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Article

Effect of Intake Water Injection on Fuel Efficiency and Performance of an Agricultural Diesel Engine

Antonina Kalinichenko [1,*], Dmytro Marchenko [2], Vasyl Hruban [2] and Vira Hovorukha [1]

[1] Institute of Environmental Engineering and Biotechnology, University of Opole, 45-040 Opole, Poland; vira.hovorukha@uni.opole.pl
[2] Department of Tractors and Agricultural Machines, Mykolayiv National Agrarian University, 54020 Mykolayiv, Ukraine; marchenkodd@mnau.edu.ua (D.M.); vasilgruban@ukr.net (V.H.)
* Correspondence: akalinichenko@uni.opole.pl

Abstract

The article presents the results of experimental investigations and regression-based analysis on the influence of a water injection system on the fuel efficiency and performance of diesel engines used in agricultural machine–tractor units. The need to improve fuel economy and operating efficiency is driven by increasing energy costs and the growing demand for more efficient agricultural machinery. The study focuses on the application of water injection into the intake manifold as a method for improving fuel consumption and engine operating performance under laboratory and field conditions. Experimental investigations were carried out on a Deutz 1000.3 W diesel engine under laboratory and field conditions. The engine was tested on a dynamometer, and field tests were performed using a Deutz-Fahr Agrolux 80 (SDF Group, Treviglio, Italy) tractor powered by the tested Deutz engine and coupled with an Amazone D9-20 Super (AMAZONEN-WERKE H. DREYER SE & Co., KG, Hasbergen-Gaste, Germany) seeder. The seeder was used as a trailed agricultural implement and did not have its own engine. The optimal water-to-fuel ratio was found to be 27–32%, ensuring a balance between increased engine power and reduced fuel consumption. The use of water injection reduced fuel consumption by 10–15%, increased effective engine power by up to 19%, and improved traction performance under field conditions. The novelty of this study lies in the adaptation and experimental evaluation of intake water injection for an agricultural diesel engine operating as part of a machine–tractor unit. Particular attention was paid to the relationship between the water-to-fuel ratio, fuel consumption, engine performance, and traction characteristics under laboratory and field conditions. The results demonstrate that water injection provides a cost-effective and technically feasible solution for improving fuel economy and operating performance of agricultural diesel engines without requiring significant modifications to existing designs. Potential environmental benefits may be associated with reduced diesel fuel consumption. However, emissions were not the main experimental focus of the present study and should be investigated separately in future work.

Keywords: diesel engine; intake water injection; agricultural tractor; fuel consumption; water-to-fuel ratio; traction performance; machine–tractor unit

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1. Introduction

Improving the fuel efficiency of agricultural diesel engines remains one of the key technical challenges in modern agricultural engineering. Machine and tractor units account for a substantial share of the total energy consumption in agricultural production, and the continuous increase in fuel prices directly affects the economic efficiency of crop cultivation and soil tillage operations. Conventional approaches to improving engine efficiency, including optimization of combustion chamber geometry and modernization of fuel injection systems, have largely reached their practical and technological limits [1].

Recent studies on thermodynamic analysis of fuel combustion and energy conversion systems also confirm that improvement of fuel-use efficiency remains an important research direction for modern power units. Such studies show that the overall efficiency of energy systems depends not only on the fuel type, but also on the organization of heat release, heat recovery, exergy losses, and operating mode. Therefore, for agricultural diesel engines, the search for technically simple methods that can reduce diesel fuel consumption under high-load operation remains relevant. In this context, intake water injection can be considered as one of the methods aimed at influencing the thermal conditions of the combustion process and improving the operating efficiency of the engine [2].

At the same time, internal combustion engines used in agricultural applications operate under severe and highly variable thermal and load conditions. This leads to increased fuel consumption, and accelerated engine wear. Therefore, there is a need to develop alternative technical solutions capable of reducing energy losses and improving the overall efficiency of the power unit without requiring fundamental structural modifications of existing engines.

One of the promising approaches is the application of water injection into the intake system of diesel engines. This method enables partial influence on the combustion process by changing the temperature conditions in the cylinder and improving charge preparation. In agricultural applications, the practical value of this approach is primarily related to reduced diesel fuel consumption and improved operating performance of the engine.

Recent journal studies confirm that intake or port water injection can significantly affect diesel engine performance, combustion development, fuel consumption, torque characteristics, and emissions [3–5]. Depending on the injection method and operating mode, the addition of water may influence brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), heat release characteristics, exhaust gas temperature, and NOx formation [6–9]. However, the reported effects are not always identical, because they depend on the water–fuel ratio, droplet size, injection pressure, nozzle location, engine load, and speed mode. Excessive water supply may worsen combustion stability or reduce the useful effect on fuel consumption. Therefore, optimization of the water–fuel ratio is especially important for agricultural diesel engines operating under variable traction load.

It should be noted that water injection is not a completely new method for internal combustion engines. This approach has been studied for many years and has been applied in different forms in automotive, high-performance, and stationary engines. However, the direct transfer of these solutions to agricultural diesel engines is limited by the specific operating conditions of machine–tractor units, including long-term operation under variable traction load, dusty field conditions, frequent changes in torque demand, and the need for simple and reliable dosing equipment.

However, despite the considerable number of studies devoted to water injection in internal combustion engines, the available experimental data remain limited and fragmented, particularly in the context of agricultural diesel engines operating under variable load conditions typical of real field applications [7–9]. Existing research is predominantly focused on automotive or stationary engines, which restricts the direct applicability of these findings to agricultural machinery.

For agricultural machine–tractor units, the influence of intake water injection should be evaluated not only by engine bench parameters, such as effective power, torque, BSFC,

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and BTE, but also by field operating indicators, including traction power, wheel slip, implement resistance, and fuel consumption during technological operations. This is important because an improvement in engine performance under laboratory conditions does not always lead to the same improvement in field operation, where the final result depends on soil–wheel interaction and traction limitations.

In this study, the engine was first investigated under controlled dynamometer conditions, after which the obtained engine performance trends were analyzed together with field data from the tractor–seeder unit. This organization was selected to separate the direct effect of intake water injection on engine performance from the combined field effect, where the result also depends on transmission mode, traction conditions, implement resistance, and wheel slip.

Therefore, the objective of this study is to evaluate the influence of intake water injection on the fuel consumption and performance of an agricultural diesel engine under dynamometer and field operating conditions. The novelty of the study lies in the adaptation and experimental evaluation of intake water injection for a tractor diesel engine operating as part of a tractor–seeder unit.

To achieve this objective, the study focuses on determining the influence of different water-to-fuel ratios on engine power and fuel consumption under dynamometer conditions, developing regression-based descriptions of the obtained experimental trends, and evaluating how the changes in engine performance are reflected in the field traction characteristics of the tractor–seeder unit.

2. Literature Review

Numerous studies have investigated methods for improving the efficiency of internal combustion engines, with particular emphasis on reducing specific fuel consumption [7–9]. Among the various approaches, the use of water as an additional working medium in diesel combustion has attracted considerable attention due to its potential to influence the thermodynamic process, fuel consumption, and overall engine performance. Similar effects have also been discussed for water-in-diesel emulsions, where the presence of water can affect diesel engine performance and fuel utilization [10]. Previous research has shown that water injection can enhance fuel utilization efficiency and contribute to changes in combustion temperature conditions and fuel consumption characteristics [3–5].

