

[F] PhD Extended Abstract Form

SUSTAINABILITY OF AGRICULTURAL TRACTORS USAGE IN OPEN FIELD AND IN SPECIALIZED CROPS, FROM THE PERFORMANCE AND ENVIRONMENTAL STANDPOINTS

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Extended Abstract

Agricultural mechanization plays a key role in modern food production. However, it still relies largely on diesel-powered machinery, which raises concerns about energy efficiency, environmental impact, and operator health. Despite increasingly stringent emission standards for non-road vehicles, tractor performance under real operating conditions remains insufficiently understood. This is mainly due to the wide variability of agricultural uses.

This study addresses this gap by providing an integrated assessment of tractor sustainability based on realistic operating scenarios. A representative sample of tractors from the Italian fleet was analysed, considering differences in power, age, and emission stage. Experimental measurements of specific fuel consumption (SFC) and exhaust gas emissions were carried out.

The methodology accounts for different agricultural contexts by reproducing real working conditions in open-field cropping, viticulture, and orchard systems. These systems are characterized by distinct load profiles, power demands, and operating patterns.

Unlike conventional approaches based on full-load testing, this study focuses on partial-load conditions, which better represent actual tractor use in the field.

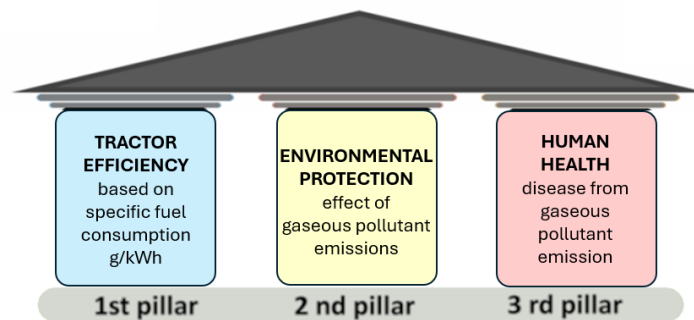


Fig.1- Conceptual representation of the three pillars used to assess tractor sustainability

Pillar 1: Energy efficiency. The aim of this analysis was to evaluate the energy efficiency of agricultural tractors under real working conditions, by comparing their performance within a representative vineyard production chain. The analysis was conducted within a vineyard production chain, considering representative field operations such as row and inter-row management, plant protection treatments, fertilization and mechanical harvesting under real working conditions. Four tractors were evaluated. They differed in typology, power, age and working hours, but performed the same tasks under comparable power requirements and partial-load conditions.

For each operation, efficiency was assessed through specific fuel consumption (SFC), expressed as fuel consumption per unit of power output (g/kWh). This approach allowed a normalized comparison between machines. The efficiency values were then weighted according to the estimated intensity of use of each operation within a representative vineyard farm. The farm was defined in terms of surface and annual workload, based on typical conditions of medium-sized vineyard farms in Northern Italy. This made it possible to evaluate performance at the level of the entire production chain rather than individual tasks.

The results highlight substantial variability in tractor performance, depending on both machine characteristics and working conditions. Differences in specific fuel consumption ranged from approximately 226 to over 303 g/kWh in vineyard operations, corresponding to variations exceeding 30% between tractors performing identical tasks (Fig.1). These findings

demonstrate that efficiency is strongly task-dependent and cannot be reliably inferred from nominal engine performance alone. They also highlight the need to optimize tractor use according to specific working conditions.

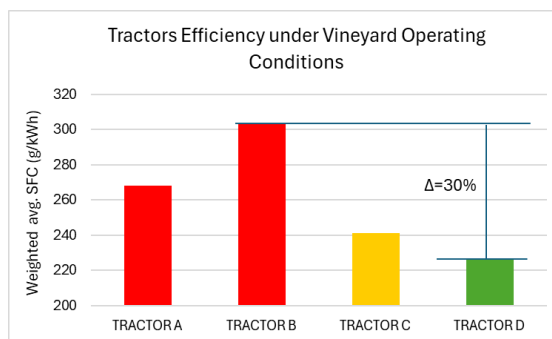


Fig.2- Weighted SFC over the production chain, accounting for operation frequency ($\Delta \approx 30\%$).

Pillar 2: Environmental impact. The aim of this analysis was to assess the environmental impact of agricultural tractors by quantifying gaseous emissions under real working conditions and evaluating their contribution along entire agricultural production chains. The study considered representative production chains, including open-field cropping (maize and forage), vineyard and orchard (apple). Each chain was characterized by a specific sequence of field operations over a full working season.

