fuel consumption associated with various tractor operations, an imperative aspect of the study entailed the meticulous

monitoring and quantification of the tractor's fuel consumption throughout the testing steps. This objective necessitated the deployment of a dual-channel flowmeter, an instrument engineered to record both the fuel flow directed from the tank towards the engine and the surplus fuel returning to the tank, unutilized in the combustion chamber. For the purposes of these measurements, the apparatus selected was the FCM-100 model, a product of KL-Maschinenbau GmbH (Rendsburg, Germany). This device, provided by the same manufacturer of the engine brake, was integrated with the dynamometer via a dedicated connection. This configuration not only facilitated the electrical power supply to the flowmeter but also enabled the synchronization of the flowmeter's functionality with the electronic framework of the engine brake. This integration ensured that the data processed by the flowmeter were accessible through the engine brake's Bluetooth transmitter and could be displayed on the same software platform used on the computer.

Contrary to traditional bidirectional flowmeters that employ two distinct sensors to monitor the incoming and returning fuel flow, the flowmeter shown uses a single sensor positioned within the fuel supply system. The adoption of a dual sensor system (one on the fuel supply and one on the return) is required in official homologation tests to account for variations in temperature and, consequently, the viscosity of diesel fuel. Pressurization of the diesel fuel results in heating, which in turn alters its viscosity. Since extreme precision in individual measurements is not required, as the objective is to gain a broader understanding of the performance of a particular tractor, this technical choice has been deemed fully acceptable.

This approach allows for the direct measurement of the net fuel consumption through a closed-loop system, handling both the fuel supply and retrieval within the meter itself, thereby eliminating the need for differential calculations to ascertain the net hourly fuel consumption. The recording of fuel consumption is executed with high accuracy and is synchronized with the sampling intervals specified by the software integrating the engine brake and flowmeter functionalities.

4.6.3. Exhaust Gas Flow

In preparation for the measurements stipulated by the second step of the study, specifically the measurement of the tractor's exhaust gas pollutants, the setting-up of a by-pass of the gas flow was essential, to locate conveniently the probe sensors. It is important to note that the positioning of the exhaust terminal is not uniform across tractor models. For instance, large tractors or those utilized in open-field operations typically feature a vertical exhaust aligned parallel to the cab's structural uprights. Conversely, smaller or specialized tractors may exhibit varied exhaust terminal placements, often oriented horizontally or ventrally relative to the tractor body. Given this variability in exhaust terminal configurations, alongside the critical considerations for ergonomics and the safety of operational procedures (especially considering fume temperatures may sometime exceed 600 °C) a customized approach was imperative. Through the application of convenient steel fittings and pipes, it was feasible to standardize the exhaust flow via strategic bends and straight sections, thereby facilitating the transition of the flow from turbulent to laminar. This was accomplished by ensuring a straight section of the pipe having a length of at least ten times its diameter.

Moreover, this reconfiguration not only enabled the accurate measurement of gas flow but also provided for the strategic positioning of probe insertion points at ground level, markedly enhancing the safety of the operations for the personnel involved.

4.6.4. Exhaust Gas Flow Rate Measurement

The pollutant concentrations are usually expressed in terms of concentrations, i.e. parts per million (ppm) or milligrams per cubic meter (mg/m^3).

Due to the need to compare emission levels with the benchmarks set by European emissions standards, which are expressed in grams per kilowatt-hour (g/kWh), it is crucial to measure also the flow rate of exhaust gases.

In this research, the measurement of exhaust gas flow was performed using a dynamic pressure anemometer equipped with a Pitot tube, made by TROTEC (Heinsberg, Germany), model TA400.

The Pitot tube measures the flow velocity of a fluid by determining the difference between the fluid's static pressure and the total pressure generated by the fluid's movement. It consists of a tube featuring a front opening that faces against the fluid flow to capture total pressure, and side openings to measure the fluid's static pressure.

4.6.5. Testo 350 gas analyser

For accurate measurement of pollutant concentrations in exhaust gases, the study employed a gas analyser, the Testo 350 produced by Testo GmbH (Titisee-Neustadt, Germany), a device tailored for exhaust gas analysis in industrial and professional environments. Notable for its high degree of modularity, the Testo 350 allows for customization through the interchange of sensors that can detect a variety of gases, including CO, CO₂, NO, NO₂, NO_x, SO₂, and others. The device setup also enables users to specify the type of fuel being analysed, with options including diesel, gasoline, methane, biomass, etc. The Testo 350 is portable, comprising a central unit that houses the sensors and a probe for sampling, alongside a smaller, lightweight portable unit that communicates with the central unit via Bluetooth. The device is supported by a dedicated software that facilitates data exchange and collection between the computer and the central unit. Sampling is straightforward, necessitating only the activation of the master unit and the positioning of the probe within the exhaust stream or a derivative thereof for analysis.

4.6.6. Testo 338 smoke meter

The Testo 338, produced by Testo GmbH (Titisee-Neustadt, Germany) is dedicated exclusively to the assessment of particulate matter. This characteristic renders it exceptionally useful for the examination of engines fuelled by diesel and biomass. By facilitating the detection of both fine and ultrafine particles, the Testo 338 significantly contributes to a more profound understanding of environmental impacts, enabling the quantification of particulate emissions into the atmosphere, both in terms of concentration and by other metrics.

The adoption of optical measurement technologies endows the instrument with directness and efficacy. Moreover, an intuitive user interface coupled with a clear display permits the execution of precise and immediate field measurements. In

addition to providing a digital readout that includes particulate concentration within the gas sample retrieved by the probe, the instrument also generates a tangible record of the analysis. This takes the form of a paper strip that accumulates particulates during measurement; the intensity of the mark on this strip varies in direct correlation with the particulate concentration in the sample, providing a visual indicator of pollution levels.

The portability of the Testo 338 extends its utility, facilitating environmental assessments in both indoor and outdoor settings, a critical requirement for contemporary environmental research demanding exceptional flexibility.

4.7. Selection of Tractors for the Research

The selection of this different groups of tractors was guided by multiple factors, such as their design features, age, operational hours and compliance with emission regulations. This approach ensured the study accurately reflected the current state of agricultural mechanization across the country.

Table 13 - Technical and performance characteristics of the tractors examined in the thesis.

Make	Model	Type of tractor	2/4 WD	Max Power	Emission stage
Same	Frutteto 85	Orchard/vineyard	4	63 kW	2
Same	Agrotron 70	Orchard/vineyard	4	46 kW	3B
Deutz Fahr	Agrofarm 430	Open field	4	80 kW	3A
Goldoni	E100	Open field/vineyard	4	60 kW	3B
Kubota	M5091	Vineyard	4	71 kW	4
Kubota	M5101	Vineyard	4	76 kW	4
Fiat	70-90	Open field	2	51 kW	n.a.
New Holland	TN70V	Orchard/Vineyard	4	52 kW	3A

Table 14 - Tests performed on the tractor models examined in the thesis.

Make	Model	Type of tractor	Tractor efficiency test	Engine pollutant emissions test
Same	Frutteto 85	Orchard/vineyard	X	
Same	Agrotron 70	Orchard/vineyard	X	
Deutz Fahr	Agrofarm 430	Open field		X
Goldoni	E100	Open field/ Vineyard	X	
Kubota	M5091	Vineyard	X	
Kubota	M5101	Vineyard		X
Fiat	70-90	Open field		X
New Holland	TN70V	Orchard/Vineyard		X

5 Method

To comprehensively analyse the data collected by the instrumentation referenced earlier, a methodological framework comprising three core pillars was developed.

The first pillar is dedicated to the efficiency analysis of diesel tractors, which are widely employed across Italy. This part of the study involved the generation of engine performance curves under various operating conditions, followed by an assessment of the tractors' efficacy in terms of power output and specific fuel consumption.

The second pillar encompasses the examination and analysis of pollutant emissions from tractors when simulating specific agricultural tasks at a constant operation point, selected via the analysis of performance curves from a range of tractors. This method facilitated a comparative analysis of the empirical data against the thresholds established by the European regulations at the time of the first tractors' market introduction. Utilizing these insights, it was feasible to evaluate the environmental footprint of each operational task for each tractor model.

The third pillar places emphasis on the health implications for the operator.

Operators routinely experience extended durations of exposure, particularly when utilizing specialized tractors that situate them in close vicinity to the exhaust outlets, thereby increasing their exposure to emissions of pollutants. Presently, there is a discernible lack of specific regulatory measures dedicated to safeguarding the operators from the potential deleterious health effects attributed to inhaling gaseous pollutants emitted by diesel engines deployed in agricultural machinery.

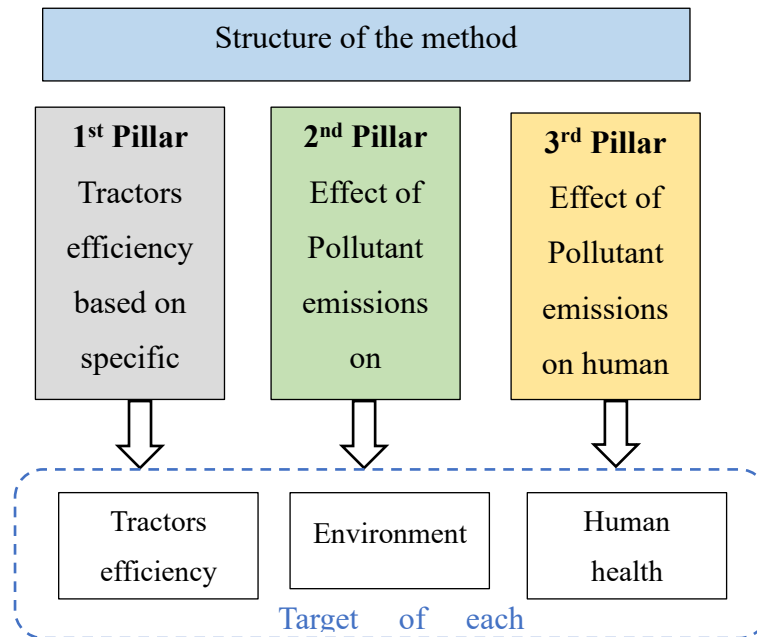


Figure 18 – Thesis structure is based on three pillars

5.1. Characteristics of Agricultural Farms

To estimate the efficiency of various agricultural tractors across different agricultural supply chains and scenarios, it was imperative to conceptualize a variety of farm types, distinguished by their production outputs and arable land. This delineation enabled the quantification of several factors, including the operational context, the extent of farmland, the planting layout, the operations planned for each farm (for instance, manual or mechanized processes in viticulture), and the frequency of operations as dictated by the scenario, among others. Upon examining the Italian agricultural landscape, a considerable variability among farms is evident, both in terms of production capacity and land area. The latter, in conjunction with the type of cultivation practiced, influences the size and diversity of the farm's machinery fleet, particularly in terms of tractors and operational machinery.

5.1.1. Supply Chain Influence on Farm Size

A scrutiny of the Italian agricultural panorama reveals how the supply chain significantly impacts the size of farmland. Among the most prevalent supply chains in Italy are open-field cultivations, such as cereals and animal feed crops. These are

complemented by a sizable number of viticultural and fruit production farms. It is logical to infer that a cereal-producing farm typically encompasses a larger productive area compared to a vineyard. The primary reason for this disparity largely lies in the value of the cultivated product. Indeed, given equal land areas, a specialized viticultural farm capable of producing certified quality grapes (and consequently, wine) will exhibit higher profitability than a farm growing grain maize. Hence, agricultural farms exhibit a vast diversity in land area based on their productive supply chain. For example, within the viticultural sector, it is not uncommon to encounter farms spanning just two hectares, as opposed to those covering several tens of hectares. Conversely, it is particularly challenging to find cereal or fodder production farms with less than 10 ha of land. Census data from the Ministry of Agriculture and ISTAT (Italian National Institute of Statistics) have estimated an average farm size in Italy, regardless of production type, to be approximately 10-11 ha.

5.1.2. Agricultural Sectors and Farm Characteristics Under Study

Section 5.3 elaborates on the scenarios that were investigated in the thesis, which include open-field agriculture split into cereal and fodder crops, alongside specialized sectors such as vineyards and orchards (with a focus on apple orchards). For each sector, assumptions were formulated regarding the average farm sizes and their crop planting patterns. These premises allowed for the calculation of various operational parameters throughout the growing season, including the potential number of crop rows (where applicable), the frequency of machinery passes required to adequately manage the farm's land area, and the regularity of these activities, among other factors. The identified parameters were:

Table 15 - Farm area defined for each production chain.

	Farm surface (ha)	Interrow (m)	location
Open field			
Cereal production (maize)	50	0.75	Northern Italy
Hay making	20	n.a.	
Specialized crops			
Vineyard	10	2.5	Northern Italy
Orchard (apple)	10	2.5	

5.1.3. Characteristics and Deployment of Agricultural Implements

For the optimal exploitation of agricultural farms, selecting and appropriately configuring the machinery deployed within the farm is imperative. The tractor's configuration, dictating its compatibility with a specific agricultural sector over another, represents merely one of several parameters that should guide the machinery selection process in an agricultural context. A principal characteristic to consider is the power class of the machinery, whether they be tractors or self-propelled machines. Notably, for specialized sectors, machinery power seldom exceeds 80-90 kW, while such power levels may be deemed marginally adequate for cereal sectors in open-field systems.

To comprehensively understand the operations on diverse farms, a detailed examination of the machinery utilized for distinct agricultural activities is imperative. This involves assessing the operational performance, efficiency, fuel utilization, and environmental impact of the machinery in question. It is vital to ascertain not only the operational width and speed of advancement but also the usage frequency of each piece of machinery throughout the growing season.

In the following, a list of the field operations scrutinized within the project framework, categorized by each specific sector, is provided.

Table 16 - Operational characteristics for the tasks proposed within the cereal production chain

Open field- cereal production				
Field operation	Working length	Working speed	Working frequency	
		km/h	hours/year	%
Ploughing	1.2	7	1	
Harrowing	2.5	5	1	
Seeding	4.5	6	1	
Fertilization	8	9	1	
Mechanical weeding	4.5	6	1	
Irrigation	40	0.1	1	
trailer (farm road)	n.a.	12	12	

Table 17 - Operational characteristics for the tasks proposed within the hay production chain

Open field- hay production				
Field operation	Working length	Working speed	Working frequency	
		km/h	hours/year	
Seeding	--	--	--	--
PPP Spraying (boom)	--	--	--	--
Fertilization	--	--	--	--
Grass mowing	--	--	--	--
Grass conditioning	--	--	--	--
Pick-up carriage	--	--	--	--
Hay racking	--	--	--	--
Balling	--	--	--	--

Wrapping	--	--	--	--
Shredding	--	--	--	--
Bale Trailer (farm road)	--	--	--	--

Table 18 - Operational characteristics for the tasks proposed within the vineyard production chain

Specialized crops- vineyard				
Field operation	Working length	Working speed	Working frequency	
		km/h	hours/year	%
Harrowing	--	--	--	--
Shredding	--	--	--	--
Hoeing	--	--	--	--
Row management	--	--	--	--
PPP spraying	--	--	--	--
Fertilization	--	--	--	--
Pre-pruning	--	--	--	--
Pruning mowing	--	--	--	--
Grass mowing	--	--	--	--
Ridging	--	--	--	--
Mechanical weeding	--	--	--	--
Sucker removing	--	--	--	--
Topping	--	--	--	--
Defoliation	--	--	--	--
Fertilization	--	--	--	--

Chemical weeding	--	--	--	--
Grape harvesting	--	--	--	--

Table 19 - Operational characteristics for the tasks proposed within the apple orchard production chain

Specialized crops- orchard (apple)				
Field operation	Working length	Working speed	Working frequency	
		km/h	hours/year	%
PPP spraying	--	--	--	--
Apple transport	--	--	--	--
Grass shredding	--	--	--	--
Pruning residues shredding	--	--	--	--
Chemical weeding	--	--	--	--
Organic fertilization	--	--	--	--
Chemical fertilization	--	--	--	--
Soil management	--	--	--	--
Pruning	--	--	--	--

Upon scrutinizing the information compiled in the aforementioned tables, it becomes evident how each supply chain significantly influences both resource consumption and the emission of pollutants, which detrimentally impact environmental and human health. Notably, the high frequency of certain agricultural practices emerges as a critical issue for the environmental sustainability.

5.2. The first pillar: Enhancing Tractor Efficiency

5.2.1. Strategic Engine Power Optimization

The efficiency of an energy system is its proficiency in harnessing the available energy to meet its demands. For vehicles equipped with internal combustion engines, efficiency hinges on the adept conversion of fuel's chemical energy into mechanical energy (delivered at the crankshaft) while minimizing energy losses.

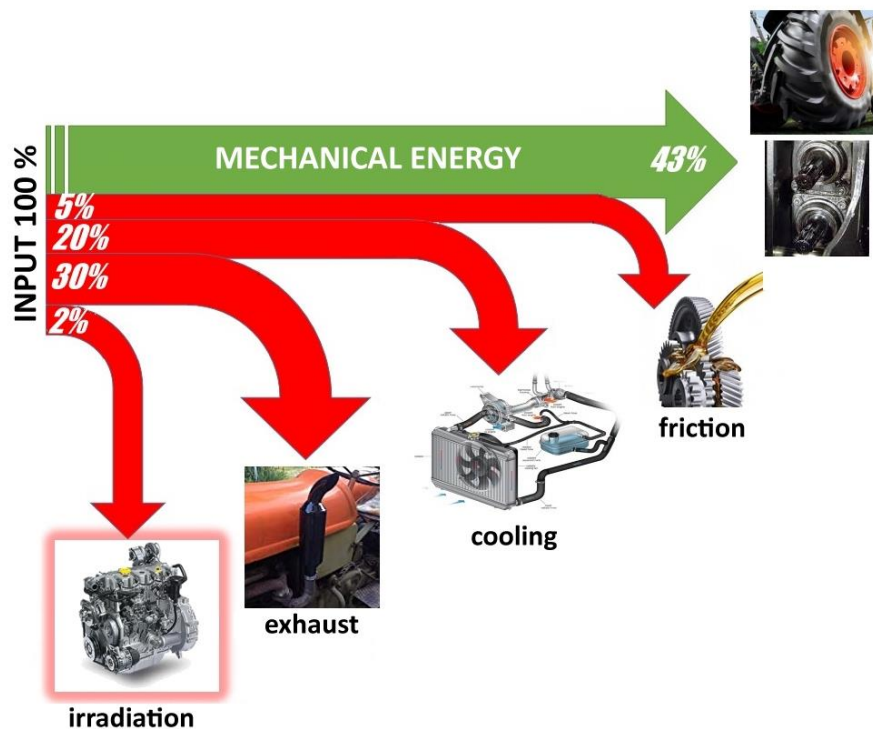


Figure 19 - Diagram of the efficiency of a heavy-duty agricultural engine and power losses.

This efficiency measures how efficiently a system converts input energy or power into useful work or output energy, usually expressed as a percentage.

Despite technological advancements and the introduction of innovative engine technologies, internal combustion engines typically cannot at present exceed 50% efficiency (excluding the new Weichai engines, which are not yet broadly available on the market). The peak efficiency of top-tier diesel engines is around 43%, achievable only at full operational capacity and under optimal conditions. It's important to note,

particularly in agricultural contexts, that a very small percentage of field operations use engines at full power, resulting in even lower efficiency levels during partial load operations. This reduction in efficiency necessitates a thorough consideration of the impacts and consequences of energy losses on the broader vehicle-environment-human system. The goal should be to minimize these losses as much as possible, for instance, by utilizing waste energy such as engine heat for supplementary purposes like cab heating, thereby improving the overall efficiency of the vehicle.

Efficiency calculation takes into account various technical and measurement parameters, including the calorific potential of the fuel, the specific fuel consumption rates as well as the conversion rate of the fuel's calorific value based on the selected measurement units.

$$\eta = \frac{E_m}{E_t}$$

$$E_t[kWh] = L_{hvf} \left[\frac{kWs}{kg} \right] \times m_f[kg] \times \frac{1 h}{3600 s}$$

$$E_m[kWh] = \frac{1}{SFC \left[\frac{g}{kWh} \right]} \times m_f[kg] \times \frac{1000 g}{1 kg}$$

$$\eta = \frac{E_m}{E_t} = \frac{1}{SFC} \times m_f \times \frac{1}{L_{hvf} \times m_f} \times \frac{1000 g}{1 kg} \times \frac{3600 s}{1 h}$$

$$\eta = \frac{1000 \times 3600}{SFC \times L_{hvf}} \approx \frac{85}{SFC}$$

where:

η : efficiency of the internal combustion engine

E_m : mechanical energy

E_t : thermal energy

SFC : specific fuel consumption (g/kWh)

L_{hvf} : lower heating value of the fuel

m_f : gravimetric fuel consumption [kg]

85: Inclusive value of the lower heating value of diesel fuel (equal to 42,400 kJ/kg) and the conversion of measurement units.

5.2.1.1. Overall balance of tractor efficiency

To obtain the energetic balance of a tractor, specifically the allocation of energy and operational power requisite for the execution of agricultural activities, taking into account the demands attributable to intrinsic power engagement is imperative.

These demands can be summarized into:

- 1. tractor's self-displacement**
- 2. transmission dissipation**
- 3. PTO usage;**
- 4. hydraulic system usage;**
- 5. wheel slip.**

The cumulative efficiency of the tractor is subsequently ascertained by considering the efficiencies of the individual demands listed above. To accurately quantify the useful power amount to be dedicated at the implement(s), an analysis involving the computation of the ratio between the tractor's engine power and the power requisites necessitated by its intrinsic consumptions is indispensable.

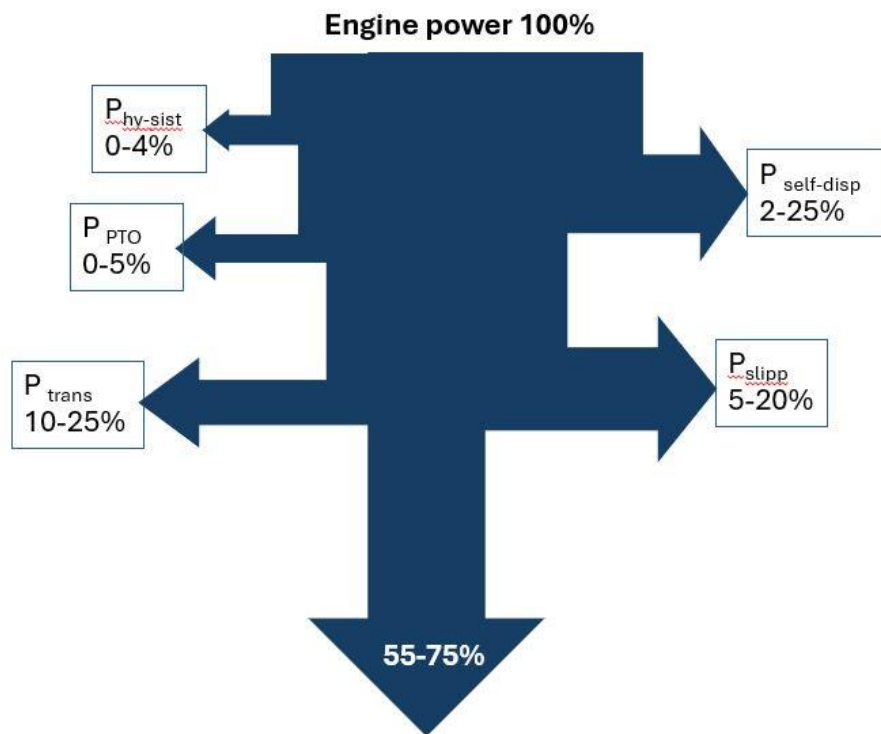


Figure 20 - Overall balance of tractor efficiency

$$P_u = P_{eng.} - (P_{self-disp.} + P_{trans.} + P_{PTO} + P_{hy.syst.} + P_{slipp.})$$

P_u : useful power

$P_{eng.}$: power delivered by the engine

$P_{self-disp.}$: power needed for self-displacement

$P_{trans.}$: power needed for transmission

P_{PTO} : power required for PTO operation

$P_{hy.syst.}$: power required by the hydraulic system

$P_{slipp.}$: power needed to compensate for slippage

To evaluate the tractor's performance, it is necessary to assess the actual power commitment required by each of the 5 items provided by this process, typically named "dynamic balance". The power commitment of each item varies depending on the characteristics of the tractor, the operation being performed (e.g., whether or not the

PTO and/or the hydraulic system are operating), and the surface characteristics over which the tractor is travelling.

5.2.1.1.1. Self-displacement

Self-displacement refers to the amount of power used by a tractor to overcome rolling resistance and move on the ground. This resistance depends on the tractor's weight, the type of propulsion organs (tyres or tracks), and the properties of the soil, such as its ability to support the weight with the minimum sinkage. The amount of power dedicated to self-displacement can vary significantly, from 2 to 25% of the total engine power (so providing an efficiency 0.98-0.75), depending on the operational conditions and specific characteristics of the tractor and soil.

5.2.1.1.2. Transmission

The power commitment of the transmission accounts substantially for the power losses generated by friction within the gears into the transmission system. Conventionally, a power loss of 2% is considered for each pair of gears transmitting the power. Therefore, the more complex a transmission is, the higher the power commitment will be. A traditional mechanical gearbox will have typically a power commitment of 10% (efficiency 0.9), while a CVT transmission, being more complicated, will have a much higher power commitment, generally between 20-25% of the engine power (efficiency 0.8-0.75), also depending on the running conditions.

5.2.1.1.3. PTO

The power commitment of the PTO accounts for whether it is engaged or not. Similarly to the transmission system, a power loss of about 2% is considered for each pair of gears that reduce the rotational speed transferred to the PTO's output. Due to that two pairs of gears are normally responsible for the motion derivation and its transfer to the PTO terminal, a power commitment of about 5% is conventionally considered (efficiency 0.95).

5.2.1.1.4. Hydraulic System

In agricultural tractors, the setup of hydraulic systems can vary based on the hydraulic pump control system, which can be of two types:

1. Traditional hydraulic system, in which the pump is constantly active while the tractor's engine is running. In this configuration, the hydraulic pump requires a fixed energy input, estimated at about 4% of the total available engine power (efficiency 0.96). This means that a small portion of the power produced by the engine is always used to keep the hydraulic system operational, even when no hydraulic work is required.
2. Load-Sensing hydraulic system, where the pump is activated only when necessary. This system optimizes energy use, as the hydraulic pump operates and consumes power only in response to an actual work demand. Therefore, when the pump is not in operation, power consumption is zero, with an efficiency of 1. During pump operation, power commitment can reach peaks of 40%, but these are maintained for a very short time, hence negligible over the whole work routine.

5.2.1.1.5. Slippage

The power loss due to slippage is a crucial factor in evaluating the dynamic balance as it defines the power dissipated by friction relative to the difference in peripheral speed of the wheels compared to the real travelling speed. Formally, the value of power commitment due to slippage can range from 0 to 100% (this last corresponding to an icy surface condition, on which it is not possible to advance due to slippage). To maximize the tractor's pulling capacity and, at the same time, reduce power losses, standard slippage values are considered. These values range from a minimum of 2% (on paved road, efficiency 0.98) to a maximum of 15% (efficiency 0.85) for 4WD tractors and 20% (efficiency 0.8) for 2WD tractors for deep tillage operations.

To evaluate the efficiency of each operation, it is necessary to assess the efficiency of each item in the dynamic balance in order to obtain the overall efficiency, which, multiplied by the engine power, provides the quota of power actually available to the operating machine.

$$P_u = P_{eng.} * \eta$$

$$\eta = \eta_{self-disp.} \times \eta_{trans.} \times \eta_{PTO} \times \eta_{hyd.syst.} \times \eta_{slipp.}$$

P_u: useful power

P_{eng.}: power delivered by the engine

η= overall efficiency

η_{self-disp.} = self-displacement efficiency

η_{trans.} = transmission efficiency

η_{PTO} = PTO efficiency

η_{hyd.syst.} = hydraulic system efficiency

η_{slipp.} = slippage efficiency

In summary:

Table 20 – Minimum and Maximum Efficiency Values of the Components for the Overall balance of tractor

	Efficiency	
	Min	Max
Self-displacement	0.85	0.95
transmission	0.75	0.9
PTO	0.95	1
Hydraulic system	0.96	1
slippage	0.8	0.97
Global efficiency	0.47	0.83

It should be remembered that these values, in addition to being influenced by external factors, can also be affected by internal characteristics of the tractor, such as the machine's maintenance level. Indeed, as the tractor is a complex mechanical machine, it requires high maintenance and care to keep all the kinematic chains and components in good condition. For instance, poor management of the PTO and transmission, both devoted to transfer the engine's motion through gears, could increase internal friction due to poor lubrication, thus increasing self-consumption and so affecting efficiency.

It is important to remember that much of the mechanical power generated and transferred in engines is through rotary motion. For this reason, the basis of the mechanical power generated by rotary motion lies in the equation according to which power is given by the product of torque (engine) and angular velocity (engine speed):

$$P = T * \omega$$

P: Power (W, kW)

T: Torque (Nm)

ω : angular speed (rad/s)

This relation delineates the power delivery mechanism of any internal combustion engine, which exhibits varied operational behaviours contingent upon its operating characteristics. Notably, as the engine speed varies (owing to alterations in the quantity of fuel injected into the combustion chamber), the performance dynamics of the engine undergo changes. These variations in performance are articulately described through engine maps, where the curves vividly illustrate the correlation between torque and power output relative to a given engine speed regime.

5.2.2. Engine curves at full load

Applying the aforementioned formula to each operating point of the engine makes it possible to describe its behaviour through curves, known as “engine performance curves”. Among these, the most known and utilized are the “full-load” curves, i.e., those obtained at the engine's maximum performance. These curves are traced by keeping the operating point fixed, placing the governor to the maximum to ensure the engine's maximum rotation speed, which is progressively reduced through the application of a resistance torque (generated by a dynamometer), often to the PTO (Power Take-Off) output. Using a dedicated software, it's possible to measure continuously the torque and power values (point by point) generated by the engine during the simulation, thus obtaining a curve that describes the engine's behaviour under different workloads.

Engine curves can vary significantly depending on the tuning of the tractor's ECU (Electronic Control Unit), which determines the fuel injection features into the combustion chamber. Based on the mapping of different ECUs, curves revealing different behaviours at various rotation speeds could be obtained.

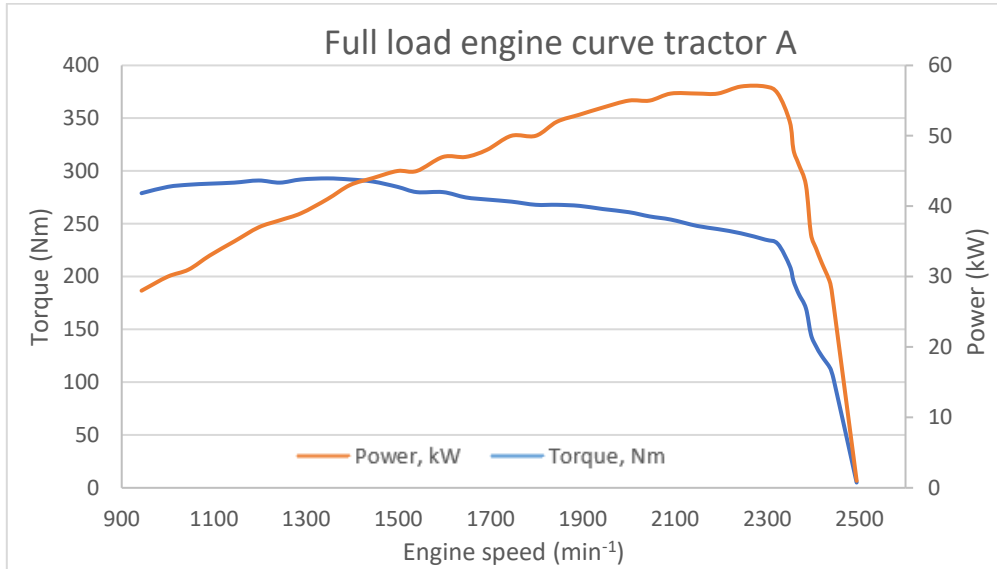


Figure 21 – example of a full load curve

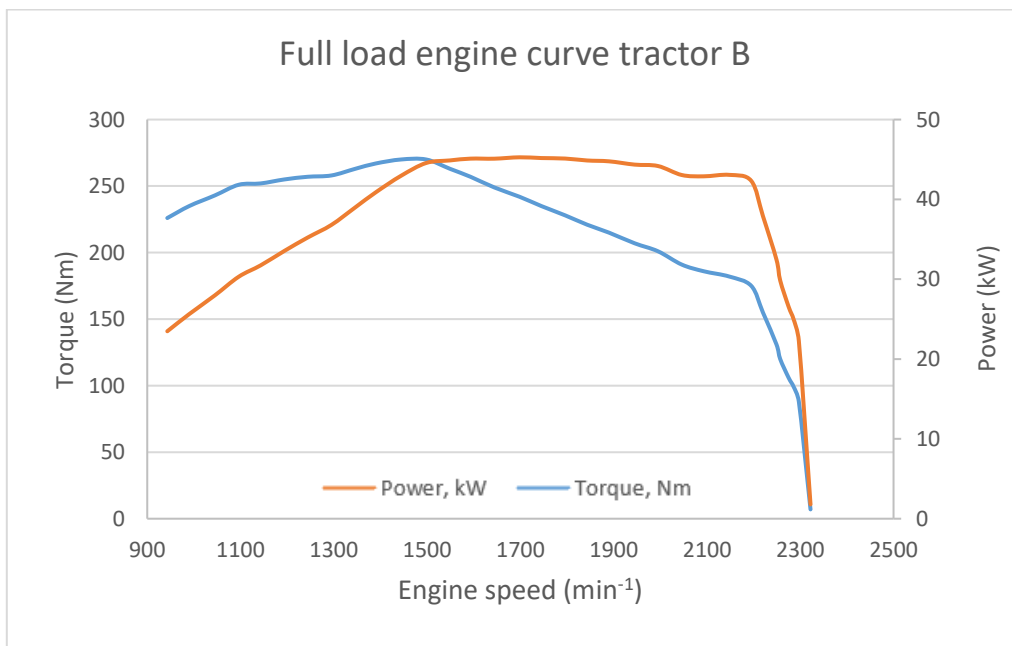


Figure 22 - example of a full load curve

As highlighted by comparing the two graphs above, despite both representing maximum power curves, they differ due to various factors, including the maximum rotation speed, which is 2500 min⁻¹ for tractor A and 2300 min⁻¹ for tractor B, the

maximum torque and power values, and especially the shape of the curves. From right to left, tractor A has a less steep power curve at the beginning but then becomes much steeper, showing a power decrease immediately after reaching the peak. In contrast, tractor B shows an almost immediate delivery of maximum power, which it manages to maintain up to a rotation speed of 1500 min^{-1} . These curves, in addition to being very useful for comparing the performance of different engines, also allow for the analysis of emission trends under conditions considered optimal, i.e., those that ensure the best efficiency and maximum power output.

5.2.3. Engine Curves under Partial Load Conditions

In a manner akin to the procedure adopted for obtaining the full-load engine curves, the engine's performance can be evaluated across a spectrum of operational speed values to examine its behaviour under partial load conditions. The development of these curves necessitates a reduction in the diesel fuel supply, consequently diminishing the engine's initial rotational speed. These partial load curves can be aggregated into collections or families that preserve a consistent shape but exhibit lower recorded values, effectively constituting scaled versions of the curve representative of maximum power output.

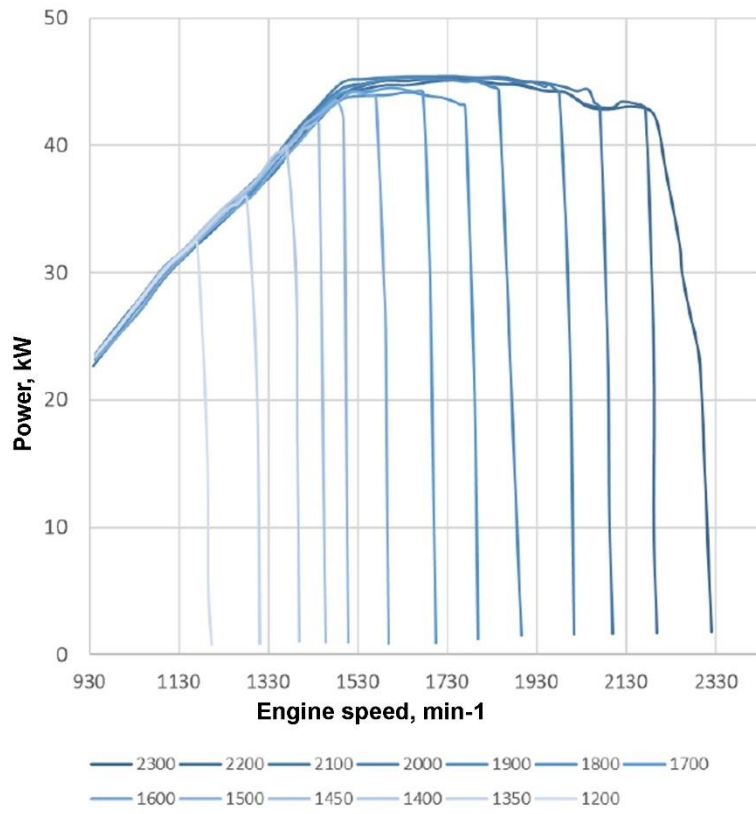


Figure 23 – Engine curves at partial load - power, kW

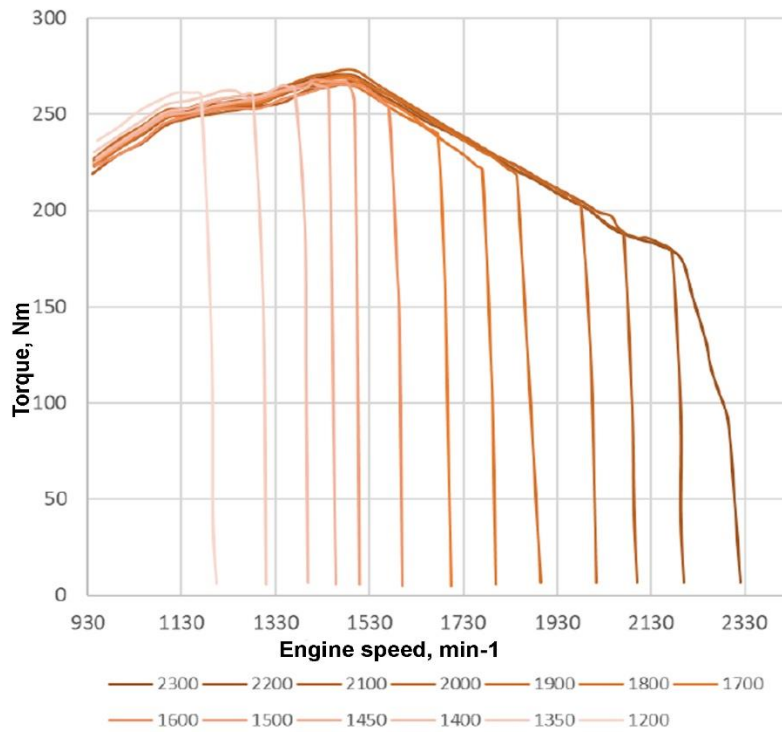


Figure 24 - Engine curves at partial load - torque, Nm

The analysis of partial load curves, despite their lesser popularity in comparison to their full-load counterparts, holds considerable significance. They provide insights into the engine's performance under real operating conditions, encompassing the starting engine speed, the decrease in the speed due to load, and the resultant power developed in those scenarios.