Recent studies on diesel engines have shown that intake or port water injection can affect several key performance and combustion indicators, including brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder temperature, heat release rate, ignition delay, and exhaust emissions. In general, the introduction of water into the intake air flow can reduce local combustion temperature and influence NOx formation; however, its effect on BSFC and BTE depends strongly on engine load, speed, water–fuel ratio, injection pressure, and atomization quality. Therefore, the use of water injection requires careful optimization rather than simple maximum water supply.

Previous experimental studies have shown that the introduction of water into the intake system, fuel mixture, or directly into the combustion chamber can influence the combustion process by changing the temperature regime, the rate of heat release, and the conditions of fuel–air mixture formation [11–13]. However, the magnitude of this effect depends strongly on the engine type, the method of water supply, the water-to-fuel ratio, the load mode, and the control strategy. Therefore, results obtained for automotive or stationary engines cannot be directly transferred to agricultural diesel engines without additional experimental verification.

For agricultural diesel engines, this issue is especially important because the engine rarely operates at one constant point. During field operations, the load is affected by soil resistance, implement working depth, wheel slip, field relief, and changes in travel speed. As a result, the same water–fuel ratio may have different effects under laboratory and field conditions. This explains the need to evaluate intake water injection not only by engine bench indicators such as power, torque, BSFC, and BTE, but also by traction and fuel consumption characteristics of the complete machine–tractor unit.

In the late 20th and early 21st centuries, leading automotive manufacturers, including BMW and Saab, developed and tested controlled water injection systems integrated into turbocharged gasoline and diesel engines. These investigations reported fuel savings of up to 15% [9]. In addition, commercially available systems such as Aquamist and Ecomax have been successfully applied in performance tuning and energy-saving applications, demonstrating the practical feasibility of this approach.

The experience of automotive manufacturers and commercial water injection systems confirms the technical feasibility of this approach. At the same time, these systems are generally designed for road vehicles or high-performance engines with different operating profiles compared with agricultural tractors. Agricultural machine–tractor units operate for long periods under traction load, and their engine load is strongly affected by soil resistance, implement working depth, wheel slip, and field conditions. This creates the need for separate experimental evaluation of water injection in agricultural applications.

Despite these advancements, the majority of existing research is focused on automotive or stationary engines, whereas studies addressing agricultural diesel engines operating under variable load and speed conditions remain relatively limited [7–9,14]. In agricultural applications, machine and tractor units operate under highly variable traction and thermal conditions, which significantly affect combustion stability, engine efficiency, and fuel consumption characteristics [14]. These specific operating conditions distinguish agricultural engines from conventional applications and require dedicated investigation.

Consequently, the influence of water injection on the performance of agricultural diesel engines remains insufficiently explored, and the available results are often fragmented or based on simplified assumptions. In particular, there is a lack of comprehensive experimental studies conducted under real field conditions, which limits the practical applicability of existing findings.

The research gap addressed in this study is the insufficient experimental substantiation of intake water injection for agricultural diesel engines operating as part of machine–tractor units. In contrast to automotive applications, this study considers not only engine bench characteristics but also the practical effect of water injection on fuel consumption and traction performance during field operation.

Thus, the present study is focused on the intake manifold water injection method, where water is supplied into the intake air duct before the working mixture enters the cylinders. This configuration was selected because it is structurally simpler than direct in-cylinder water injection and can be more easily adapted to agricultural diesel engines without major changes to the engine design. The analysis of previous studies also shows that the main unresolved issue is the selection of a rational water–fuel ratio that improves fuel efficiency and engine performance without reducing combustion stability under variable operating conditions.

In addition, previous studies mainly describe the effect of water injection at the engine level, while the practical transformation of these effects into tractor field performance is less clearly presented. For this reason, the present work separates engine dynamometer results, regression-based description of experimental trends, and field evaluation of the tractor–seeder unit. Such an organization makes it possible to distinguish between the direct influence of water injection on the Deutz engine and the combined field effect determined by the tractor, seeder, transmission mode, wheel slip, and soil conditions.

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Another issue that should be considered in intake water injection systems is the possible formation of a liquid film on the walls of the intake duct. When the injected droplets do not fully evaporate or remain non-uniformly distributed in the air flow, partial wall wetting may occur. The formation, fluctuation, and breakup of a liquid film can influence the uniformity of water distribution between cylinders and may affect combustion stability. Previous studies on droplet and liquid-film behavior have shown that local film thickness depends on droplet impact, pulsation, surface wetting conditions, and transient film breakup processes. Although the present study did not directly measure liquid film formation in the intake duct, this phenomenon should be considered as one of the limitations of simple intake water injection systems and as a direction for further research [15].

3. Equipment, Experimental Conditions and Test Procedure

3.1. Tested Engine and Machine–Tractor Unit

To evaluate the influence of water injection on the performance and fuel efficiency of diesel engines, a series of experimental investigations and regression-based analyses was conducted using a Deutz 1000.3 W engine (DEUTZ AG, Cologne, Germany), which is widely applied in agricultural tractors of class 1.4, including the Deutz-Fahr Agrolux 80 (SDF Group, Treviglio, Italy).

The tested engine was selected as a representative agricultural diesel engine used in tractors of the corresponding traction class. The field part of the study was performed using a Deutz-Fahr Agrolux 80 tractor coupled with an Amazone D9-20 Super (AMAZONEN-WERKE H. DREYER SE & Co. KG, Hasbergen-Gaste, Hasbergen, Germany) seeder. This combination was used to evaluate whether the changes observed during engine testing could be reflected in the traction and fuel consumption characteristics of a real machine–tractor unit.

The Deutz-Fahr Agrolux 80 tractor used in the field tests was powered by the tested Deutz 1000.3 W engine. The Amazone D9-20 Super seeder was used as a trailed agricultural implement and did not have its own engine. Therefore, the field tests were performed with a tractor–seeder unit, where the tractor provided the tractive power and the seeder created the working resistance during field operation. After the first full mention, the tested engine, tractor, and seeder are referred to as the Deutz engine, the tractor, and the seeder, respectively.

The main experimental parameters and operating conditions used in the laboratory and field tests are summarized in Table 1. This table was added to improve the clarity, reproducibility, and technical completeness of the experimental procedure.

Table 1. Main experimental parameters and operating conditions.

Parameter	Value/Description
Engine model	Deutz 1000.3 W diesel engine
Engine manufacturer	DEUTZ AG, Germany
Tractor model	Deutz-Fahr Agrolux 80
Implement used in field tests	Amazone D9-20 Super seeder
Water injection method	Intake manifold/port water injection
Nozzle location	In the intake air duct upstream of the intake manifold runners and before the intake valves
Water-to-fuel ratio	0%, 10%, 20%, 30%; additional preliminary points up to 40% for trend identification; rational range 27–32%

Table 1. *Cont.*

Parameter	Value/Description
Water supply pressure	Approximately 2 atm
Nozzle diameter	0.1–0.4 mm
Laboratory speed range	1400–2350 rpm
Maximum torque mode	1400 rpm
Rated operating mode	2350 rpm at rated load
Ambient temperature	20–30 °C
Atmospheric pressure	90–100 kPa
Fuel type	Commercial diesel fuel
Main measured parameters	Engine power, torque, crankshaft speed, diesel fuel consumption, traction force, engine load, operating speed
Test comparison	Baseline diesel operation and operation with intake water injection

3.2. Laboratory Test Equipment and Procedure

Laboratory tests were carried out using an electric dynamometric stand, Froude Hofmann AG150 Dynamometer (AVL (Froude Hofmann), Worcester, United Kingdom), equipped with data acquisition and control systems. The experimental program included measurements of engine power, torque, fuel consumption, and crankshaft rotational speed under various water-to-fuel ratios ranging from 0% to 30%. The optimal range of water supply was determined to be approximately 25–30% of the fuel mass flow rate [11]. Within this range, the most favorable combination of increased engine power and reduced specific fuel consumption was achieved without compromising engine stability.