For each production chain, the main operations were identified, together with their frequency and duration, based on typical conditions of medium-sized farms in Northern Italy and considering representative farm size and crop distribution. The tractors analysed differed in architecture, age, emission standards and working hours, reflecting the heterogeneity of the Italian tractor fleet. They were evaluated under working conditions representative of real use.

Gaseous emissions (CO, HC, NOx and PM) were experimentally measured under steady-state conditions and expressed as emission factors (g/kWh), allowing comparison with current regulatory limits. These values were then combined with the estimated annual working time of each operation in order to evaluate total emissions and their distribution along each production chain.

The analysis revealed the presence of emission hotspots, directly linked to specific operations and working conditions. In the vineyard production chain, tasks such as soil management and fertilization were associated with increased emissions. These operations are typically characterized by higher load demands. The increase was particularly evident for NOx, with values reaching up to 22.67 g/kWh and particulate matter peaks of 1.37 g/kWh. When extended to a seasonal perspective, a limited number of operations accounted for a disproportionate share of total emissions (Fig.3). This result confirms the uneven distribution of emissions across field operations.

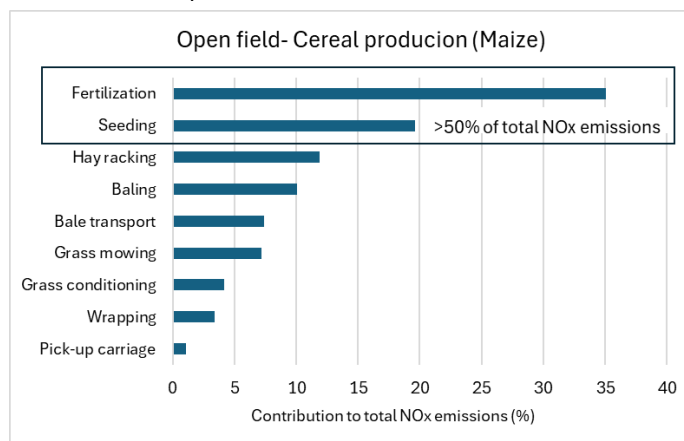


Fig.3 - Distribution of NOx emissions across field operations in the maize production chain.

This highlights the importance of identifying critical operations where targeted interventions can effectively reduce the overall environmental impact. Furthermore, tractors not compliant with recent emission standards (pre-Stage or older Stage levels) were shown to contribute more significantly compared to newer Stage-compliant machines.

Pillar 3: Operator health. The aim of this analysis was to investigate the potential health implications associated with tractor use in agricultural environments, with particular focus on operator exposure to exhaust emissions under real working conditions, based on a review of technical and medical literature.

The integration of technical and medical literature indicates that prolonged exposure to diesel exhaust can represent a relevant occupational risk for agricultural operators. This exposure occurs during field operations, often in close proximity to the exhaust outlet. It is particularly critical in areas with limited dispersion, such as vineyards and orchards. In addition, many specialized tractors are not equipped with enclosed cabins, resulting in limited protection from exhaust gases.

These findings confirm that exposure to exhaust emissions is associated with potential effects on the respiratory and cardiovascular systems, as well as with emerging evidence related to neurodegenerative conditions. The analysis also pointed out the lack of specific regulatory thresholds for occupational exposure in agricultural settings, identifying a critical gap in current standards.

By explicitly linking tractor performance to real working conditions, this work proposes a comprehensive framework for assessing the sustainability of agricultural tractors. The results provide actionable insights for improving tractor selection and management, enabling more efficient, lower-emission and safer agricultural operations. Ultimately, this work demonstrates that tractor sustainability cannot be defined by the machine alone, but by how it is used within agricultural production chains.

Final remarks concerning benchmarks and strength points of the the Pellizzi Prize 2026

Current benchmarks for agricultural tractors, such as OECD Codes, are mainly based on full-load testing and do not adequately represent real operating conditions. This work addresses this limitation by introducing a context-based evaluation framework that reproduces realistic scenarios across different agricultural production chains. The results show that tractor performance is strongly task-dependent, with efficiency differences exceeding 30% and more than 50% of total emissions concentrated in a limited number of operations. These findings also highlight the potential environmental and occupational implications of emission hotspots, particularly in terms of operator exposure. Overall, this work demonstrates that tractor sustainability cannot be defined by the machine alone but must account for how it is used in practice, providing a robust basis for improving efficiency, reducing emissions, and advancing sustainable agricultural mechanization.

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