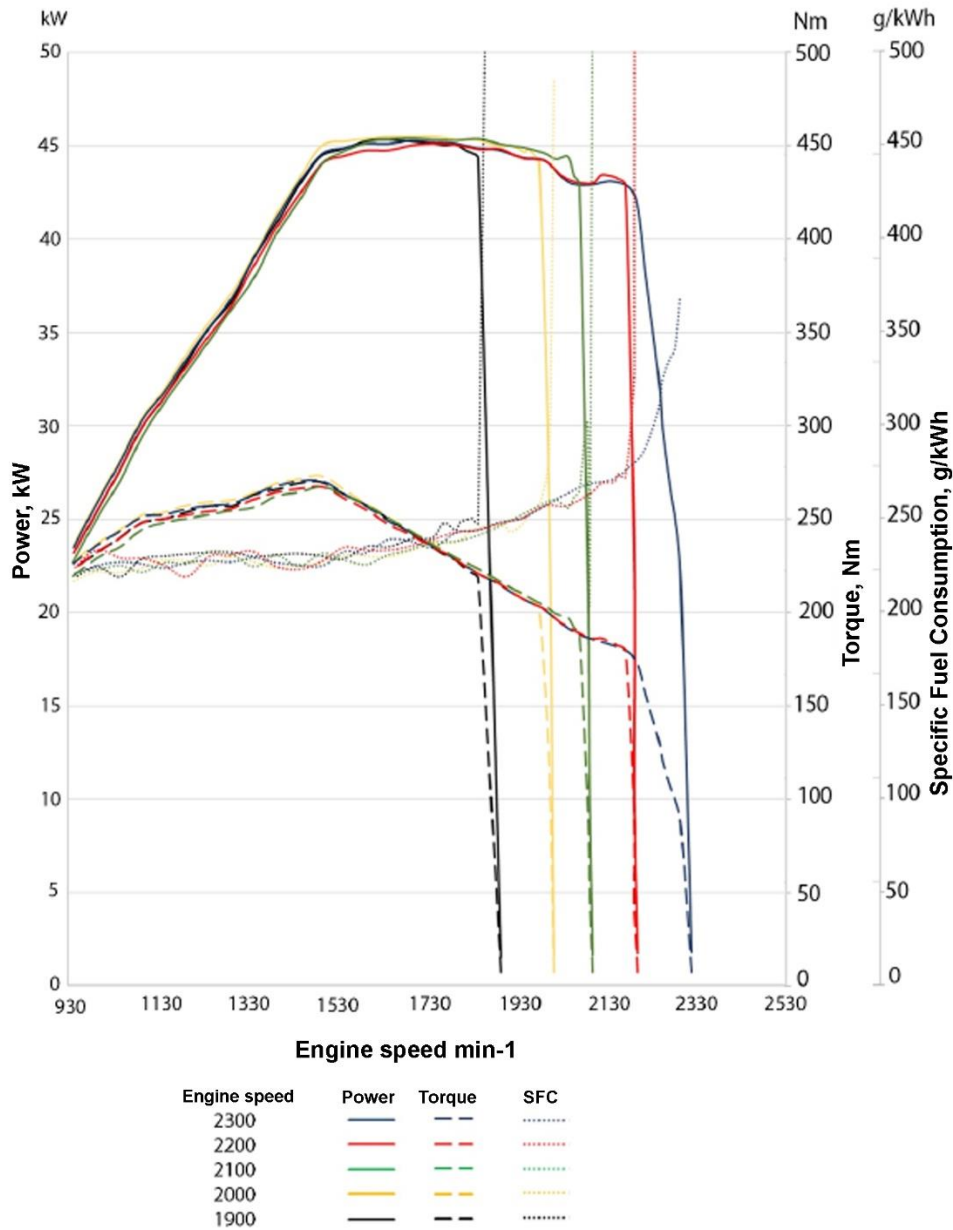


Figure 25 – an example of partial load curves at different engine speed (2300-1800 min⁻¹)

Throughout the array of partial load curves analysis, points delineating the performance characteristics of various operations have been defined. Hence, for a given partial load curve, with a defined starting engine speed, measurements were

taken of torque, power, and—where feasible—Specific Fuel Consumption (SFC) produced by the engine at a specific decrease, ascertained for each operation. For these identical points, employing the methodology described in the second pillar, an investigation will be conducted into the emission values of pollutants generated by the engine in the examined operating conditions.

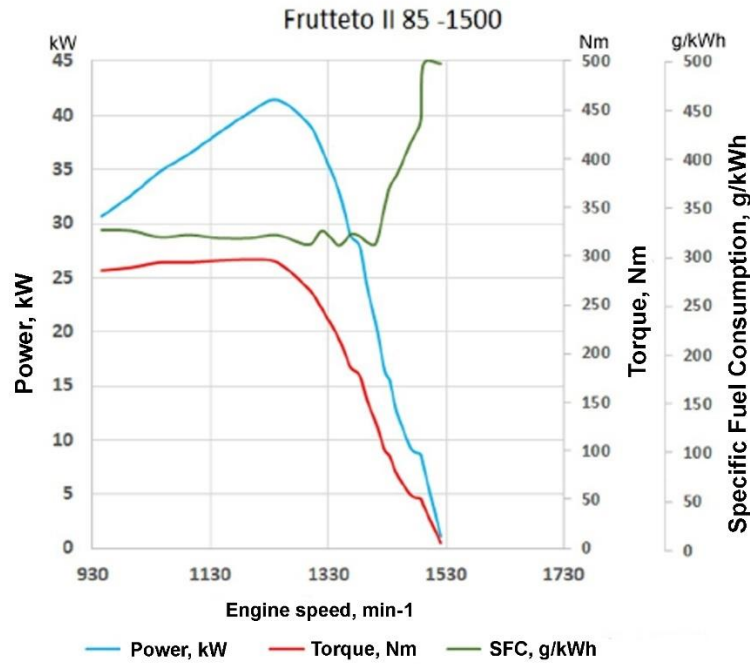


Figure 26 – example of an engine curve at partial load

5.2.4. Analysis of SFC values (diesel engine efficiency)

By examining fuel consumption data, particularly focusing on specific fuel consumption (SFC) derived from testing tractor performance under various loads, the engine efficiency across different operating scenarios was monitored. Notably, while a new tractor operating under optimal conditions can achieve a maximum efficiency of 43%, the real efficiency values recorded in agricultural work are considerably lower. So, the efficiency for each was calculated starting from the SFC (in g/kWh) in accordance with the following formula:

$$\eta = \frac{85}{SFC}$$

and adopting the measure unit shown above.

5.2.4.1. Classifying Tractors Based on SFC Values

To facilitate the interpretation of results, a classification system was established to be able to find the tractor models showing lower specific fuel consumption values.

In accordance with the approach used in similar studies in Spain and Turkey, 7 classes were defined, spaced at 10 g/kWh intervals and labelled A through G, covering SFC values from 220 to 290 g/kWh.

The selection of intervals with a width of 10 g/kWh, particularly within the range of 220 to 290 g/kWh, was motivated by the fact that the data obtained fall within this range. Additionally, a 10 g/kWh interval width is particularly significant when considering the total fuel consumption over the entire operational lifespan of a tractor. This level of detail allows for more precise and targeted assessments in the analysis of the vehicle's energy efficiency and sustainability.

For quick and easy identification, these classes were then grouped into 3 main categories, represented by a colour code similar to traffic lights: green for vehicles with SFC below 240 g/kWh (classes A and B), yellow for SFC between 241 and 260 g/kWh (classes C and D), and red for SFC above 260 g/kWh (classes E to G).

Tag	SFC, g/kWh	Colour tag
A	220-229	Green
B	230-239	
C	240-249	Yellow
D	250-259	
E	260-269	Red
F	270-279	
G	280-289	

Figure 27 – Ranges of SFC values for defining classes (A-G) and their respective colour labels using a traffic light system

This criterion was not only applied to individual operations to identify those with higher fuel consumption (and thus potentially greater pollution) but also across different supply chains and scenarios. This is crucial because the impact of specific fuel consumption varies with factors such as the frequency of operations and the scale of the enterprise. To obtain an aggregate value reflecting the entire supply chain, the

SFC value considered was calculated as a weighted average of the expected operations within that chain.

5.3. 2nd Pillar: Environmental Impact of Engine Gaseous Emissions

5.3.1. EU and EPA Emission Standards: An Academic Overview

Agricultural tractors, predominantly diesel-powered, play a significant role in atmospheric pollution, emitting a wide array of pollutants that vary in their chemical features and impacts on both environmental and human health. The operation of internal combustion engines results in the release of various pollutants including Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NO_x), and Particulate Matter (PM). Diesel engines, in particular, are noted for their higher emissions of NO_x and PM. The former is generated due to the high combustion temperatures within the engine, while the latter results from the incomplete combustion of hydrocarbons, subsequently released as exhaust gases in the form of PM₁₀, PM_{2.5} and PM₁.

In response to the growing concern over the environmental and health impacts of such emissions, international organizations have endeavoured to establish and enforce emission limits. Commencing in 1996, the European Union and the Environmental Protection Agency (EPA) of the United States independently proposed a series of quite similar emission limits. These were aimed at reducing the amount of pollutants emitted into the atmosphere by non-road vehicles, including tractors, in a manner similar to regulations applied within the automotive sector.

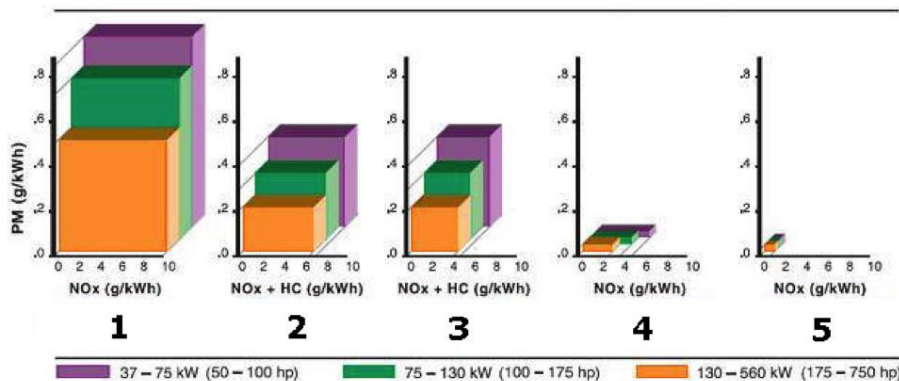


Figure 28 - Limit values of PM and NOx (in g/kWh) across the various homologation stages (Stage I to Stage V) for different power classes (35-75 kW: purple; 75-130 kW: green; 130-560 kW: orange)

This regulatory path has been akin to a "bottleneck" process, where limits have progressively tightened in alignment with advances in technical and technological capabilities. This evolution of standards signifies a concerted effort to compel manufacturers towards the production of tractors that are progressively less polluting, reflecting an intersection of environmental stewardship and technological innovation within the agricultural machinery industry.

5.3.1.1. ISO 8178 and Measurement Protocols for Automotive, Road vehicle, and Non-Road Vehicle Emissions

Within the fields of environmental engineering and automotive technology, measuring vehicle emissions is crucial for both comprehending and reducing their environmental impact. To this end, standardized measurement protocols, such as those outlined in the ISO 8178/2020 standard, have been developed. This standard delineates operating cycles for the assessment of pollutants emitted by a diverse array of vehicle types, encompassing automotive, road, non-road, generators, marine vehicles, etc. It specifies measurement points for both steady-state and transient engine cycles for each vehicle category.

As articulated within the standard, the primary objective of ISO 8178 is to facilitate the analysis of pollutant emissions from vehicles when coupled with a dynamometer. The document asserts:

"This document specifies the test cycles, the test procedure, and the evaluation of gas and particulate exhaust emissions from reciprocating internal combustion (RIC) engines coupled to a dynamometer. Subject to certain limitations, this document is also applicable to on-site measurements. The testing procedure incorporates both steady-state and transient operations, employing test cycles that accurately reflect the operational conditions specific to each application."

The standard meticulously defines the testing requirements and the procedural methodology. All tests are mandated to proceed under uniform conditions, incorporating an initial engine warming step to ensure consistent performance across all vehicles. Notably, Protocol C elaborates on the procedures and specific points of power modulation to be scrutinized, particularly targeting the emissions from non-road and industrial vehicles. For non-road vehicles, the protocol mandates pollutant measurement across the full engine load curve, adjusting modulation on torque and/or power to mimic real-world operational conditions. The C1 operation cycle specifies eight sampling points for pollutant emissions, aiming to aggregate these data points into a composite measure. This aggregation is achieved through a weighted average, taking into account the operational point distribution within a hypothetical work routine of a tractor.

Mode number	1	2	3	4	5	6	7	8
Speed ^a	100 %				Intermediate			Idle
Torque ^b (%)	100	75	50	10	100	75	50	0
Weighting factor	0,15	0,15	0,15	0,1	0,1	0,1	0,1	0,15
^a See 7.2, 7.4 and 7.7 for determination of required test speeds.								
^b The % torque is relative to the maximum torque at the commanded engine speed.								

Figure 29 – Specific running points extracted from ISO 8178

This approach to pollutant measurement facilitates the derivation of a unique emission value for each vehicle, subsequently enabling the classification of the vehicle into the appropriate Stage/Tier emission level. Such standardization is crucial for both regulatory compliance and the advancement of pollution reduction technologies, underscoring the intersection of environmental policy, mechanical engineering, and sustainability practices within the automotive sector.

5.3.1.2. Emission Stages

To mitigate atmospheric pollution and foster the development of more environmentally friendly vehicles, increasingly stringent emission limits have been established since 1996. Specifically, regarding the European Union, the prescribed and implemented limits from 1996 to the present for engine to be fitted on non-road vehicles extend from Stage 1 to Stage 5. Similarly, the Environmental Protection Agency (EPA) in the USA has proposed a similar number of stages, named Tier. Though both reached the same standards, they did so on different schedules and with varying implementation dates. Each Stage/Tier outlines limits for CO, HC, NO_x, and PM emissions in grams per kilowatt-hour (g/kWh). Emission categories are further refined based on the vehicles' engine power under evaluation. For instance, the emission limits for the Stage 2, whether for a 50 kW tractor or a 200 kW one, are not identical. It is estimated that a vehicle equipped with an engine of the same nominal power, one certified under Stage 1 and the other under Stage 5, the former produces up to 100 times more pollutants than the latter under identical usage conditions.

Cat.	Net Power	Date*	CO	HC	NO _x	PM
	<i>kW</i>					
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

* Stage II also applies to constant speed engines effective 2007.01

Figure 30 – European limits for non-road vehicles, stage 1 and stage 2

Stage 1 was issued in 1999, but was quickly superseded by Stage 2, which imposed slightly more stringent limits for NO_x and PM emissions, particularly for vehicles with more than 75 kW.

Cat.	Net Power	Date†	CO	HC	HC+NOx	NOx	PM
	<i>kW</i>						
Stage III A							
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 III B							
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

† Dates for constant speed engines are: 2011.01 for categories H, I and K; 2012.01 for category J.

Figure 31 - European limits for non-road vehicles, stage 3A and stage 3B

Stage 3 was divided into two phases, 3A and 3B, implemented respectively between 2006 and 2008 for 3A, and between 2011 and 2013 for 3B. Stage 3A consolidated the measurement of HC and NOx pollutants into a single category, which were then separated again in the Stage 3B limits.

Cat.	Net Power	Date	CO	HC	NOx	PM
	<i>kW</i>					
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

Figure 32 - European limits for non-road vehicles, stage 4

Stage 4, introduced simultaneously with Stage 3B at the start of 2014, established particularly strict limits for NOx emissions.

Category	Ign.	Net Power	Date	CO	HC	NOx	PM	PN
		<i>kW</i>						
NRE-v/c-1	CI	P < 8	2019	8.00	7.50 ^{a,c}		0.40 ^b	-
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.60	7.50 ^{a,c}		0.40	-
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.00	4.70 ^{a,c}		0.015	1×10 ¹²
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.00	4.70 ^{a,c}		0.015	1×10 ¹²
NRE-v/c-5	All	56 ≤ P < 130	2020	5.00	0.19 ^c	0.40	0.015	1×10 ¹²
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.50	0.19 ^c	0.40	0.015	1×10 ¹²
NRE-v/c-7	All	P > 560	2019	3.50	0.19 ^d	3.50	0.045	-

^a HC+NOx
^b 0.60 for hand-startable, air-cooled direct injection engines
^c A = 1.10 for [gas engines](#)
^d A = 6.00 for [gas engines](#)

Figure 33 - European limits for non-road vehicles, stage 5

Stage 5, the latest to be implemented in 2019, is currently (2024) in force. It specifies emission limits for tractors and non-road vehicles with power outputs ranging from 8 kW to over 560 kW. Owing to the significant variability in tractor power and thus performance, it has not always been possible to uniformly update emission limits for

all power classes. Consequently, periods of overlapping or concurrent emission standards are not uncommon in the history of emission stages.

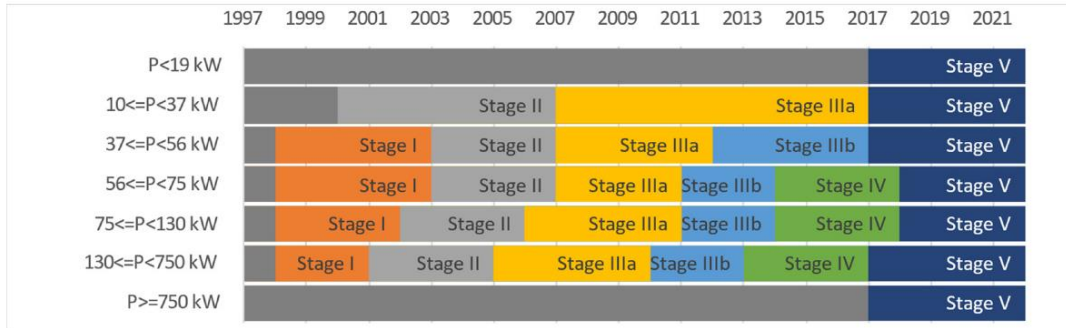


Figure 34 - Chronology of the enactment of emission stages for the various power classes of tractors

Despite advancements in technology and market shifts, it's important to acknowledge that tractors registered between 1990 and 2010 are still in widespread use. As a result, they are not subject to the latest emission standards, instead having a significantly higher environmental impact.

5.3.1.3. Operational Conditions and Running Points (Steady State Conditions)

In order to analyse the real emissions generated by engines and released into the atmosphere during specific agricultural operations across various production chains, a testing protocol was developed to assess the real operational conditions of tractors. This approach was based on the productive chains analysed in section 5.1, focusing in particular on individual operations and their running points.

Drawing upon the part-load curves discussed in section 5.2.3 and the operational points of individual tasks (determined through engine speed reduction), it became feasible to conduct pollutant measurements under true operating conditions. The analyses were carried out at fixed points to reduce the impact of variability and outliers potentially caused by transient conditions, i.e., changes in power output that could lead to alterations in fuel flow and, consequently, in the quantity and type of emissions produced during combustion.

Conducting analyses under constant conditions, albeit an approximation of the actual operational scenario, allows for an evaluation of emissions with the engine maintained in stable conditions, thereby facilitating the normalization of values. Utilizing the instrumentation specified in sections 4.6.5 and 4.6.6, continuous measurements were possible over several minutes at a fixed point, and their values averaged to minimize both human and instrumental measurement errors.

5.3.2. Experimental Setup

For the purpose of pollutant measurements, a test bench setup was configured to allow for the simultaneous performance of engine and curve realization (1st pillar), the definition of running points, and the measurement of pollutants and particulate matter. Each tractor under test was connected via the Power Take-Off (PTO) to an electromagnetic brake to analyse specific operational conditions.

At the same time, the tractor's exhaust outlet was connected to a steel duct engineered to straighten, cool down, and facilitate the measurement of the exhaust flow. This setup, comprised of various bends and tubes, included the insertion of a Pitot pipe for exhaust flow measurement (sections 4.6.3 - 4.6.4) and, at the pipe's end, the placement of probes for the measurement of pollutants.

Once the engine speed and torque applied by the brake were adjusted to accurately replicate the target operating condition, it became necessary to measure the exhaust flow. Pollutants produced by the engine under test were simultaneously measured using the Testo 350 analyser (section 4.6.5). Each measurement session with this instrument lasted between 2 and 3 min, during which the device continuously monitored the concentration of pollutants, amassing a considerable volume of data and yielding an averaged and stable value. Following the initial pollutant quantity measurement, the Testo 350 probe was quickly replaced with the Testo 338 opacimeter probe (section 4.6.6). This automatic measurement lasted between 20 and 40 s, depending on the particulate matter quantity emitted by the tractor, as directly determined by the instrument. Data measurements were performed using the analysis of mean values over the specified time interval and were replicated to ensure accuracy. For both types of measurements, the reported measurement unit was concentration, expressed in mg/m^3 .

5.3.2.1. Conversion of Instrumental Data to European Emission Stage Benchmarks

The equipment used for measuring the emission levels of pollutants reports concentrations in volumetric units. This system allows for the selection of the unit of measurement, which can be either parts per million (ppm) or milligrams per cubic meter (mg/m³). As discussed in section 5.3.1.2, the emission limits specified by the European Stage regulations are expressed in grams per kilowatt-hour (g/kWh). To align the experimentally obtained values with the regulatory emission limits specified in g/kWh, a comprehensive dimensional analysis and unit conversion were essential. In detail:

$$pe = c \times 10^3 \times f \times \frac{1}{p}$$

pe = pollutant emission (g/kWh)

c = pollutant concentration (mg/m³)

f = exhaust gas flow (m³/h)

p = specific power measured (kW)

$$\text{pollutant emission} \left(\frac{\text{g}}{\text{kWh}} \right) = \frac{\text{mg}}{\text{m}^3} \times 10^3 \times \frac{\text{m}^3}{\text{h}} \times \frac{1}{\text{kW}}$$

5.3.2.1. Colour Tagging Based on Emission Stages

Similar to what was done in the 1st pillar in section 5.2.4.1, to facilitate understanding of the efficiency of tractor engine performances color-coded labels have been devised based on the limits of different emission stages.

In more detail, 7 categories were identified, of which 6 represent the limits of the homologation stages according to European legislation (1, 2, 3A, 3B, 4, and 5) and are color-coded using a traffic light logic from red (Stage 1) to deep green (Stage 5). An additional category, called "out of standards" and coloured in dark red, is applied to all recorded values that do not fit within any of the emission stages due to excessively high values.

For each of the six color-coded categories representing stages 1-5, threshold values have been reported for each pollutant. This way, the values of individual pollutants,

obtained from instrumental measurements, can be compared with the homologation limits and color-coded accordingly.

These colour labels will be applied for each detected pollutant, in various operations, in order to provide at first glance an idea of the amount of different pollutants generated during various operating conditions. This implies that not all operations will necessarily be labelled all green or all red but might display different colours or shades depending on the pollutants, thus facilitating readability.

Building on the foundational methodology outlined in section 6.2, which utilized six standard colour codes (plus one non-standard) to clarify the efficiencies of tractor engine performance, this section introduces a more sophisticated colour-tagging framework. This new system is designed to delineate emissions across different regulatory stages, ranging from red (Stage 1) to a rich green (Stage 5), intuitively signifying emission severity. The framework aims to enhance the interpretability of emissions data while aligning it with the regulatory thresholds established by European standards.

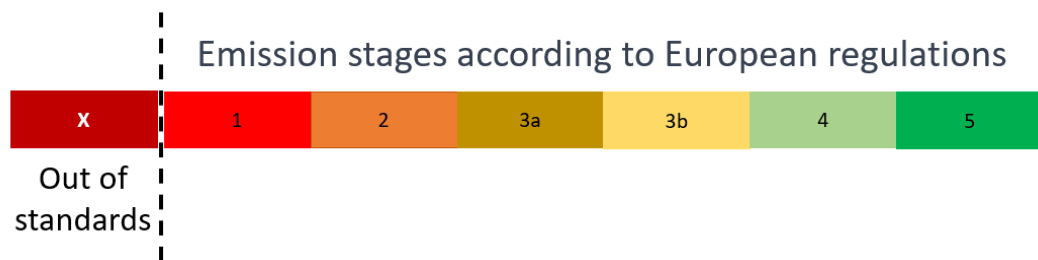


Figure 35 - The traffic light colour logic has been assigned to seven classes: six corresponding to the regulatory emission stage limits, and one for values that significantly deviate from the Stage 1 limits.

For the sake of precision and clarity, threshold levels for a variety of pollutants have been established for each emission stage, delineated by their respective colour codes. This approach allows for a straightforward comparison between the measured pollutant levels, obtained through rigorous instrumental analysis, and the defined regulatory limits, facilitating a seamless categorization process.

P < 56 kW

Stage	CO	HC	NOx	PM	Range
g/kWh					kW
1	6.5	1.3	9.2	0.85	
2	5	1.3	7	0.4	
3a	5	4.7		0.4	37≤P<75
3b	5	0.19	3.3	0.025	37≤P<56
4	5	0.19	0.4	0.025	56≤P<130
5	5	4.7		0.015	37≤P<56

Figure 36 – Emission stage limits for tractor with power below 56 kW

56 kW ≤ P ≤ 75 kW

Stage	CO	HC	NOx	PM	Range
g/kWh					kW
1	6.5	1.3	9.2	0.85	
2	5	1.3	7	0.4	
3a	5	4.7		0.4	37≤P<75
3b	5	0.19	3.3	0.025	56≤P<75
4	5	0.19	0.4	0.025	56≤P<130
5	5	0.19	0.4	0.015	56≤P<130

Figure 37 - emission stage for tractors with power between 56 kW and 75 kW

75 kW ≤ P ≤ 130 kW

Stage	CO	HC	NOx	PM	Range
g/kWh					kW
1	6.5	1.3	9.2	0.85	
2	5	1.3	7	0.4	
3a	5	4		0.3	75≤P<130
3b	5	0.19	3.3	0.025	75≤P<130
4	5	0.19	0.4	0.025	56≤P<130
5	5	0.19	0.4	0.015	56≤P<130

Figure 38 - Emission stage limits for tractor with power between 75 kW and 130 kW

The implementation of this colour-coded labelling system across different pollutants and operational scenarios promises to deliver an immediate, visual summary of the emission profile associated with varying operational conditions. This system is designed to reflect the complexity of emissions data, recognizing that operational

modalities may not correspond uniformly to a single colour category but rather present a kaleidoscope of colours indicative of the varied pollutant emissions. This refined representation markedly augments the framework’s proficiency in disseminating pivotal information promptly, thereby broadening its scope for detailed analysis.

Table 21 - Example of application of the traffic light colour logic

Tractors	CO	HC	NOx	PM
Model A	Yellow	Red	Light Green	Green
Model B	Light Green	Red	Yellow	Light Green
Model C	Light Green	Yellow	Light Green	Green
Model n...	Red	Olive	Red	Red

5.3.2. Impact of Supply Chains on the Environment

To obtain a more comprehensive understanding of the emissions generated by each operational supply chain, the extension of pollutant measurements from fixed points to the entire supply chain was planned. This required identifying five distinct supply chains, each characterized by different operations, performed with various tractors and engine loads. For each supply chain, a specific farm area was assumed, and for each farm, the hourly commitments for each operation were estimated. By accounting for the number of annual interventions for each operation, it was possible to estimate the total tractor usage time over the season and the percentage of hourly commitment for each operation.

Table 22 - Table for data collection on operating frequencies in different production chains

Productive chain							
	Working length	Working speed	Working frequency	working capacity	surface on hour	intensity of use	
Field operation	m	km/h	time/year	h/ha	ha/h	h/year	%
Op.1							
Op.2							
Op.							
Op. n.							
Total							

Once the hourly usage frequencies have been determined, these values can be combined with the exhaust gas flow rate (m³/h) and emissions (mg/m³) to calculate the total emissions released into the atmosphere by an entire production supply chain (kg/year).

Table 23 - Table for data collection on gaseous pollutant emissions in different production chains

Productive chain						
	intensity of use	flow	NOX	CO	HC	PM
Field operation	h/year	m ³ /h	kg/year			
Op. 1						
Op. 2						
Op. 3						
Op. n						
Total						

This study was conducted by applying the same tractor models considered for fixed-point surveys to each supply chain. Specifically:

Table 24 - Assignment of the most realistic operating chain for each analysed tractor

Productive chain	Tractor used for the analysis
Corn production	Deutz Fahr Agrofarm 430
Hay production	Fiat 70-90
Vineyard (mechanical harvesting)	Kubota M5101
Vineyard (hand harvesting)	New Holland TN70V
Apple orchard	New Holland TN70V

5.4. Third Pillar: The Impact of Emissions on Human Health

In conjunction with the 1st and 2nd second pillars, which delineated technical and quantifiable aspects, a 3rd pillar has been conceptualized to scrutinize the repercussions of emissions on human health. Notwithstanding the current absence of universally acknowledged regulations specifically designed to safeguard agricultural workers from the adverse effects of high concentrations of gaseous pollutants, the detrimental impact of such pollutants on health is extensively corroborated by scientific evidence. (Agarwal A. et al. 2016; Pandya R. J. et al. 2002; McClellan R.O. et al, 2012) The corpus of occupational health literature is replete with studies elucidating the myriad health conditions that may ensue from prolonged exposure to gaseous pollutants. (Czerczak S. & Szymczak M. 2003; Parent M.E. et al. 2007; Villeneuve P.J. et al. 2011, Sibanda E. & Makaza N. 2019) These conditions range from rhinitis and asthma to more severe respiratory difficulties and, in extreme cases, chronic lung diseases including bronchitis and lung cancer.

It is pertinent to note the existing regulatory vacuum concerning specific protections for individuals working in close proximity to diesel engines, which release gaseous pollutants into the atmosphere.

European guidelines exist for maximum permissible limits of indoor air pollutants; however, such guidelines are absent for outdoor environments. A key parameter employed in the establishment of these limits is the MAK value (Maximum Allowable Concentration), which is generally derived from the NOAEL (No Observed Adverse Effect Level), representing the concentration at which no adverse effects are detected.

(Significance, Use and Derivation of MAK Values, 2018; Nielsen, G. D., & Øvrebo, S. 2008; Bevan, R. et al. 2017)

This regulatory lacuna is particularly evident in the lack of established maximum permissible concentrations of pollutants, affecting both enclosed spaces and open environments alike.

This regulatory lacuna is particularly evident in the lack of established maximum permissible concentrations of pollutants, affecting both enclosed spaces and open environments alike. Consequently, in the absence of definitive guidelines promulgated by regulatory authorities, the principle of precaution, encapsulated in the maxim "less is better," is invoked. (Greim H. 2019) Therefore, it becomes imperative to conduct a thorough analysis of the real-world operational conditions of tractors and the quantum of pollutants they discharge, with the aim of instituting suitable protective measures for those exposed.

6. Results and Discussion

6.1. First Pillar

The 1st pillar aimed to scrutinize the efficiency of 4 models of specialized tractors, all operating under identical conditions within the vineyard, one of the most popular Italian agricultural scenarios.

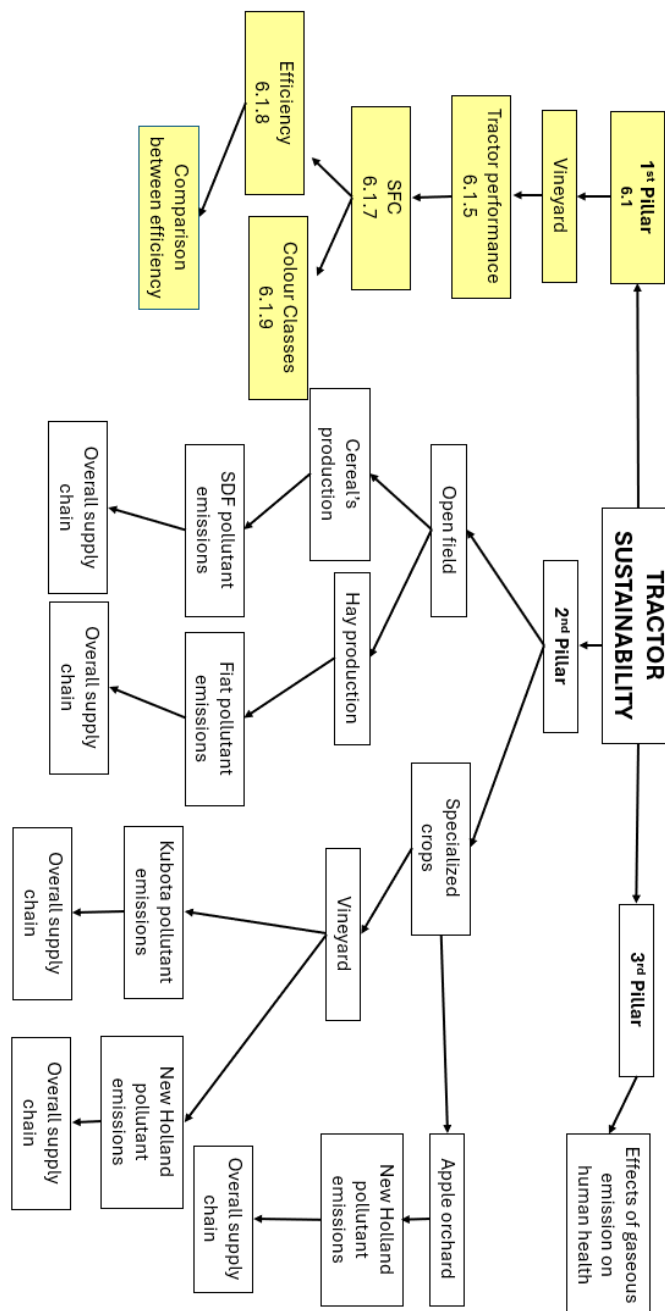


Figure 39 – 1st Pillar

6.1.1. Scenario of the Vineyard

For a more nuanced understanding of the characteristics pertinent to viticulture, specifically within the context of the vineyard scenario (refer to paragraph 5.1.3.), ten viticultural operations were identified and examined, commonly carried out in the major part of mechanized vineyards, different in terms of power demand and the timing of deployment within the growing season.

Table 25 – legend of abbreviation for vineyard operations

n.	Field operation	Abbreviation
1	Pruning residues shredding	P.R. shredding
2	PPP spraying	PPP spraying
3	Fertilising (mineral/organic)	Fertilising (M/O)
4	Pre-pruning	Pre-pruning
5	Grass shredding	Grass shredding
6	Chemical/Mechanical weeding	(C/M) weeding
7	Sucking	Sucking
8	Topping	Topping
9	Defoliation	Defoliation
10	Grape harvesting	G. harvesting

Despite the vineyard farms in Italy averaging around 2 ha as an average, to facilitate an accurate and comprehensive mechanization of production, the analysis extended to operations within a vineyard covering 10 ha. The diversity of the Italian climate significantly impacts agricultural works, particularly the frequency and timing of treatments using PPP, highlighting the need of a selection of a specific environmental and geographical context for study. Practical considerations, as well as production needs and the selected farm scale, lead to consider this hypothetical vineyard as located in the northern regions of Italy. To accommodate the highest level of mechanization, planting rows were envisaged to be sufficiently spaced at 2.2-2.5 m, allowing the travelling of all machinery.

Concurrently, to minimize field entries and thus reduce soil compaction in the inter-row spaces, machinery was assumed to be of such dimensions that would enable the completion of operations in a single pass. This method, beyond mitigating soil compaction, aims to prevent wasteful overlaps (in terms of both products and time) within the same inter-row space.

For each operation, specific parameters were identified, including the location of the work area (row or inter-row), the operation's width (meters), the progression speed during the operation (km/h), and the working capacity (hectares/hour).

Taking into account the cultivation strategy and the climatic conditions of Northern Italy, it was feasible to estimate the number of interventions (field passes) required for each operation.

Table 26 – Characteristics of the wine production chain adopted for the 1st pillar: task characteristics, farm size, and frequency of operations

Field operation	Working speed, km/h	Working capacity, ha/h	Overall farm surface, ha	Seasonal Working frequency	Intensity of use, h/year	Intensity of use, %
P. R. shredding	2.50	1.60	10	1	6.25	2.22
PPP spraying	5.00	0.80		12	150.00	53.33
Fertilising (M/O)	5.00	0.80		1	12.50	4.44
Pre-pruning	2.50	1.60		1	6.25	2.22
Grass shredding	5.00	0.80		3	37.50	13.33
(C/M) weeding	3.50	1.14		3	26.25	9.33
Sucking	3.00	1.33		1	7.50	2.67
Topping	7.00	0.57		1	17.50	6.22
Defoliation	4.00	1.00		1	10.00	3.56
G. harvesting	3.00	1.33		1	7.50	2.67
Total (h)					281.25	100%

Considering the working capacity for each implement, referred to the known cultivated area of 10 ha and taking into account the frequency of field passes, the utilization of tractors was calculated, over the entire growing season. Consequently, each operation shows a given impact on the overall usage intensity, which is estimated at



approximately 280 hours/year. This figure is crucial for further analyses, aimed at determining the impact of individual operations on the fuel consumption.