The experimental program included measurements of engine power, torque, crankshaft rotational speed, and diesel fuel consumption under various water-to-fuel ratios ranging from 0% to 30%. The optimal range of water supply was determined to be approximately 25–30% of the fuel mass flow rate [11]. Within this range, the most favorable combination of increased engine power and reduced specific fuel consumption was achieved without compromising engine stability.

The experimental program included the measurement of the main engine and traction parameters required to evaluate the influence of intake water injection on the operation of the engine and the tractor–seeder unit. During laboratory tests, engine power, torque, crankshaft speed, and diesel fuel consumption were recorded. During field tests, fuel consumption, traction force, engine load, and operating speed of the tractor–seeder unit were measured.

The laboratory tests were conducted to determine the influence of water injection on engine power, torque, and diesel fuel consumption under controlled operating conditions. The tests included baseline operation without water injection and operation with different water-to-fuel ratios. This made it possible to compare the engine response under identical speed and load conditions.

Laboratory experiments were performed in a ventilated test room at an ambient temperature of 20–30 °C. Atmospheric pressure ranged from 90 to 100 kPa (675–760 mm Hg). Key engine operating parameters, including torque, crankshaft speed, and fuel consumption, were measured simultaneously. The duration of each fuel consumption measurement was not less than 30 s. The experiments were conducted in accordance with ISO 3833:1977 and ISO 3780:2009 standards [16,17].

Laboratory testing of the engine was also organized with consideration of ISO 3046-1:2002 requirements for reciprocating internal combustion engines [18]. During each test series, ambient temperature and atmospheric pressure were recorded because these parameters influence engine power and fuel consumption. Fuel consumption was determined by measuring the diesel fuel mass flow rate over a fixed time interval of not less than 30 s. The measured fuel consumption values were then used to calculate specific fuel consumption as a function of effective engine power. Since the tests were carried out within a limited range of recorded ambient conditions, the obtained results were interpreted for the stated test conditions without extrapolation beyond the investigated range.

The laboratory part of the study included two groups of measurements. First, stabilized engine operating points were used to evaluate the effect of water-to-fuel ratio on effective power. Second, engine speed characteristics were obtained over the investigated speed range from 1400 to 2350 rpm. These data were later used for regression-based approximation of the engine performance trends.

To improve measurement reliability, the MotoDoc III diagnostic system developed by QUANTEX Laboratory (Figure 1) was used in parallel. The system was connected to the tested engine using a set of dedicated sensors and connecting cables.

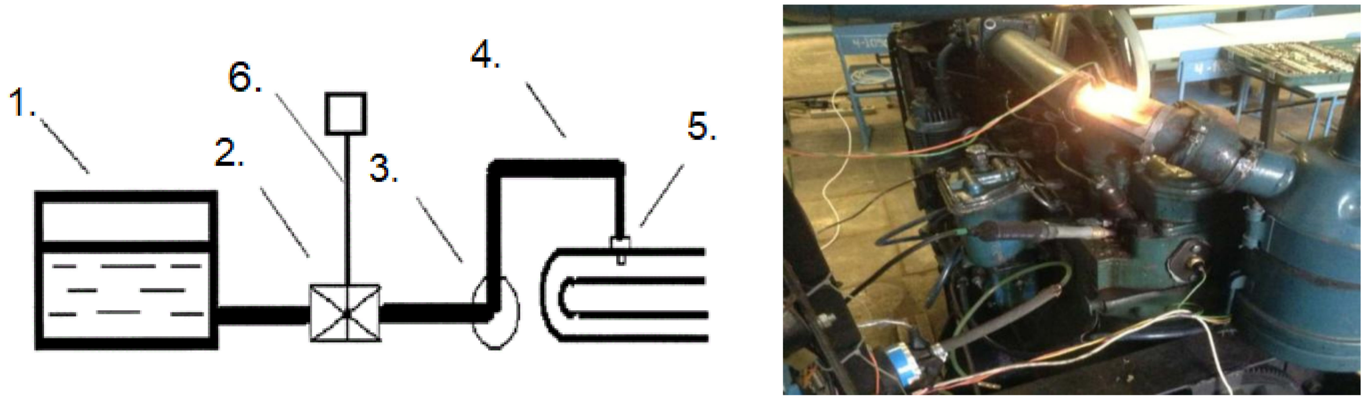

Figure 1. Schematic of the water injection system applied to the Deutz 1000.3 W engine:1—water storage tank; 2—metering ball valve; 3—centrifugal pump; 4—high-pressure water line; 5—injector nozzle; 6—mechanical connection with the fuel control rail.

3.3. Field Test Conditions

Field tests were conducted using an experimental machine–tractor unit consisting of a Deutz-Fahr Agrolux 80 tractor and an Amazone D9-20 Super stubble seeder (Amazone-Werke H. Dreyer GmbH & Co. KG, Germany). During traction operations, real-time measurements of fuel consumption, traction force, and engine load were recorded.

The field tests were conducted with the tractor powered by the tested Deutz engine and coupled with the seeder. The seeder was a trailed implement; therefore, it did not generate power independently and did not have its own engine. The measured field response was determined by the interaction of the tractor engine, transmission, driving wheels, soil conditions, and seeder working resistance.

The field tests were used to verify the practical effect of intake water injection during traction operation. During these tests, the machine–tractor unit operated under field conditions with the same technological implement. The main measured parameters were diesel fuel consumption, traction performance, engine load, and operating speed. The field results were compared with the laboratory results to determine whether the improvement in engine characteristics was reflected in the operation of the tractor–seeder unit.

Unlike the laboratory tests, the field tests reflected the combined influence of engine operation, soil–wheel interaction, implement resistance, and traction conditions. Therefore, the field part of the study was used not only to confirm changes in engine performance but also to evaluate how these changes affected the practical operation of the tractor–seeder unit.

3.4. Studied Operating Cases

The studied operating cases used during the laboratory and field tests are summarized in Table 2.

Table 2. Studied operating cases during laboratory and field tests.

Case	Operating Mode	Water-to-Fuel Ratio	Purpose
1	Baseline diesel operation	0%	Reference mode for comparison
2	Intake water injection	10%	Evaluation of low water supply
3	Intake water injection	20%	Evaluation of medium water supply
4	Intake water injection	30%	Evaluation of high water supply
5	Additional preliminary engine points	up to 40%	Identification of the power trend and verification that excessive water supply was not beneficial
6	Field tractor–seeder operation	Rational range determined from laboratory tests	Verification under field traction conditions

3.5. Intake Water Injection System

The water supply system consisted of a storage tank (1) connected to a dosing ball valve (2), which was mechanically linked to the fuel control system. The position of the valve was adjusted according to the position of the fuel rail, allowing regulation of the injected water flow within a range corresponding to 0.1–0.4 mm displacement. The injector was located in the intake air duct upstream of the intake manifold runners and before the intake valves, ensuring effective atomization and mixing of the injected liquid with the intake air.

The injector was installed in the intake air duct in such a way that the injected water could mix with the intake air before entering the cylinders. The selected nozzle diameter was intended to ensure fine atomization and stable mixing of water with the air flow. The system was designed as a simple mechanically controlled dosing system suitable for agricultural applications, where reliability and ease of maintenance are important.

In the present study, intake manifold water injection was used. Water was injected into the intake air duct after air filtration and before the air entered the intake manifold runners and intake valves. The injector nozzle was placed in the intake air stream to provide atomization and mixing of water droplets with the incoming air before the charge entered the cylinders. The system did not use direct in-cylinder water injection. This solution was selected because it can be adapted to agricultural diesel engines without major modifications to the cylinder head, fuel injection system, or combustion chamber.

Only water was injected during the experiments. No alcohol or water–alcohol mixture was used in this study. Therefore, the system is described as an intake water injection system throughout the revised manuscript.

Figure 1 illustrates the configuration of the intake water injection system used in the study. The scheme shows the storage tank, metering valve, centrifugal pump, high-pressure line, injector nozzle, and mechanical connection with the fuel control rail. This arrangement explains how the water supply was linked to engine fuel demand and why the system should be considered a proportional mechanical dosing system rather than a fully electronic closed-loop system.

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The operating principle of the system is as follows. The water is supplied from the storage tank (1) to the metering ball valve (2), which is mechanically linked to the fuel rail (6) of the engine. Depending on the position of the fuel rail, the valve regulates the flow rate of the injected water, enabling its supply in varying volume and mass fractions.

The water then enters the centrifugal pump (3), which generates an operating pressure of approximately 2 atm. Subsequently, the pressurized water is delivered through the high-pressure line (4) to the injector nozzle (5), located in the intake air duct upstream of the intake manifold runners and before the intake valves. The nozzle has a diameter of 0.1–0.4 mm, which ensures fine atomization of the injected water.

The selected nozzle diameter allows the formation of small droplets, which improves dosing accuracy and promotes efficient mixing of the injected water with the intake air. The location of the injector in the intake air duct before the intake manifold runners further enhances the uniform distribution of the water droplets within the air stream.

3.6. Control of the Water-to-Fuel Ratio

The water-to-fuel ratio was controlled by adjusting the position of the metering valve mechanically linked to the fuel control rail. Under steady-state laboratory conditions, the required water supply level was set before each measurement point and verified by measuring the mass flow rates of diesel fuel and injected water. Therefore, the system provided proportional mechanical dosing rather than fully electronic closed-loop control.

Under transient field conditions, short-term deviations of the water-to-fuel ratio were possible due to rapid changes in engine load and fuel supply. For this reason, the field test results were analyzed as average values obtained during stabilized operating intervals. This limitation is important for the interpretation of the results and indicates the need for further development of electronically controlled water injection systems for agricultural diesel engines.

The selected control approach was sufficient for comparing stabilized operating modes under laboratory and field conditions. However, it should be noted that the system did not provide independent control of injection timing, droplet size, or closed-loop correction based on exhaust gas parameters. Therefore, the obtained results characterize the effectiveness of a simple intake manifold water injection system with proportional mechanical dosing.

The water-to-fuel ratio was calculated as the ratio of the injected water mass flow rate to the diesel fuel mass flow rate at the corresponding stabilized operating point. During transient field operation, this ratio could deviate from the set value because the system was mechanically linked to the fuel control rail and did not include electronic feedback control.

3.7. Diesel Fuel and Measurement Conditions

Commercial diesel fuel was used during all laboratory and field tests. The same fuel batch was used throughout the experimental program to avoid the influence of fuel composition on the comparison of the tested operating modes. No biodiesel, alcohol-containing diesel blend, or additional fuel additive was used. The comparison of the tested cases was therefore based on the same diesel fuel properties and different water-to-fuel ratios. The main diesel fuel parameters used in the study are presented in Table 3.

The experimental program was organized as a sequence of two connected stages. The first stage consisted of laboratory dynamometer tests of the Deutz engine. These tests were used to determine the direct influence of intake water injection on engine power, torque, crankshaft speed, and diesel fuel consumption under controlled and repeatable conditions. At this stage, different water-to-fuel ratios were compared, and the rational range of water supply was identified as 27–32% of the diesel fuel flow, with the most stable positive effect observed close to 28–30%.

Table 3. Diesel fuel parameters used in the study.

Parameter	Value
Fuel type	Commercial diesel fuel
Lower heating value	42.5 MJ/kg
Density at 15 °C	820–845 kg/m^3
Cetane number	not lower than 51
Biodiesel or alcohol additive	not used

The second stage consisted of field tests of the tractor–seeder unit. In this stage, the rational water-to-fuel ratio determined during laboratory testing was applied to the tractor operating with the seeder under real agricultural traction conditions. The purpose of the field stage was not to repeat all laboratory speed-load points, but to verify whether the engine-level improvements obtained on the dynamometer could be reflected in the practical operation of the machine–tractor unit.

Thus, the laboratory tests characterized the direct response of the engine to intake water injection, whereas the field tests characterized the combined response of the tractor–seeder unit. This combined response depended not only on engine performance, but also on transmission mode, implement draft, wheel slip, soil resistance, and operating speed. Such a two-stage experimental structure makes it possible to connect the controlled engine results with the practical performance of the machine–tractor unit under field conditions.

4. Results and Discussion

The analysis of the obtained laboratory and field data was focused on the parameters directly measured and evaluated in this study: effective engine power, torque, diesel fuel consumption, traction performance, and operating behavior of the tractor–seeder unit. Since emissions and detailed combustion diagnostics were not included as separate experimental outcomes, the discussion of environmental effects is limited to potential indirect benefits associated with reduced diesel fuel consumption.

The results are presented in four main stages. First, the engine dynamometer results are analyzed to determine the direct influence of intake water injection on engine power and fuel consumption. Second, regression-based relationships are used to describe the experimental trends within the investigated operating range. Third, field tests of the tractor–seeder unit are considered to evaluate whether the dynamometer-observed changes are reflected under agricultural operating conditions. Finally, the traction performance of the tractor–seeder unit is discussed separately because it depends not only on engine output but also on transmission mode, wheel slip, soil conditions, and implement resistance.

4.1. Engine Dynamometer Research

Laboratory testing of the Deutz engine was conducted in accordance with ISO 3046-1:2002. The performance characteristics of the engine were determined for different levels of water supply to the intake system under a range of operating conditions [19]. The experimental investigation covered a crankshaft speed range from 1400 rpm, corresponding to the maximum torque mode, to 2350 rpm, corresponding to the rated operating mode.

The determination of engine characteristics was performed over the investigated speed range under stabilized operating conditions, which had been previously identified during preliminary tests. The experiments were initially conducted without water injection (baseline operation on pure diesel fuel), followed by tests with water injection into the intake manifold. The water supply was varied stepwise in increments of 10% relative to the fuel flow rate, with a maximum level of 30% in the main comparative test program. Additional preliminary points up to 40% water supply were also recorded to identify the trend of engine power and to verify whether further water addition was beneficial. The corresponding results are presented in Figure 2.