6.1.2. Tractors selected for the Study

To properly represent the diversity of machinery used in vineyard operations, the vineyard scenario's included operations carried out in simulation considering 4 tractor models.

The tractors were all specialized, narrow-tracked, different in architecture (traditional or isodiametric), max engine power (ranging from 50 to 70 kW), and notably, in fuel delivery management. The management of fuel delivery is identified as a critical factor, impacting not only the maximal power generation but also the optimization of power and torque across a range of operating conditions.

Table 27 – Tractor models analysed in the 1st Pillar

Model		Brief description	Emission stage
Kubota M5091		Narrow track tractor Traditional architecture ROPS: Front rollbar Power: 62 kW Mechanical transmission	4
Same Frutteto II 85		Narrow track tractor Traditional architecture ROPS: Cab Power: 63 kW Mechanical transmission	3A

Same Argon 70		Narrow track tractor Traditional architecture ROPS: Rear rollbar Power: 46 kW Mechanical transmission	3B
Goldoni E100		Narrow track tractor Isodiametric tractor ROPS: Front rollbar Power: 63 kW Mechanical transmission	3A

To enhance comprehension of the different performances shown by the tractors, it is quite important to examine their operation at full load conditions and to scrutinize their engine performance curves.

6.1.3. Full Load Tractor Performance

In fig. 39 is proposed a comparative analysis of the power curves at full load for the 4 tractors tested.

Three of the four tested tractors exhibit the typical behaviour of the power curve, characterized by a progressive decrease from the maximum value as the rotational speed decreases.

Conversely, the curve of Same Argon 70 delineates a different pattern, achieving its maximum power at 1700 min^{-1} , a notably lower benchmark relative to the other depicted curves. Nonetheless, a closer view between 2200 and 1500 min^{-1} interval reveals a minimal fluctuation in power, suggesting that in this engine the fuel injection management facilitates a nearly consistent power delivery across a substantial portion of the engine speed interval, pertinent to viticultural applications.

The introduction of electronic management of engine operating parameters has facilitated the development of engines characterized by the so-called "flat power" curve. This curve is defined by the engine's ability to maintain power nearly constant from the nominal speed, even with a significant reduction in engine speed. Specifically, the power varies by less than 10% over a range of more than 400 min^{-1} in decreasing speed. Under these circumstances, and with the integration of advanced powershift transmissions, it is no longer strictly necessary for the engine to exhibit high values of torque reserve and elasticity, as the consistency of power ensures stable and efficient performance even under varying operating conditions.

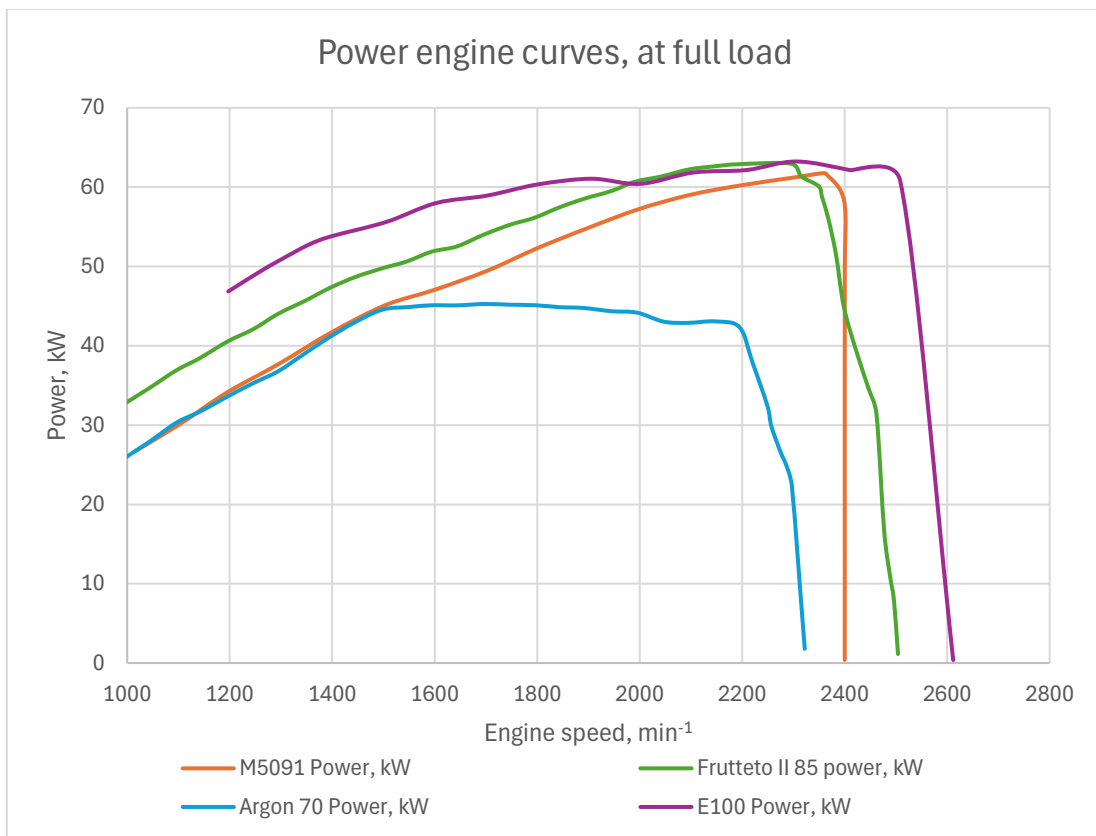


Figure 40 – Full load engine curves; power

Table 28 – Maximum power values and maximum power engine speeds

Tractor	Maximum power, kW	Starting engine speed, min ⁻¹	Maximum power engine speed, min ⁻¹
Kubota M5091	61.7	2400	2350
Same Frutteto II 85	62.9	2500	2300
Same Argon 70	45.3	2300	1700
Goldoni E100	63.2	2600	2400

In analysing the data presented in the table, a detailed comparison can be made of the maximum power output conditions across different engines. Among the engines reviewed, three—the Kubota M5091, Same Frutteto II 85, and Goldoni E100—demonstrate very similar maximum power outputs. In contrast, the Same Argon 70 tractor has a significantly lower output at only 45.3 kW, which is about 15 kW less than the other models. This shortfall in power is, however, offset by an alternative engine management strategy that ensures consistent performance across varying engine speeds, as evidenced by a “flat” power curve (refer to figure 39).

A flat power curve is essential for providing consistent power output and is defined by minimal variability in power levels—specifically, a variation that does not exceed 10% across at least 400 revolutions per minute (min⁻¹). This specification is met in the present case, as the power output varies by only 3.5% between 2200 and 1400 min⁻¹, a range well beyond the considered 400 min⁻¹ interval minimum threshold. This involves the need of an advanced engine management, for maintaining efficient and stable performance.

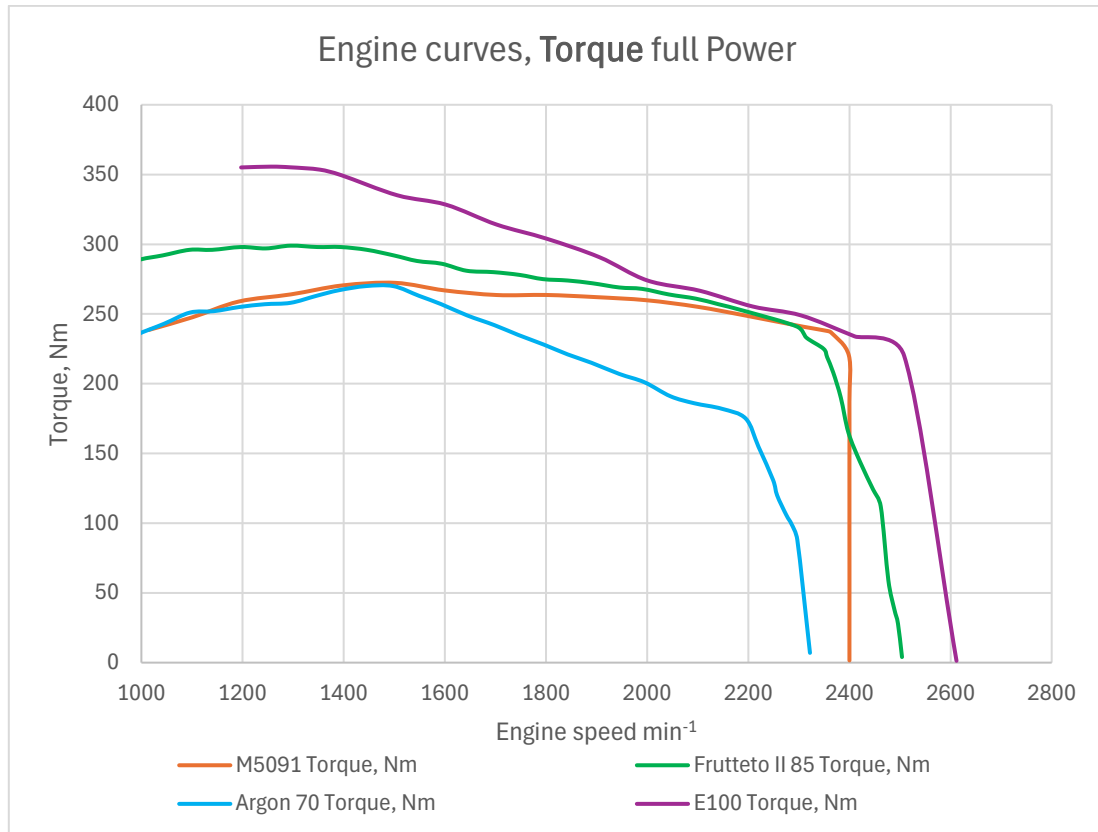


Figure 41 - Full load engine curves; torque

Also the torque curves display comparable behaviour for Same Argon 70 in comparison with the other 3 tractor models. In more detail, parameters such as torque rise and elasticity were taken into account. These parameters are essential for assessing an engine's ability to handle and respond to sudden peak in power demands without undue stress, thereby preserving efficient engine functionality.

Torque rise, as explored in the referenced table (tab. 29), is calculated as a percentage by correlating the max torque value to the torque at the engine's maximum power regime. According to widely shared considerations, a torque rise is deemed sufficient if it is higher than 15%. Examination of the data reveals that only the Same Frutteto II 85 and the Goldoni E100 tractors exhibit a sufficient torque reserve. Conversely, the Kubota M5091 displays a torque reserve very close the conventional threshold (14.4%), while Same Argon 70 shows a torque reserve of only 11.6%.

This value is seemingly low but is justified by the flat power curve and, more importantly, by the adoption of the power-shift transmission.

Table 29 - Maximum torque values and torque values at maximum power engine speeds

Tractor	Maximum Torque, Nm	Torque at maximum power engine speed, min ⁻¹	Torque increase, %
Kubota M5091	272.3	237.9	14.4
Same Frutteto II 85	299.0	241.0	24.1
Same Argon 70	270.0	242.0	11.6
Goldoni E100	354.5	266.7	32.9

Another essential parameter for assessing torque performance is elasticity, which denotes the difference between the engine speed at maximum power and the engine speed at maximum torque. This parameter is crucial for ensuring enhanced responsiveness during sudden peaks in traction pull or unexpected peak power demands coming from the implement.

Table 30 – Torque values and elasticity

Tractor	Maximum power engine speed, min ⁻¹	Maximum torque engine speed, min ⁻¹	Torque elasticity, min ⁻¹
Kubota M5091	2350	1500	850
Same Frutteto II 85	2300	1295	1005
Same Argon 70	1700	1490	210
Goldoni E100	2400	1450	950

Except for the Same Argon 70 tractor, which exhibits a different engine mapping, all the other three tractors demonstrate relatively high torque elasticity values, positioned between 900 and 1000 revolutions per minute (min⁻¹).

Focus on Same Argon 70 engine behaviour

The engine fitted on Same Argon 70 exhibits some features directly linked to the mapping of the engine control unit managing the fuel delivery. In fact, the engine develops the maximum power at approx. 1700 min^{-1} , despite a max no-load speed of 2300 min^{-1} . This feature can be attributed to the trend of the power curve, which is notably flat (fig. 41). Indeed, the engine maintains a performance close to the maximum power from 2200 min^{-1} down to 1400 min^{-1} . This feature facilitates the tractor's operation with optimal efficiency and power across a broad spectrum of engine regime.

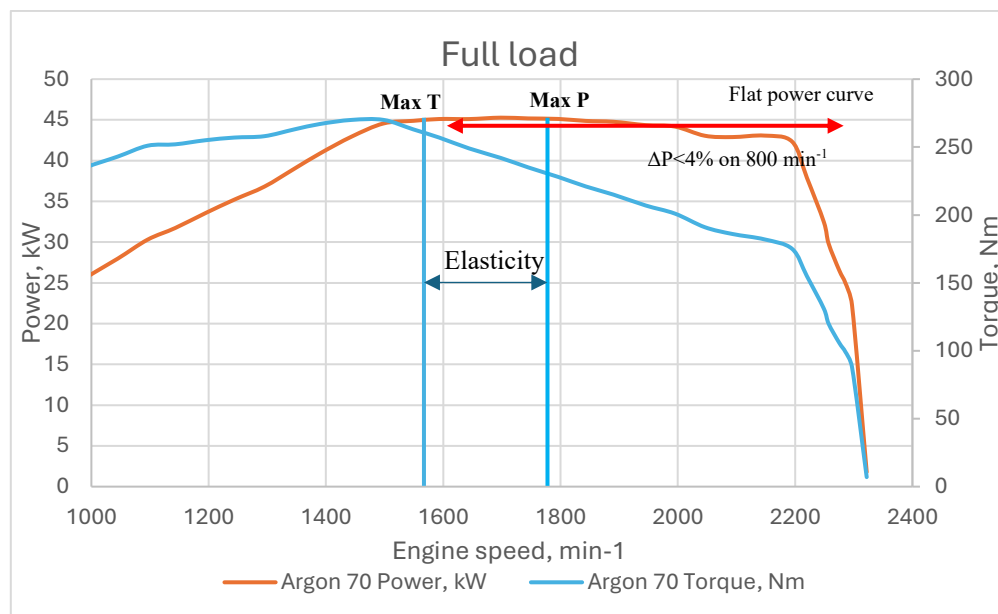


Figure 42 – Same Argon 70 full load curves (power and torque)

6.1.4. Comprehensive Power Balance

For each of the 10 operations designated in the vineyard scenario, identical working efficiencies were postulated for the 5 elements of the dynamic balance (referenced in paragraph 5.2.1.1) for all 4 tractors, so reflecting their similar structural and functional characteristics.

The overall efficiency values ranged from a minimum of 66% for the pruning residue shredding, identified as the most energy-intensive in this scenario, to a maximum of 75% for the pre-pruning, the chemical and mechanical weeding, the topping and the defoliation.

Table 31 – specific power balance for vineyard tasks

Field operation	Self displace.	Transmis.	PTO	Hydra. Sys.	Slippage	Global eff.
P. R. shredding	0.9	0.9	0.95	0.96	0.9	0.66
PPP spraying					0.94	0.69
Fertilising (M/O)					0.96	0.71
Pre-pruning	1.0		0.75			
Grass shredding	0.88		0.95		0.95	0.69
(C/M) weeding	0.9		1.0		0.75	
Sucking			0.95		0.71	
Topping			1.0		0.75	
Defoliation			0.75			
G. harvesting			0.95		0.94	0.69

In more detail, all tractors featured a basic mechanical transmission, highlighting an efficiency of 0.9 and a continuously engaged hydraulic pump, which consistently engages 4% of power (efficiency 0.96). The efficiency of the PTO, solely reliant on its running, was established at a standard rate of 0.95.

6.1.5. Tractor Performance in Real Working Conditions

To compute the efficiency for each designated operation, it was imperative to identify the running points on the engine curves of each tractor at varying levels of power modulation.

Comprehensive curves capturing full and partial load data concerning power, torque, and specific fuel consumption were plotted for each tractor. Having identified the engine's operating points for all the operations, considering the initial engine speed and the speed under load, it was feasible to ascertain the real power output of the engines, under different working conditions. The range of values varied from a minimum of 8.5 kW for the Kubota M5091 executing the topping to a maximum of 60.8 kW for the Goldoni E100 when carrying out the pruning residue shredding.

Table 32 – Power detected at specific running points

Field operation	Nominal engine speed	Speed reduction	Engine speed under load	Kubota M5091	Same Fruttet o II 85	Same Argon 70	Goldoni E100
	<i>min⁻¹</i>			<i>kW</i>			
P. R. shredding	2100	200	1900	56.0	52.0	45.1	60.8
PPP spraying	1700	150	1550	38.8	38.5	43.2	56.6
Fertilising (M/O)	1500	100	1400	31.7	21.0	41.2	53.8
Pre-pruning	1500	50	1450	15.4	10.5	43.0	28.6
Grass shredding	1700	100	1600	31.4	28.0	42.3	57.9
(C/M) weeding	1400	50	1350	8.5	11.0	38.7	52.7
Sucking	1500	50	1450	15.4	10.5	43.0	28.6
Topping	1400	50	1350	8.5	11.0	38.7	52.7
Defoliation	1400	100	1300	17.5	20.3	36.7	51.3
G. harvesting	1800	200	1600	48.9	47.9	43.9	57.9
<i>Std. deviation</i>				<i>16.8</i>	<i>15.7</i>	<i>2.7</i>	<i>11.7</i>

By juxtaposing these data against the previously analysed maximum power curves, it becomes apparent that the Same Argon 70 tractor is capable of delivering a nearly constant power output for each operation. This characteristic is particularly pronounced when considering the standard deviation of the measured power outputs. Specifically, the standard deviation among the power values provided by the Same Argon 70 tractor is 2.7, in contrast to the other three models where it ranges from a minimum of 11.7 (Goldoni E100) to a maximum of 16.8 (Kubota M5091).

6.1.6. Tractors' Usable Power in Real Working Conditions

To account for all power losses and friction generated by the operation of various tractor components, the usable power values detailed in section 6.1.4 were adjusted by multiplying them with the specific efficiency associated with each operation. This method enabled a precise calculation of the real power available for operating the machinery under different usage conditions.

Table 33 – Available power detected at specific running points

Field operation	Global efficiency	Kubota M5091	Same Frutteto II 85	Same Argon 70	Goldoni E100	Std. Deviation
		Available power, kW				
P. R. shredding	0.66	37.23	34.57	29.96	40.42	4.42
PPP spraying	0.69	26.94	26.73	29.98	39.30	5.89
Fertilising (M/O)	0.71	22.48	14.89	29.22	38.15	9.89
Pre-pruning	0.75	11.50	7.84	32.10	21.35	10.88
Grass shredding	0.69	21.55	19.21	28.99	39.73	9.23
(C/M) weeding	0.75	6.35	8.21	28.90	39.34	16.09
Sucking	0.71	10.92	7.45	30.49	20.28	10.34
Topping	0.75	6.35	8.21	28.90	39.34	16.09
Defoliation	0.75	13.06	15.15	27.37	38.30	11.72
G. harvesting	0.69	33.96	33.26	30.48	40.21	4.10

Standard deviation values of available power for different tractors during each operation reveals significant variability in power available for certain agricultural operations. The relationship between engine speed in various operational conditions and the available power underscores the crucial role of electronic engine management. The management of fuel delivery is identified as key to influencing engine performance and behaviour across various operational conditions and at different running points.

The data specifically show that the standard deviation of power values for the same operation increases as the engine operates at lower speeds. For instance, operations conducted at low engine speeds (e.g., 1400 min⁻¹) show the highest standard deviation values, 16.09 for chemical and mechanical weeding and topping and 11.72 for defoliation. This reflects the significant variability in tractor performance at lower speeds.

6.1.7. Tractors SFC in Real Working Conditions

In order to evaluate the efficiency of the tractors considered across various operations within vineyard management, an analysis of specific fuel consumption (SFC) at different running points was conducted. This analysis aimed to identify the most efficient and optimized tractor for vineyard operations. The SFC curves were compared among tractors, with curve characteristics reflecting the performance capabilities of each engine.

To ensure clarity and comparability, standardized procedures were employed to identify the data points for the SFC curves of the four tractors. However, it was noted that the SFC data from the Goldoni E100 tractor displayed instability at rotational speeds below 1200 min^{-1} , leading to the data collection interruption near this threshold.

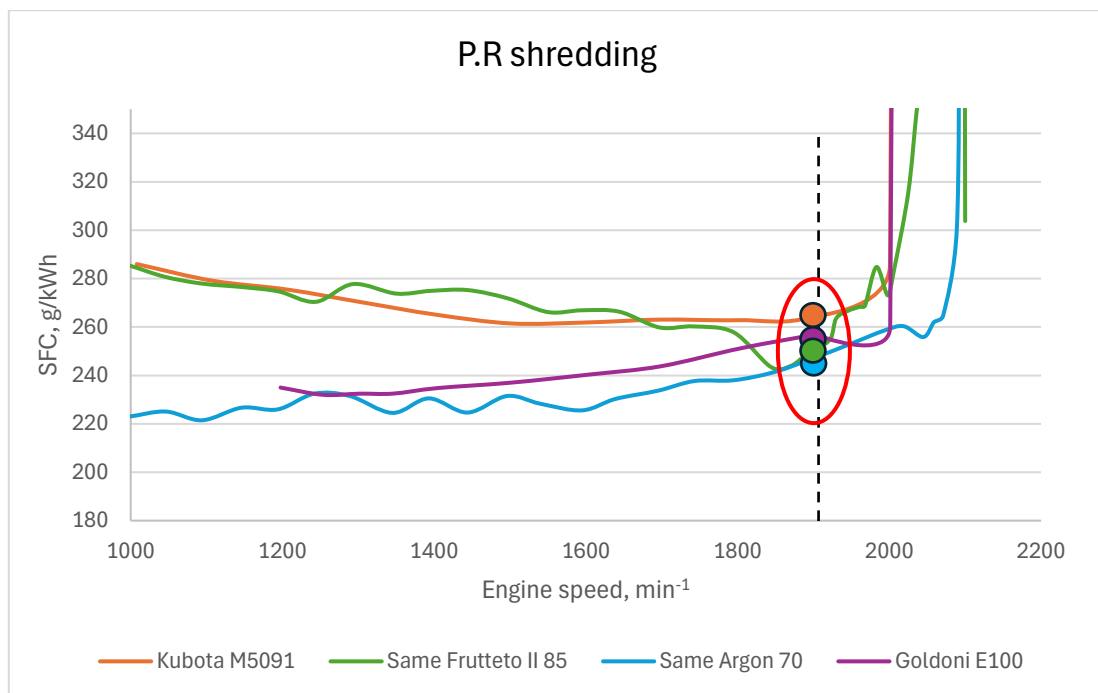


Figure 43 – SFC values at the P.R. shredding running point (2200 min^{-1} -> 1900 min^{-1})

In the specified range of engine speeds most commonly adopted, specific fuel consumption values typically range from 220 to 290 g/kWh, influenced by factors such as the type of engine under examination, its maintenance, and its power output.

Each graph illustrates the running points under load for various operations.

The Specific Fuel Consumptions (SFC) were calculated as follows:

$$SFC = \frac{FC * d}{P}$$

SFC: specific fuel consumption (g/kWh)

FC: hourly fuel consumption (l/h)

d: fuel density (g/l)

P: suitable power (kW)

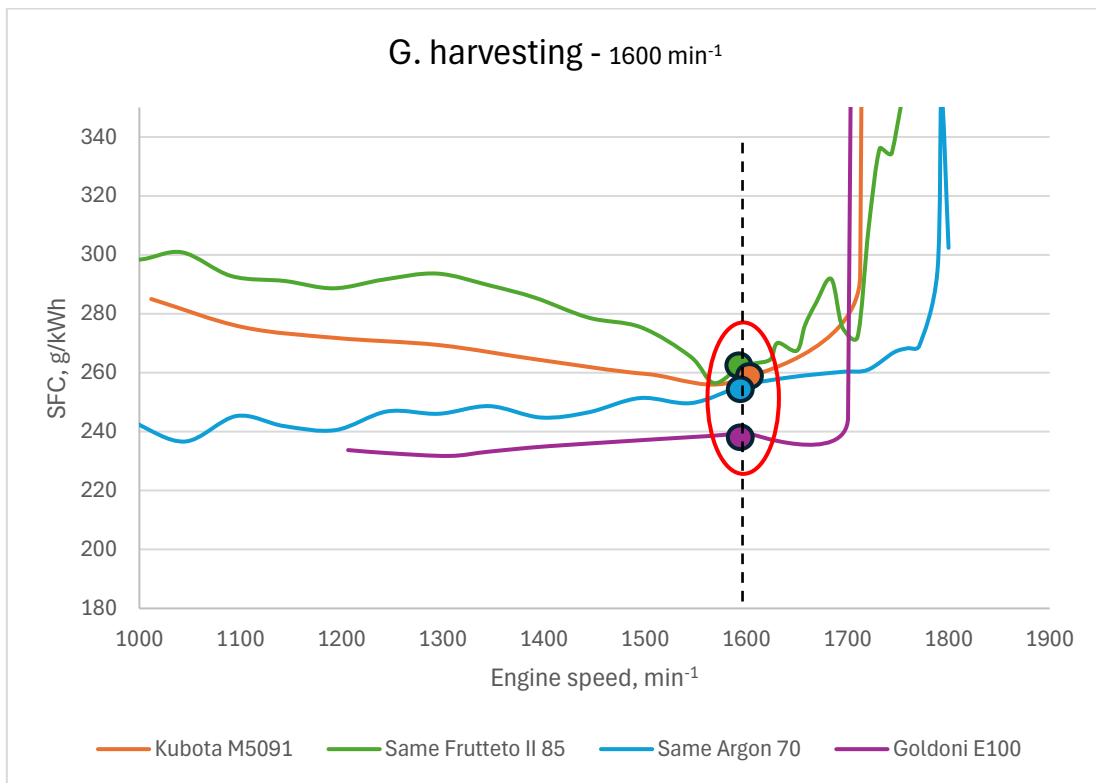


Figure 44 - SFC values at the G. Harvesting running point (1800 min⁻¹ ->1600 min⁻¹)

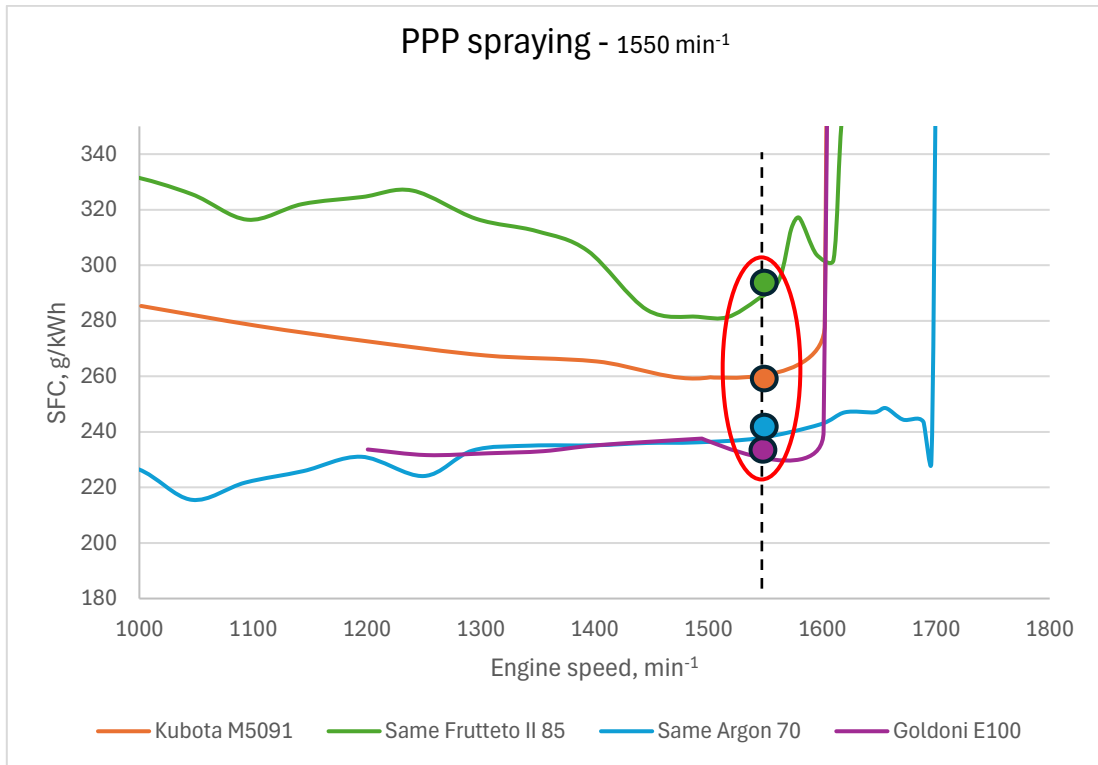


Figure 45 - SFC values at the P.P.P. spraying running point (1700 min⁻¹ ->1550 min⁻¹)

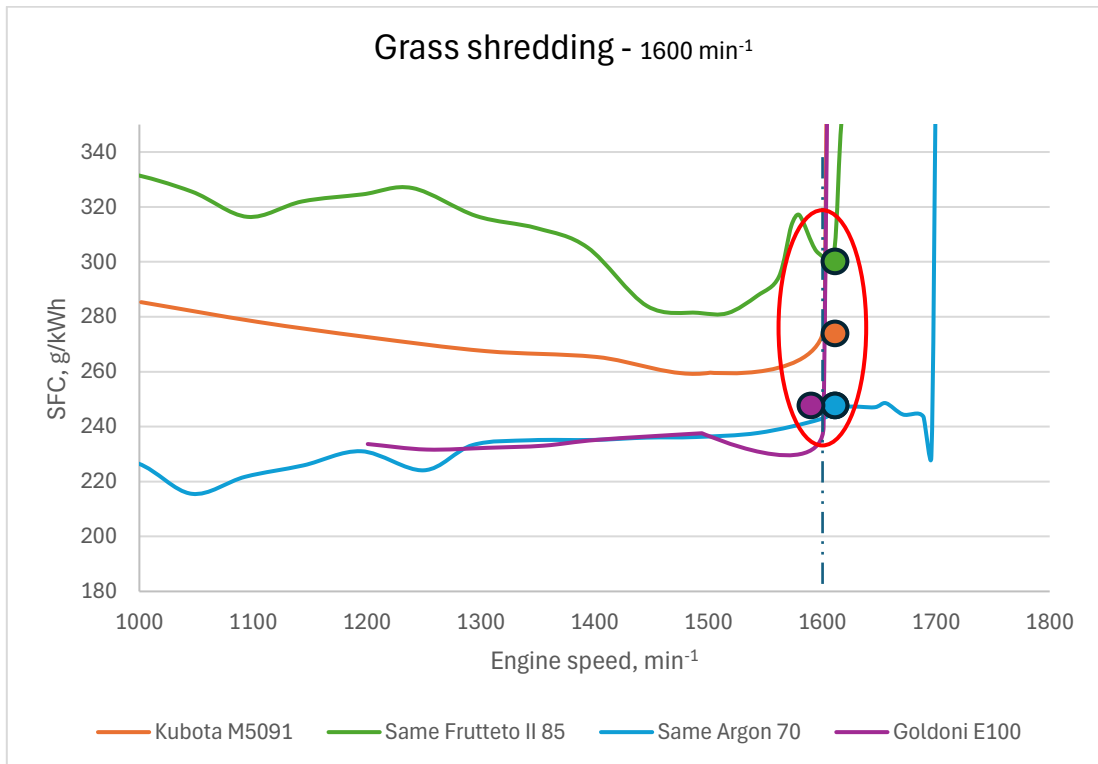


Figure 46 - SFC values at the Grass shredding running point (1700 min⁻¹ ->1600 min⁻¹)

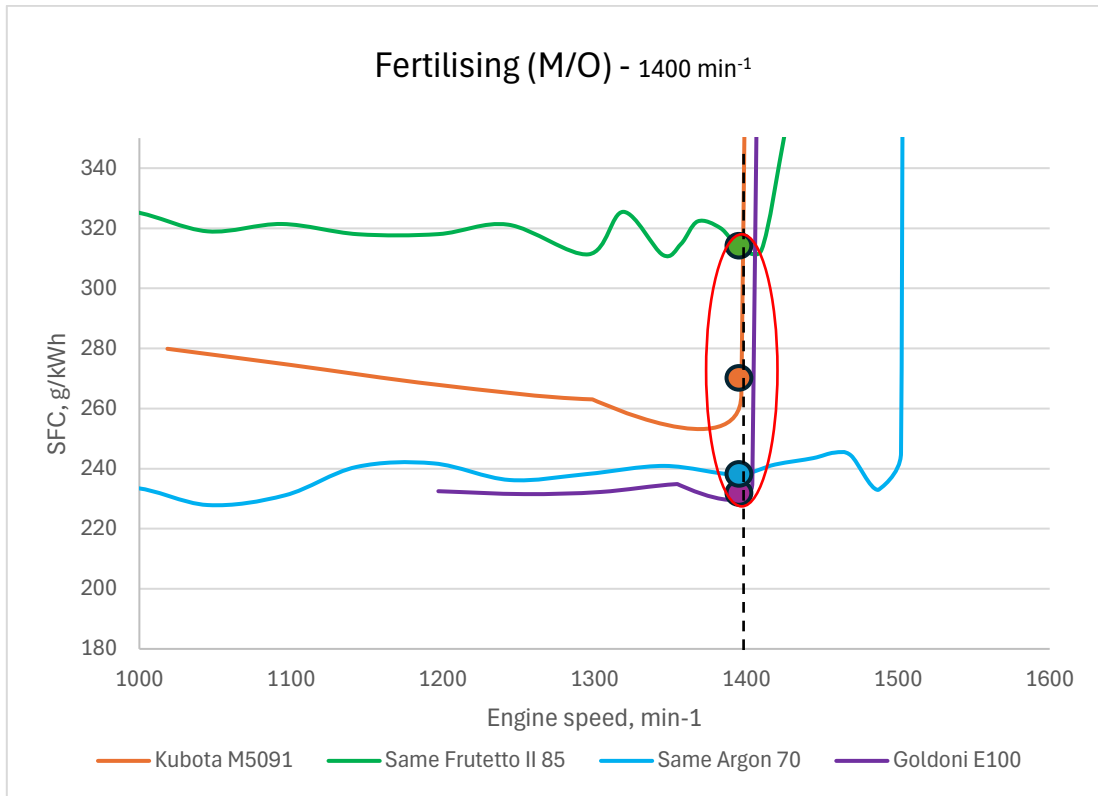


Figure 47 - SFC values at the Fertilising (M/O) running point (1500 min⁻¹ ->1400 min⁻¹)

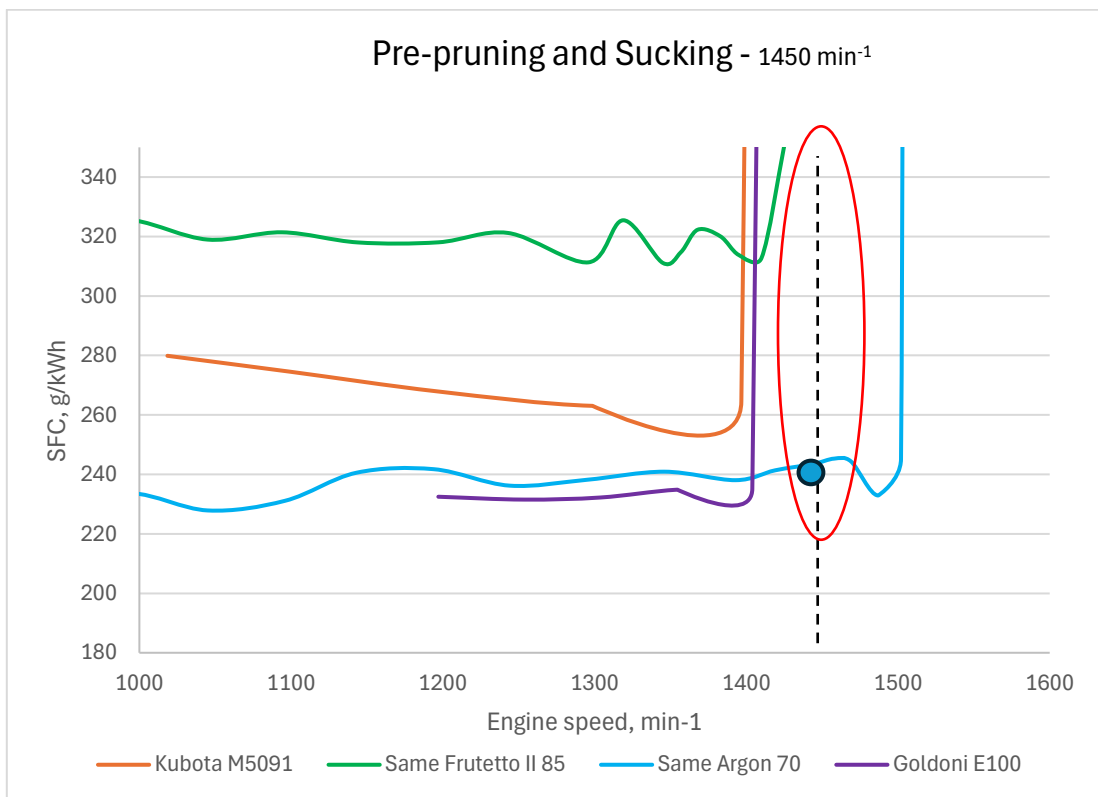


Figure 48 - SFC values at the Pre-pruning and Sucking running point (1500 min⁻¹ ->1450 min⁻¹)

Certain operations, due to reduced power demands, generate particularly high specific fuel consumption values that fall outside the established range. In these cases (pre-pruning and sucker removal), systematic experimental measurements could not be conducted for the exceptionally high specific consumption values exceeding the previously established range. The elevated values of SFC were caused by limited power output at the running points. It is likely that, for the two tractors (Goldoni E100 and Kubota M5091), the running points of pre-pruning and sucker removal were unsuitable for the type of engine and power delivery. It can be hypothesized that, in real conditions, farmers would have modified the engine speed to optimize it for enhancing the efficiency of the operations.