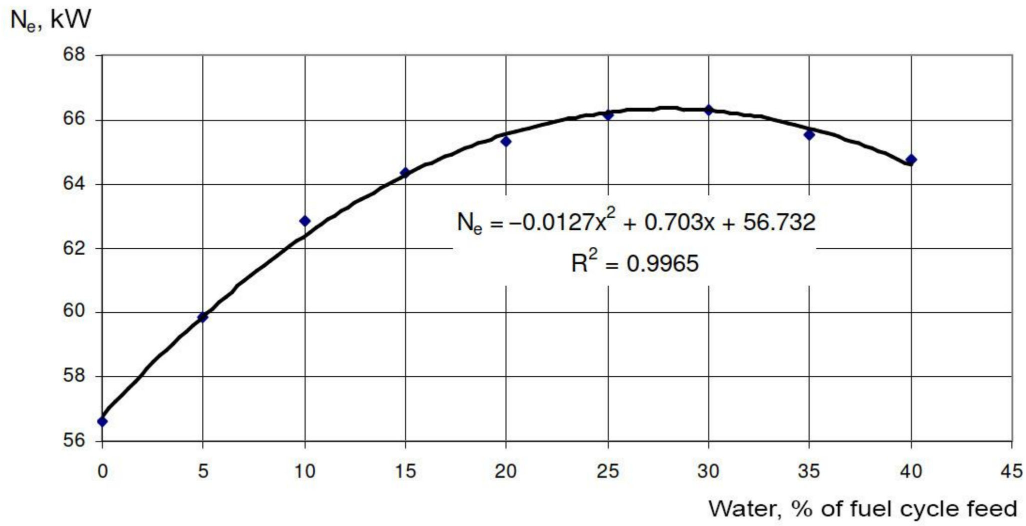

Figure 2. Effect of water injection rate on engine power of the Deutz 1000.3 W engine.

Figure 2 corresponds to a stabilized engine operating point at the rated operating mode. The figure shows the influence of the water–fuel ratio on the effective power of the Deutz engine. The curve demonstrates that increasing the water supply from 0% to approximately 28–30% of the diesel fuel cycle supply leads to a gradual increase in effective engine power. Further increase in water supply up to 40% does not provide additional improvement and indicates the beginning of a decrease in the useful effect. Therefore, the main test program was limited to 0–30%, while the additional 35–40% points were used only to identify the general trend.

The difference between the points around 25–30% water supply and the neighboring points should be interpreted with consideration of measurement uncertainty. Since the available repeated measurements were not sufficient to calculate full 95% confidence intervals for every point, Figure 2 presents the measured values and the fitted trend line. This limitation was considered when selecting the rational range of water supply rather than relying on a single maximum point.

Based on the obtained results, the optimal water injection rate was determined to be approximately 28% of the diesel fuel cycle supply.

This finding is generally consistent with previous experimental results reported in the literature, according to which the rational water supply level for diesel engines is usually close to one-third of the fuel supply. However, the exact value depends on engine design, operating mode, water atomization quality, and the method of water-to-fuel ratio control [14].

At this stage of the research, it can be concluded that the optimal water injection level is approximately 30% of the diesel fuel cycle supply, corresponding to about 17–19 mg/cycle at the rated operating mode of the Deutz 1000.3 W engine, i.e., at the rated crankshaft speed and rated load used during the laboratory test program.

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4.2. Development of Regression Models and Full-Load Speed Characteristics

The experimental data were further analyzed using regression methods, and the obtained relationships describing the influence of water injection on engine performance parameters were found to be statistically significant at a confidence level of not less than 95% [20]. Based on these results, the full-load speed characteristics of the experimental Deutz 1000.3 W engine equipped with the water injection system were determined (Figure 3).

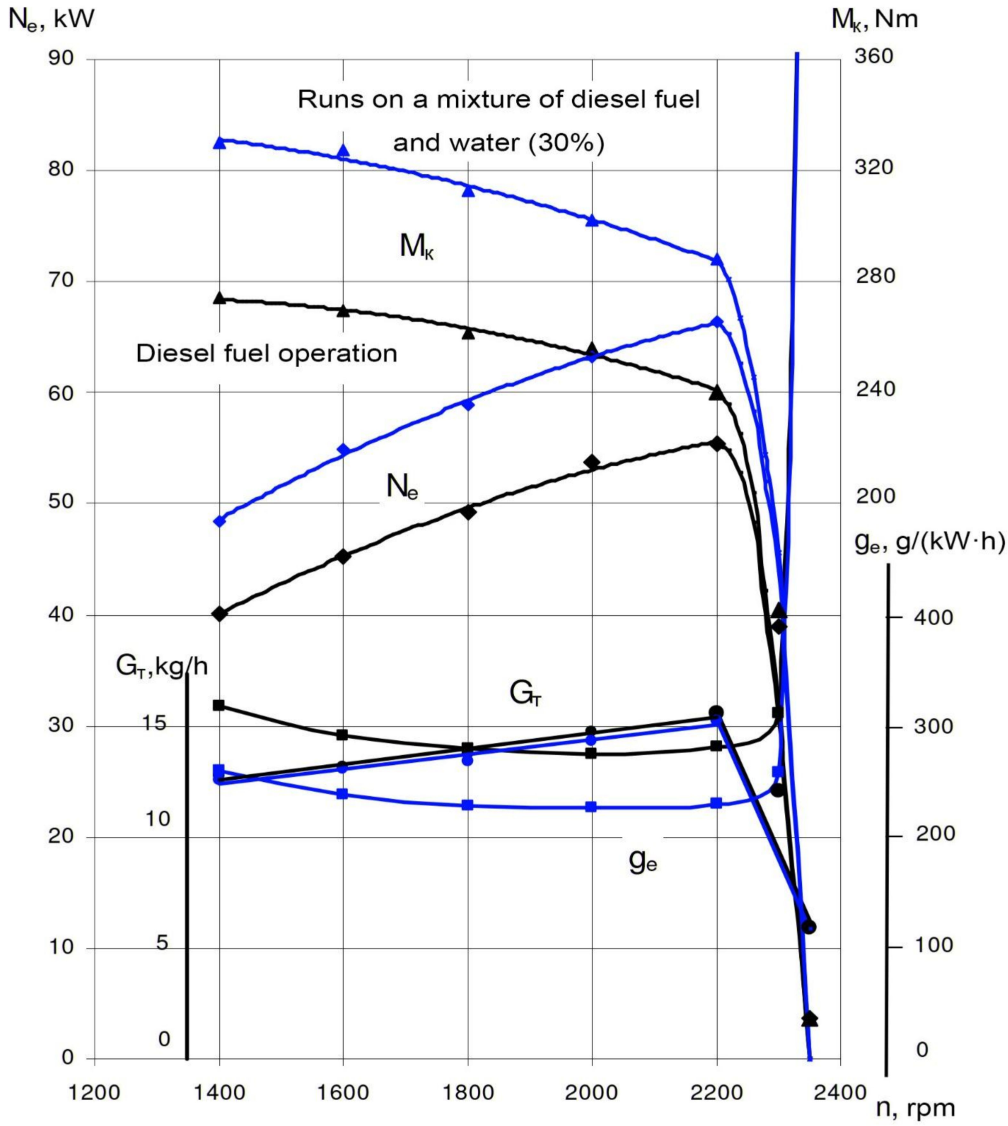

Figure 3. Full-load speed characteristics of the Deutz 1000.3 W engine with and without water injection.

In this study, the term full-load speed characteristic refers to the dependence of effective engine power, torque, hourly fuel consumption, and specific fuel consumption on crankshaft speed under full-load or near full-load operating conditions. This term is used instead of "external speed characteristic" to make the meaning clearer for readers.

Regression analysis was used not as an independent theoretical model, but as a tool for approximating the experimental relationships and describing the trends obtained under different operating modes. The main input variables used in the approximation were water–fuel ratio, crankshaft speed, effective engine power, and torque, depending on the analyzed characteristic. The coefficient of determination R^2 was used to evaluate the quality of approximation. The regression relationships were applied only within the investigated experimental range and were not intended for extrapolation beyond the tested operating conditions.

Figure 3 was generated using the experimental engine data and regression-based approximation of the measured trends. Therefore, it should be interpreted as a fitted representation of the full-load speed characteristics of the engine rather than as a set of raw measurement points only. Where possible, the scatter of experimental data was considered during approximation; however, separate experimental error bars are not shown because the figure represents regression-based characteristics.

The analysis of the obtained characteristics indicates that the overall engine power of the standard and modified configurations remained comparable. The observed discrepancies, which did not exceed 5%, can be attributed to measurement uncertainties, variations in crankshaft rotational speed, and minor instabilities in the operation of the control system, including mechanical clearances and dynamic effects in the fuel injection mechanism [21].

The relatively small influence of water injection on the fuel delivery system can be explained by the mechanical linkage between the fuel injection pump and the engine crankshaft, which ensures that the cyclic fuel supply remains governed by the engine operating mode rather than by the composition of the intake mixture. Since the injected water is introduced into the intake manifold and does not directly affect the fuel injection system, its influence on fuel dosing is indirect [22].

At the same time, the application of water injection resulted in a noticeable increase in effective engine power. Under rated operating conditions, the power increased by about 10.8 kW, or 19.6%, while in the maximum torque mode the increase reached about 8.2 kW, or 20.5%.

Figure 3 compares the full-load speed characteristics of the engine during baseline diesel operation and operation with intake water injection. The graph shows that the engine equipped with the water injection system provides higher effective power and torque over the main operating speed range. This is important for agricultural tractors because field work is usually performed under variable load conditions, where the engine must maintain sufficient torque reserve. The increase in torque and power indicates that the selected water–fuel ratio can positively affect engine performance not only at a single operating point but across a wider range of crankshaft speeds.

A noticeable increase in engine torque was observed. Under rated operating conditions, the torque increased by about 47.1 Nm, or 19.6%, while in the maximum torque mode the increase reached about 56.2 Nm, or 20.5%.

4.3. Fuel Consumption Characteristics from Dynamometer Testing

Based on the obtained experimental data and the analysis of engine performance characteristics, a combined characteristic of the Deutz 1000.3 W engine was developed to evaluate diesel fuel consumption as a function of effective engine power (Figure 4).

The analysis of the obtained relationships indicates that the experimental data can be described by linear regression models with a confidence level of approximately 99% [23]. Under conditions of water injection exceeding 30% of the fuel cycle supply, the average reduction in diesel fuel consumption reached up to 36 g/kW·h of effective power.

Figure 4 presents the relationship between diesel fuel consumption and effective engine power for two operating modes: baseline diesel operation and operation with intake water injection. The slope of the regression line for the water injection mode is lower than that for baseline diesel operation, which indicates a reduction in diesel fuel consumption per unit increase in effective power. This result confirms the main objective of the study, namely the evaluation of intake water injection as a method for improving fuel economy of an agricultural diesel engine.

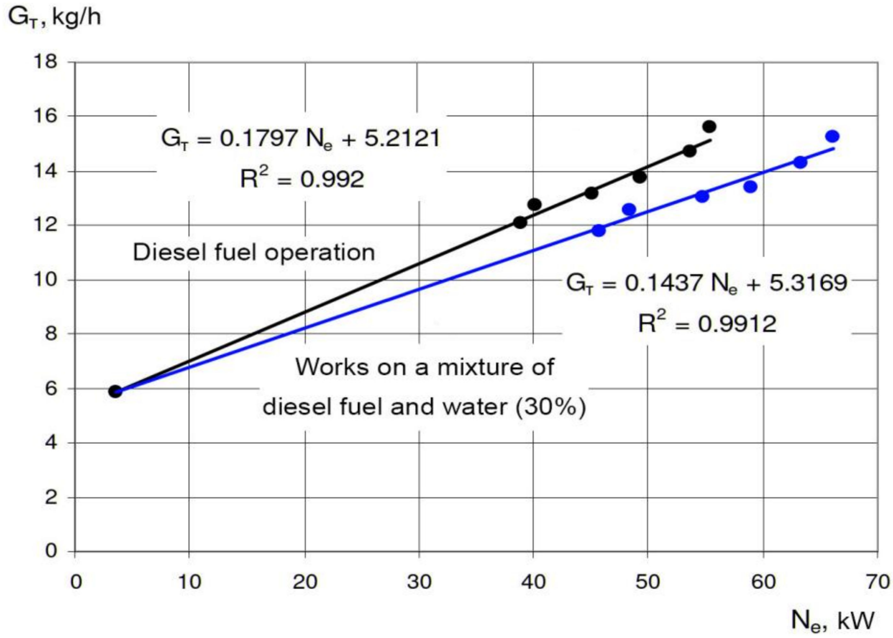

Figure 4. Fuel consumption as a function of effective engine power for the Deutz 1000.3 W engine.

The data points in Figure 4 correspond to experimental measurements obtained during dynamometer testing. At lower power levels, the difference between baseline operation and water injection is relatively small, which is expected because the positive effect of water injection is usually more pronounced at higher load. As engine power increases, the difference between the regression lines becomes more visible, indicating that intake water injection has a stronger effect under higher-load operation. Experimental error bars are not shown because the available repeated measurements were not sufficient to calculate reliable 95% confidence intervals for all points; therefore, the graph should be interpreted together with the regression trends and the reported measurement conditions.

4.4. Field Testing of the Tractor–Seeder Unit

The field tests were based on the rational water supply range obtained during the dynamometer stage. Therefore, the field experiment was designed as a practical verification of the laboratory results rather than as an independent set of unrelated operating points. This approach allowed the effect of intake water injection to be evaluated at two levels: first at the engine level and then at the level of the complete tractor–seeder unit.

The traction performance of the machine–tractor unit was analyzed separately from the engine bench characteristics. This was necessary because the effect of increased engine power under field conditions depends not only on engine operation but also on soil–wheel interaction, wheel slip, implement resistance, and load transfer during field work.

The field tests were performed with the tractor coupled to the seeder. The seeder was a trailed agricultural implement without its own engine; therefore, it did not generate power independently. All changes in fuel consumption and traction performance were associated with the tractor engine and with the interaction between the tractor, seeder, transmission, driving wheels, and soil. Thus, any improvement in field performance should not be interpreted as a change in the mechanical properties of the seeder or its support wheels.

To extend the range of analyzed operating conditions and reduce the cost and time required for experimental studies, mathematical modeling was applied based on the results of both experimental investigations. As a result, the traction characteristics of the Deutz-Fahr Agrolux 80 tractor were determined for two configurations: a standard Deutz 1000.3 W engine and the same engine equipped with a water injection system in the intake manifold.

The development of traction characteristics was based on experimental data obtained during the main testing program, as well as additional tests conducted to determine the maximum traction force. The experimental design was implemented using the method of active experimentation based on a Box–Behnken design. The input data for modeling included parameters describing the slip characteristics of the tractor under varying operating conditions.

The purpose of the traction modeling was to extend the interpretation of the experimental engine results to the operating conditions of the complete machine–tractor unit. The regression models were used to approximate the relationship between traction force, wheel slip, gear number, and drawbar power. The main statistical criterion used to assess the quality of the approximation was the coefficient of determination R^2. Therefore, the regression analysis served as a supporting tool for interpreting field performance trends and did not replace the experimental measurements.

Figure 5 was developed using field traction test data and regression approximation of the measured traction characteristics. Therefore, the figure should be interpreted as a fitted representation of field performance trends rather than as raw experimental data only. The absence of a clear effect in the lower transmission numbers may be related to the limited statistical significance of the difference at lower drawbar power values and to the stronger influence of traction limitations and wheel slip.

According to ISO 15550:2002 [24], the maximum traction force is defined as the maximum horizontal force at the coupling point, corresponding to the onset of unstable engine operation and the limiting value of wheel slip. This definition was used as the basis for evaluating the traction performance of the tractor.