For instance, a value of 389 g/kWh was recorded for the Same Frutteto II 85. However, an exception is the Same Argon 70, which recorded a value of 244 g/kWh at the established operating point.

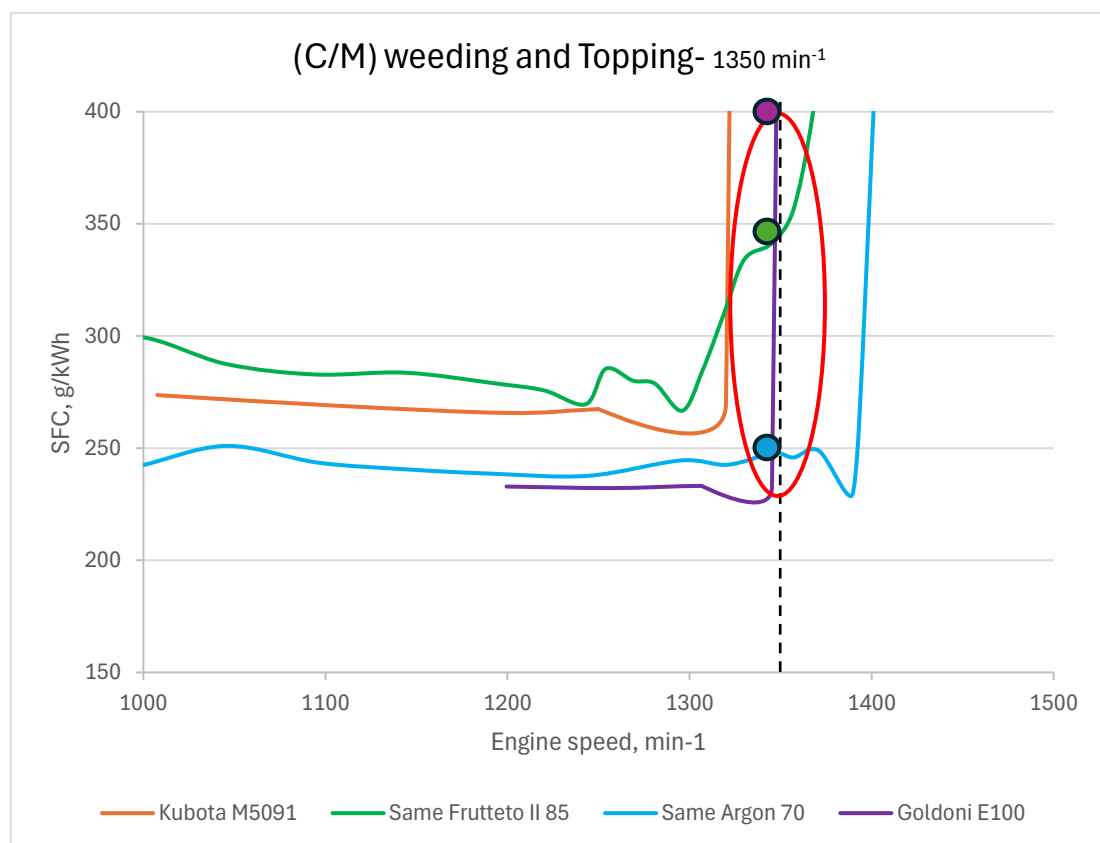


Figure 49- SFC values at the (C/M) weeding and Topping running point (1400 min⁻¹ ->1350 min⁻¹)

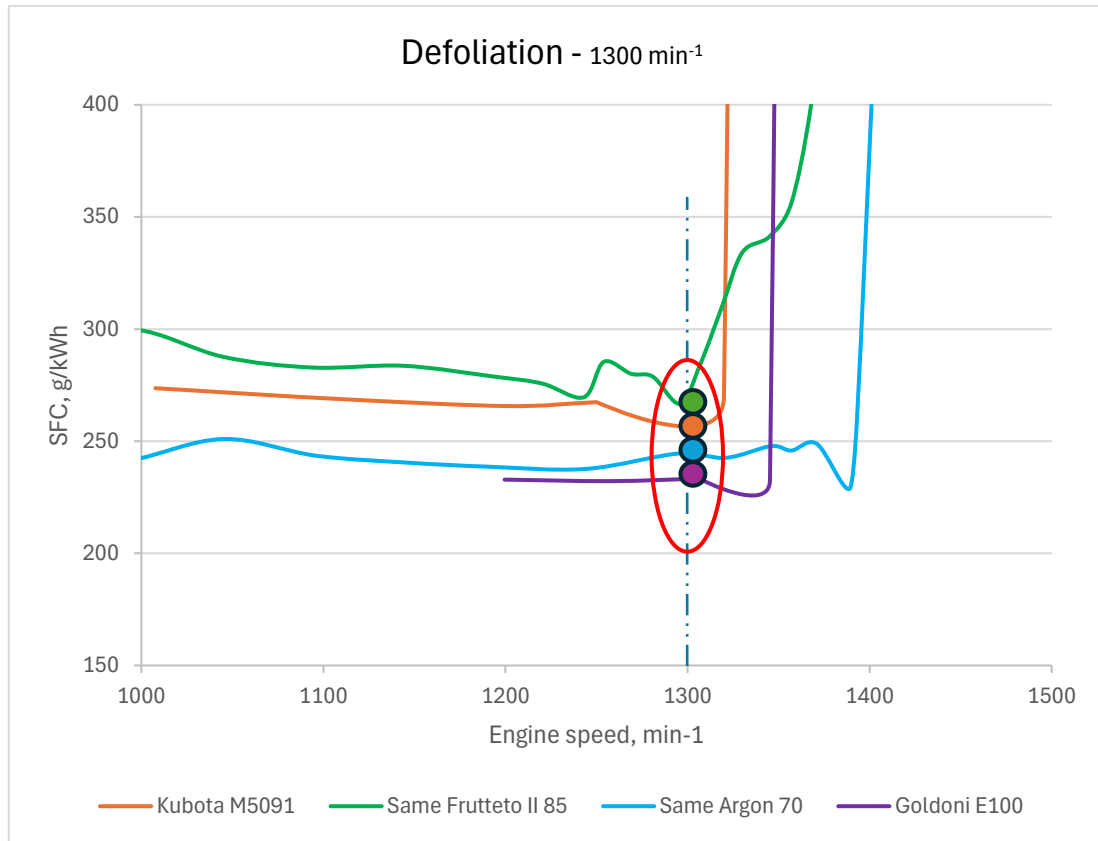


Figure 50 - SFC values at the Defoliation running point (1400 min⁻¹ -> 1300 min⁻¹)

6.1.8. Tractor Efficiency Analysis

The specific fuel consumption (SFC) values gathered from the performance tests are systematically organized in a comprehensive table, which includes all designated agricultural operations for the 4 tractor models studied. It was not feasible to record the SFC values for the pre-pruning and sucking operations for the Kubota M5091 and Goldoni E100 models due to exceptionally high readings related to minimal power outputs, as referenced in Table 34. To maintain the integrity of the data analysis, these outliers were excluded to prevent a skewed interpretation of the overall trends.

For a full comprehensive evaluation of the specific fuel consumption for different models under identical operational scenarios, both the arithmetic mean and the weighted mean were calculated. The weighted mean is particularly insightful as it considers the relative frequency of each operation throughout the year, thereby offering

a nuanced understanding of how each operation influences the overall fuel consumption for each tractor within the vineyard context.

Table 34 – SFC values detected at specific running points

Field operation	SFC, g/kWh			
	Kubota M5091	Same Frutteto II 85	Same Argon 70	Goldoni E100
P. R. shredding	264.36	250.61	246.39	256.76
PPP spraying	269.03	290.19	237.72	238.91
Fertilising (M/O)	264.58	313.81	238.05	235.18
Pre-pruning	*Out of scale	389.43*	244.26*	*Out of scale
Grass shredding	278.58	302.54	242.66	240.12
(C/M) weeding	342.17	341.24	247.84	232.59
Sucking	*Out of scale	389.43*	244.26*	*Out of scale
Topping	342.17	341.24	247.84	232.59
Defoliation	269.13	266.68	244.49	233.17
G. harvesting	258.36	262.21	255.60	239.63
Avg.	286.05	314.74	244.91	238.62
Weighted Avg.	267.91	303.18	241.17	226.43
Weighted Avg. (8 operations)	267.91	284.14*	229.23*	226.43

Same Frutteto II 85 exhibits a higher weighted average SFC slightly exceeding 300 g/kWh, so the highest fuel consumption among the tractors evaluated. In contrast, the Goldoni E100 tractor demonstrates the lowest consumption, with a recorded SFC of approximately 225 g/kWh. However, it is crucial to consider that the analysis for this tractor, as well as for the Kubota M5091, omitted two operations, thus rendering the comparison not entirely equivalent. The second most efficient tractor regarding fuel consumption is the Same Argon 70, with a measured SFC of about 240 g/kWh. This model accounts for emissions across all 10 planned operations, thereby making its consumption data fully comparable with the highest consuming tractor.

To assess whether the omission of two outlier SFC values for Kubota M5091 and Goldoni E100 tractors significantly influenced the ranking of specific consumption among the tractors, a weighted average calculation for the remaining 8 operations was also conducted for the other tractors. The analysis confirmed that, despite the exclusion of outliers, the tractor with the lowest SFC is still Goldoni E100, followed by the Same

Argon 70 and then the Kubota M5091. Concurrently, the model with the highest SFC, Same Frutteto II 85, is reaffirmed.

By considering the calorific value of diesel fuel, it was possible to compute the tractor's efficiency in various operational conditions based on the SFC values.

$$Efficiency, \% = \frac{85}{SFC} \times 100$$

For each specific fuel consumption (SFC) value, efficiency was calculated, and the results, including minimum and maximum values, were documented. The highest efficiency levels among the models varied from 33% to 36.5%. Although these percentages are not particularly high, it is important to remember that the optimal efficiency of a diesel agricultural engine operating under ideal conditions is at present approximately 43%. Consequently, the results obtained are deemed valid and reliable. A comparative analysis of the values across different operations facilitated the examination of the standard deviation and the weighted average of efficiencies.

Table 35 – Calculated efficiency based on SFC values

Field operation	Efficiency, %			
	Kubota M5091	Same Frutteto II 85	Same Argon 70	Goldoni E100
P. R. shredding	32.2	33.9	34.5	33.1
PPP spraying	31.6	29.3	35.8	35.6
Fertilising (M/O)	32.1	27.1	35.7	36.1
Pre-pruning	--	21.8	34.8	--
Grass shredding	30.5	28.1	35.0	35.4
(C/M) weeding	24.8	24.9	34.3	36.5
Sucking	--	21.8	34.8	--
Topping	24.8	24.9	34.3	36.5
Defoliation	31.6	31.9	34.8	36.5
G. harvesting	32.9	32.4	33.3	35.5
Std deviation	3.3	4.3	0.7	1.1
Avg.	29.7	27.0	34.7	35.6
Weighted Avg.	31.7*	28.0	35.2	37.5*

The standard deviation underscores that the two tractors characterized by lower specific fuel consumption exhibit efficiencies with minimal variability among their values. In contrast, Kubota M5091 and Same Frutteto II 85 show greater variability in

efficiency. When examining the values of weighted efficiency, which is derived from specific fuel consumption data, the analysis corroborates the highest efficiency in Goldoni E100 tractor, followed by Same Argon 70, Kubota M5091, and ultimately, Same Frutteto II 85. This assessment aligns the efficiency metrics closely with the specific consumption profiles, providing a consistent basis for evaluating the operational effectiveness of each tractor model under varying agricultural conditions.

6.1.9. SFC efficiency colour tag

To enhance the comprehension and analytical process of Specific Fuel Consumption (SFC) for each operation, a colour-coding system based on a traffic light logic was implemented for each value. Seven distinct classes (A-G) were formulated, which were then aggregated into three colour codes: green for consumptions up to 239 g/kWh, yellow for consumptions ranging from 240 to 259 g/kWh, and red for consumptions equal to or exceeding 260 g/kWh. This methodological approach allows for a more intuitive visualization and assessment of fuel efficiency across various operational settings.

Tag	SFC, g/kWh	Colour tag
A	220-229	Green
B	230-239	
C	240-249	Yellow
D	250-259	
E	260-269	Red
F	270-279	
G	280-289	

Figure 51 – SFC values for different tags (A-G) and colour tag (traffic light colour logic)

When applying colour codes to the various specific fuel consumption (SFC) values identified for different operations, the resulting visualization facilitates an immediate understanding. The tractors with the lowest specific fuel consumptions are readily identifiable by the green colour, while those with the highest consumptions are marked

in red. This colour-coding effectively underscores the performance disparities between the different tractor models under evaluation.

Table 36 – Traffic light colour logic applied to SFC values of vineyard tasks

Field operation	SFC, g/kWh			
	Kubota M5091	Same Frutteto II 85	Same Argon 70	Goldoni E100
P. R. shredding	264.36	250.61	246.39	256.76
PPP spraying	269.03	290.19	237.72	238.91
Fertilising (M/O)	264.58	313.81	238.05	235.18
Pre-pruning	Out of scale	389.43	244.26	Out of scale
Grass shredding	278.58	302.54	242.66	240.12
(C/M) weeding	342.17	341.24	247.84	232.59
Sucking	Out of scale	389.43	244.26	Out of scale
Topping	342.17	341.24	247.84	232.59
Defoliation	269.13	266.68	244.49	233.17
G. harvesting	258.36	262.21	255.60	239.63
Weighted Avg.	267.91*	303.18	241.17	226.43*
Colour class	E	G	C	A

Applying the traffic-light colour coding logic to the weighted Specific Fuel Consumption (SFC) allows for the classification of the 4 tractors into different categories.

This visual methodology facilitates immediate identification of the tractors' fuel efficiency levels. The Goldoni E100 and, to a lesser extent, the Same Argon 70 are classified as the most fuel-efficient, corresponding to categories A and C respectively. Conversely, the Kubota M5091 and the Same Frutteto II 85 exhibit higher SFC values, with the latter surpassing the thresholds set for category G. This classification underscores the variability in fuel efficiency among the tractors analysed.

6.2. 2nd Pillar

The 2nd pillar of the study focuses on assessing the real emissions of gaseous pollutants from tractor engines under specific running conditions. Similar to the methodology used in the 1st pillar, these conditions are simulated at a stationary point, employing engine performance curves to establish the effective engine speed values for each agricultural operation. This comprehensive analysis encompasses several agricultural sectors: open-field agriculture, which is further divided into cereal production and forage crop cultivation, as well as orchard and vineyard management. For each defined scenario, emissions measurements were conducted using a tractor model specifically selected for its suitability of usage with the environmental and operating requirements of that scenario.

The measurements conducted at each running point within the various production chains were recorded in terms of both concentration (mg/m^3) and energy efficiency (g/kWh). This latter metric was selected to facilitate comparisons between the observed values and the emission stage limits established in the relevant Standards.

It is acknowledged that the limit values for the different stages are determined under specific running conditions and, as such, do not directly correlate with limits measured under varying working conditions.

However, employing this comparative framework enhances the interpretability of the results.

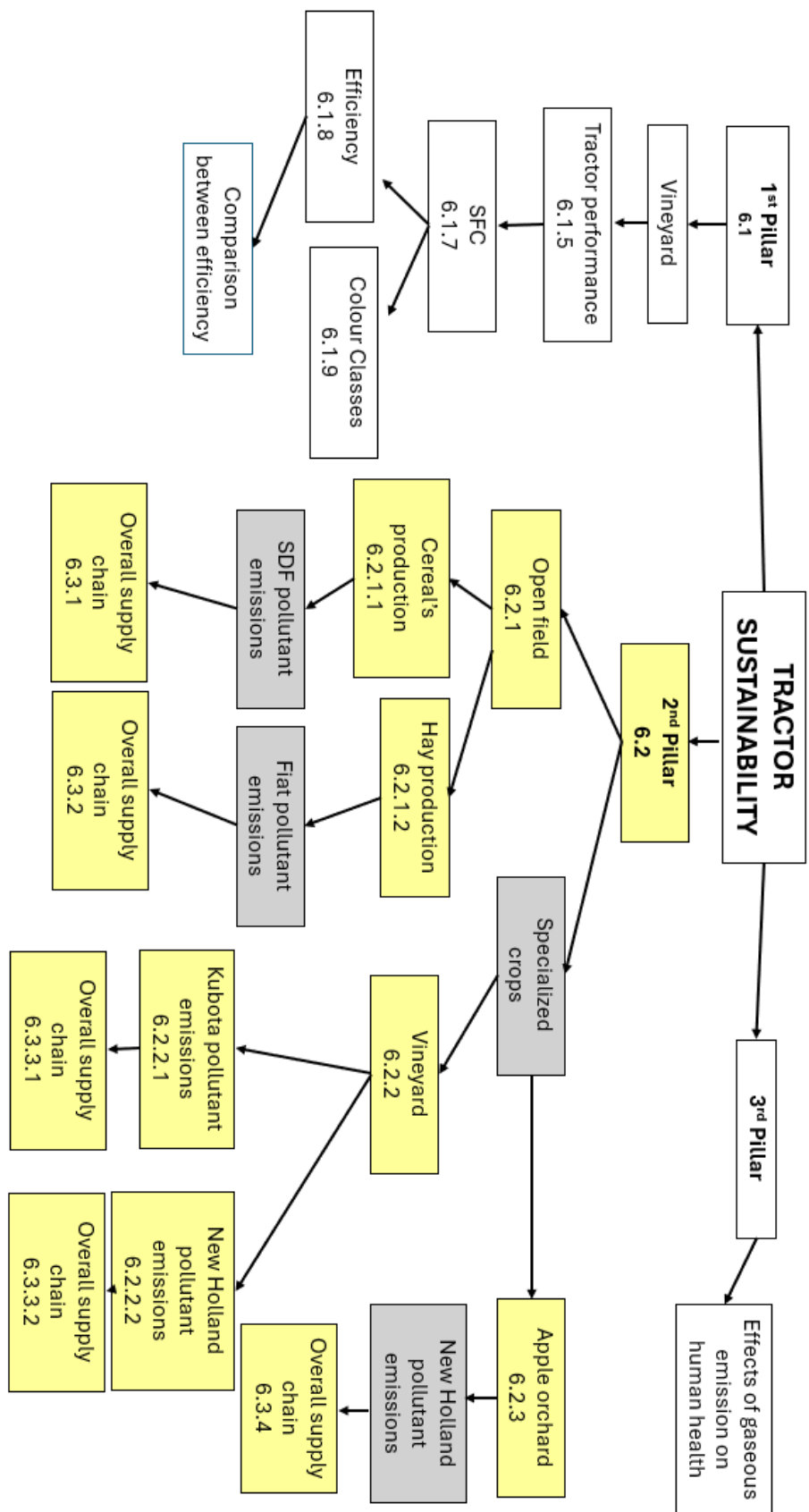


Figure 52 – 2nd Pillar


6.2.1. Open Field Agriculture Chain

For the analysis of open-field agriculture chains, two tractors having different ages were employed, both used in the university experimental farm “Cascina Baciocca” located at Cornaredo (MI – Italy). These tractors differ in power, architectural design, transmission systems, maintenance histories, and notably, age.

6.2.1.1. Cereal Production – Maize

To assess the emissions of pollutants in the maize cultivation scenario, a Deutz Fahr Agrofarm 430 tractor was selected as the reference model, with the specified features in the tab. 37.

Table 37 - Deutz Fahr Agrofarm 430 characteristics

Model	Features	Image
Deutz Fahr Agrofarm 430	Power: 85 kW Transmission: Power shift 4 WD Architecture: open field Hours of work: 1200	

In this study, focused on the scenario of open-field maize cultivation, the subject of analysis was a Deutz Fahr tractor with a nominal power output of 115 CV, featured of a conventional architecture and four-wheel drive system. A full load power curve was generated to obtain the engine's performance characteristics. The power delivered to the Power Take-Off (PTO) was approximately 80 kW, with the maximum power achieved between 2000 and 2100 min^{-1} . The maximum torque curve displayed an increase until the maximum value at around 1550 min^{-1} .

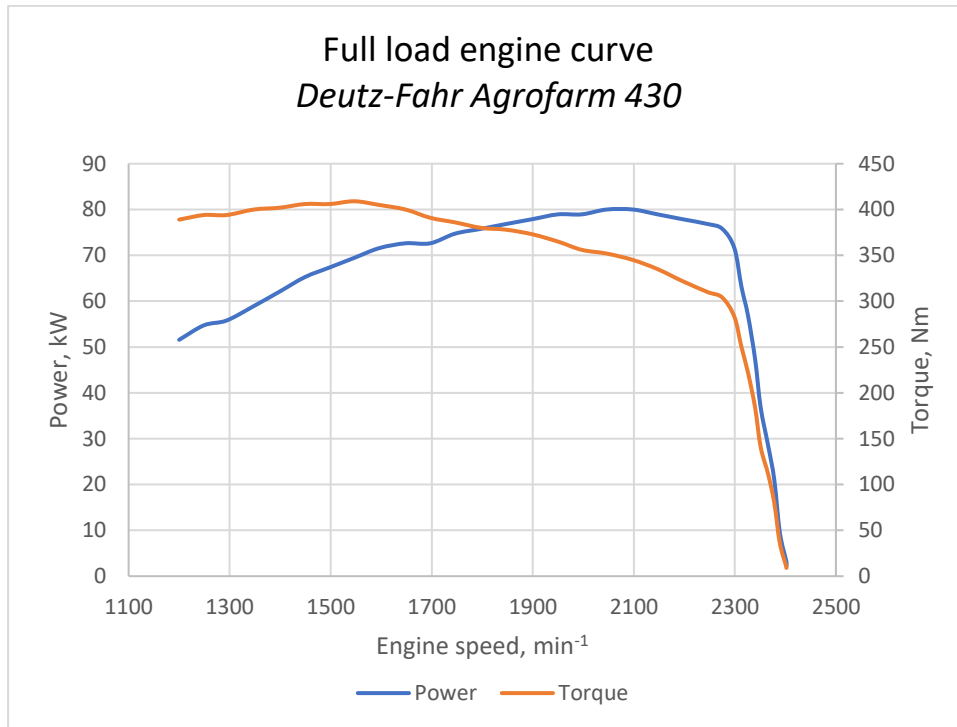


Figure 53 – Full load engine curve; Deutz Fahr Agrofarm 430

More engine curves were generated for each level of power modulation to ascertain specific and representative running points for each agricultural operation. Following the methodology used in the 1st pillar, for each operation, the defined initial engine speed, the engine speed under load (and then the speed decrease), and the power output at each specific running point were identified. Within the cereal production chain, seven key operations were determined, and their operational parameters were systematically documented in the subsequent table.

Table 38 – Running points for cereal production chain

Field operation	Engine speed	Engine speed under load	Engine Power
	Min ⁻¹		kW
Ploughing	1800	1740	66.3
Harrowing	1600	1538	60.0
Seeding	1200	1186	33.7
Fertilization	1300	1292	60.0
Mech. weeding	1500	1472	65.3
Irrigation	1500	1474	64.2
Maize transport	1200	1186	60.0

Although the maximum power curve was obtained at 2400 min⁻¹, the operations envisaged in this scenario do not require high power levels. As a result, engine speeds are adjusted between 1800 and 1200 min⁻¹, with corresponding power outputs ranging from 33 to 65 kW. For each running point, emissions of the primary diesel pollutants were accurately measured using the anemometer (Trotec TA400) and two specialized gas analysers (Testo 338 and Testo 350). The collected data included measurements of the gas flow rate and pollutant concentrations (reporting to one decimal place), in accordance with the chosen methodological framework of the study.

Table 39 – Instrumental data of gaseous pollutant emitted and flow rates

Tasks	Power	Flow	CO	HC	NOx	PM
	kW	m ³ /h	mg/m ³			
Ploughing	66.3	418.8	267.0	1083.0	1412.4	34.6
Harrowing	60.0	236.4	429.0	1830.0	1368.6	23.5
Seeding	33.7	111.0	485.0	2290.0	1402.8	41.8
Fertilization	60.0	208.2	405.0	1411.0	1377.3	29.0
Mech. weeding	65.3	330.6	282.0	978.0	1374.1	19.6
Irrigation	64.2	357.0	257.0	1394.0	1471.0	20.2
Maize transport	60.0	208.2	405.0	1411.0	1377.3	29.0

To facilitate the usability and comparability of the measured values across different operational conditions with the reference limits set by homologation standards (in this case, Stage IIIA), the flow measurements were converted to m³/h and the pollutant concentrations were recalculated into g/kWh, taking into consideration the power delivered during various operations.

Table 40 – Calculated values of gaseous pollutant emitted

Tasks	CO	HC	NOx	PM
	g/kWh			
Ploughing	1.69	6.84	8.92	0.22
Harrowing	1.69	7.21	5.39	0.09
Seeding	1.60	7.55	4.62	0.14
Fertilization	1.41	4.90	4.78	0.10
Mech. weeding	1.43	4.95	6.96	0.10
Irrigation	1.43	7.75	8.18	0.11
Maize transport	1.41	4.90	4.78	0.10
Std deviation	0.13	1.32	1.78	0.04

Upon comparing the emission values calculated for each operational scenario, the standard deviation of different pollutants was analysed. This analysis showed that the levels of carbon monoxide (CO) and particulate matter (PM) were remarkably consistent across various operations, despite differing running conditions. The deviations in these measurements nearly approached zero. In contrast, hydrocarbons (HC) presented a standard deviation of 1.32, and nitrogen oxides (NOx) exhibited a standard deviation of 1.78.

These findings were subsequently individually compared with the thresholds stipulated by the reference emission stage (Stage IIIA). Stage IIIA, distinct from other stages, required a joint measurement of HC and NOx. This necessitated the consolidation of previously separate values to enable a direct comparison. To streamline this comparison process, a system of colour-coded labels using traffic light logic was introduced, as outlined in the table below, aligning with the tractor's specified emission stage certification.

Stage	CO	HC	NOx	PM
<i>g/kWh</i>				
1	6.5	1.3	9.2	0.85
2	5	1.3	7	0.4
3a	5	4		0.3
3b	5	0.19	3.3	0.025
4	5	0.19	0.4	0.025
5	5	0.19	0.4	0.015

Figure 54 – Traffic light colour logic applied to reference stage limits for engine powers between 75 kW and 130 kW

Table 41 – Traffic light colour logic applied to Deutz Fahr Agrofarm 430 tractor: open field – cereal production (in accordance with tractor stage 3A)

	CO	NOx+HC	PM
<i>g/kWh</i>			
Ploughing	1.7	15.8	0.2
Harrowing	1.7	12.6	0.1
Seeding	1.6	12.2	0.1
Fertilization	1.4	9.7	0.1
Mech. weeding	1.4	11.9	0.1
Irrigation	1.4	15.9	0.1
Maize transport	1.4	9.7	0.1

Upon comparing the obtained values with various emission thresholds, it was determined that for the open field production chain, specifically maize cultivation using the Deutz Fahr Agrofarm 430 tractor, the carbon monoxide (CO) levels were significantly lower than those specified by Stage IIIA, closely aligning with the more severe Stage V standards. The particulate matter (PM) levels were found to be in full compliance with the emission stage. However, the combined measurements of nitrogen oxides (NOx) and hydrocarbons (HC) exceeded the prescribed limits, surpassing even those set by Stage I.

Applying the same analytical methodology to the individual values of nitrogen oxides (NOx) and hydrocarbons (HC) would provide further insights:

Table 42 - Traffic light colour logic applied to Deutz Fahr Agrofarm 430 tractor: open field – cereal production (NOx and HC as separated values)


	CO	HC	NOx	PM
<i>g/kWh</i>				
Ploughing	1.7	6.8	8.9	0.2
Harrowing	1.7	7.2	5.4	0.1
Seeding	1.6	7.5	4.6	0.1
Fertilization	1.4	4.9	4.8	0.1
Mech. weeding	1.4	5.0	7.0	0.1
Irrigation	1.4	7.8	8.2	0.1
Maize transport	1.4	4.9	4.8	0.1

In this analysis, while the measured values of nitrogen oxides (NOx) and hydrocarbons (HC) remain elevated, it is observed that the NOx values generally comply with Stage II standards, except for those recorded during ploughing and irrigation, which meet Stage I standards. On the other hand, the HC values even exceed the limits prescribed by Stage I. This pattern suggests that the disproportionately high emissions of HC are the primary contributors to the exceedance of combined NOx+HC limits as documented in Figure 54.

6.2.1.2. Hay Production

The forage sector often involves operations that require minimal power for operating machinery. As a result, it is common to employ tractors with low power or even older models. The use of older tractors is justified by the low power demands of these operations, which can be sufficiently met by less efficient machines. Importantly, this practice significantly impacts the environment due to the absence of pollution control regulations for tractors manufactured before 1996. In this specific case, a tractor over 40 years old was chosen for analysis. Such tractors, characterized by their quite old design and age, are still widely used in Italy for operations that require minimal power.

Table 43 Fiat Agri 70-90 characteristics

Model	Features	Image
Fiat Agri 70-90	Power: 37 kW Transmission: Mechanical 2 WD Architecture: open field Hours of work:: 1400 h	

The maximum power, occurring within the full-load curve at 2200 min^{-1} , is nearly reached between 1850 min^{-1} and 2050 min^{-1} , where it attains 37 kW. After this plateau, as expected it declines to around 700 min^{-1} . Although this engine does not deliver high power, its stable power output across a range of engine speeds makes it well-suited for less demanding operations. On the other hand, the torque curve continues to rise until it reaches its maximum at 800 min^{-1} .

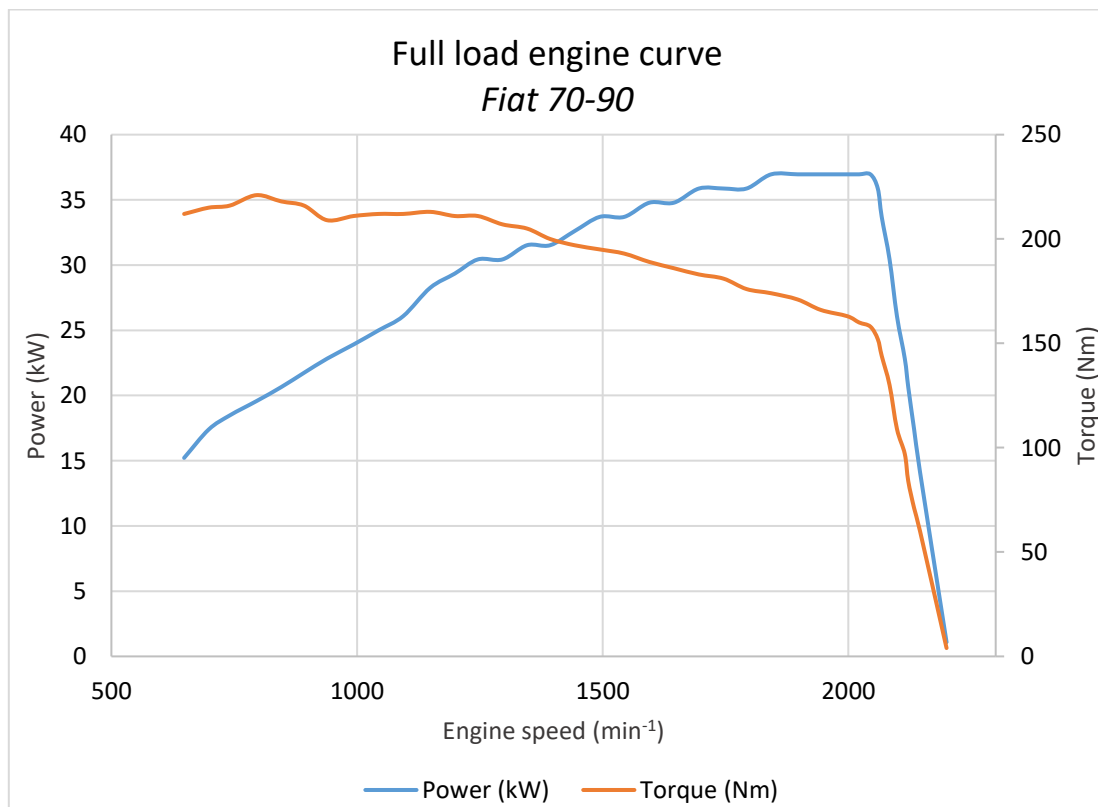


Figure 55 - Full load engine curve; Fiat 70-90

In line with the analyses conducted on other tractors, eleven typical operations within the hay production sector were identified. Operating conditions were determined at various power settings, involving engine speeds ranging from 1200 to 1700 min⁻¹. As expected, the application of these diverse running points resulted in significantly reduced usable power outputs, with the lowest reaching 4 kW only.

Table 44 - Running points for hay making production chain

Field operation	Engine speed	Engine speed under load	Power
	min ⁻¹		kW
Seeding	1300	1200	7.2
PPP Spraying (boom)	1300	1250	4.3
Fertilization	1400	1350	4.6
Grass mowing	1600	1400	14.4
Grass conditioning	1700	1400	29.3
Pick-up carriage	1400	1350	4.6
Hay racking	1250	1200	4.0
Baling	1700	1450	25.8
Wrapping	1700	1400	29.3
Shredding	1500	1300	12.9
Bale transportation (farm road)	1200	1100	7.5

Alternatively, two operations, specifically bale making and bale wrapping, were identified as the most energy-demanding within the forage production chain, requiring power outputs fairly close to 30 kW, at 25.8 kW and 29.3 kW respectively. For each running point, measurements were taken of the exhaust gas flow rates and the primary gaseous pollutants emitted by the diesel engines.

Table 45 - Instrumental data of gaseous pollutant emitted and flow rates

Operation	Power	Gas Flow	CO	HC	PM	NOx
	kW	m ³ /h	mg/ m ³			
Seeding	7.2	159	2143	1047	1.6	1827.1
PPP Spraying (boom)	4.3	160.8	2418	2342	1.97	1609.4
Fertilization	4.6	165	3172	3243	1.15	1572.0
Grass mowing	14.4	148.8	1363	1907	4.01	1913.6
Grass conditioning	29.3	148.8	3819	1496	78.8	2225.7
Pick-up carriage	4.6	165	3172	3243	1.15	1572.0
Hay racking	4.0	151.2	2177	2923	2.75	1664.0
Baling	25.8	133.2	1112	1404	72	2979.8
Wrapping	29.3	148.8	3819	1496	78.8	2225.7
Shredding	12.9	140.4	1234	2852	4.16	2149.4
Bale transportation (farm road)	7.5	156	1433	3880	3.03	2308.6

Although the Fiat Agri 70-90 tractor dates back to before 1996 and therefore does not comply with pollution regulations, the recorded values were nonetheless converted into g/kWh to enable a consistent comparison with other tested models and corresponding emission thresholds.

Table 46 - Calculated values of gaseous pollutant emitted

Tasks	CO	HC	NO _x	PM
	g/kWh			
Seeding	47.60	23.25	40.58	0.04
PPP Spraying (boom)	90.88	88.03	60.49	0.07
Fertilization	113.97	116.52	56.48	0.04
Grass mowing	14.06	19.67	19.74	0.04
Grass conditioning	19.40	7.60	11.31	0.40
Pick-up carriage	113.97	116.52	56.48	0.04
Hay racking	81.89	109.96	62.60	0.10
Baling	5.74	7.25	15.38	0.37
Wrapping	19.40	7.60	11.31	0.40
Shredding	13.45	31.09	23.43	0.05
Bale transportation (farm road)	29.87	80.89	48.13	0.06
Std. deviation	42.12	46.85	20.91	0.16

Analysing the standard deviation values reveals a significant contrast to the findings in the cereal production chain; emission levels in this instance exhibit substantial variability, with the exception of particulate matter (PM) which maintains values close to zero. Carbon monoxide (CO) and hydrocarbons (HC) demonstrate considerable variation, with standard deviations exceeding 42 g/kWh and 46 g/kWh, respectively. Employing colour-coded labels based on a traffic-light logic, as implemented in the cereal chain analysis, facilitates a clear visualization of emission behaviours of various agricultural operations.

The application of the traffic-light coding system to this tractor within the forage production chain yielded unexpected results. Despite the levels of nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC) being considerably high and thus labelled with a dark red colour to indicate surpassing Stage I limits, the particulate matter (PM) values did not conform to this pattern.

Table 47 - Traffic light colour logic applied to Fiat Agri 70-90; open field – hay production

Task	CO	HC	NOx	PM
<i>g/kWh</i>				
Seeding	47.60	23.25	40.58	0.04
PPP Spraying (boom)	90.88	88.03	60.49	0.07
Fertilization	113.97	116.52	56.48	0.04
Grass mowing	14.06	19.67	19.74	0.04
Grass conditioning	19.40	7.60	11.31	0.40
Pick-up carriage	113.97	116.52	56.48	0.04
Hay racking	81.89	109.96	62.60	0.10
Baling	5.74	7.25	15.38	0.37
Wrapping	19.40	7.60	11.31	0.40
Shredding	13.45	31.09	23.43	0.05
Bale transportation (farm road)	29.87	80.89	48.13	0.06

In contrast to the CO, NOx, and HC values, which are consistent with those of a non-emissioned tractor (i.e. tractor built before 1996, when the first anti-pollution regulations came into force) such as the Fiat 70-90, the PM values are relatively low, thereby complying with Stage IIIA limits. Although the PM values recorded by the instrument (mg/m³) might initially appear excessively high, they are significantly reduced when analysed in terms of g/kWh. This reduction allows them to meet the limits established by certain homologation standards, attributable to the provision of a relatively high power output in relation to the tractor's maximum capacity.