The results indicate that the application of a water injection system in the intake manifold of the Deutz 1000.3 W engine leads to an improvement in the traction characteristics of the Deutz-Fahr Agrolux 80 tractor, as illustrated in Figure 5.

Figure 5 shows the traction characteristics of the tractor–seeder unit with the standard engine configuration and with intake water injection. The curves demonstrate that the positive effect of increased engine power becomes more visible in higher gear ranges, where the tractor is able to convert a larger part of the available engine power into useful drawbar power. In lower gears, the difference between the two configurations is smaller because the operation is limited mainly by traction conditions and wheel slip rather than by engine power. This confirms that field performance cannot be evaluated only from engine bench data and must be analyzed at the machine–tractor unit level.

An analysis of the traction characteristics of the Deutz-Fahr Agrolux 80 tractor indicates that, under the investigated operating conditions, the shape of the traction force curves remains generally smooth and stable. As a result, the differences observed between the standard engine and the engine equipped with the water injection system are relatively small under certain field conditions.

This explains the limited differences observed during field testing of the seeding unit consisting of the Deutz-Fahr Agrolux 80 tractor and the Amazone D9-20 Super stubble seeder, when comparing configurations with and without water injection.

In most operating cases, the performance of the seeding unit was influenced not only by engine characteristics but also by traction and soil conditions. However, the results of the experimental study indicate that the most pronounced effect of water injection is observed under nominal load conditions and during engine operation in higher gear ranges, corresponding to typical working regimes in field applications.

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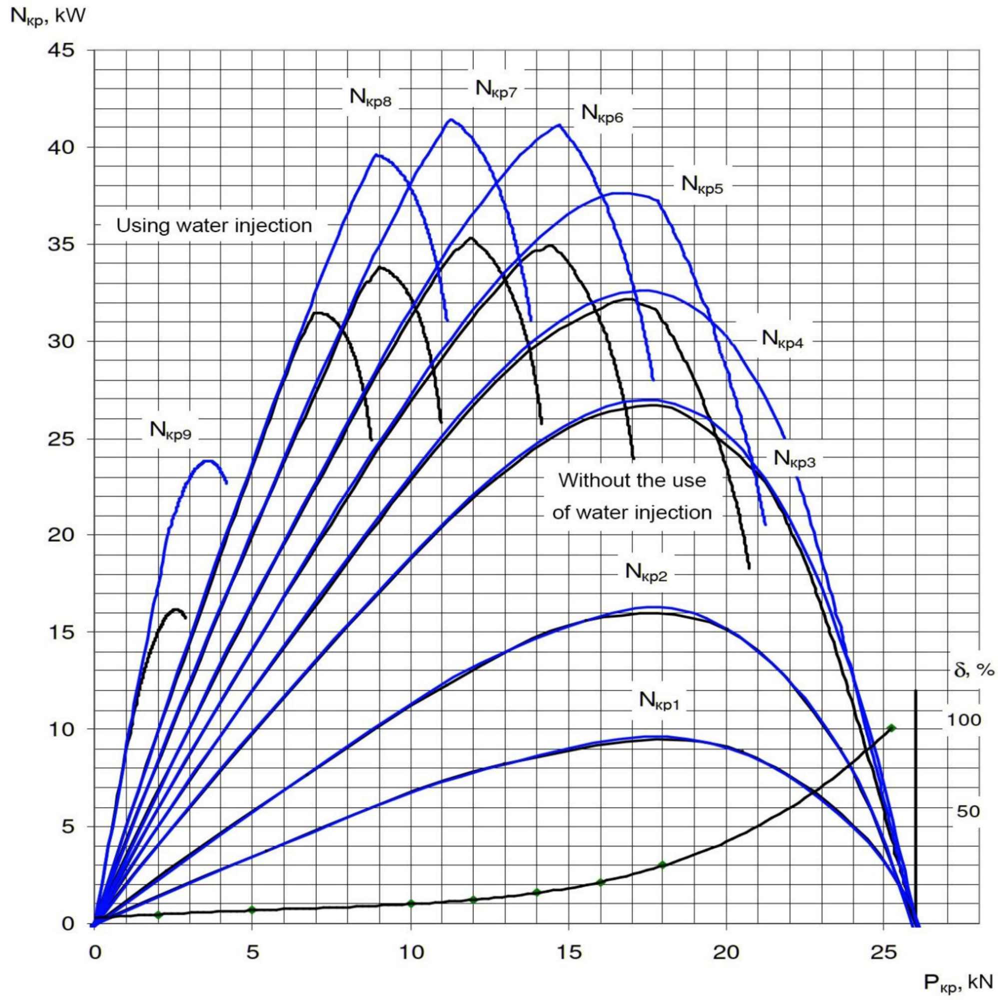

Figure 5. Traction characteristics of the Deutz-Fahr Agrolux 80 tractor with the Amazone D9-20 Super seeder under field conditions: comparison of baseline diesel operation and intake water injection mode.

Table 4 presents the absolute and relative increase in traction power resulting from the application of water injection into the intake manifold of the Deutz 1000.3 W engine across different gears of the Deutz-Fahr Agrolux 80 tractor.

Table 4. Traction power of the Deutz-Fahr Agrolux 80 tractor under stubble-field conditions.

Gear Number	Standard Engine Traction Power, kW	Water Injection Traction Power, kW	Absolute Increase, kW	Relative Increase, %
1	9.63	9.64	0.01	0.10
2	16.10	16.20	0.10	0.62
3	26.70	27.00	0.30	1.11
4	32.14	32.60	0.46	1.43
5	34.94	37.61	2.67	7.11
6	35.32	41.12	5.80	14.11
7	33.83	41.43	7.60	18.36
8	31.44	39.60	8.16	20.60
9	16.17	23.84	7.67	32.17

The revised form of Table 4 presents each gear as a separate row and includes complete units for all traction power indicators. This improves the readability of the results and makes it easier to compare baseline diesel operation with intake water injection mode. The data show that the relative increase in traction power is minimal in the 1st–4th gears, ranging from 0.10% to 1.43%, while in the 6th–8th gears it increases to 14.11–20.60%. This confirms that the effect of water injection is most pronounced under operating conditions where the tractor can effectively use the additional engine power.

An analysis of the presented data indicates that the effect of increased engine power resulting from water injection becomes more pronounced in higher gears (from the 5th gear and above). The relatively low increase in traction power observed in lower gears can be explained by insufficient traction and soil–wheel interaction, which limit the ability of the Deutz-Fahr Agrolux 80 tractor to effectively convert engine power into drawbar pull [22].

At the same time, the efficiency of tractor operation in traction mode can be evaluated using an integral traction efficiency coefficient. In this study, the traction efficiency coefficient was defined as the ratio of drawbar power to the effective engine power available at the corresponding operating mode:

$$\eta_{tr} = N_{drawbar}/N_e,$$

where η_{tr}—is the traction efficiency coefficient, $N_{drawbar}$—is the drawbar power, kW, and N_e—is the effective engine power, kW.

The variation in the maximum value of this coefficient for the Deutz-Fahr Agrolux 80 tractor across different gears is presented in Figure 6.