6.2.2. Vineyard


Italy's landscape is exceptionally well-suited for fruit cultivation, particularly in the northern regions where vineyards and apple orchards are the most prevalent.

The subsequent sections will explore two case studies involving distinct wine grape cultivations.

6.2.2.1. Kubota M5101

For the initial vineyard scenario, a narrow-track, 4WD tractor was chosen. This machine, loaned from a Kubota dealership, was certified to Stage IV emissions standards and had accumulated a negligible amount of working hours.

Table 48 – Kubota M5101 characteristics

Model	Features	Image
Kubota M5101	Power: 70 kW Transmission: Power shift 4 WD Architecture: narrow track tractor Hours of work: 100 h	

The maximum power value was recorded at 2290 min^{-1} , reaching nearly 70 kW. Beyond this peak, the power curve demonstrates a consistent downward trend. In contrast, the torque curve mirrors this pattern up to the torque value at maximum power, after which it continues to increase, reaching its maximum at 1500 min^{-1} .

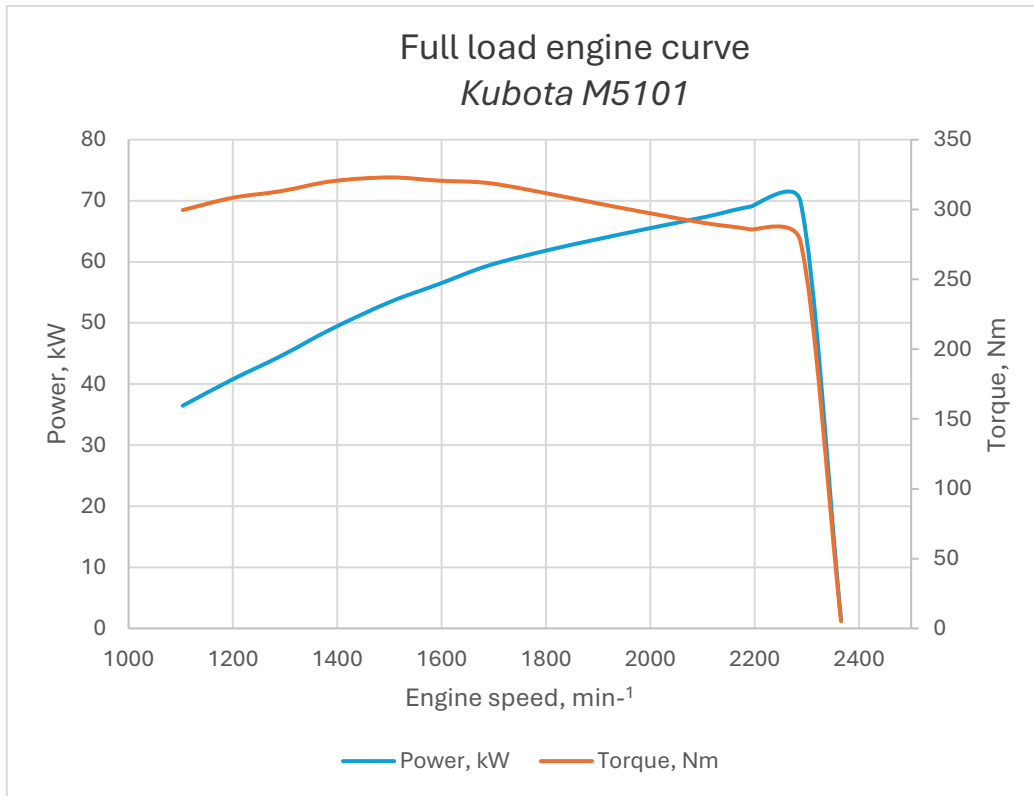


Figure 56 - Full load engine curve; Kubota M5101

For this production chain, 7 operations have been identified, encompassing activities ranging from soil cultivation to vine row management and various treatments.

Table 49 - - Running points for vineyard production chain

Field operation	Engine speed	Engine speed under load	Power
	min ⁻¹		kW
Harrowing	2350	2200	69.0
P.R. Shredding	2100	1900	62.9
Hoeing	1900	1800	33.8
G. Harvesting	1900	1750	47.0
Pruning/Topping	1700	1600	29.8
PPP Spraying	1700	1550	40.4
M. fertilizing	1500	1400	24.0

Table 50 Instrumental data of gaseous pollutant emitted and flow rates

Field operation	Power	Gas flow	CO	HC	NOx	PM
	kW	m ³ /h	mg/ m ³			
Harrowing	69.0	435	3	86	958.4	0.00
P.R. Shredding	62.9	414	0	34	976.6	0.00
Hoeing	33.8	312	0	33	934.2	0.04
G. Harvesting	47.0	366	0	79	999.7	0.04
Pruning/Topping	29.8	276	0	186	1034.6	0.04
PPP Spraying	40.4	312	0	214	1116.6	0.12
M. fertilizing	24.0	234	0	54	980.1	0

From the analysis of the table, it is evident that the CO and PM levels are significantly reduced, a result attributed to the tractor being equipped with a Diesel Particulate Filter (DPF).

On the other hand, the HC and NOx values are found to be particularly elevated for an engine homologated to Stage IV. The most significant data are the NOx values.

Table 51 - Calculated values of gaseous pollutant emitted

Field operation	CO	HC	NOx	PM
	g/kWh			
Harrowing	0.02	0.54	6.04	0.00
P.R. Shredding	0.00	0.22	6.43	0.00
Hoeing	0.00	0.30	8.62	0.00
G. Harvesting	0.00	0.62	7.78	0.00
Pruning/Topping	0.00	1.72	9.58	0.00
PPP Spraying	0.00	1.65	8.62	0.00
M. fertilizing	0.00	0.49	8.82	0.00
Std deviation	0.01	3.08	1.31	0.00

The collected data demonstrate that the diesel particulate filter (DPF) installed on the tractor operates with full efficiency, effectively eliminating all particulate matter (PM) generated by combustion, as indicated by the zero values. This high level of performance is also attributed to the very short operational lifespan of the engine installed on the tractor.

Further analysis of the standard deviation values among pollutant groups reveals that CO and PM values show negligible deviations, effectively zero. In contrast, NOx displays a standard deviation of 1.31, indicating some variability. More concerning are the HC values, which demonstrate considerable variability with a standard deviation of 3.08, markedly higher compared to other pollutants.

By applying colour-coded labels based on traffic light logic to the emission values, obtained from the vineyard production chain and comparing these with legislative benchmarks for different emission stages, it can be ascertained that the PM and CO levels comply with Stage V standards under the specified usage conditions. While the HC values show significant variability, all but the last measurement meet Stage IIIA requirements, with some nearing Stage IIIB compliance. Conversely, the NOx levels are substantially higher, with two out of six operations conforming to Stage II limits, four operations meeting Stage I standards, and one value exceeding the scale altogether.

Table 52 - Traffic light colour logic applied to Fiat Agri 70-90; specialized crops- vineyard


Tasks	CO	HC	NOx	PM
	<i>g/kWh</i>			
Harrowing	0.02	0.54	6.04	0.00
P.R. Shredding	0.0	0.22	6.43	0.00
Hoeing	0.0	0.30	8.62	0.00
G. Harvesting	0.0	0.62	7.78	0.00
Pruning/Topping	0.0	1.72	9.58	0.00
PPP Spraying	0.0	1.65	8.62	0.00
M. fertilizing	0.0	8.82	8.82	0.00

6.2.2.2. New Holland TN70V

The second scenario in the vineyard production chain featured the evaluation of a New Holland TN70V narrow-track tractor. This scenario was devised by taking into account a range of operations, some of which are closely related and typically challenging to

conduct in the same vineyard setting. The purpose was to examine the widest possible array of vineyard management practices.

Table 53 – New Holland TN70V characteristics

Model	Features	Image
New holland TN70V	<p>Power: 53 kW</p> <p>Transmission: Mechanical</p> <p>4 WD</p> <p>Architecture: narrow-track tractor</p> <p>Hours of work: 2600</p>	

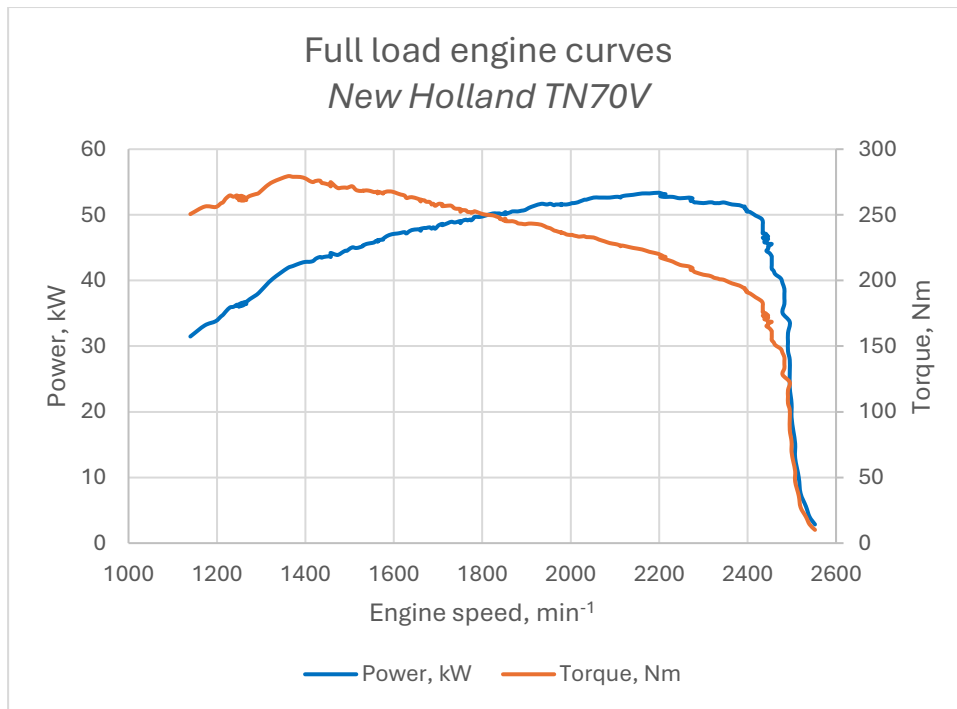


Figure 57 - Full load engine curve; New Holland TN70V

As previously mentioned, this scenario encompassed 16 distinct operations that cover the full spectrum of possible tasks within the vineyard. To facilitate the replication of

each task at a fixed running point, several power settings were designed, with power curves ranging from 1200 to 2100 min⁻¹.

Despite the diversity of the operations, the power levels designated for each running point are relatively low, with only two operations necessitating a power output exceeding 15 kW.

Table 54 - Running points for vineyard production chain (mechanical harvesting)

Field operation	Engine speed	Engine speed under load	Power
	min ⁻¹		kW
Harrowing	2100	1950	21.06
PPP Spraying 2	2000	1750	31.38
Hoeing	1900	1750	14.26
P.R. Shredding	1800	1650	13.83
G. Harvesting	1800	1700	11.38
G. Shredding	1700	1600	10.32
PPP Spraying. 1	1700	1550	12.13
G. Transport	1600	1550	5.96
Topping	1500	1450	4.89
Defoliation/ Pruning	1500	1400	7.66
O. Fertilization	1500	1350	10.53
Sucking	1300	1250	4.57
M. Fertilization	1300	1200	7.23
Pre-pruning	1300	1250	4.57
Ridging	1300	1200	7.23
M. Weeding	1200	1150	5.00

Table 55 - Instrumental data of gaseous pollutant emitted and flow rates

Field operation	Power	Gas Flow	HC	CO	NOx	PM
	kW	m ³ /h	mg/m ³			
Harrowing	21.06	528.60	832.00	492.00	1882.00	3.79
PPP Spraying 2	31.38	272.40	1516.00	231.00	2187.00	8.31
Hoeing	14.26	264.60	2782.00	467.00	1873.00	2.31
P.R. Shredding	13.83	246.60	3527.00	850.00	1934.00	2.93
G. Harvesting	11.38	253.80	3631.00	950.00	1993.00	3.16
G. Shredding	10.32	234.60	3769.00	1066.00	2064.00	3.36
PPP Spraying. 1	12.13	208.80	3499.00	972.00	2075.00	2.61
G. Transport	5.96	220.20	4834.00	1746.00	1923.00	3.12
Topping	4.89	187.80	5829.00	2332.00	1925.00	2.28
Defoliation/ Pruning	7.66	194.40	4624.00	178.00	1937.00	3.18
O. Fertilization	10.53	165.00	3871.00	1355.00	2057.00	3.16
Sucking	4.57	165.00	5579.00	2195.00	2065.00	2.42
M. Fertilization	7.23	132.60	4227.00	1264.00	2178.00	3.35
Pre-pruning	4.57	165.00	5579.00	2195.00	2065.00	2.42
Ridging	7.23	132.60	4227.00	1264.00	2178.00	3.35
M. Weeding	5.00	134.40	4709.00	1359.00	2182.00	3.53

Upon acquiring and converting all emission values relative to the power output in g/kWh, the standard deviation for each pollutant was evaluated. It was observed that only the particulate matter (PM) values were below 1 g/kWh, whereas all other pollutant values were significantly higher, ranging in the tens and, for hydrocarbons (HC), even in the hundreds. The standard deviation values mirror this pattern, with PM displaying a near-zero standard deviation. Conversely, nitrogen oxides (NOx) and carbon monoxide (CO) exhibited standard deviations below 30, and HC showed a notably higher standard deviation close to 70, indicating it as the most pervasive pollutant emitted by this engine.

Table 56 - Calculated values of gaseous pollutant emitted

Field operation	CO	HC	NO _x	PM
	g/kWh			
Harrowing	12.35	20.88	47.23	0.10
PPP Spraying 2	2.01	13.16	18.98	0.07
Hoeing	8.67	51.64	34.77	0.04
P.R. Shredding	15.16	62.89	34.49	0.05
G. Harvesting	21.18	80.96	44.44	0.07
G. Shredding	24.23	85.69	46.92	0.08
PPP Spraying. 1	16.73	60.24	35.72	0.04
G. Transport	64.54	178.67	71.08	0.12
Topping	89.49	223.70	73.87	0.09
Defoliation/ Pruning	4.52	117.36	49.16	0.08
O. Fertilization	21.23	60.65	32.23	0.05
Sucking	79.17	201.23	74.48	0.09
M. Fertilization	23.17	77.48	39.92	0.06
Pre-pruning	79.17	201.23	74.48	0.09
Ridging	23.17	77.48	39.92	0.06
M. Weeding	36.53	126.58	58.65	0.09
Std. deviation	28.73	65.89	17.24	0.02

The tractor under discussion was certified according to Stage IIIA standards, which entail the combined measurement of nitrogen oxides (NO_x) and hydrocarbons (HC). To objectively and consistently evaluate the emission limits in line with regulatory requirements, colour-coded labels were applied to the aggregated values of HC and NO_x.

Table 57 - Traffic light colour logic applied to New Holland TN70V; specialized crops- vineyard (mechanical harvesting; in accordance with tractor stage 3A)

Field operation	CO	HC	PM
	g/kWh		
Harrowing	12.35	68.11	0.10
PPP Spraying 2	2.01	32.14	0.07
Hoeing	8.67	86.41	0.04
P.R. Shredding	15.16	97.38	0.05
G. Harvesting	21.18	125.40	0.07
G. Shredding	24.23	132.61	0.08
PPP Spraying. 1	16.73	95.96	0.04
G. Transport	64.54	249.75	0.12
Topping	89.49	297.57	0.09
Defoliation/ Pruning	4.52	166.52	0.08
O. Fertilization	21.23	92.88	0.05
Sucking	79.17	275.71	0.09
M. Fertilization	23.17	117.40	0.06
Pre-Pruning	79.17	275.71	0.09
Ridging	23.17	117.40	0.06
M. Weeding	36.53	185.23	0.09

The combined measurements of hydrocarbons (HC) and nitrogen oxides (NOx) resulted in exceptionally high values, prompting the need for individual analysis of each pollutant. Despite this approach, the levels recorded were substantially higher than any prescribed emission limits.

Table 58 - Traffic light colour logic applied to New Holland TN70V; specialized crops- vineyard (mechanical harvesting)


Field operation	CO	HC	NOx	PM
	g/kWh			
Harrowing	12.35	20.88	47.23	0.10
PPP Spraying 2	2.01	13.16	18.98	0.07
Hoeing	8.67	51.64	34.77	0.04
P.R. shredding	15.16	62.89	34.49	0.05
G. Harvesting	21.18	80.96	44.44	0.07
G. Shredding	24.23	85.69	46.92	0.08
PPP spraying. 1	16.73	60.24	35.72	0.04
G. transport	64.54	178.67	71.08	0.12
Topping	89.49	223.70	73.87	0.09
Defoliation/ Pruning	4.52	117.36	49.16	0.08
O. fertilization	21.23	60.65	32.23	0.05
Sucking	79.17	201.23	74.48	0.09
M. fertilization	23.17	77.48	39.92	0.06
Pre-pruning	79.17	201.23	74.48	0.09
Ridging	23.17	77.48	39.92	0.06
M. weeding	36.53	126.58	58.65	0.09

The high values observed can be attributed both to the elevated concentrations of emitted pollutants and to the low power settings applied during various operations. It is hypothesized that increasing the power allocated to these operations, which serves as the denominator in the emission conversion formula, could lead to a reduction in pollutant emissions.

6.2.3. Orchard chain – Apple

The apple production exhibits several similarities to the viticulture scenario. A key commonality is the requirement for machines to be compact thanks to a narrow track width, to properly travel between rows. To examine the operations typical of this scenario, the University of Bolzano collaborated to investigate the main activities involved in apple production in Trentino Alto Adige. These activities were subsequently replicated in lab using a dynamometer linked to a 70 CV New Holland tractor (New Holland TN70V).

Table 59 - New Holland TN70V characteristics

Model	Features	Image
New holland TN70V	Power: 53 kW Transmission: Mechanical 4 WD Architecture: narrow-track tractor Hours of work:2600	

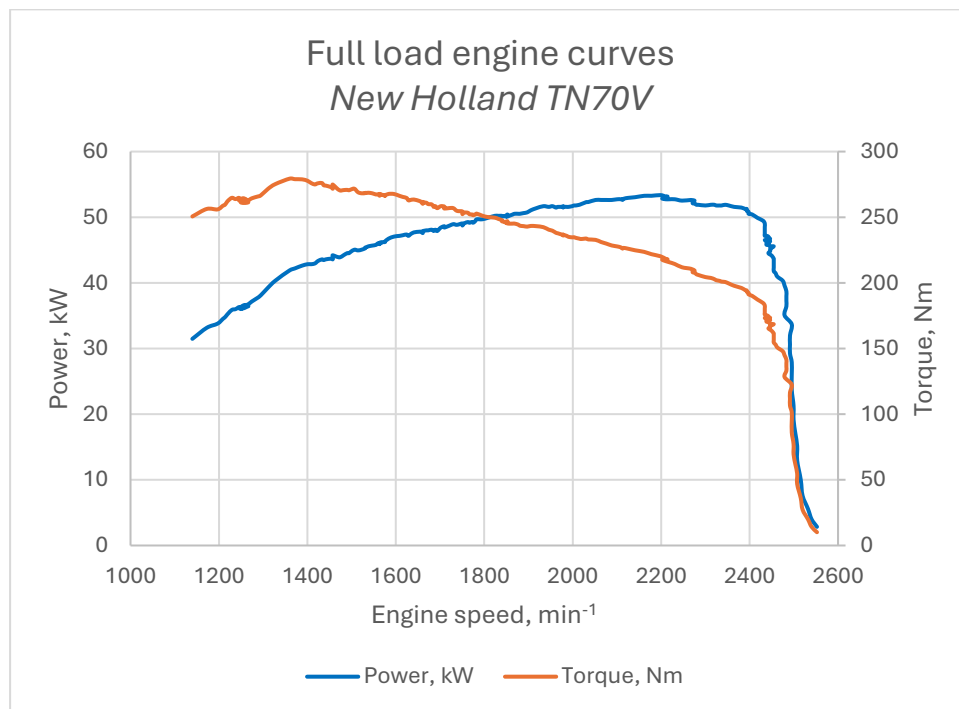


Figure 58- Full load engine curve; New Holland TN70V

According to statements provided by farmers in this region, operations are conducted at very low engine speeds, around 1500 min⁻¹. In this context, a factor that can significantly impact these operations is the slope.

Mountainous topography can impact tractor performance, with operations potentially occurring either along contour lines or on steep gradients. When working along contour lines in both directions, there is no significant variation in power demand,

though careful attention must be given to the stability of the machine. Conversely, on steep gradients, the power requirements differ markedly between ascending and descending slopes.

The planned operations and their corresponding power requirements at a fixed location are as follows:

Table 60 - Running points for apple orchard production chain

Task	Nominal engine speed	Engine speed under load	Power
	min ⁻¹		kW
PPP spraying	1500	1300	17.2
Apple transport	2200	1700	48.9
Grass shredding	1500	1350	12.7
Pruning residues shredding	1500	1300	17.2
Chemical weeding	electric		--
Organic fertilization	1400	1350	6.0
Chemical fertilization	1300	1250	6.5
Soil management	1500	1100	26.5
Pruning	Hand pruning		--
Thinning wood cutting	electric		--

The engine speeds characteristic of this scenario consistently exhibits relatively low values, ranging between 1300 min⁻¹ and 1500 min⁻¹, with the exception of the engine speed required for transporting bins on public roads, which necessitates an engine speed of 2200 min⁻¹. Despite this apparent uniformity, the available power values display considerable variability, ranging from a minimum of 6 kW to a maximum of 48.9 kW. Furthermore, for comprehensive coverage, three additional tasks (chemical weeding, pruning, and wood cutting) are concurrently listed. These tasks do not entail the tractor serving as a power source but are instead performed manually or with the aid of electrical equipment.

Table 61 - Instrumental data of gaseous pollutant emitted and flow rates

Field operation	Power	Gas Flow	CO	HC	NOx	PM
	kW	m ³ /h	mg/m ³			
PPP spraying	17.2	84.0	141.0	1426	758.0	6.88
Apple transportation	48.9	306.0	312.0	1183	1706.0	43.45
Grass shredding	12.7	78.0	98.0	1176	606.0	4.13
Pruning residues shredding	17.2	84.0	141.0	1471	758.0	6.88
Organic fertilization	6.0	162.0	397.0	788	406.0	3.59
Chemical fertilization	6.5	126.0	305.0	745	384.0	3.56
Soil management	26.5	276.0	2179.0	1537	792.0	131.61

Analysing the instrumental data acquired, it is notable to compare the levels of NOx and PM emissions between the apple transportation and soil management operations. Despite these operations being conducted under markedly different working conditions, they consistently produced the highest emissions. The disparity in emission levels between these operations stems from variations in pollutant ratios, specifically NOx and PM. In the context of apple transportation, elevated NOx levels are observed, indicative of heightened combustion chamber temperatures, alongside increased PM emissions attributed to engine strain.

In contrast, soil management operations exhibit relatively consistent NOx levels compared to other metrics, suggesting minimal engine stress and consequently, moderate combustion chamber temperatures. However, notable increases in PM emissions (the maximum observed in the scenario) imply inefficient fuel combustion, likely resulting from substantial reductions in engine revolutions.

Upon converting the obtained values to adhere to the units of measurement prescribed by current regulations and assessing their standard deviation, it becomes apparent that CO emissions display the most significant fluctuations.

Table 62 - Calculated values of gaseous pollutant emitted

Field operation	CO	HC	NOx	PM
	mg/m ³			
PPP spraying	0.69	7.35	3.71	0.03
Apple transport	1.95	7.78	10.67	0.27
Grass shredding	0.60	7.58	3.71	0.03
Pruning residues shredding	0.69	7.58	3.71	0.03
Organic fertilization	10.72	22.39	10.96	0.10
Chemical fertilization	5.89	15.15	7.41	0.07
Soil management	22.67	16.83	8.24	1.37
<i>Std. deviation</i>	<i>8.19</i>	<i>6.05</i>	<i>3.25</i>	<i>0.49</i>

These exhibit a standard deviation of over 8 g/kWh, with a sample wherein the maximum and minimum are 22.67 g/kWh and 0.60 g/kWh, respectively.

The engine of the tractor examined was certified according to Stage IIIA standards, which involve the combined measurement of nitrogen oxides (NOx) and hydrocarbons (HC). To ensure an objective and consistent assessment of emission limits in compliance with regulatory mandates, colour-coded labels were affixed to the combined values of HC and NOx.

Table 63 - Traffic light colour logic applied to New Holland TN70V; specialized crops- apple orchard

Field operation	CO	HC	NOx	PM
	g/kWh			
PPP spraying	0.69	7.35	3.71	0.03
Apple transport	1.95	7.78	10.67	0.27
Grass shredding	0.60	7.58	3.71	0.03
Pruning residues shredding	0.69	7.58	3.71	0.03
Organic fertilization	10.72	22.39	10.96	0.10
Chemical fertilization	5.89	15.15	7.41	0.07
Soil management	22.67	16.83	8.24	1.37

The various operations performed in the apple orchard result in emissions that are quantitatively varied.

More in detail, the NO_x values include levels that could be associated with Stage 3A; similarly for PM, except for the soil management tasks.

However, the CO values appear to be significantly more optimistic, however quite bad, even proposing 4 values suitable for Stage 5.

6.3. Impact on the Environment of Tractor Use in the Production Chain Investigated

The analyses conducted within the 2nd pillar have provided only a point-in-time snapshot of the pollutants produced.

To achieve a more comprehensive understanding, the objective was to estimate the amount of emissions released into the environment over an entire growing season by different tractors across various production chains. So, the tractors previously analysed were imagined as working in the production chains considered, to evaluate their yearly environmental impact.

Table 64 - Assignment of the most realistic operating chain for each analysed tractor

Productive chain	Tractor considered for the analysis
Maize production	Deutz Fahr Agrofarm 430
Hay production	Fiat 70-90
Vineyard (mechanical harvesting)	Kubota M5101
Vineyard (hand harvesting)	New Holland TN70V
Apple orchard	New Holland TN70V

To achieve this goal, certain farm sizes were estimated to represent a sort of standard for the northern Italian regions. Each hypothetical farm was characterized according to specific operations, which were identified with the aim of adapting them to the local conditions. Specifically, farms with areas of 10 ha, 20 and 50 ha were considered.

All production chains include the most common operations that are deemed representative of the operational reality and the prevalence of these practices in the region.

6.3.1. Open Field-Maize Production

Compared to those for other crops, in northern Italy farms dedicated to maize cultivation generally encompass larger areas. For the purposes of this study, a hypothetical maize grain production farm was assumed to have an area of 50 ha.

To ensure uniformity, it was assumed that fields were distributed around the farm/collection centre, within a radius of approximately 400 m. This scenario considered the most prevalent operations in the region, conducted using tractors (excluding self-propelled machines) for soil tillage, sowing, weeding, emergency irrigation and transportation of the harvested material to the farm centre.

Table 65 – Intensity of use in cereal production, maize

Open field, maize							
	Working length	Working speed	Working frequency	Working capacity	Surface on hour	Use intensity	
Field operation	m	km/h	time/year	h/ha	ha/h	h/year	%
Ploughing	1.2	3.51	1	0.84	1.19	42	4.0
Harrowing	3	8.78	1	2.10	0.48	105	0.09
Seeding	3	3.76	1	0.90	1.11	45	0.04
Fertilization	6	22.57	3	1.80	0.56	270	0.23
Mech. weeding	3	11.29	3	0.90	1.11	135	0.11
Maize collection (field)	6	15.05	1	3.60	0.28	180	0.15
	surface	-	water depth	working capacity			-
	ha	-	m	h/ha			-
Irrigation	1	34.82	0.05	8.33	0.12	417	0.35
	average distance	-	transport per year	yield	trailer size		-
	m	-	time/year	t/ha	t		-
Maize transport	400	0.22	100	12	6.0	3	0.00
Total						1196	100.00

As a consequence, the total emissions produced by the Deutz-Fahr Agrofarm 430 employed in this scenario were calculated: over 450 kg/year of NO_x and HC, more than 105 kg/year of CO, and 8 kg/year of PM.

Table 66 – Gaseous pollutant emitted in kg/year in open field, cereal production, maize

Field operation	Intensity of use	flow	CO	HC	NOX	PM
	h/year	m ³ /h	kg/year			
Ploughing	42	418.8	4.7	19.0	24.8	0.6
Harrowing	105	236.4	10.6	45.4	34.0	0.6
Seeding	45	111.0	2.4	11.4	7.0	0.2
Fertilization	270	208.2	22.8	79.3	77.4	1.6
Mech. weeding	135	330.6	12.6	43.6	61.3	0.9
Maize harvesting (field)	180	208.2	15.2	52.9	51.6	1.1
Irrigation	417	357.0	38.2	207.3	218.7	3.0
Maize transport	2,67	208.2	0.2	0.8	0.8	0.0
		Total	106.7	459.8	475.7	8.0

6.3.2. Open field- hay production

The production of forage holds significant importance in agricultural operations, providing basic feed for animal husbandry. It is a widely practiced activity, also contributing to biodiversity preservation, encompassing both plant and animal species. For this scenario, a theoretical farm covering of 20 ha was considered. Following a methodology similar to that employed for the maize production chain, a square distribution of the plots was considered, with approximately 450 m in length, as well as an average distance between the farm and the plots of 250-300 m.

Table 67 - Intensity of use in hay production

Open field- Haymaking							
Field operation	Working length	Working speed	Working frequency	Working capacity	Surface on hour	Use intensity	
	m	km/h	time/year	h/ha	ha/h	h/year	%
Seeding	8.00	5.00	1.00	4.00	0.25	80.00	19.40
Fertilization	8.00	5.00	2.00	4.00	0.25	160.00	38.81
Grass mowing	2.50	3.00	2.00	0.75	1.33	30.00	7.28
Grass conditioning	2.50	3.00	1.00	0.75	1.33	15.00	3.64
Pick-up carriage	2.00	2.50	0.50	0.50	2.00	5.00	1.21
Hay racking	4.00	7.00	1.00	2.80	0.36	56.00	13.58
Baling	2.00	3.00	2.50	0.60	1.67	30.00	7.28
Wrapping	2.00	3.00	1.00	0.60	1.67	12.00	2.91
	average distance	working speed	transport per year	yield	trail dimension		
	m	km/h	time/year	t/ha	t		
Bale transportation (farm road)	270.00	10.00	90.00	9.00	6.00	24.30	5.89
Total						412.30	100.00

As previously mentioned, in Italy, it is not uncommon for light production chains, such as haymaking, to utilize underpowered or particularly outdated tractors. For this specific production chain, to assess the production's annual impact using an old, non-emission-compliant tractor (Fiat 70-90) were taken into account.

Table 68 - Gaseous pollutant emitted in kg/year in open field, Hay production

Field operation	Intensity of use	Gas Flow	CO	HC	NOx	PM
	h/year	m ³ /h	kg/year			
Seeding	80.00	159	27.26	13.32	23.24	0.02
Fertilization	160.00	165	83.74	85.62	41.50	0.03
Grass mowing	30.00	148.8	6.08	8.51	8.54	0.02
Grass conditioning	15.00	148.8	8.52	3.34	4.97	0.18
Pick-up carriage	5.00	165	262	2.68	1.30	0.00
Hay racking	56.00	151.2	18.43	24.75	14.09	0.02
Baling	30.00	133.2	4.44	5.61	11.91	0.29
Wrapping	12.00	148.8	6.82	2.67	3.97	0.14
Bale transportation (farm road)	24.30	156	5.43	14.71	8.75	0.01
Total			163.35	161.20	118.27	0.71

Despite the tractor's remarkable age, a comparison of the obtained values with those of the previous production chain (although they entail different uses) reveals relatively lower emissions. Only slightly higher values are observed for HC and CO, just above 160 kg/year. In contrast, emissions of the "typical pollutants of diesel engines," namely NOx, are less than 120 kg/year, with PM emissions below 1 kg/year.

6.3.3. Specialized crops - Vineyard

The production of wine grapes is one of the primary agricultural activities in Italy and is among the most profitable. This cultivation involves various operations tailored to the specific needs of the crops and the cultivation areas.

Indeed, two vineyards of identical size may be cultivated using remarkable different techniques and levels of mechanization. One significant difference lies in grape harvesting. While self-propelled or towed machines are available for mechanized harvesting, in certain areas, this practice is not feasible due to land constraints (often caused by steep slopes and/or narrow row spacing) or regulatory requirements. In the latter case, specific regulations are provided for the production of particular types of wine, particularly concerning the harvesting method, to ensure adherence and qualify for designation under a specific production region.

6.3.3.1. Vineyard - mechanical harvesting

For this scenario of the vineyard production chain, an area of approximately 10 ha was considered. In this scenario, the level of mechanization is minimal and involves managing the inter-row and row spaces. Although the level of mechanization is not excessive, mechanized harvesting of the grape has been considered. For this reason, it is conceivable to position the plots in the Oltrepò Pavese area (Pavia province), one of the few areas in northern Italy (Lombardy) where mechanized harvesting of grapes is allowed. By analysing the frequency of usage and the working width of various machinery, it was possible to estimate a tractor usage of around 200 hours/year.

Table 69 - Intensity of use in vineyard, mechanical harvesting

Specialized crop - vineyard							
Field operation	Working length	Working speed	Working frequency	Working capacity	Surface on hour	Use intensity	
		km/h	Time/year	h/ha	ha/h	h/year	%
P.R. Shredding	Row	2.5	1.0	0.6	1.6	6.3	3.2
Hoeing	Row	3.0	1.0	0.8	1.3	7.5	3.9
G. Harvesting	Row	3	1	0.75	1.3	7.5	3.9
Pruning/Toppping	Row	4.0	1.0	1.0	1.0	10.0	5.2
PPP Spraying	Row	5.0	12.0	1.3	0.8	150.0	77.4
M. fertilizing	Row	5.0	1.0	1.3	0.8	12.5	6.5
Total						193.8	100.0

Applying this scenario to the Kubota M5101 tractor and hypothesizing the emissions generated by the tractor within the farm setting, it was feasible to estimate the quantity of pollutants emitted over a year of operation. Analysis of the data indicates that this tractor demonstrates commendable performance, exhibiting minimal levels of CO and PM emissions and reduced levels of HC. Among the four primary pollutants associated with internal combustion engines, NO_x is the only one with a relatively higher value, approximately 65 kg/year.

Table 70 - Gaseous pollutant emitted in kg/year in specialised crops, vineyard, mechanical harvesting

Field operation	Intensity of use	Gas flow	CO	HC	NOx	PM
	<i>h/year</i>	<i>m³/h</i>	<i>kg/ year</i>			
P.R. Shredding	6.25	414	0.00	0.09	2.53	0.00
Hoeing	7.5	312	0.00	0.08	2.19	0.00
G. Harvesting	7.5	366	0.00	0.22	2.74	0.00
Pruning/Topping	10	276	0.00	0.51	2.86	0.00
PPP Spraying	150	312	0.00	10.02	52.26	0.01
M. fertilizing	12.5	234	0.00	0.16	2.87	0.00
Total			0.00	11.07	65.44	0.01

6.3.3.2. Vineyard - manual harvesting

In Italy, many vineyards, constrained by production protocols, cannot employ mechanized harvesting. While this limitation enhances grape quality and diminishes the likelihood of crushed grapes from bunches squeezed in harvesters' hoppers, it results in a significant rise in labour requirements and, consequently, costs. For this particular production chain, a scenario of a vineyard employing manual harvesting was taken into account.

Within this production chain, various mechanized operations have been envisioned, spanning from inter-row management to treatments, and onward to the transfer of grapes to the farm centre. Similarly to the previous condition, a total farm area of 10 ha, with the farm buildings located centrally in respect to the plots has been assumed. Consequently, transportation is presumed to occur via inter-farm roads for the transfer of grapes from the field to the centre.

An overall commitment of approximately 300 h/year has been estimated, with 50% allocated to PPP treatments, for 150 h/year.

Table 71 - Intensity of use in vineyard, manual harvesting

Specialized crop- vineyard							
Field operation	Working length	Working speed	Working frequency	Working capacity	Surface on hour	Intensity of use	
		Km/h	Time/year	h/ha	ha/h	h/year	%
Hoeing	Row	3.0	1.0	0.8	1.3	7.5	2.5
P.R. shredding	Row	2.5	1.0	0.6	1.6	6.3	2.1
G. Shredding	Inter-row	5.0	3.0	1.3	0.8	37.5	12.6
PPP spraying. 1	Row	5.0	12.0	1.3	0.8	150.0	50.2
Topping	Row	7.0	1.0	1.8	0.6	17.5	5.9
Defoliation / Pruning	Row	4.0	1.0	1.0	1.0	10.0	3.3
O. fertilization	Row	5.0	1.0	1.3	0.8	12.5	4.2
Sucking	Row	3.0	1.0	0.8	1.3	7.5	2.5
M. fertilization	Row	5.0	1.0	1.3	0.8	12.5	4.2
M. weeding	Row	3.5	3.0	0.9	1.1	26.3	8.8
	Average distance	Working speed	Transport per year	Yield	Trail dimension		
	m	km/h	time/year	t/ha	t		
G. transport	350.0	10.0	31.7	9.5	6.0	5.5	1.9
Total						293.0	100

By correlating the annual frequency of usage with emissions measured in laboratory (on New holland TN70V tractor) settings under various operational conditions, it was feasible to estimate the amount of pollutants released into the atmosphere during the execution of this production chain. The data revealed that over the course of a year, the vineyard production chain with manual harvesting would produce approximately 0.2 kg of PM, over 60 kg of CO, and a substantial 120 kg of NOx. However, for this particular tractor, the predominant emission appears to be HC due to the high temperatures in the combustion chamber, amounting to over 200 kg/year.

Table 72 - Gaseous pollutant emitted in kg/year in specialised crops, vineyard, manual harvesting

Field operation	Intensity of use	Gas Flow	CO	HC	NOx	PM
	<i>h/year</i>	<i>m³/h</i>	<i>kg/year</i>			
Hoeing	7.5	264.6	0.9	5.5	3.7	0.0
P.R. shredding	6.3	246.6	1.3	5.4	3.0	0.0
G. Shredding	37.5	234.6	9.4	33.2	18.2	0.1
PPP spraying	150.0	208.8	30.4	109.6	65.0	0.1
Topping	17.5	220.2	6.7	18.6	7.4	0.0
Defoliation/ Pruning	10.0	187.8	4.4	10.9	3.6	0.0
O. fertilization	12.5	194.4	0.4	11.2	4.7	0.0
Sucking	7.5	165	1.7	4.8	2.5	0.0
M. fertilization	12.5	165	4.5	11.5	4.3	0.0
M. weeding	26.3	132.6	4.4	14.7	7.6	0.0
G. transport	5.5	134.4	1.0	3.5	1.6	0.0
Total			65.2	229.0	121.6	0.2

6.3.4. Specialized crop - Apple orchard

Among the widely practiced agricultural activities in Northern Italy, apple cultivation stands out, particularly in the northern regions. The techniques employed in apple orchards closely resemble those used in vineyards in terms of equipment and intervention frequency. Primarily, this involves row and inter-row management and PPP spraying to ensure suitable product protection. For this production chain, an estimated commitment of over 850 hours per year has been calculated, to be distributed across a farm area of 10 ha. Similarly to the previous scenario, a farm with all plots located around the centre was assumed. Consequently, product transportation is limited to travelling between the plot and the farm centre.

Table 73 - Intensity of use in apple orchard

Specialized crop- apple orchard							
Field operation	Working length	Working speed	Working frequency	Working capacity	Surface on hour	Intensity of use	
		km/h	time/year	h/ha	ha/h	h/year	%
PPP spraying	Row	5	10	1.25	0.80	125	14.66
Grass shredding	Row	5	3	1.25	0.80	37.5	4.40
Pruning residues shredding	Row	3	1	0.75	1.33	7.5	0.88
Organic fertilization	Inter-row	5	1	1.25	0.80	12.5	1.47
Chemical fertilization	Row	5	1	1.25	0.80	12.5	1.47
Soil management	Row	3	1	0.75	1.33	7.5	0.88
	average distance	working speed	transport per year	yield	trailer gross mass		
	m	km/h	time/year	t/ha	t		
Apple transport	350	15	1	65	6.00	650	76.25
Total						852.5	100.00

The total workload of 852.5 hours/year, applied to the New Holland TN70V tractor, was estimated by considering various tasks, among which transportation of the apples to the farm centre emerges as the most polluting. This was due to the high productivity of the apple orchard and the limited size of the trailer, which was chosen for compatibility with the tractor's towing capacity.

Table 74 - Gaseous pollutant emitted in kg/year in specialised crops, orchard, apple

Field operation	Intensity of use	Gas Flow	NOx	HC	CO	PM
	h/year	m ³ /h	kg/year			
PPP spraying	125	84	7.96	15.0	1.48	0.07
Grass shredding	37.5	78	1.77	3.5	0.29	0.01
Pruning residues shredding	7.5	84	0.48	0.7	0.09	0.00
Organic fertilization	12.5	162	0.82	3.0	0.80	0.01
Chemical fertilization	12.5	126	0.60	1.2	0.48	0.01
oil management	7.5	276	1.64	1.5	4.51	0.27
Apple transport	650	306	339.32	305.7	62.06	8.64
Total			352.60	330.7	69.71	9.02

By interpolating the tractor's annual usage data across various operating conditions with the emissions values measured at fixed points, it was possible to compute and subsequently estimate the quantity of pollutants emitted into the atmosphere by this production chain. Notably, among the pollutants generated, PM emissions reached 9.02 kg/year, surpassing those of all other production chains, while NOx emissions exceeded 350 kg/year.

6.4. Overall Production Chains

Although the production chains differ significantly in terms of crop produced, the tractors used for scenario simulation, the number of operations, and the hourly commitment, a general comparison concerning the analysis of the total emission values in kg/year was attempted.

Despite requiring a higher hourly commitment, approximately 1200 hours/year, the "maize production" scenario yielded the highest emission values for both HC and NOx. Conversely, the highest values for CO and PM were observed in the "forage production" and "apple production" production chains, respectively.

Notably, it was evident that the lowest pollutant values were all derived from the scenario with the lowest hourly commitment. Specifically, scenario no. 3, representing the minimally mechanized vineyard, entailed an hourly commitment of less than 200 hours per year, emitting the least amount of pollutants among all production chains.

Table 75 – Comparison of the amounts of pollutants emitted during a growing season across different production chains

n.	Productive chain	usage	CO	HC	NOx	PM
		<i>h/year</i>	<i>kg/year</i>			
1	Maize production	1196.17	106.7	459.8	475.7	8.0
2	Hay production	412.30	163.35	161.20	118.27	0.71
3	Vineyard (mechanical harvesting)	193.8	0.00	11.07	65.44	0.01
4	Vineyard (hand harvesting)	293.0	65.21	229.0	121.6	0.2
5	Apple orchard	852.5	69.71	330.7	352.60	9.02

6.5. 3rd Pillar

The third pillar upon which this thesis is based concerns the detailed analysis of the impacts of pollutant emissions on the health of workers exposed in occupational settings.

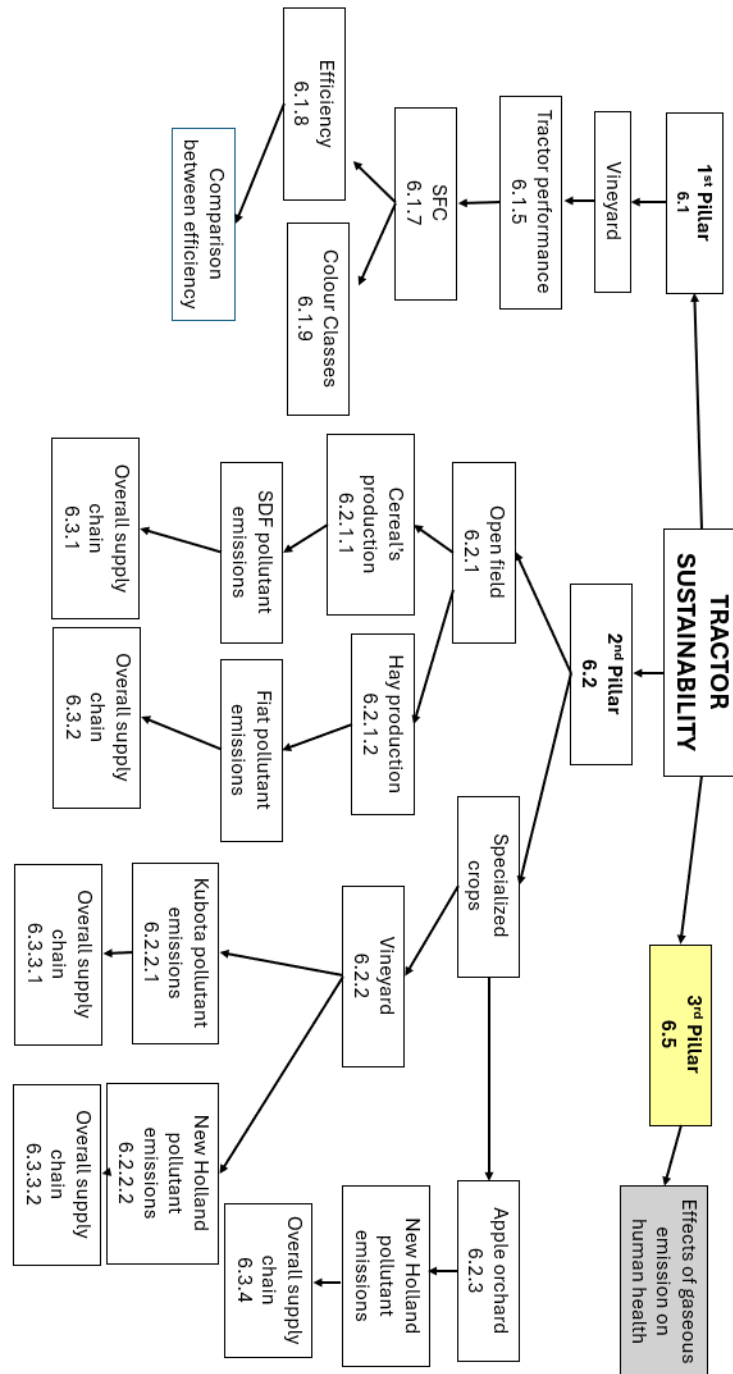


Figure 59 – 3rd Pillar

It is well-established, both in the scientific literature and public opinion, that environmental pollutants, particularly fine particulate matter (PM), pose a significant and tangible risk to human health (Ayodhya A.S & Narayanappa K.G. 2018). Regulatory standards already exist to evaluate air quality in high-traffic environments, such as urban and industrial areas (Bie P. et al. 2023). However, in Italy, there is a notable regulatory gap concerning specific exposure limits designed to ensure the safety of workers who are exposed to exhaust gases over extended periods, especially in occupational settings where exposure is continuous and may occur in enclosed or poorly ventilated environments (Hart J.E. et al. 2012).

It is crucial to recognize that certain professional categories, such as those in agriculture or logistics, are particularly vulnerable to these risks. These roles often involve prolonged exposure, throughout the entire work shift, to pollutants emitted by internal combustion engines, especially those powered by diesel, which are known to be more polluting than other types of engines (Debia M. et al. 2016). Despite growing awareness of the associated risks, the lack of specific regulations to protect these workers stays a significant concern.

In recent decades, a substantial body of scientific research has been conducted to understand the multifaceted harmful effects that atmospheric pollutants can exert on human health, both directly and indirectly. Direct effects include all physiological alterations and diseases resulting from the inhalation or immediate contact with pollutants. These effects range from minor irritations of the upper respiratory tract to more severe conditions such as chronic bronchitis and lung cancer (Lloyd A.C. & Cackette T.A. 2001; Taxell P. & Santonen T. 2017; Debia M. et al. 2016; Costa L.G. et al. 2020; Guo B & Ba Q. 2023). Furthermore, a significant link has been highlighted between prolonged exposure to diesel engine emissions, particularly fine particulate matter and polycyclic aromatic hydrocarbons (PAHs), and the development of pulmonary diseases, whether malignant or not (Connellan S.J. 2017).

Simultaneously, considering the indirect effects of gaseous pollutants, which are largely responsible for global climate change, is essential. This phenomenon has induced significant modifications in ecosystems, altering precipitation patterns and ecological balances, and has contributed to the emergence of new diseases and zoonoses (Louis S. et al. 2023). These environmental changes have a profound and

complex impact on human health, showing that the effects of pollutants are not limited to immediate and direct impacts but extend over the long term.

In addition to distinguishing between direct and indirect effects, it is crucial to consider the impacts in relation to the frequency and duration of exposure. Both occasional and prolonged exposure can be harmful to health, though in different ways, leading to acute and/or chronic diseases. Recent studies have shown that exposure to atmospheric pollutants can significantly increase sensitivity to allergenic substances, raising the risk of asthma, allergic rhinitis, and other forms of allergies, particularly in healthy individuals, or worsening the condition of those already suffering from such pathologies. Children growing up in highly trafficked urban areas are especially vulnerable, showing a greater predisposition to developing allergic diseases (Sydbom A et al. 2001). These disorders are often associated with acute symptoms such as rhinitis, ocular and nasal irritations, persistent coughing, and, in some cases, dermatological alterations such as atopic dermatitis (Heinrich J & Wichmann H.E. 2004; Takano H. & Inoue K.I. 2017).

These conditions can be further aggravated by pre-existing health issues or activities that induce more stress, such as smoking (Velavanidis A et al. 2013) or working in highly exposed environments (Ferguson J.M. et al. 2020). Beyond respiratory complications, atmospheric pollutants also pose significant potential risks to the cardiovascular system. It has been found that pollutants can alter the structure and function of certain cells, limiting their essential physiological capabilities (Lloyd A.C. & rCackette T.A. 2001; Taxell P. & Santonen T. 2017; Costa L.G. et al. 2019; Lawal A.O. et al. 2016; Ghio A.J. et al. 2012; Costa L.G. et al. 2020). In various studies, incidents of cardiac arrhythmias have been documented during and after exposure to high concentrations of atmospheric pollutants, alongside thrombotic effects and microvascular and renal diseases (Langrish J.P. et al. 2012; Robertson S. & Miller M.R. 2018; Li F.R. et al. 2022).

In addition to more common and widespread disorders, research has also begun to explore other areas of impact related to atmospheric pollutants, such as fertility and neurodevelopmental disorders. Specifically, some studies have suggested a correlation between fetal exposure to specific pollutants during pregnancy and the onset of neurodevelopmental disorders in newborns (Costa L.G. et al. 2019; Costa L.G. et al.

2020). Furthermore, studies have been started to investigate a possible relationship between increased concentrations of atmospheric pollutants and the incidence of neurodegenerative diseases such as Alzheimer's and Parkinson's (Garrick J.M. et al. 2023; Hullmann M. et al. 2017; Murata H. et al. 2022; Costa L.G. et al. 2020; Guo B. & Ba Q. 2023). These preliminary studies show that air pollution may also play a significant role in the development of these complex pathologies, opening new avenues for future research.

In light of this scientific evidence, it becomes clear that there is a pressing need for more stringent regulations to protect workers exposed to atmospheric pollutants, especially in sectors such as agriculture and industry, where the use of diesel engines is still prevalent. It would be advisable to conduct specific studies capable of defining safe exposure limits, which could then be translated into regulations aimed at safeguarding the health of workers in the workplace (both indoors and outdoors) by minimizing their exposure to pollutants.

In a broader context, existing anti-pollution regulations, both for on-road and off-road vehicles, have undoubtedly provided significant environmental benefits by drastically reducing emission levels. However, in a continuous improvement perspective, it is imperative to further develop sustainable technologies that can further reduce the impact of vehicles and industrial activities on the environment and ecosystems. In conclusion, scientific research and technological innovation should advance hand in hand to ensure a safer and more sustainable future for the environment and public health, with particular attention to workers who are most exposed.

Although all operations conducted in this study occur outdoors, leading to a reduced accumulation of pollutants compared to enclosed environments, it is essential to assess the potential risks. Specifically, while the risk of inhalation of gaseous pollutants may be mitigated in tractors equipped with cabs, this cannot be said for those lacking such features. Often, these vehicles have horizontal exhaust outlets positioned at hood height or on the structural protection pillar. In these instances, the direction of the exhaust gases is influenced by external factors, including the placement of the exhaust outlet and prevailing wind conditions. To achieve comprehensive and unambiguous results, it is advisable to conduct measurements near the operator's position, particularly at the inhalation point.

7. Conclusion

The study focused on a range of representative tractors, each reflecting different levels of usage and technical advancement within the Italian machinery fleet, specific to their respective operational contexts.

In line with the overall objectives of the research, this approach yielded substantial and meaningful results, providing valuable insights that can guide the adoption of more sustainable practices in the use of self-propelled machinery in agriculture

7.1. 1st Pillar: Improving Tractor Efficiency

The first pillar of the study involved an analysis of 4 specialized tractors used in viticulture, one of the most important sectors in the Italian agricultural sector. These tractors, characterized by a narrow-track architecture to manoeuvre effectively in confined spaces (both at the headlands and between rows), generally exhibited a significant over-dimensioning relative to the actual needs of the production chain. The agricultural implements used in vineyards are often small and, in most cases, do not require high power output for their operation. This results in low operational efficiency, with several negative environmental and economic consequences.

Specific fuel consumption (and thus engine efficiency) was calculated for a series of operations, varying in power demands. Ten operations were considered, including many with low power requirements, such as pre-pruning, topping and suckering, while only a few, like mechanical harvesting and mulching of grass and pruning residues, were more demanding.

Each of these operations was defined based on the power requirements necessary for the operation of the agricultural equipment involved. The results revealed significant variability in operational efficiency, ranging from just over 20% for light tasks to a maximum of 36.6% for more demanding operations.

The four tractors tested had engine power ranging from 70 to 100 CV, placing them in the middle-upper range for the segment considered. For the Same Frutteto II 85, Kubota M5091 and Goldoni E100, the engine performance curves (at full throttle) displayed a classic pattern, in contrast to the Same Argon 70, which exhibited a "flat"

power curve, a modern solution that resulted in very good efficiency, despite the model's lower maximum power compared to the other 3 models analysed.

Notably, the tractor with the most efficient engine was the Goldoni E100, which, despite its considerable maximum power of 100 CV (not always utilized efficiently), stood out with an average specific fuel consumption of only 226 g/kWh in the scenario considered.

As expected, tractor efficiency is generally highly influenced by operating conditions. Therefore, a thorough analysis of operational needs prior to purchase could benefit farmers (in this case, viticulture farmers) in terms of purchase costs, maintenance and, most importantly, sustainability. Unfortunately, even today, the final purchasing decision often depends on factors other than those discussed. Farmers frequently prefer more powerful and unnecessarily accessorized tractors rather than those precisely tailored to their needs. In essence, energy and environmental sustainability are not yet given the importance they should have in the selection of new machinery.

It would be advisable for the relevant legislative bodies to take a more active role in promoting the sustainability of agricultural machinery. Agriculture is a sector that has long relied heavily on funding, incentives and subsidies; this support should continue, perhaps with greater intensity than before, to facilitate the renewal of the machinery fleet with a focus not only on sustainability but also on operator safety and environmental protection.

Legislative promotion (especially economic and financial incentives) or even mandates for a robust shift in this direction could prove effective, rather than leaving the matter to individual actions driven solely by personal awareness. Recent examples of this approach have been implemented in South Korea, Spain and Turkey, where parameters have been established to assign efficiency classes to different models of newly marketed tractors, thereby promoting the sale of more environmentally friendly models.

7.2. 2nd Pillar: Pollutant Gaseous Emissions

Since the introduction of the first regulations in 1996, which imposed progressively stricter limits on pollutant emissions from engines installed in non-road vehicles, technological advancements and strategies for reducing these emissions have made

significant strides. For example, a modern diesel engine used in agriculture that complies with Stage 5 standards emits at least 100 times fewer pollutants under the same operating conditions compared to a non-compliant engine of equivalent power (often referred to as "non-emissionized"). In comparative terms, this means that one hour of operation of a non-emissionized tractor can generate the same amount of pollutants as 100 hours of operation of a modern Stage 5 tractor, which adheres to the most advanced anti-pollution standards and significantly reduces emissions.

In mechanized agricultural operations, the absolute quantity of pollutants released into the atmosphere varies depending of course on the number of running hours of tractors and, more broadly, of self-propelled agricultural machinery. Therefore, the primary objective, which is not addressed in this study, is to optimize the intensity of mechanization by avoiding unnecessary operations and optimizing the duration of those deemed as essential, for instance by adopting appropriate forward speeds. However, an equally important aspect concerns the risk of over-mechanization, which involves the use of more powerful tractors than necessary. Optimization in this respect automatically leads to reduced production of gaseous pollutants and tangible economic savings, particularly in terms of variable costs.

For each scenario examined, typical farm sizes and cultivation practices in Italy were considered, based on which the time required for individual operations was calculated. Specifically, for maize cultivation, a farm size of 50 ha was assumed, with an estimated tractor usage of approximately 1,200 h/year, i.e. 24 h/ha·year. Conversely, for forage production, a typical farm size of 20 ha was considered, with a tractor usage of 415 h/year, or almost 21 h/ha·year, 13% less than the maize crop scenario.

Absolute emissions in terms of h/year are generally higher for the maize sector compared to the forage sector. Except for CO, where 8.1 kg/(ha·year) are emitted in forage production compared to 2.1 kg/(ha·year) for maize, other pollutants showed 9.2 kg/(ha·year) compared to 8.1 for HC, 9.5 kg/(ha·year) compared to 6.0 for NO_x, and 0.2 kg/(ha·year) compared to 0.04 for PM.

Briefly, forage production results in a reduction of 13% for HC, 38% for NO_x, and 88% for PM compared to maize cultivation.

Thus, despite the more modern tractors used in the cereal sector compared to those in the forage sector, the analysis of the former revealed significant concerns, particularly regarding NO_x and PM, the main pollutants from diesel engines.

A similar study was conducted for specialized crops, where 3 operational scenarios were considered, each for farms covering 10 ha. The resulting tractor usage intensity was 193 h/year for vineyards with mechanical harvesting (approximately 19 h/(ha·year)), 293 hours per year for vineyards with manual harvesting (approximately 29 h/ha·year), and 852 hours per year for apple production (approximately 85 h/ha·year).

The vineyard with mechanical harvesting proved to be the least impactful for all pollutants. Regarding the most harmful components from diesel engines, NO_x emissions were recorded at 6.5 kg/(ha·year) for mechanically harvested vineyards, 12 kg/(ha·year) for manually harvested vineyards, and 35 kg/(ha·year) for apple orchards. Similar differences were observed for PM emissions.

Although technological advancements have established increasingly stringent thresholds for emissions from non-road vehicle engines, these standards have yet to reach parity with the current automotive sector standards, where the Euro 6D level has been in place for about 5 years, and discussions are already underway for a potential Euro 7 level.

However, it is crucial to recognize that agricultural engines are characterized by significantly different loads and operating cycles compared to those in the automotive sector, suggesting that different parameters may be more appropriate. One key difference is the reference unit: for on-road vehicles, it is typically "distance travelled" (usually per kilometer), while for non-road vehicles, it must be necessarily converted to "hours of work".

Another future opportunity could be to expand the scope of targeted gaseous emissions. So far, the focus has been on the 4 well-known main components (CO, NO_x, HC, and PM), but the automotive sector has long considered CO₂ emissions as well, which are widely recognized as having a significant environmental impact.

While updating these regulations is both necessary, and in some respects urgent, there is a risk that they may become obsolete by the time they are issued, given that the primary declared goal is the complete prohibition of fossil fuel use. This represents an

energy revolution, envisioning the abandonment of traditional internal combustion engines in favour of alternatives such as the progressive electrification of non-road vehicles.

The European Commission has set 2035 as the deadline for the cessation of fossil fuel use, a target that has sparked considerable controversy (and some legislative backtracking).

Although a complete transition is still far off and almost impossible to achieve by the indicated date, the replacement of fossil fuels remains inevitable, given that for many years now, oil consumption has far outpaced its rate of replenishment. This trend will inevitably lead to the depletion of reserves and the necessity to identify viable alternative energy solutions. It will be crucial to be prepared for that moment by developing practical, virtuous and sustainable solutions.

Electrification is currently the most promising path, although it faces significant challenges, particularly concerning the energy density of existing batteries, which is still insufficient to provide effective power in terms of autonomy for many non-road applications. This issue is particularly relevant in the agricultural sector, where, given the high power demands, the main challenge lies in the volume (rather than the weight) of batteries that need to be stored on board. Electrification could indeed prove to be a successful choice from a sustainability perspective, but only if the electricity generation chain is fully understood and respected. For electricity to be truly sustainable, it must not only come from renewable and sustainable sources (an indispensable requirement) but also minimize the overall environmental impact of the entire lifecycle of the production process. To gain these insights, it is crucial to apply Life Cycle Assessment (LCA) to thoroughly analyse all the impacts across the production chain (*see chapter 1.9*).

7.3. 3rd Pillar: operators' health

The issue of the progressive deterioration of air quality represents an increasing threat to global public health, adding to the numerous actual challenges in this field. Air pollution is diffusely recognized as a significant risk factor not only for respiratory diseases but also for cardiovascular, and neurological disorders, as well as developmental issues in children.

The literature highlights that exposure to traffic-related pollutants, particularly fine and ultrafine particulate matter, can have degenerative effects on the development of the nervous system. Understandably, the younger the individual exposed to pollution is, the more significant the long-term effects can be. This is likely due to both the prolonged duration of exposure and the heightened sensitivity of a rapidly growing organism, such as a developing child.

Emerging evidence also suggests a potential link between prenatal exposure to pollutants and the development of autism spectrum disorders. This could pose a potential risk for pregnant women who operate agricultural machinery during pregnancy.

Other studies have identified a correlation between early-life exposure to polluted environments and the development of neurodegenerative diseases in later life, such as Alzheimer's disease, which has seen a rising incidence in recent decades. This could have a particularly significant impact on individuals who are exposed to inhaling pollutants from an early age due to their involvement in agricultural activities, often being present in areas where agricultural machinery is in operation.

Environmental medicine, the discipline that studies the interaction between human health and the environment, is called upon to play a crucial role in addressing these challenges. However, despite the progress made, this field still faces numerous challenges in establishing stringent and enforceable guidelines that can guide experts in determining precise exposure limits. Defining such limits is essential for all human activities that contribute to air quality deterioration, including specific sectors such as agriculture, where exposure to pollutants can be particularly high.

To effectively address these emerging threats, it is essential that research in environmental medicine continues to advance, developing new knowledge and technologies. Only through a rigorous epidemiological approach will it be possible to establish standards that adequately protect the health of agricultural workers, mitigating the risks associated with intense and prolonged exposure to gaseous pollutants.

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9. Annex

Chronological list of scientific publications, related to the project, produced over the course of the three years of the PhD program.

- A Method for Energy Efficiency Rating of Low-power Tractors Based Also on Intensity of Use (2022), Biosystems Engineering Towards the Green Deal (pp.565-574), http://dx.doi.org/10.1007/978-3-031-30329-6_58
- Environmental Impact of Real Gaseous Pollutants Emission of Agricultural Tractors (2022), AIIA 2022: Biosystems Engineering Towards the Green Deal (pp.555-563), http://dx.doi.org/10.1007/978-3-031-30329-6_57
- A survey on driver's health impact of pollutant gaseous emissions of an old agricultural tractor (2024), Ragusa Shwa 2023, Safety, Health and Welfare in Agriculture and Agro-Food Systems, https://doi.org/10.1007/978-3-031-63504-5_49
- Efficiency and environmental impact of tractors used in specialized crops of Autonomous Province of Bolzano (2024 – *under submission*)
- Compact Tractor 4.0: an Investigation for the Development of a Low-Profile Full Electric Specialized Tractor (2024), Ragusa Shwa 2023, Safety, Health and Welfare in Agriculture and Agro-Food Systems, https://doi.org/10.1007/978-3-031-63504-5_17

A Method for Energy Efficiency Rating of Low-power Tractors Based Also on Intensity of Use

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Abstract. The efficiency of the so-called “low-power” tractors is affected not only by the evolution of their engine and transmission design, but also by the usage modes adopted. Especially in specialized crops, such as vineyards and orchards, many tasks do not require high engine power and/or traction pull, being the power of the tractor used by the hydraulic system. A customizable method to analyze and evaluate the real efficiency of narrow tractors (N-TRE) have been developed in 2019, taking into account some tractor models working in different scenarios. These scenarios have been characterized in given working activity and usage intensity, along the growing season. The working conditions and the power requirement of the main operations carried out in viticulture were simulated in a stationary mode by means of an electromagnetic dynamometer, integrated with devices for measuring the fuel consumption. The basic output has been a series of engine performance curves (power, torque and Specific Fuel Consumption, SFC), both at full and partial loads. On these curves, some characteristic working points were identified, simulating the typical tractor running conditions in vineyard. The aim of this study is to validate the N-TRE model by testing its robustness with a given number of tractors, to build a suitable database. The database will be finalized to classify the machines in some efficiency classes, identified with letters from A to G, similarly to what happens for example in several electric and electronic household appliances. Furthermore, the classes A to G were associated to a colour tag, adopting the traffic light criterion (green/yellow/red). These codes could immediately and easily show the tractor global efficiency in different working scenarios, to offer at a glance to farmers a comprehensive machine evaluation.

Keywords: Narrow tractors, Vineyard, Efficiency, Specific fuel consumption

1. Foreword

The maximum efficiency of agricultural tractor use is obtained primarily with its best coupling with the implements. Moreover, the most correct tractor setting, above all in terms of engine speed and fuel delivery, assures the best exploitation of energy potential of the diesel fuel. Along their entire lifecycle, most of the tractors are working at engine partial loads [1, 2, 3, 4, 5, 6]. In these conditions, the tractor should be conveniently work at reduced engine speed, because at high speed the friction and heat losses are higher, and moreover due to the rise of the temperature,

the cooling system engages more power to work properly, till to 10% of the max engine power [7].

The efficiency of an internal combustion engine is strictly linked with an inverse relationship to the Specific Fuel Consumption (SFC), i.e. the amount of the fuel (diesel, e.g. expressed in g) burned to produce a given energy (e.g. expressed in kWh). As a consequence, the SFC is usually measured in g/kWh.

For a given engine, the SFC will vary over the range of operating speeds and loads. To better understand its performance, manufacturers, dealers, and end users sometimes construct engine performance maps. More in detail, engine manufacturers generally supply some curves to ascertain the performance over the range of operating speeds, for some percentages of the maximum load (partial loads) [8].

On the other hand, the use of biofuels is offering more options to users at the progressive scarcity of oil based fuels. Among the various alternatives for diesel engines, e.g. the use of biodiesel and/or ethanol, besides reducing dependence on fossil fuel, would help to reduce emissions of some greenhouse gases [9, 10, 11], but change the performance of the diesel engine cycle, causing variations in the power and SFC. More in detail, the addition of ethanol in diesel fuel lead to a decrease of the power and the engine torque and an increase of fuel consumption, as a consequence of lower calorific value, cetane number, and delay in the injection point of ethanol. Several studies have been carried out in the last decades on the performance and efficiency of agricultural tractors. In this view, the most popular test procedures are the OECD Code 2 [12] and, more recently, the PowerMix settled out by DLG (Deutsche Landwirtschafts-Gesellschaft, Germany). PowerMix in particular is a procedure finalized to evaluate the performance of agricultural tractors normally used in open field, by measuring the engine power required at the PTO, at the drawbar and by the hydraulic system [13, 14]. These tests are basically carried out thanks to a dynamometer wagon travelling on tracks, trying to simulate the tractor real working conditions in the field. The data obtained, mainly in terms of Specific Fuel Consumption (SFC) values, allow an overall calculation of the performance and therefore the efficiency index of the tested machine. The tractor efficiency based on SFC values has been recently considered also by many other organizations/laboratories. Some country, as USA [15, 16], Spain [17], Turkey [18] and Korea [19], defined test protocols adopting SFC criteria to evaluate the tractors efficiency.

Anyway, although several protocols are available for the assessment of the energy efficiency of agricultural tractors, they do not usually classify the models into different categories, based on the architecture (e.g. open field, utility, narrow-track, tracked, etc. tractors) and/or the power class. Moreover, these protocols do not generally take into account the real usage intensity of the tractors neither the most frequently operations carried out by them.

1.1 The narrow-track tractors

Tractors used in orchards and vineyards (but also in the green maintenance sector) are usually included in the low-power category: for these models, the engine power ranges between 35 and 90 kW, being the major part of the models included in the interval 50-75 kW. Due to the typical tasks carried out, the drawbar power request is frequently very low, while the power needed at the PTO and for the hydraulic system is often remarkable.

These models are defined “narrow track” because their reduced overall width, suitable to travel smoothly into the crop rows. As a consequence, the tractor-implement mass distribution on the two axles is a quite important feature to be taken into account, because it is affecting the stability, and so the roll-over risk. In these cases, to reach a satisfactory stability condition, the use of an over-sized tractor (in terms of mass and so power) is practically due, even if the implement power demand is very frequently low or negligible. This is fatally affecting negatively the engine efficiency.

Also the time of operation is likewise influencing the overall machine efficiency: for example, in specialized cultivations the pruning (including also the topping) is usually executed twice in a year (before and in the middle of the growing season), while on the contrary pesticide treatments are much more frequently carried out, up to 15-20 times/year.

To consider properly all these parameters, an efficiency model, named N-TRE (Narrow Tractors Real Efficiency) specifically dedicated to the tractors used in orchards and vineyards was then created, taking into account their usage characteristics, both for power demand and the working time.

The aim of this paper is to apply the N-TRE model to two narrow-track tractors, considering two usage scenarios, different for number and frequency of the operations carried out. Moreover, the two tractor models examined were equipped with engines having a slight different max power and also compliant to different anti-pollution emission stages, to point out the overall efficiency and the expected benefits, mainly in terms of fuel saving.

2. Materials and method

The main technical characteristics of the two tractors examined are shown in tab. 1.

Tab. 1. Main technical characteristics of the two tractors investigated in the survey.

Tractor	Type	Mass, kg	Wheel-base, mm	Engine					
				Cylinder, no.	Displacement, cm ³	Max power, kW (CV)	Rated speed, rpm	Emission Stage	Devices for emission reduction
A	4WD, isodiametric	2275	1550	3	2227	60 (82)	2600	III B	EGR+DOC+DPF
B	4 WD, traditional	3420	2250	4	3769	71 (97)	2300	IV	SCR+DPF

The usage scenarios involved the operations carried out in two typical wineries located in Northern Italy: the first has a cultivated extension of 3.5 ha with slight slope terrain, while the UA of the second is 10 ha, completely flat. More in detail, the first scenario includes 6 tasks: only 15 % of the total working time is referred to an operation performed in the inter-row, while 75 % of them have been carried out on the canopy or in the row. The remaining 10 % regards the grape transport. In the second

scenario, 10 tasks have been considered: 20 % of the time was engaged for operations in the inter-rows and the remaining 80 % regards activity on the canopy or in the row. Obviously, these working times were defined taking into account the repetitions of a given operation along the entire growing season (tab. 2).

Thanks to dedicated interviews of the users of the two tractors, the running conditions of the engines were ascertained, in terms of nominal engine speed at zero load (i.e. at the starting of each task) and subsequent speed reduction due to the increase of the load (i.e. the engine speed under load). For example, for the grass shredding, a nominal engine speed of 2000 rpm and a working speed under load of 1900 rpm were considered for tractor A in scenario 1. This protocol made easy the subsequent simulation of the work cycles, through the electromagnetic dynamometer connected to the tractor PTO. To make possible a suitable data elaboration, for the execution of each task a constant running speed of the engine was considered, so not taking into account the usual load variation caused by the correspondent resistance produced by the implement work.

Tab. 2. Operations and relative time of usage for the two scenarios taken into account.

No.	Scenario 1	Time, % of the total	Scenario 2	Time, % of the total
1	grass shredding	15	pre-pruning	5
2	pruning shredding	10	pruning shredding	5
3	pneumatic spraying	50	grass shredding	10
4	chemical weeding	10	shoot pruning	5
5	topping	5	topping	5
6	grape transport	10	defoliation	5
7	--		spreading	10
8	--		chemical weeding	10
9	--		pneumatic spraying	35
10	--		mechanical harvesting	10

To get information about the SFC values in the defined working conditions, a series of power curves at partial load of the engine were obtained (fig. 1), connecting the PTO of the two tractors investigated to the wheeled electromagnetic dynamometer Eggers-Dynamometer PT 301 MES (KL-Maschinenbau GmbH Rendsburg - Germany), integrated with its dedicated fuel consumption meter (fig. 2) and its dedicated software.

All the working conditions previously defined were then fixed on the correspondent power curve, ascertaining the relative value of SFC (in g/kWh), to obtain the so-called "Typical Running Points" (TRP). In fig. 3 an example of this type of data elaboration is shown.

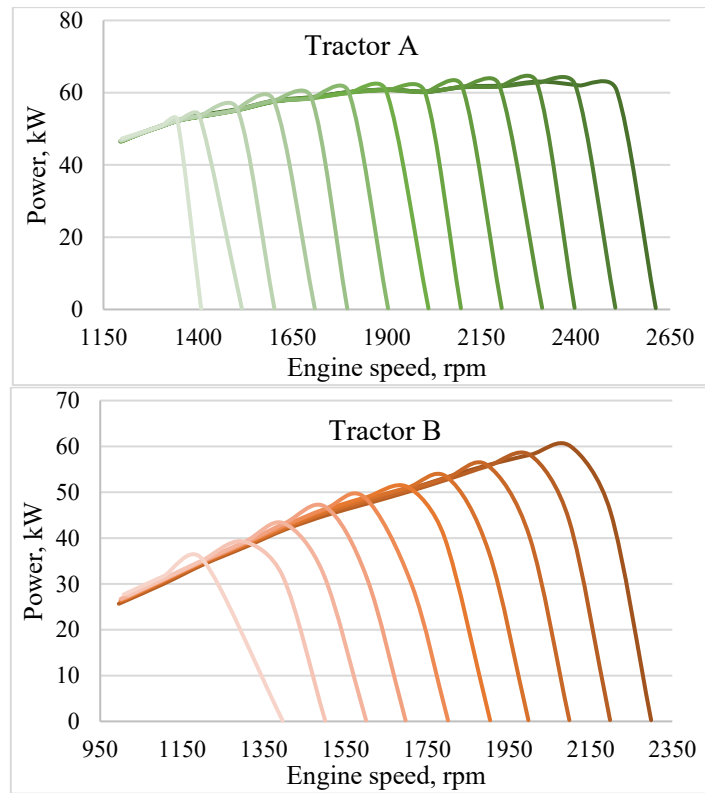


Fig. 1. Power curves at partial load of the investigated tractors A and B.



Fig. 2. Left: the wheeled electromagnetic dynamometer Eggers-Dynamometer PT 301 MES (KL-Maschinenbau GmbH Rendsburg - Germany). Right: the control panel located on the device (top) and the screen of the control through the computer, via Bluetooth (bottom).

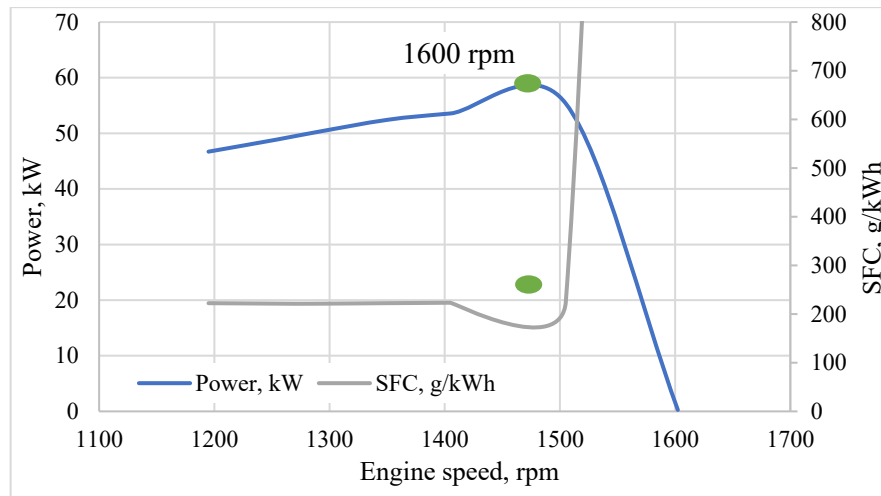


Fig. 3. An example of “Typical Running Points” (TRP), identifying a given working conditions previously defined.