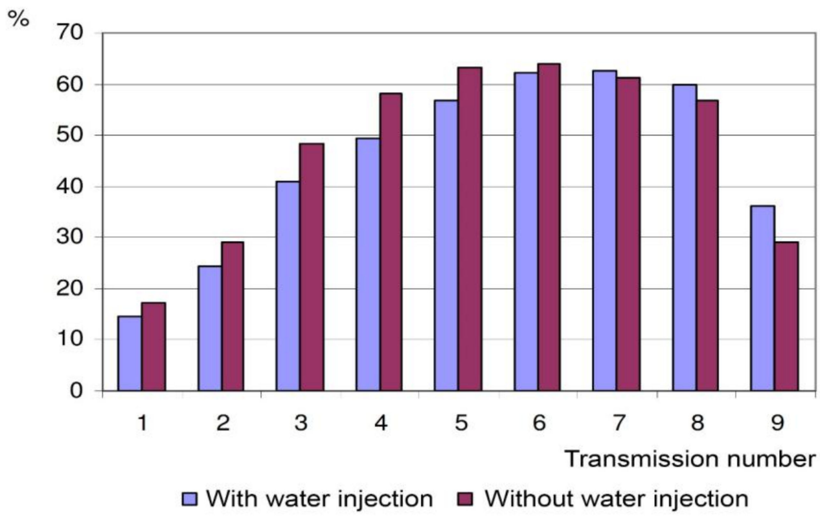

Figure 6. Variation in the maximum traction efficiency coefficient of the Deutz-Fahr Agrolux 80 tractor across different gears under stubble conditions.

The analysis of Figure 6 indicates that the values of the traction efficiency coefficient for the Deutz-Fahr Agrolux 80 tractor equipped with the water injection system are lower in the lower gear range (up to the 5th gear) compared to the standard configuration. This behavior can be explained by limited traction capacity and insufficient load transfer under these operating conditions, which restrict the effective utilization of the increased engine power.

In lower gears, the available engine power exceeds the traction capability of the tractor–soil system, resulting in increased wheel slip and reduced efficiency of power transmission to the ground. As a consequence, the benefits of water injection, which primarily enhance engine performance, cannot be fully translated into useful drawbar power.

To improve the overall efficiency of the traction system, it is recommended to use combined traction–drive agricultural units, in which a portion of the engine power can be transmitted through the power take-off system. This approach enables more effective utilization of the available engine power, particularly under conditions where traction is the limiting factor, and contributes to improved operational efficiency in field applications.

4.5. Practical Limitations of the Proposed System

The obtained results confirm that intake water injection can improve fuel consumption and performance characteristics of the tested agricultural diesel engine. However, the proposed system used proportional mechanical dosing of water, which is simpler and more suitable for agricultural machinery but less precise than electronic closed-loop control. Under transient operating conditions, deviations of the actual water-to-fuel ratio may occur. Therefore, the results should be interpreted primarily for stabilized operating intervals. Further development should focus on electronic control of water supply based on engine speed, load, fuel consumption, and intake air parameters, because automatic regulation of diesel engine operating parameters is important for stable engine operation under variable load conditions [25].

In addition, the present study mainly evaluated fuel consumption, power, torque, and traction characteristics. Although the literature indicates that intake water injection can influence BTE, BSFC, combustion temperature, and emissions, a detailed emissions analysis and in-cylinder combustion diagnostics were beyond the scope of the present experimental program. Therefore, future research should include direct measurement of NOx, CO, smoke opacity, exhaust gas temperature, and brake thermal efficiency under controlled agricultural engine operating conditions.

A further limitation of the proposed intake water injection system is the possible formation of a liquid film in the intake duct. Since water was injected into the intake air flow before the charge entered the cylinders, part of the injected water could interact with the duct wall depending on droplet size, air velocity, nozzle position, and operating mode. Such wall wetting may influence the uniformity of water distribution between cylinders and the stability of the combustion process. In the present study, liquid film thickness and film breakup were not measured directly. Therefore, future research should include a more detailed analysis of droplet transport, wall film formation, and film breakup in the intake system.

5. Conclusions

The conducted experimental investigation and regression-based analysis confirm that water injection into the intake system is an effective approach for improving the fuel efficiency of diesel engines used in agricultural machine–tractor units.

The study confirmed that intake water injection can improve the fuel consumption and performance characteristics of the tested agricultural diesel engine operating as part of a machine–tractor unit. The main experimentally confirmed effects were related to diesel fuel consumption, engine power, torque, and traction performance under field conditions.

The most rational water–fuel ratio was found to be 27–32%, with the maximum positive effect observed close to 28–30% of the diesel fuel cycle supply. Within this range, intake water injection provided a reduction in diesel fuel consumption of up to 36 g/kW·h and an increase in effective engine power of approximately 19%. These results confirm that the selected water supply range is important for improving fuel efficiency without excessive water addition.

The application of water injection affected the operating characteristics of the engine, particularly effective power and torque. However, since the present study was focused

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mainly on fuel consumption and traction performance, the influence of water injection on detailed combustion and emission parameters should be considered as a direction for further investigation rather than as the main confirmed result of this work.

The full-load speed characteristics showed that the positive effect of intake water injection was observed not only at one operating point but also across the main working speed range of the engine. Under rated operating conditions, effective power increased by about 10.8 kW, or 19.6%, while in the maximum torque mode the increase reached about 8.2 kW, or 20.5%. Engine torque increased by about 47.1 Nm under rated operating conditions and by about 56.2 Nm in the maximum torque mode.

Field tests demonstrated that the benefits of water injection are most pronounced under higher load conditions. The maximum drawbar power of the tractor reached 41.1–41.4 kW in the 6th–7th gear range, representing an increase of 14–18% compared to operation without water injection. At the same time, under conditions of limited traction (lower gears), the effect of increased engine power is partially constrained by the traction capacity of the tractor–soil system.

The traction analysis confirmed that the influence of intake water injection depends on the operating load and gear range. In lower gears, the relative increase in traction power was small, ranging from 0.10% to 1.43%, because the tractor operation was limited mainly by soil–wheel interaction and traction capacity. In higher gears, especially from the 6th to the 8th gear, the relative increase in traction power reached 14.11–20.60%, indicating more effective use of the additional engine power under field operating conditions.

From a practical perspective, the proposed approach can be considered a technically feasible solution for improving the fuel economy and operating performance of agricultural diesel engines without requiring significant modifications to existing engine designs. Potential environmental benefits may be associated mainly with reduced diesel fuel consumption; however, a separate detailed emissions study is required to confirm this effect quantitatively.

The results also show that intake manifold water injection is a technically simple method that can be adapted to agricultural diesel engines without direct in-cylinder water injection or major changes to the engine design. However, the proposed system used proportional mechanical dosing of water; therefore, under transient field conditions, short-term deviations of the actual water–fuel ratio may occur. This limitation should be considered when interpreting the obtained results.

In addition, the present study showed that the laboratory and field stages should be interpreted as complementary parts of the same experimental program. Laboratory dynamometer tests were necessary to identify the rational water-to-fuel ratio and the direct engine-level effect of intake water injection. Field tests were necessary to evaluate whether these effects could be reflected in the operation of the tractor–seeder unit under real traction conditions.

Future studies should include direct measurements of brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature, NOx, CO, smoke opacity, and in-cylinder combustion characteristics under controlled agricultural diesel engine operating conditions. This will make it possible to more accurately determine the influence of intake water injection on combustion characteristics and emission reduction, especially under variable load and speed conditions typical of machine–tractor units. In addition, future work should include repeated measurements sufficient for calculating confidence intervals for the main experimental points and for evaluating the statistical significance of differences between baseline diesel operation and intake water injection, especially at low-load operating conditions.

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It is also necessary to investigate droplet transport, wall wetting, liquid film formation, and film breakup in the intake duct, because these processes may affect the uniformity of water distribution between cylinders and the stability of engine operation.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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