All the TRPs were then divided into some classes, as a function of the correspondent SFC value. Similarly to what established in other several production fields (e.g. buildings, household appliances, etc.) each SFC value, i.e. the energy efficiency, was classified into 7 classes, identified with letters, from A (the best) to G (the worst), matching to those a colour tag, adopting the “traffic light” criterion (green/yellow/red). All the data were managed with the MS Excel software, thanks to predefined sheets. The addition of the colour tag makes easy an immediate identification of the energy efficiency level. For this survey, the SFC classes have been established with reference to the values measured in the tests (tab. 3).

Tab. 3. Classification of the measured SFC values into energy efficiency classes and colour tags.

Tag	SFC, g/kWh	Colour tag
A	220-229	Green
B	230-239	Yellow
C	240-249	Yellow
D	250-259	Yellow
E	260-269	Red
F	270-279	Red
G	280-289	Red

Matching the time dedicated to the various tasks considered and the SFC values attributed to each TRP, some weighted average SFC were then calculated, for both tractors A and B in the two scenarios examined. Also in these cases the results were classified in classes and colour tags.

3. Results and discussion

In tabs. 4 and 5 each operation was classified, as well as the weighted average for the two tractors and the two scenarios.

Tab. 4. SFC values and classification of each operation for tractor A and both scenarios.

Tractor A					
	Nominal engine speed, rpm	Working engine speed, rpm	Power, kW	SFC, g/kWh	Time of usage, %
Scenario 1					
Grass shredding	2000	1900	60,5	245	15
Pruning shredding	2100	1900	60,7	245	10
Pneumatic spraying	2000	1800	57,4	240	50
Chemical weeding	1500	1300	50,8	221	10
Topping	1600	1500	55,3	226	5
Grape transport	1400	1300	51,0	222	10
Class/average				B	236.9
Scenario 2					
Pre-pruning	1400	1200	47,3	222	5
Pruning shredding	1800	1600	57,7	228	5
Grass shredding	1700	1600	57,7	229	10
Shoot pruning	1500	1400	53,6	224	5
Topping	1600	1500	55,3	226	5
Defoliation	1500	1400	53,6	224	5
Spreading	1400	1350	52,5	222	10
Chemical weeding	1400	1350	52,5	222	10
Pneumatic spraying	1800	1500	55,2	226	35
Mechanical harvesting	1700	1500	55,0	226	10
Class/average				A	225.2

For tractor A in the first scenario, the average SFC (250 g/kWh) was noticeably influenced by the SFC assigned to the pneumatic spraying (249 g/kWh), because this operation is very frequently executed along the growing season, and so weights for 50 % of the total working time. At the opposite, tasks as chemical weeding and grape transport evidenced low SFC values (221 and 222 g/kWh respectively), but they were carried out for limited time. Always for tractor A, in the second scenario the SFC values were similar for all the operations, ranging from 222 to 229 g/kWh. Therefore, the average value is included in this range, not being affected by the different time dedicated to the various tasks.

Tractor B showed in general SFC values higher of approx. 8-9 % than tractor A. In the first scenario, the SFC values for the various tasks are similar, ranging from 249 to 253 g/kWh. As a consequence, in this case the remarkable time for pneumatic spraying is not affecting the average SFC. In scenario 2, the grass shredding evidenced an SFC of 265 g/kWh, the highest measured. This is due to the high power

request to the engine to carry out this heavy task. Nevertheless, this operation is executed only for 10 % of the total time, not affecting significantly the average SFC. In this second scenario, the pneumatic spraying is weighting for 35 % of the whole working time, and consequently the relevant SFC value is less influencing the average value.

Tab. 5. SFC values and classification of each operation for tractor B and both scenarios.

Tractor B					
	Nominal engine speed, rpm	Working engine speed, rpm	Power, kW	SFC, g/kWh	Time of usage, %
Scenario 1					
Grass shredding	2000	1800	53	249	15
Pruning shredding	2100	1900	56	252	10
Pneumatic spraying	2000	1800	53	249	50
Chemical weeding	1500	1300	39	251	10
Topping	1600	1500	32	250	5
Grape transport	1400	1200	35	253	10
Class/average				D	250.0
Scenario 2					
Pre-pruning	1400	1200	35	253	5
Pruning shredding	1800	1600	49	246	5
Grass shredding	1700	1600	31	265	10
Shoot pruning	1500	1400	32	252	5
Topping	1600	1300	39	252	5
Defoliation	1500	1400	32	252	5
Spreading	1400	1100	32	256	10
Chemical weeding	1400	1200	35	253	10
Pneumatic spraying	1800	1500	46	247	35
Mechanical harvesting	1700	1500	47	247	10
Class/average				D	251.3

Referring to the tags assigned to the single and the average SFC values, the most evident difference between the two tractors is the dominance of green (classes A and B) for tractor A and yellow (class D) for tractor B. More in detail, tractor B shows an increase in the average SFC of 5.5% in scenario 1, and 11.6% in scenario 2, with a resulting colour and class change. This is justified observing the partial load curves of the engine fitted on the two tractors (Fig. 1): tractor A showed a power curve more “constant” over the speed in respect of that of tractor B, very probably due to a different working setting, managed electronically. In this case, because the power remain high for a wide range of rotation speed, the SFC values remain likewise low in the same range.

Conclusions

Although based on the efficiency evaluation of only two tractors, the advanced N-TRE model highlighted promising features to build specific usage scenarios, on which evaluate the performance of different tractor models.

Moreover, similarly to other production sectors, the classes and colour tags assignment was confirmed as being an immediate and easy solution to recognize the efficiency of a given tractor.

The model described could be easily adapted to other agricultural tractor segments (e.g. utility, open field, high power, etc.) by building appropriate scenarios, considering suitable tasks and time durations. The most important goal is in fact to offer a useful instrument for farmers' evaluation, to identify the most efficient tractor for their needs. A future step could be the building of a robust database of tractors and scenarios, to find the best machine for any working situation.

Finally, the model could find fruitful application in the public administration sector, to select the most efficient tractor models, in view of an assignment of dedicated financial supports for farmers purchasing.

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Environmental Impact of Real Gaseous Pollutants Emission of Agricultural Tractors

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Abstract. The gaseous pollutants produced by the internal combustion engines fitted on vehicles powered with fossil fuels are considered one of the main sources causing the global warming and consequently the climate change. In this scenario, the agricultural self-propelled machinery, in particular tractors, are believed to have a significant role, due to the generalized fitting of diesel engines. Trying to improve the situation, from 1996 for non road vehicles (therefore also for self-propelled agricultural machinery) some Standards were issued, based on steps referred to the time, defining progressively stringent emission limits, from Stage I to Stage V (in Europe), roughly correspondent to Tier 1 to Tier 5 in USA. The compliance of an engine to a given step is referred to dedicated homologation tests, on the basis of a series of defined running conditions.

At present, no subsequent tests are provided to check the conformity of the engine along its service life. Consequently, there is no assurance that the engine is respecting the emission limits provided by its homologation step, especially in case it is heavily used and/or is not submitted to a diligent periodical maintenance.

To ascertain the real pollutants gaseous emission of used tractors, a model equipped with an engine compliant to the Stage IIIA level was tested, using PEMS (Portable Emission Measurement System), measuring NO_x, CO, HC and PM emissions, in comparison with the limits established by its homologation stage.

Keywords: Agricultural tractors, Environment, Gaseous pollutants, PEMS.

1 Foreword

The main pollutants found in gaseous emission of internal combustion engines powered with fossil fuels are carbon monoxide (CO), unburned hydrocarbon

(HC), nitrogen monoxide and dioxide (NO and NO₂, combined in NO_x) and particulate matter (PM). In this scenario, the agricultural self-propelled machinery, in particular tractors, are believed to have a significant role, due to the generalized fitting of diesel engines, producing important amounts especially of NO_x and PM. The studies on these pollutants, regarding the so-called off-road machines (thus including also the agricultural machinery) have been carried out from the beginning of the '90 of the last century, both in Europe in 1990 [1] and in the USA [2].

Therefore, both the EU Commission and US Environmental Protection Agency (EPA), issued standards to regulate the exhaust emission coming from off-road vehicles [3, 4], based on steps referred to the time, defining progressively stringent emission limits. More in detail, the European legislation refers to emission Stages (from I to V for tractors) while in the US legislation they correspond to Tier (from 1 to 5). Then, the manufacturers of the engines were compelled to respect the restrictions, applying several both known and new technologies. The most popular of them were the Exhaust Gas Recirculation (EGR), the Selective Catalytic Reduction (SCR), the Diesel Oxidation Catalyst (DOC) and the Diesel Particulate Filtration (DPF) [5], at a first time fitted alone and later also in combination.

More in detail, the diesel combustion is usually producing a remarkable amount of nitrogen monoxide and dioxide (NO_x) and particulate matter (PM), while the pollution of carbon monoxide (CO) and unburned hydrocarbon (HC) is normally less significant. On the contrary, the gasoline combustion is generating more CO and HC in respect to NO_x and PM. As a consequence, due to the generalized adoption of diesel engines on non-road machinery, the various device used in this case were devoted especially to reduce the emission of NO_x (the EGR and SCR) and/or the PM (the DPF and partially the DOC). More recently the dramatic restrictions imposed lead to the adoption of a combination of these devices, finalized to the maximum reduction of all the pollutants.

Starting approx from the new millennium, the studies and researches in this topic, focused on agricultural self-propelled machinery emissions, increased remarkably, so confirming a keen interest on the scientific point of view. The pollutant ascertainment was approached in different ways, measuring the gaseous emissions in some well-defined engine conditions, sometime in accordance to the running cycles stated by the dedicated standards (e.g., torque at rated speed, max torque, etc.) [6, 7, 8, 9, 10, 11, 12], but also quantifying the pollution in real field working conditions [13, 14, 15, 16, 17, 18].

The European Directive 97/68/EC (and the following amendments) established the limits, in terms of their amount in mass referred to the energy produced (g/kWh), for gaseous pollutants emission produced by engines of rated power in the range 37-560 kW, divided in some classes (Fig. 1). The engine has to be tested in accordance to a steady-state cycle consisting of 8 different modes, referring to its rated speed and torque loads (Tab. 1). The gaseous emissions are measured in each individual mode, and properly weighted according given factors based on usage time, to calculate a comprehensive value for each pollutant and then compared to the prescribed limits provided for the relevant homologation Stage (Tab. 2).

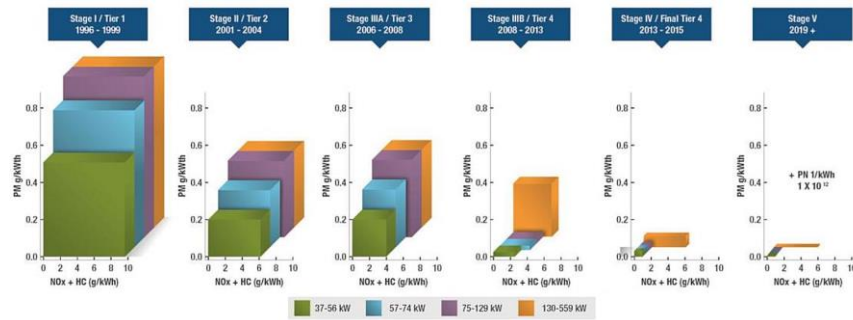


Fig. 1. Limits of emissions of gaseous pollutants established by the European Directive 97/68/EC (and following amendments) for non-road machinery, regarding PM (Particulate Matter) and NOx (nitrogen mono and dioxide).

Table 1. Load and weighting factors for evaluating the pollutants gaseous emission of engines fitted on non-road machines, according to ISO 8178-4 standard (C1 cycle) [19].

Mode no.	1	2	3	4	5	6	7	8
	torque at rated speed				max torque			low idle
	100%	75%	50%	10%	100%	75%	50%	0%
Weighting factor	0.15	0.15	0.15	0.10	0.10	0.10	0.10	0.15

Table 2. Pollutants limits (in g/kWh) and timetable for their coming in force established for the most recent emission EU Stages, for engines fitted on non-road machinery.

Power [kW]	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
0 < P < 8																Stage V CO 0.00 / HC+NOx 7.50 / PM 0.40 / PN-	
8 ≤ P < 19																Stage V CO 0.00 / HC+NOx 7.50 / PM 0.40 / PN-	
19 ≤ P < 37			Stage III A CO 5.5 / HC+NOx 7.5 / PM 0.5													Stage V CO 0.00 / HC+NOx 4.70 / PM 0.20 / PN 1x10 ⁻¹² [MKNW]	
37 ≤ P < 56			Stage III A CO 5.0 / HC+NOx 4.7 / PM 0.4				Stage III B CO 5.0 / HC+NOx 4.7 / PM 0.025									Stage V CO 0.00 / HC+NOx 4.70 / PM 0.20 / PN 1x10 ⁻¹² [MKNW]	
56 ≤ P < 75			Stage III A CO 5.0 / HC+NOx 4.7 / PM 0.4			Stage III B CO 5.0 / HC 0.18 / NOx 3.3 / PM 0.025		Stage IV (01.10.2013) CO 5.0 / HC 0.19 / NOx 3.4 / PM 0.025							Stage V CO 0.00 / HC+NOx 4.70 / PM 0.20 / PN 1x10 ⁻¹² [MKNW]		
75 ≤ P < 130			Stage III A CO 5.0 / HC+NOx 4.5 / PM 0.3			Stage III B CO 5.0 / HC 0.18 / NOx 3.3 / PM 0.025		Stage IV (01.10.2014) CO 5.0 / HC 0.19 / NOx 3.4 / PM 0.025							Stage V CO 0.00 / HC+NOx 4.70 / PM 0.20 / PN 1x10 ⁻¹² [MKNW]		

No subsequent tests are provided to check the conformity of the engine along its service life. Consequently, there is no assurance that the engine is respecting the emission limits provided by its homologation stage, especially in case it is heavily used and/or is not submitted to a diligent periodical maintenance.

This paper shows the pollutants gaseous emission of the engine fitted on a used tractor, by using a dedicated instrumentation chain (PEMS, Portable Emissions

Measuring System) [20], to verify if, and in case to what extent, the limits of gaseous pollutants established for the homologation emission stage of the engine are exceeding the reference values.

2 Materials and method

2.1 The PEMS

PEMS measure emissions from combustion engines as the vehicle or the equipment is being used, which allows real-world in-use testing, offering an innovative counterpart to check the impact of emissions from combustion engines upon the environment. The PEMS provide a complete and very accurate real-time monitoring of the main pollutants emitted by the engines (HC, CO, CO₂, NO_x [or NO + NO₂], PM, etc.).

For the tests of this survey, the following instrumentation chain was used:

1. a portable flue gas analyser for professional flue gas analysis, Testo 350 (Testo SE & Co KGaA, Titisee Neustadt - Germany), consisting in a control unit, for displaying readings, and a measuring box, controlled via Bluetooth. Among several tasks, the analyser is specifically designed also for the emission control and inspection of compliance with emission guidelines. To make possible the comparison with the limits established by the correspondent EU Directive, for the purposes of the present survey the parameters analyzed were the concentration (in terms of mg/m³) of NO, NO₂, NO_x, HC and CO. Also the exhaust gases temperature was monitored, at the level of the testing probe, just to obtain information about the engine running conditions;
2. a portable hand-held smoke tester, Testo 338 (Testo SE & Co KGaA, Titisee Neustadt - Germany), for measuring the degree of blackening in the diesel engines in terms of soot concentration (mg/m³). The smoke tester working principle is based on a LED white light reflectance on to a blackening mark, consisting in a filter paper on which the soot is deposited in a given time;
3. a flow meter, Trotec TA 400 (Trotec GmbH, Heinsberg - Germany), to measure the volumetric flow in gases duct (of known shape and dimensions), in terms of m³/h.

2.2 The tested tractor and other device used

The agricultural tractor tested was a 4WD, medium powered model, Deutz-Fahr Agrofarm 430, equipped with the Deutz-Fahr engine TCD2012 L04 of nominal 80 kW (109 CV), complying the EU Stage IIIA level for the pollutants gaseous emission. Although manufactured in 2011, the tested tractor has been working for approx. 1400 hours only.

To reproduce properly the running steady-state cycle established by the EU emission Directive, the tractor was coupled through its standard 540 rpm PTO to the electromagnetic dynamometer Eggers-dynamometer PT 301 MES (KL-

Maschinenbau GmbH Rendsburg - Germany). Starting from the power recorded at the PTO, the effective engine power was calculated taking into account the mechanical transmission efficiency, previously ascertained.

The gases coming from the tractor exhaust were conveyed into a duct, where the probes of the measuring instruments were conveniently placed (Fig. 2).



Fig. 2. Experimental arrangement of the tested tractor. Left: general view; top right: the gas probe; bottom right: the flow meter.

3 Results and discussion

To define the 8 running points provided for the measurement of the gaseous emissions, the engine torque and power curves at full delivery have been previously obtained (Fig. 3).

To compare the amount of any pollutant produced by the tractor with the limit established by the correspondent homologation EU Stage, the data coming from the instrumentation were managed in accordance the following formula:

$$P_a = (P_c \cdot Q) / P$$

where:

P_a = pollutant amount (g/kWh)

P_c = pollutant concentration (g/m³)

Q = gas flow (m³/h)

P = engine power (kW)

In Tab. 3 the results for each pollutant and for all the running conditions are shown, while in Tab. 4 the overall results are compared with the limits established by the corresponding homologation emissive Stage.

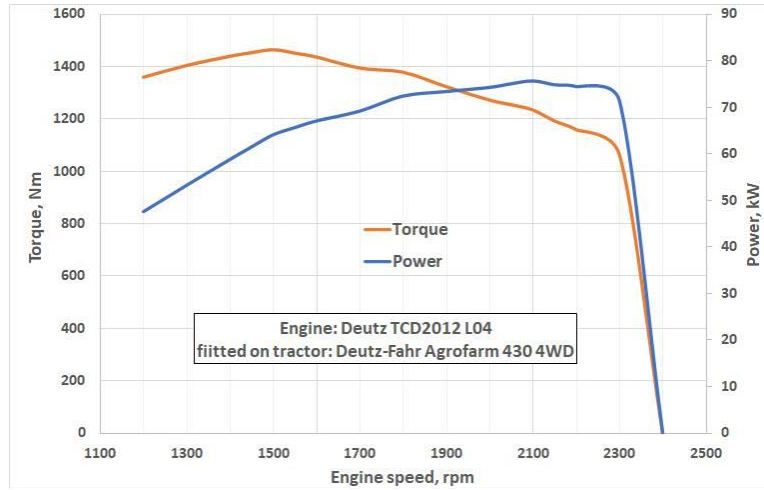


Fig. 3. Torque and power curves at full delivery of the engine fitted on the tested tractor.

Tab. 3. Concentration values of the pollutants measured for all the running conditions considered (g/m³).

Mode no.	1		2		3		4		5		6		7		8	
	torque at rated speed								max torque				low idle			
	100%	75%	50%	10%	100%	75%	50%	~ 0%	100%	75%	50%	~ 0%	100%	75%	50%	~ 0%
NO _x	8.75	9.04	11.62	34.12	8.08	8.96	10.53	35.40								
CO	1.44	1.92	2.76	20.70	1.14	1.68	2.14	8.46								
HC	6.62	9.36	14.10	23.20	3.94	8.16	11.78	29.45								
PM	0.13	0.14	0.19	0.35	0.09	0.14	0.16	0.05								
Temp.(°C)	413	372	315	244	416	397	350	157								

Tab. 4. Overall amount for each pollutants compared to the homologation emission Stage (III A) limits for the engine fitted on the tested tractor.

Pollutant	Limit (Stage III A)	Measured (g/kWh)
NO _x +HC	4.00	29.53
CO	5.00	4.15
PM	0.30	0.15

To reduce the gaseous pollutant emission, the engine of the tested tractor (compliant to Stage III A) was equipped only with external cooled Exhaust Gas Recirculation (EGR), managed electronically. In general, the trend of the pollutants amount is strictly related to the power produced by the engine, as well as the smoke temperature. More in detail, they increase when the power (but also the torque) decrease. As expected, when a low power is produced by the engine, all the pollutants highlighted a dramatic increase, due to a poor fuel combustion. Because the overall values are coming from the weighted average of those measured in the different running conditions, the low power running (10% of the torque recorded at the max power speed) as well as the low idle conditions affected remarkably the final outcome.

In particular, the CO and PM overall values were inside the provided limits, while the combination NO_x+HC showed a value exceeding more than 7 times the limit. With reference to the tested tractor, this represents a quite important outcome of the research, also taking into account that the tested engine worked for only 1400 hours, a much shorter time than that considered as the normal lifecycle of a modern diesel engine fitted on agricultural machinery, established generally in 4-5000 hours before submitting it to a general maintenance service. Moreover, the heavy overcome of the NO_x (and HC) limits, recorded in this case with the only application of the EGR, led in recent years to the addition of the Selective Catalytic Reduction (SCR) to meet the subsequent more stringent homologation stages. SCR is in fact a post-treatment solution, to reduce in particular the NO_x production, applied without any modification of the combustion efficiency, that shows its maximum according with high working temperature.

4. Conclusions

While CO and PM were found below the limits, the tests carried out highlighted a dramatic overshoot of the NO_x+HC limit for the investigated engine. This outcome confirms the need to check along the entire tractor service life the pollutants produced. In this view, a certain increase of measured amounts could be admitted, taking into account the natural worsening of the engine running conditions (made even more burdensome in case of neglected maintenance).

The periodical inspection of agricultural tractors, including the gaseous pollutants check is not yet in force in Italy. On the other hand, the regulatory proposal in preparation are providing only the check of the PM, but its extension to other pollutants, and primarily the NO_x, would contribute to an effective reduction of the environmental impact.

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A survey on driver's health impact of pollutant gaseous emissions of an old agricultural tractor

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Abstract. In addition to numerous other human activities, the agricultural sector plays a pivotal role in the generation of pollutants contributing to global warming and climate change. Beyond the resultant environmental damage, gaseous emissions emanating from diesel engines pose a potential occupational risk for operators. Occupational health studies indicate that prolonged exposure to gaseous pollutants, particularly those generated by internal combustion engines such as diesel engines, may be linked to the development of respiratory ailments, including asthma, rhinitis, and lung diseases. To mitigate these adverse effects, a meticulous analysis of the quantity of gaseous emissions produced by self-propelled agricultural machinery during diverse field operations becomes imperative. The findings, juxtaposed with existing literature data on professional exposure to prevalent air pollutants, serve to carry out risk assessment. Furthermore, these outcomes contribute to the promotion of initiatives aimed at diminishing exposure duration and conditions, while concurrently optimizing the operational efficiency of the machinery. This paper presents an assessment of gaseous pollutant emissions from a Fiat 70-90 tractor, a venerable model still extensively utilized in Italy, under simulated typical working conditions. In comparison to the limits set by Stage and Tier standards, aimed to reduce pollutant emissions in new tractor models, the examined tractor displayed significantly heightened levels of nitrogen oxides, carbon monoxide, and unburned hydrocarbons. Nevertheless, unexpectedly, the levels of particulate matter emissions remained within acceptable limits.

Keywords: efficiency, internal combustion engine, exhaust fumes, operator's wellness, environment

1 Introduction

Among the significant challenges of the present century, the mitigation of air pollution emerges as a crucial undertaking in efforts to curb global warming and address climate change. Within the agricultural sector, pollutant emissions can be ascribed to livestock farming, specific crops, and notably, mechanization. Agricultural mechanization entails

the deployment of diesel internal combustion engines, which power tractors and self-propelled machinery.

The conversion of chemical energy from fuel into mechanical energy through combustion results in the emission of fumes into the atmosphere. Gaseous pollutants in diesel engines encompass mainly particulate matter (PM), nitrogen oxides (NO_x), hydrocarbons (HC) and carbon monoxide (CO). The generation of these pollutants is contingent upon various factors [1], including the type of fuel employed (such as diesel or biodiesel, [2]), engine/tractor usage patterns [3] and operating conditions.

Apart from their adverse environmental impact, these pollutants pose health risks, particularly during prolonged exposure. Pollutant gases are widely implicated in numerous respiratory disorders [4]. Occupational medicine has long been concerned with the harmful effects on human health regarding exposure to such gases [5, 6, 7]. For instance, over a span of 20 years, from 1990 to 2010, Bidoli et al. [8] observed a notable rise in the risk of lung cancer mortality among residents residing in close proximity to major national roads in Italy. This rise was notably conspicuous, especially when examining roads situated in rural municipalities. Similarly, Parent et al. [9] carried out a study in Canada that provided some limited support for the hypothesis of an excess lung cancer risk due to diesel exhaust. In 2014, Tadano et al. [10] observed that Brazilian bus drivers operating buses equipped with Selective Catalytic Reduction (SCR) systems, which notably reduce the levels of nitrogen oxides (NO_x) in diesel engine exhaust emissions, demonstrated a diminished risk of developing chronic non-cancerous diseases. Specifically, asthma and rhinitis are the most commonly documented non-cancerous diseases observed in individuals subjected to prolonged exposure to emissions from diesel engines. Sibanda and Makaza [11] documented a case involving a 36-year-old female bank employee who relocated her office to a space in close proximity to a diesel-powered electricity generator. The emissions from the generator significantly lowered her baseline spirometry values, and the administration of a bronchodilator demonstrated limited reversibility.

Certainly, mitigating these adverse effects involves a reduction in the production of pollutant gaseous emissions. To achieve this, a roadmap has been in place since 1996 to gradually decrease emissions from non-road vehicles, including agricultural tractors. This initiative involved the issuance of Mandatory European Regulations in Europe and EPA requirements in the USA. To adhere to the specified limits, tractor engines have been equipped with diverse anti-pollution systems, including Exhaust Gas Recirculation (EGR), Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR), and Diesel Oxidation Catalyst (DOC). The integration of these pollution control devices has become essential to meet increasingly stringent emission limits, implemented at successive time intervals. In compliance with these regulations, a substantial reduction in the emission levels of particulate matter (PM) and nitrogen oxides (NO_x) from diesel engines was recorded.

However, the age of agricultural tractors in Italy is dramatically high, estimated as an average of around 27 years, based on some unofficial assessments. A significant portion of these tractors, estimated at around 300,000 units, continues to operate without any anti-pollution devices.

This study aims to offer insights into the potential impact on both the health of drivers and the environment, linked to this old segment of the Italian agricultural tractor

fleet. Specifically, the study focuses on evaluating the actual quantity of gaseous pollutants produced by an aging tractor operating under real working conditions.

2 Materials and method

The study focused on an approx. 40-year-old Fiat 70-90 tractor, a model still widely used in Italy (Fig. 1)



Fig. 1. To measure the gas flow, the Fiat 70-90 exhaust terminal was linked to a bypass pipe.

The examined tractor is equipped with a two-wheel drive, a mechanical transmission, and a power take-off (PTO) operating at 540 min^{-1} . Despite its advanced age, the tractor has accumulated only 1400 working hours, indicating minimal usage.

To replicate the typical working conditions of the tractor, a usage scenario was delineated within a identified production chain. This scenario considered a series of agricultural operations, to be simulated in a laboratory under stationary conditions. Given the tractor age and low power capacity, the forage chain was selected, encompassing various field operations (Table 1) featuring modest power requirements.

Table 1. Field operations considered in the forage chain.

Chain	Operation
Forage	Seeding
	Spraying (boom)
	Mineral fertilization

Grass mowing
Grass conditioning
Loader wagon
Hayracking
Baling
Wrapping
Shredding
Bale transportation (on farm road)

For each operation, specific engine “running” points, determined by the expertise of some farmers involved, were replicated under stationary conditions. In greater detail, the engine speed and load values were determined for each considered operation. This was achieved utilizing an electromagnetic dynamometer (mod. PT 301 MES, made by Eggers Dynamometer, Grundhof - Germany) connected to the tractor's Power Take-Off (PTO) through a cardan shaft. An overview of the identified running points is presented in Table 2, which also includes the decreased speed of the engine under load. The engine speed under load considers the expected reduction in speed resulting from the increased load incurred by connecting the implement to the engine through the PTO.

Concurrently with determining power engagement, an analysis of significant gaseous pollutants was conducted. The following instrumental chain was employed for these measurements:

- for the gas flow rate : a flowmeter, make Trotec (Wervaltung, Germany) mod. TA 400;
- for the NO_x, CO and HC measurement: a gas analyzer, make Testo (Titisee-Neustadt, Germany) mod. 350
- for PM: a smoke tester make Testo (Titisee-Neustadt, Germany), mod. 338.

Table 2. Working width of the implements, rated and under load engine speed values, and power need for each operation of forage chain.

Operation	Working width, m	Nominal engine speed, min ⁻¹	Engine speed under load, min ⁻¹	Power, kW
Seeding	3.0	1300	1200	7.2
Spraying (boom)	8.0	1300	1250	4.3
Fertilization	12.0	1400	1350	4.6
Grass mowing	2.8	1600	1400	14.4
Grass conditioning	2.8	1700	1400	29.3
Loader wagon	--	1400	1350	4.6
Hayracking	--	1250	1200	4.0
Baling	--	1700	1450	25.8

Wrapping	--	1700	1400	29.3
Shredding	--	1500	1300	12.9
Bale transportation (farm road)	--	1200	1100	7.5

Among the various options, the instrumental dataset is providing measures as substance concentration (mg/m^3); to compare the obtained data with the emission limits, based on the European Stages standards, expressed in g/kWh , the following equation was adopted (1):

$$Pe = c \times 10^3 \times f \times \frac{1}{P} \quad (1)$$

where :

Pe = pollutant emission (g/kWh)
 c = pollutant concentration (mg/m^3)
 f = exhaust gas flow (m^3/h)
 P = power measured (kW)

To enhance the assessment of the correlation between recorded pollutant values and emission stage limits, a "traffic light logic" has been devised and implemented (Fig. 2). In finer detail, the color spectrum ranges from red (Stage 1/Tier 1) to dark green (Stage 5/Tier 5).

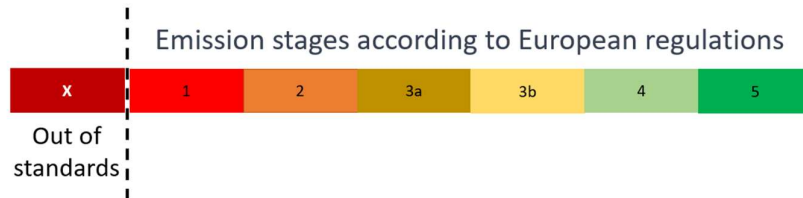


Fig. 2. "Traffic light logic" employed for a quick and intuitive comprehension of the levels of gaseous pollut

ants in comparison to the established standard limits.

3 Results and discussion

In addition to the full-load engine curve (Fig. 3), we obtained the most representative partial-load engine curves for the tested tractor. Subsequently, these curves underwent analysis to identify on them the specific operational points considered in the survey.

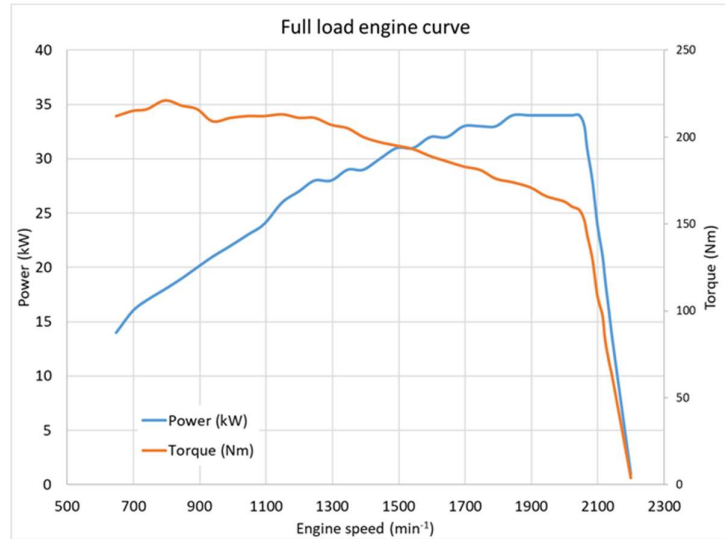


Fig. 3. Torque and power engine curves, at full load.

The torque, and consequently the power, was gauged at the tractor PTO, with a subsequent application of an appropriate efficiency coefficient (0.92) to derive the actual power delivered by the engine. This coefficient was determined through well-established empirical knowledge regarding power transmission efficiency from the engine to the PTO, particularly in older tractor models.

Hence, each running point was replicated through manual control of the dynamometer, ensuring the engine remained in a steady state, and pollutants were measured by inserting probes into the exhaust pipe. Each PM measurement required 20-30 s, whereas measurements for other pollutants were conducted with a focus on data consistency, taking approximately 3 min each (Tab. 3).

The investigated tractor, Fiat 70-90, does not comply with mandatory European pollution regulations, given that it was manufactured well before 1996, the year of the first regulation issuance (Fig. 4). Therefore, it is expected that the emissions will exceed the limits outlined in the Stage 1 standard.

STAGE	CO	HC	NOX	PM	g/kWh				
					CO	HC	NOX	PM	CO
1	6.5	1.3	9.2	0.85	CO	HC	NOX	PM	CO
2	5	1.3	7	0.4	CO	HC	NOX	PM	CO
3a	5	0.19	4.7	0.4	CO	HC	NOX	PM	CO
3b	5	0.19	3.3	0.025	CO	HC	NOX	PM	CO
4	5	0.19	0.4	0.025	CO	HC	NOX	PM	CO
5	5	0.19	4.7	0.015	CO	HC	NOX	PM	CO

Fig. 4. Application of the “traffic light colour logic” to the Stage/Tier official limits defined by the European regulations.

Table 3. Raw data of pollutants amount, recorded at the running points and expressed in mg/m³.

Operation	PM	NOX	CO	HC
Seeding	1.60	1827	2143	1047
Spraying (boom)	1.97	1609	2418	2342
Fertilization	1.15	1572	3172	3243
Grass mowing	4.01	1914	1363	1907
Grass conditioning	78.80	2226	3819	1496
Loader wagon	1.15	1572	3172	3243
Hayracking	2.75	1664	2177	2923
Baling	72.00	2980	1112	1404
Wrapping	78.80	2226	3819	1496
Shredding	4.16	2149	1234	2852
Bale transportation (farm road)	3.03	2309	1433	3880

Indeed, the levels of NOx, HC, and CO surpassed Stage 1 limits significantly (indicated by the dark red colour). Surprisingly, the PM levels exhibited notably better results, with some values aligning with the limits of Stage 3A (Fig. 5).

Operation	PM	NOX	CO	HC
		g/kWh		
Seeding	0.035	48.58	17.11	14.41
Spraying (boom)	0.074	60.49	90.88	88.03
Fertilization	0.041	56.48	113.97	116.52
Grass mowing	0.041	19.74	14.06	19.67
Grass conditioning	0.400	11.31	19.40	7.60
Pick-up carriage	0.041	56.48	113.97	116.52
Hayraking	0.103	62.60	81.89	109.96
Baling	0.371	15.38	5.74	7.25
Wrapping	0.400	11.31	19.40	7.60
Shredding	0.045	23.43	13.45	31.09
Bale transportation (farm road)	0.063	48.13	29.87	80.89

Fig. 5. Results of pollution test on Fiat 70-90 tractor, classified in accordance with the “traffic light colour logic”.

4 Conclusion

Due to its advanced age coupled with limited usage, the pollutant emissions from the Fiat 70-90 tractor revealed contradictory outcomes. The obsolete technical state of its engine resulted in high levels of NO_x, CO, and HC. However, when operated at partial load, the PM results were relatively favorable. This could be attributed to a modest degree of engine wear, considering the tractor's usage was confined to only 1400 hours. In any case, aligning with the principle of "less is better", the investigated tractor cannot be deemed a "green" option in terms of environmental sustainability and human health. Given the current absence of dedicated standards, a substantial effort could indeed be directed towards effectively establishing the connection between the short and long-term adverse effects of diesel pollutant gases on operators' health.

Furthermore, considering that the examined tractor holds significant representativeness within the Italian tractor fleet, there is a compelling need to upgrade the machinery. This includes a substantial improvement with more modern models equipped with efficient anti-pollution devices. To facilitate this transition, robust economic support should be extended by public bodies and administrations.

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Efficiency and environmental impact of tractors used in specialized crops of Autonomous Province of Bolzano

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Abstract. Agricultural production involves many specialized chains, in which machinery plays a fundamental role. Each chain is organized in terms of production inputs, processes, and execution frequency of operations. In open fields, the large area allows for profitable use of tractor power. Conversely, fruit and wine production requires small, low-power (narrow-tracked) tractors, due to crop characteristics and low power demand of many operations.

This study analyzes the operating conditions of specialized tractors in Bolzano, an area suited for apple and wine grape cultivation. It focuses on the engine efficiency and environmental impact of a popular narrow-track tractor model. The study ascertains the most common operations in these production chains and defines the engine operating conditions (at rated speed and under load) simulating them in steady state, by using an electromagnetic brake connected to the PTO. Specific fuel consumption has been calculated for each operating condition to determine engine efficiency, while analyzing emissions of pollutants (PM, NO_x, HC, CO, CO₂). Emission data will be compared with regulatory limits according to the engine's homologation stage.

Keywords: Narrow-track tractor, engine, specific fuel consumption, gaseous emissions, pollutant, apples and wine grapes cultivations.

Introduction

For decades, agricultural production has leveraged machinery to enhance efficiency. The use of agricultural machinery in open fields is not usually subjected to specific constraints imposed by the crop; conversely, the use of mechanized equipment in specialized crops necessitates certain precautions (1). Specialized crops differ significantly from one another (even within the same species) and are heavily influenced by the cultivation area features. In addition to orographic factors,

influential variables include the planting pattern, which may cause incompatibility with tractors of traditional architecture (2). In specialized crops, narrow-track tractors are typically employed. These tractors are designed with reduced overall width and height, to minimize damage to canopy and/or plant branches. However, the compact design of these tractors, lacking empty spaces under the bonnet, poses significant challenges for installing devices designed to reduce emissions of pollutants (primarily CO, HC, NO_x, and PM) generated by the engine (3).

The primary goal of this study is to analyze the performance efficiency and pollutant emissions in two specialized production chains of typical farms located in the autonomous province of Bolzano. This area is distinguished by unique pedoclimatic conditions, a distinctive orographic distribution and a significant tradition in agriculture and machinery management. The main crops selected for this study are vineyards and apple orchards (4-5). Through direct interviews with local farmers, the study aimed to identify the most relevant operations for each production chain. Following a specific testing protocol, inspired to the OECD and DLG Powermix performance tests (6-7), several operating points were defined based on working conditions, tractor efficiency, and pollutant emissions (8). The obtained data on efficiency and pollutant emissions for both production chains were compared to discover the most efficient working conditions for the tested tractor. The amount of pollutants were compared with the limits of the correspondent anti-pollution stage of the engine, to understand the relationship between regulatory limits and the real amount emitted under the defined working conditions (9-10).

Materials and methods

The study focuses on the most common specialized crops found in northern Italy, particularly in the Bolzano autonomous province. Two scenarios were developed to better understand the working routines in these productive chains, collecting the most frequently used field operations in vineyards and apple orchards (4).

To establish the typical working conditions of the tractor, a usage scenario was defined within each considered production chain, encompassing a series of agricultural operations to be simulated at the lab level, under stationary conditions. For each scenario, the operations representing the best practice carried out throughout the entire season were ascertained, on the basis of interviews with farmers, as shown in Table 1.

Table 1: field operations considered in the forage chain

Chain	Operation	Chain	Operation
	Harrowing		PPP spraying
Vineyard	PPP spraying	Apple orchard	Apple transport
	Grass and pruning shredding		Grass shredding
	Topping		Pruning shredding

Defoliation	Organic fertilization
Organic fertilization	Mineral fertilization
Mineral fertilization	Soil tillage
Pre-pruning	
Mechanical weeding	

To measure the tractor performance and emissions generated under different working conditions, a New Holland TN70VA tractor was tested, representing a model widely used in the autonomous province of Bolzano (Fig. 1). It is a 4 WD tractor equipped with a mechanical transmission and a standard PTO at 540 min⁻¹.

Drawing upon knowledge gleaned from farmers' experiences, some engine operating points identified for various agricultural operations were exactly replicated under controlled, stationary conditions, thanks to an electromagnetic dynamometer connected with the tractor PTO through a cardan shaft (6, 7, 8).



Figure 1: the tested tractor New Holland TN70VA was connected to a dynamometer Froment Sygma 50, to measure its performance

The dynamometer used for this tests was the model Sygma 50, manufactured by Froment Ltd (Stamford, UK). Othe than the dynamometer, a gravimetric system was developed for the indirect measurement of fuel consumption, using a precision scale placed beneath an auxiliary tank. This approach allowed for the calculation of hourly fuel consumption, and by relating this data to the power over time, the Specific Fuel Consumption (SFC) value was also determined (11).

To ensure best similarity to real-world conditions, high attention was devoted to determine the working parameters, for both the tractor and implements used across different scenarios. This process involved establishing rated (no-load) starting engine speeds, and implementing specific reductions to simulate operational loads, to find the so called "running points", as shown as an example in Table 2.

Table 2: information collected during the analysis of the tractor performance during the PTO test

Operation	Working width, m	Rated engine speed, min^{-1}	Engine speed under load, min^{-1}	Power, kW
n. 1				
n. 2				
n. 3				
n.				

For each field operation, evaluations were conducted on the power requirements under steady state conditions, and efficiency was assessed based on measured Specific Fuel Consumption (SFC) values. At the same time, an analysis of main gaseous pollutants was performed (Fig. 2). The instrument set employed for these assessments included:

- a flowmeter, make Trotec model TA 400 (Wervaltung, Germany), for measuring gas flow rates;
- a gas analyzer make Testo, model 350 (Titisee-Neustadt, Germany), for the measure of NO_x, CO, and HC emissions;
- a smoke tester Testo, model 338 (Titisee-Neustadt, Germany), for the ascertainment of particulate matter emissions.



Figure 2: in order to measure the emissions level, a pipe was inserted in the exhaust gas line, including the probe of the flowmeter, and those of the gas analyzer and smoke tester.

This methodology aimed to provide comprehensive insights into both the efficiency of the tractor and its environmental impact, thereby facilitating evidence-based decision-making for sustainable agricultural practices.

Among other several options available, the instrumental dataset provides measurement of concentrations. To compare the raw data offered by the instrumentation with the emission limits specified by the European standard, expressed in g/kWh, equation (1) was used:

$$pe = c \times 10^3 \times f \times \frac{1}{p} \quad (1)$$

pe = pollutant emission (g/kWh)

c = pollutant concentration (mg/m³)

f = exhaust gas flow (m³/h)

p = power measured (kW)

To better assess at a glance the correlation between recorded pollutant values and emission stage limits, a "traffic light colour logic" system was developed and put into operation (Fig. 3). This system uses a color range from red (representing Stage 1/Tier 1) to dark green (representing Stage 5/Tier 5).



Figure 3: the "traffic light colour logic" was adopted to better understand, at a glance, the amount of gaseous pollutants recorded compared with the standard limits

Results

The specific fuel consumption of each running point was converted in efficiency values taking into account the diesel lower calorific value.

The values obtained from each operation were then averaged, through the arithmetic mean, to estimate an average value for each scenario. Tables 3 and 4 respectively show the scenarios for the vineyard and apple orchard chains.

Table 3: tractor performance in vineyard scenario

Vineyard					
Tasks	Nominal engine speed	Engine speed under load	Power	SFC	Efficiency
		min ⁻¹	kW	g/kWh	%
Harrowing	2100	1950	22.2	273.5	0.31
PPP spraying	2000	1750	33.0	237.1	0.36
Grass and pruning shredding	1800	1650	14.6	268.9	0.32
Topping	1500	1450	5.2	392.4	0.22
Defoliation	1500	1400	8.0	313.3	0.27
Organic fertilization	1500	1350	11.1	284.9	0.30
Mineral fertilization	1300	1200	7.6	298.6	0.28
Pre-pruning	1300	1250	4.8	367.3	0.23
Mechanical weeding	1200	1150	5.3	336.0	0.25
				avg.	0.28

Table 4: tractor performance in the apple orchard scenario

Apple orchard					
Tasks	Nominal engine speed	Engine speed Under load	Power	SFC	Efficiency
		min ⁻¹	kW	g/kWh	%
PPP spraying	1500	1300	17.2	234.8	0.36
Apple transport	2200	1700	48.9	226.3	0.38
Grass shredding	1500	1350	12.7	259.1	0.33
Pruning shredding	1500	1300	17.2	234.8	0.36
Organic fertilization	1400	1350	6.0	340.8	0.25
Mineral fertilization	1300	1250	6.5	310.6	0.27
Soil tillage	1500	1100	26.5	235.7	0.36
				avg.	0.33

The average efficiency obtained for the vineyard production chain (0.28) is lower than that of the apple orchard production chain (0.33), but in both cases they are significantly lower than the best efficiency of the diesel engines fitted on agricultural tractors, that ranges between 0.43 and 0.45. These findings suggest an oversizing of the tractor investigated, when used for both production chains.

The evaluation of pollutants amount produced revealed that in both scenarios the engine fitted on the tractor tested is not conforming to the regulatory homologation limits.

This deviation was partly expected, because the type approval test are carried out under certain working conditions, specified by international standard, that are not precisely covering the real world. Notwithstanding this, the levels of certain pollutants are particularly high.

Table 5: tractor emission performance in vineyard scenario

Tasks	CO	HC	NOX	PM
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	<i>g/kWh</i>			
Harrowing	12.35	20.88	47.23	0.10
PPP spraying	2.01	13.16	18.98	0.07
Grass and pruning shredding	15.16	62.89	34.49	0.05
Topping	89.49	223.70	73.87	0.09
Defoliation	4.52	117.36	49.16	0.08
Organic fertilization	21.23	60.65	32.23	0.05
Mineral fertilization	23.17	77.48	39.92	0.06
Pre-pruning	79.17	201.23	74.48	0.09
Mechanical weeding	36.53	126.58	58.65	0.09

Table 5 reports emissions measured simulating the vineyard scenario: the majority of the values are marked in dark red, i.e. values exceeding emission limits. However, PM values comply with the engine homologation stage (III A), while the values of CO in two operations performed quite better.

Conversely, Table 6 (apple orchard) is showing slightly better values. Although all the HC values and some CO and HC measurements fall into the dark red category, nine figures are aligning with Stage IIIA for PM and NOx values, and other four for CO are more better.

Table 6: tractor emission performance in apple orchard scenario

Tasks	CO	HC	NOX	PM
	<i>g/kWh</i>			
PPP spraying	0.69	7.35	3.71	0.03
Apple transport	1.95	7.78	10.67	0.27
Grass shredding	0.60	7.58	3.71	0.03
Pruning shredding	0.69	7.58	3.71	0.03
Organic fertilization	10.72	22.39	10.96	0.10
Mineral fertilization	5.89	15.15	7.41	0.07
Soil tillage	22.67	16.83	8.24	1.37

Conclusions

The tractor investigated was fitted with an engine with mechanical fuel injection; as expected, the findings confirmed that the best efficiency and at the same time the minimum pollutant emission levels are obtained when the power output is high. In this view, due to the higher engagement, the apple orchard scenario highlighted a better average efficiency and lower pollutant emissions.

These evaluations could be quite useful to better select the tractor purchase (or use), for a better alignment to the farm specific needs. Moreover, this assessment could serve as a pivotal tool for determining whether modernizing the machinery fleet could enhance production chain efficiency, through improved engine power management and reduced emissions, facilitated by sophisticated engine technologies and advanced anti-pollution devices.

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Compact Tractor 4.0: an Investigation for the Development of a Low-Profile Full Electric Specialized Tractor

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Abstract. The main goal of this paper is to set up the an adequate research program for the development of a low-profile, full-electric tractor model for orchard and vineyard. The prototype, properly arranged to support the agriculture 4.0 technology, will be equipped with a non-foldable and non-tiltable protective structure in case of overturning (ROPS), suitable to reduce the overall height of the machine, while effectively protect the driver in all working situations. To assure also a proper ergonomic level, reference was made to the European regulation 1322/2014; more in detail concerning safety, ISO 4254-1 and OECD Codes 4 and 7 were taken into account.

In addition, to respect a front and/or rear track width less than 1150 mm (to make possible the classification as a narrow tractor), the prototype should have an overall height not exceeding 1600 mm and a minimum ground clearance of 250 mm.

The research was initially aimed to the ascertainment of the tractor power required for the most common operations carried out in vineyards and orchards. As a reference, the CAN-bus data coming out of some high powered models (for the category, i.e. 74 kW) were analyzed, to investigate the real power requirement involving vineyard operations. The heaviest conditions were recorded in plant protection products distribution, carried out with the pneumatic sprayer.

Moreover, a parametric analysis was conducted on a one degree-of-freedom 4WD tractor model to determine power needs for traction in different working conditions, concerning slope, travelling speed, terrain features, etc.

Keywords: agriculture 4.0, safety, electric power, tractor dynamics, ROPS.

1 Introduction and objectives

1.1 Tractor overturning in agriculture

Tractor overturning is the main cause of fatality in agriculture. From 2008 to 2019, a total of 1414 fatal overturning accidents were detected in Italy [7] and 434 of them were classified according to ROPS type and arrangements adopted.

The majority (57.6%) of the tractors involved in the fatal events did not have any ROPS fitted, while about 80% of tractors equipped with a 2-post front-mounted tiltable roll-bar (19.4%), the ROPS was in the lowered position at the moment of the overturning, so not assuring any protection.

In fact, the operations commonly carried out in specialized orchard and vineyard set strict constraints for the width and height of specialized tractors, in contrast to the high power required by heavy applications [5], and require narrow-track tractor equipped with a cab or, as an alternative, a two-post front-mounted roll-bar.

This roll-bar can be typically tilted of about 90°, from a vertical (protection) position to a horizontal (rest) position, allowing the vehicle to travel between the rows with no contact and possible damage of protruding and low branches, also making possible easy access to areas with low openings. Nevertheless, the tiltable roll-bars lead to an incorrect and high-risky use of protection devices, because the ROPS is very frequently maintained in horizontal position [4]. The fitting of non-tiltable, low profile protective structure does not completely solve the problem, since an excessive overall height of the vehicle is maintained, due to the adoption of a traditional (mechanical) transmission system.

1.2 Agricultural machinery electrification

A considerable amount of pollutant emissions in agriculture sector comes from internal combustion engines (ICEs), in particular diesel engines, which are the most widespread power sources in the agriculture and forestry industries for moving self-propelled machinery and tractors [6].

The powertrain electrification represents one feasible solution to deal with fuel savings, emissions reduction and could bring other advantages in machine operating costs, efficiency, controls and functionality. Specifically, the major advantages of machinery electrification are torque and speed control, noise reduction, and a more flexible design. In fact electric drives represent a valuable option to simplify the layout of power transmission with consequent space saving, and a competitive option to replace hydrostatic powertrains, increasing efficiency with lower power losses [2].

Electrification enhances significantly the overall efficiency of the system through a smart management of the energy that is exchanged between the powertrain units [3].

In addition, electric systems could improve vehicle control accuracy and allow new functionalities, especially for autonomous and precision farming purposes [8].

Nowadays the powertrain electrification of a farming tractor can result in a diesel-hybrid electric tractor (HET) architectures, with series, parallel and mixed configurations, or full-electric (FET) drivetrain, used for battery (BETs) and fuel cell (FCETs) electric tractors [6].

HET architectures are proven to have comparable and even better performances than conventional architectures [9]. In particular, the parallel HET configuration performs better in terms of peak power, while the series HET configuration shows better overall performance and thus more fuel economy and a lower environmental impact of the vehicle. FETs certainly have the advantage of simplifying transmission, which can translate into greater simplicity in terms of construction. However, the following two main disadvantages prevent the widespread adoption of such a configuration: the high on-vehicle volume to meet the energy needs and lack of charging infrastructure in rural areas [10].

1.3 Objectives

To encourage agricultural machinery powertrain electrification and to improve the safety in tractor overturning, INAIL (Italian National Institute for Insurance against Accidents at Work) financed the project “Compact Tractor 4.0”, finalized to the development of a low-profile tractor with hybrid or full electric propulsion system able to support 4.0 technologies and equipped with a not-tiltable and not-foldable protective structure (ROPS), for protecting the operator in all working conditions. To assure also a proper ergonomic level, reference was made to the European regulation 1322/2014; more in detail concerning safety, ISO 4254-1 and OECD Codes 4 and 7 were taken into account.

The objective of the project is to set up a physical specimen of the tractor, with the following features:

- suitable for vineyard and orchard, featuring functions and performance similar to the most common models used in those production chains;
- narrow track width less than 1150 mm and compact profile (overall height not exceeding 1600 mm);
- equipped with a not-tiltable and not-folding ROPS;
- powered by a hybrid or full electric propulsion system;
- supporting Agriculture 4.0 technologies.

A possible prototype tractor sizing is shown in Figure 1, including that of the driver’s volume, according to safety and ergonomic constraints.

The preliminary design choices are listed below.

- 4-wheel drive to ensure the best traction pull capacity;
- BET (Battery electric tractor) configuration, consisting of a full-electric propulsion system and a rechargeable battery pack.
- transmission system based on two driving axles with differential, each equipped with an independent electric motor, to avoid a mechanical system linking the axles;
- likewise, power take-off powered by an independent electric motor;
- a battery with a capacity of about 20 kWh for energy storage (being the tractor prototype designed for demonstration purposes only).

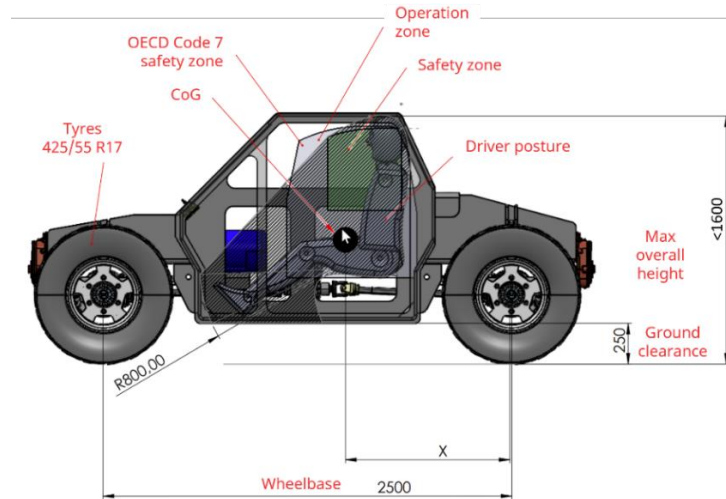


Figure 1: Lateral view of the tractor. Study of dimensions in function of space available for operator according to safety and ergonomic constraints.

This work aims to lay the foundations for the prototype design, ascertaining the typical features of a vineyard/orchard tractor, mainly in terms of power and traction pull needs, to carry out properly the most common tasks. The output of this step will be the basis for the complete development of the prototype.

2 Materials and methods

2.1 PTO power requirements

The most suitable dimensioning of tractor power system depends on the operations the machine has to perform. As a consequence, different working scenarios have been preliminary considered, involving a narrow-track tractor, equipped with a 74 kW engine, carrying out the main vineyard operations in a nearly-flat field. The power requirement has been defined quantifying the needs in terms of PTO, traction and hydraulic systems.

To detect the tractor main working parameters, the analysis of CANBUS data is a quite good solution [11]. The study carried out involved 6 orchard tractors, all with 74 kW max power and 408 Nm max torque, working for an entire year (1st May 2021- 30th April 2022) in a vineyard located in Tuscany (Italy). The tractors have been enhanced with a real-time data monitoring system, which added GPS information and provided an internet connection to upload CANBUS data to a fleet management server. Machinery data regarding engine speed and torque, travelling speed, oil and coolant temperatures and PTO running have been collected from the tractor's electronic control unit (ECU) with a frequency rate of 1 min.

2.2 Traction power requirements

To determine the power required for traction pull, a parametric analysis was conducted on a one degree-of-freedom vehicle model [1] with two driving axles. The analysis was performed using the programming and numerical calculation software Matlab.

$$\sum F_x = F_{xf} + F_{xr} - \frac{1}{2} C_{dt} \rho_{air} A_{ft} v^2 - mg \sin \alpha = ma \quad (1)$$

$$\sum F_y = F_{yr} + F_{yf} - mg \cos \alpha = 0 \quad (2)$$

$$\sum M_{z,t} = F_{xr}(h_G - h_{rw}) + F_{xf}(h_G - h_{fw}) + F_{yf}a - F_{yr}b = 0 \quad (3)$$

$$\sum M_{z,wr} = T_r - F_{yr}\delta - F_{xr}r = T_r - F_{yr}c_r r - F_{xr}r = 2 \frac{J_w a}{r} \quad (4)$$

$$\sum M_{z,wf} = T_f - F_{yf}\delta - F_{xf}r = T_f - F_{yf}c_r r - F_{xf}r = 2 \frac{J_w a}{r} \quad (5)$$

$$F_{xr} = \mu_s F_{yr} \quad (6)$$

$$F_{yf} = \mu_s F_{yf} \quad (7)$$

$$F_{xr} \leq c_a F_{yr} \quad (8)$$

$$F_{yf} \leq c_a F_{yf} \quad (9)$$

$$Hp: \frac{T_f}{T_f + T_r} = \frac{b}{a + b} = \frac{m_f}{m_f + m_r} \quad (10)$$

A list of variable used in force balance equations can be found In Table 1.

In Figure 2 is reported the model of the vehicle, in motion along the longitudinal direction, subject to the different types of forces considered in the balance: gravitational, aerodynamic, dynamic, contact, self-dislocation and friction forces.

The mathematical model is derived from the analysis of the longitudinal dynamics of the vehicle, and takes into account the equilibrium equations at translation in the longitudinal direction (of the forward motion) of the vehicle (1), in the vertical direction (perpendicular to the ground) of the vehicle (2), and rotational equilibrium with respect to the transverse axis (exiting from the longitudinal plane) of both the tractor body (3) and the wheels (4),(5) on the front and rear axle. The Coulomb friction model was adopted, described by eq.(6),(7),(8) and (9). The torque distribution between axles is supposed to be dependent on mass distribution of the vehicle, as described by eq.(10). Some assumptions, made about vehicle geometry, inertial and aerodynamic properties, are listed in Table 2. Other parameters, describing tyre-ground interaction and soil conditions, were defined, in addition to forward speed and slope intervals to describe two different working conditions of the tractor, summarized in Table 3.

By setting up all the balance equations and iterating on the variables forward speed and slope, it is possible to calculate the torque and power required to drive the front and the rear axle.

Table 1: List of variables from longitudinal dynamics analysis.

Name	Description	Name	Description
a	CoG-front axle longitudinal distance	J_w	Wheels moment of inertia
A_{ft}	Frontal area of the tractor	m	Overall mass of the vehicle
b	CoG-rear axle longitudinal distance	m_f	Static front axle load
c_a	Maximum static friction coefficient	m_r	Static rear axle load
C_{dt}	Drag coefficient of the tractor	$M_{z,t}$	Z moment acting on the tractor
c_r	Rolling resistance coefficient	$M_{z,wf}$	Z moment acting on front wheels
F_x	Overall longitudinal tractive force	$M_{z,wr}$	Z moment acting on rear wheels
F_{xf}	Front axle longitudinal tractive force	r	Wheel radius
F_{xr}	Rear axle longitudinal tractive force	T_f	Drive torque on the front axle
F_y	Overall vertical support force	T_r	Drive torque on the rear axle
F_{yf}	Front vertical support force	v	Vehicle forward speed
F_{yr}	Rear vertical support force	α	Slope angle
g	Gravity acceleration	δ	Vertical reaction offset
h_{fw}	Height of front wheel centre	μ_s	Static friction coefficient
h_g	Height of CoG	ρ_{air}	Air density
h_{rw}	Height of rear wheel centre	ω	Angular velocity of the wheel

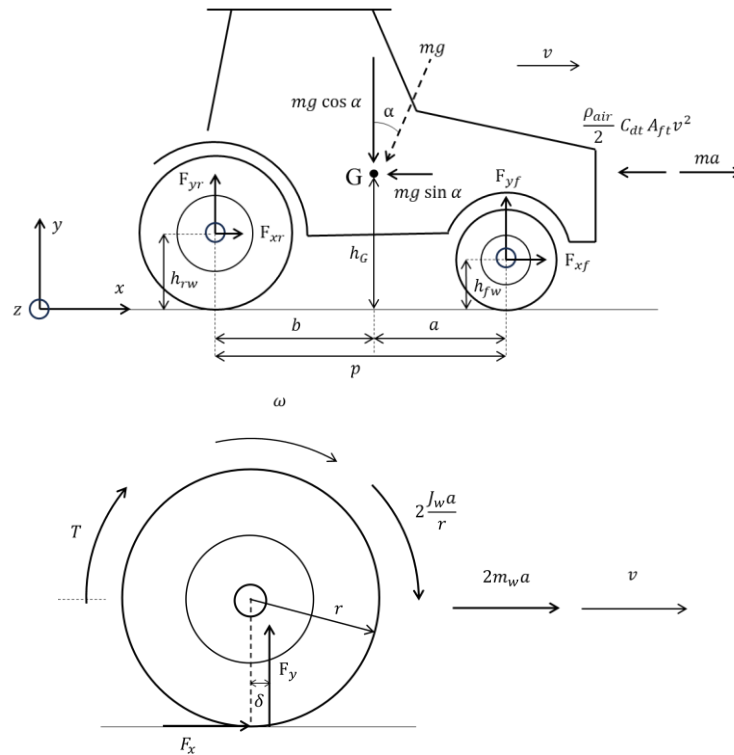
**Figure 2:** Scheme of force and moment acting on both the tractor and the wheels in the longitudinal plane.

Table 2: Sizing of the parameters concerning the dimensions and inertial and aerodynamic properties of the machine.

Symbol	Description	Value
m_v	Mass of the vehicle	2640 kg
m_e	Pulled equipment mass	1000 kg
m_b	Ballast mass	300 kg
p	Wheelbase	2500 mm
a	Distance of CoG from the front axle	1500 mm
b	Distance of CoG from the rear axle	1000 mm
h_G	Height of the CoG from the ground	760 mm
r_r	Wheel rolling radius	484 mm
A_f	Frontal area	1.75 m ²
C_d	Drag coefficient	1.5

Table 3: Parameters describing tyre-soil interaction, travelling speed and slope intervals used for the case study.

Case study		Dry paved road	Agricultural bare or grassy dry ground
c_r	Rolling resistance coefficient [-]	0.02	0.07
c_a	Maximum static friction coefficient [-]	1	0.5
v	Forward speed [km/h]	0÷40	0÷10
i	Slope [%]	0÷15	0÷30

3 Results

3.1 PTO power requirements

In Table 4 are reported different working scenarios, involving a narrow-track width tractor with a maximum power of 74 kW, carrying out the main vineyard operations in a nearly-flat field, defining power needs between traction, PTO and hydraulic systems.

The analysis of CAN-BUS data on tractors working in vineyards made possible to determine the parameters associated to each operation, to quantify the engine power need. In Figure 3 and Figure 4 are shown torque and power absorbed, engine, PTO and wheel speed, respectively for a 90 min mulching and a 70 min spraying operations.

The mulching was performed at about 5 km/h; a power absorption around 30-40 kW was recorded. On the other hand, the pneumatic spraying represents usually one of the most energy-consuming operations; in this case, a 50-70 kW of power need was registered, carrying out the operation at 7 km/h. In both cases the 540 rpm PTO was used, with the engine running at about 2000 rpm. These results confirmed the data already listed in Table 4.

Table 4: Power needs for traction, PTO and hydraulic systems, to carry out main vineyard operations using a narrow track tractor in a nearly-flat field.

Agricultural operation	Traction [kW]	PTO [kW]	Hydraulic system [kW]	Total [kW]
Defoliation	0	22	0	22
Pre-pruning	0	0	15	15
Suckering	0	0	4	4
Fertilizer mineral spreading	7	11	0	18
PPP mechanical spreading	11	22	0	33
PPP pneumatic spreading	10	40	0	50
Pruning	11	18	0	29
Grass mulching	11	15	0	26
Grape harvesting	11	22	4	37
Subsoiling	33	0	4	37
Ploughing	29	0	4	33
Harrowing	4	18	4	26

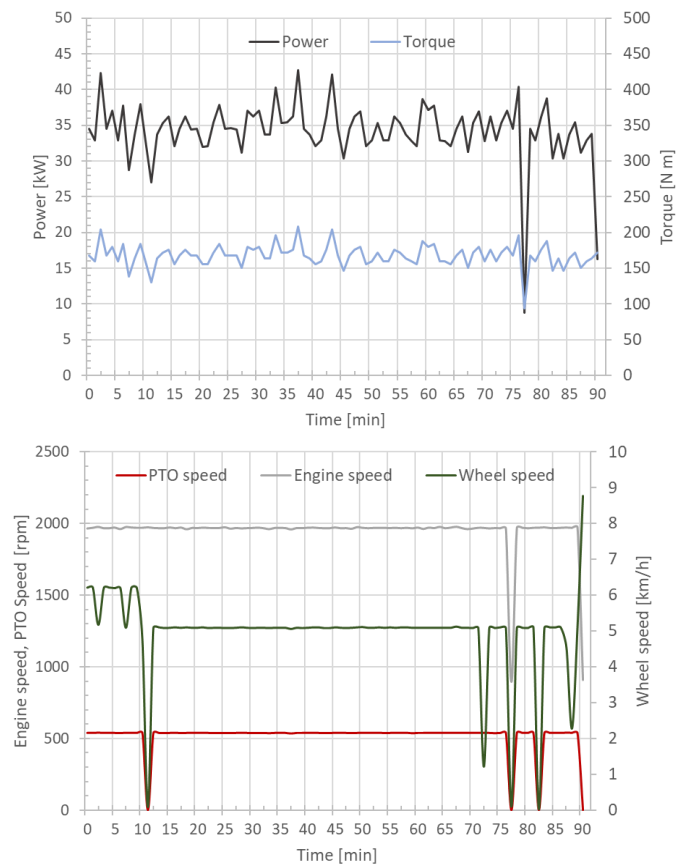


Figure 3: Main working parameters during mulching, lasted 90 minutes, in function of time.

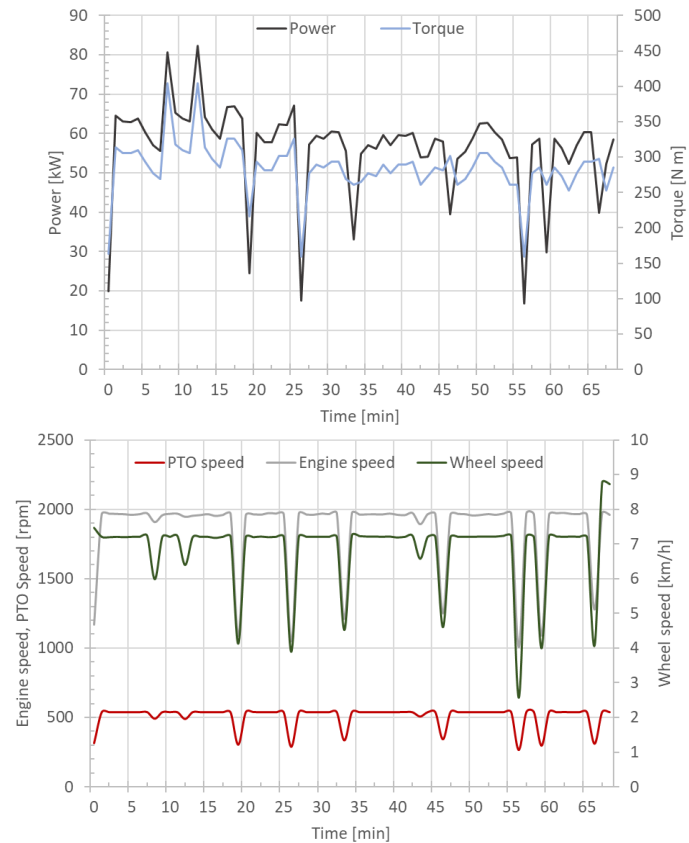


Figure 4: Main working parameters during a PPP pneumatic spreading, lasted 70 minutes, in function of time.

3.2 Traction power requirements

The parametric analysis carried out on Matlab led to the calculation of torque and power required for each axle, as a function of both speed and the slope. Two working situations were taken into account, the travelling on agricultural soil (Figure 5) and on the paved road (Figure 6).

When the tractor is travelling on the road, a motor of 30 kW on each axle would be sufficient to satisfy 77% of the travelling scenarios analyzed. Viceversa, if the tractor is travelling on agricultural soil, the same motors would be able to satisfy 100% of the scenarios. However, it's important to underline that, according to the friction model adopted, the slip conditions were never reached in explored case studies.

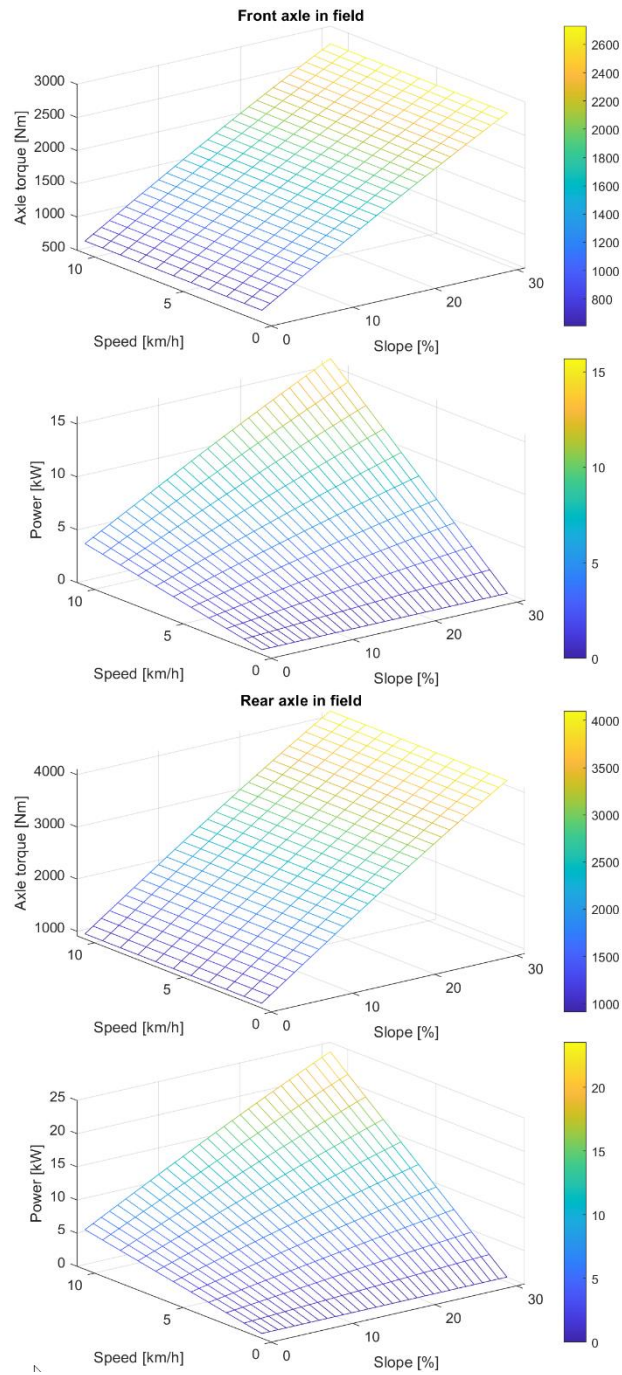


Figure 5: Front and rear axle torque and power need versus forward speed and slope, considering the vehicle travelling on a dry bare or grassy soil.

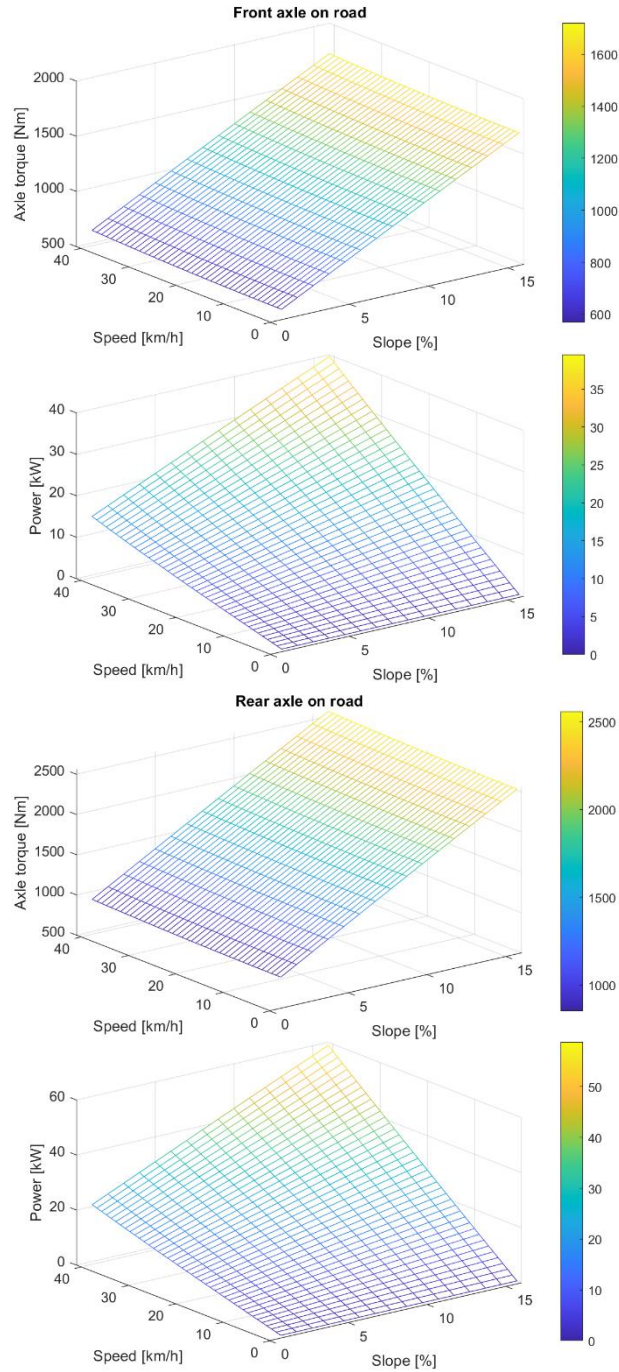


Figure 6: Front and rear axle torque and power need versus forward speed and slope, considering the vehicle travelling on a dry paved road.

4 Conclusions

This research provided the preliminary steps for the design of a low-profile orchard tractor with a full electric propulsion system. Design constraints were defined, concerning vehicle geometry and dimensions, functionality, field of application and safety requirements. Additional choices have been made, regarding transmission system layout and energy storage. Finally, by means of numerical simulations and analysing experimental data, power requirements to perform the desired tasks were then established. Future steps of this work should include:

- among the most suitable models available on the market, the selection of most suitable power transmission and traction-pull systems, according to power requirements defined in section 3;
- the modelling of the vehicle chassis via CAD 3D;
- the virtual prototyping of the ROPS through FEM analysis, to ensure that the elastic-plastic deformations of the protective structure during rollover are likely to keep the driver safe;
- the manufacturing and assembly of the prototype parts, that presumably will include sheet metal cutting, forming, metal profile cutting, welding and assembly of components;
- first preliminary lab and field tests, including the physical test of the ROPS and the study of the prototype concerning the vehicle stability and overturning risk;
- the fitting of the provided sensors and data acquisition systems, followed by extensive field tests, devoted to ascertain the general correct working of the tractor.

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