Research Article

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Determination of the effect of biodiesel use on power take-off performance characteristics of an agricultural tractor in a test laboratory

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Abstract: Tractor performance tests conducted under laboratory test conditions are important because these tests determine the performance characteristics used to compare strengths and weaknesses of tractors. The objective of this study was to determine the effect of diesel fuel (B0) and 3 different biodiesel blends made of canola oil (B10, B20, B30) on tractor power take-off (PTO) performance characteristics. Performance characteristics studied were PTO power, engine torque, engine fuel consumption, and specific fuel consumption on an agricultural tractor (Massey Ferguson 3056 2WD) at the test laboratory of the Directorate of Agricultural Machinery Test Center (TAMTEST), Ministry of Agriculture and Rural Affairs, Ankara, Turkey. The maximum PTO power (32.35 ± 0.06 kW), the minimum specific fuel consumption (288.72 ± 0.11 g kW^{-1} h^{-1}), and the minimum fuel consumption (11.08 ± 0.13 L h^{-1}) were achieved by using B20 at an engine speed of 2100 min^{-1}. The nominal engine speed for petrodiesel was 2200 min^{-1}, whereas the greatest engine power was accomplished at 2100 min^{-1} for all biodiesel blends. Even though 2%-4% reduction was obtained in fuel consumption by using biodiesel blends at 2100 min^{-1}, the mean fuel consumption was statistically insignificant ($P > 0.05$), whereas average fuel consumption was higher with petrodiesel at 2200 min^{-1} ($P < 0.05$). It was concluded that B20 (20% biodiesel + 80% petrodiesel) could be a more efficient alternative to petrodiesel fuel.

Key words: Tractor, power take-off, performance characteristics, biodiesel

Biyodizel kullanımının test laboratuarında bir tarım traktörünün kuyruk mili performans değerlerine etkisinin belirlenmesi

Özet: Laboratuar test koşullarında yapılan traktör performans testleri, traktörlerin güçlü ve zayıf yönlerinin karşılaştırılmasında kullanılan performans karakteristiklerinin belirlenmesini sağladığı için önem taşımaktadır. Bu çalışmanın amacı, dizel yakıtının (B0) ve kanola yağından elde edilmiş üç faklı katkılı biyodizel yakıtının (B10, B20, B30) traktör kuyruk mili (PTO) performans karakteristiklerine etkisini belirlemektir. İncelenen performans karakteristikleri kuyruk mili gücü, motor torku, motor yakıt tüketimi ve özgül yakıt tüketimi olup testler bir tarım traktörü (Massey Ferguson 3056 2WD) kullanılarak T.C. Tarım ve Köy İşleri Bakanlığı Tarım Alet ve Makinaları Test Merkezi Müdürlüğü

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(TAMTEST) test laboratuarında yapılmıştır. Maksimum kuyruk mili gücü (32.35 ± 0.06 kW), minimum yakıt tüketimi (11.08 ± 0.13 L h^{-1}) ve minimum özgül yakıt tüketimi (288.72 ± 0.11 g kW^{-1} h^{-1}) B20 yakıtı kullanılarak 2100 min^{-1} motor devrinde bulunmuştur. Nomimal motor devri petrodizel için 2200 min^{-1} iken tüm biyodizel karışımları için en büyük motor gücü 2100 min^{-1} motor devrinde bulunmuştur. Biyodizel karışımları kullanılarak 2100 min^{-1}'da yakıt tüketimi % 2-4 azalmışsa da ortalama yakıt tüketimi istatistiksel olarak farksız bulunmuş ($P > 0.05$), 2200 min^{-1}'da ise petrodizel kullanımında ortalama yakıt tüketimi istatistiksel olarak daha yüksek bulunmuştur ($P < 0.05$). En büyük tork ve en düşük özgül yakıt tüketimini sağlayan B20'nin (% 20 biyodizel + % 80 petrodizel) petrodizel yakıtına göre daha verimli bir alternatif olabileceği sonucuna varılmıştır.

Anahtar sözcükler: Traktör, kuyruk mili, performans karakteristikleri, biyodizel

Introduction

The main energy source of agricultural tractor engines is diesel fuel. Due to the possibility of depletion of oil reserves in this century, usage of renewable energy sources are being considered as alternative energy sources, and biodiesel is one of these energy sources (Oğuz and Öğüt 2001; Ulusoy and Alibaş 2001; Sabancı et al. 2006).

Biodiesel is the mono alkyl esters of fatty acids derived via catalyst transesterification reaction from vegetable oils, waste cooking oil, animal fat, and all sorts of vegetable-based oil (Karaosmanoğlu 2005). In other words, biodiesel, designated as B100 and produced from vegetable oil or animal fat using chemical methods, is environmentally friendly, liquid, and renewable biofuel (NBB 2003; Öğüt and Oğuz 2006). Vegetable-based oils can be used as pure fuel or blended with petroleum diesel in any percentage (Ulusoy and Alibaş 2001).

The tractor is the most important power source among all agricultural machinery used in agricultural enterprises (Liljedahl et al. 1996). The farm manager is dependent upon the tractor to perform most farm operations (Sümer and Sabancı 2005), and the productivity of agricultural enterprises can be increased by selecting the most proper agricultural tractor and machinery for the agricultural work and the size of farm (Grisso et al. 1988). Tractors purchased for agricultural purposes must meet the power needs of the enterprise. The power performance parameters that are the most important factors for selecting the appropriate tractor are determined by tractor performance tests.

In the majority of previous studies, biodiesel was usually tested on one-cylinder engines under workshop test conditions. The most commonly studied parameters in biodiesel use on engines are specific fuel consumption, emission values, and maximum power. Some examples of the previous studies are as follows.

Rodjanakid and Charoenphonphanich (2004) tested the performance of biodiesel fuels derived from refined palm oil and unprocessed coconut oil on a small engine. The effects of different biodiesel blends (B10, B50, B90, and B100) on the performance of the engine were compared. It was found that the biodiesel mixtures, derived from coconut oil and palm oil, caused a reduction in the power and an increase in the specific fuel consumption. However, it was also stated that test results in the case of palm oil were better than those for coconut oil.

Alpgiray (2006) studied the effects of canola oil on the performance and emission characteristics of a one-cylinder diesel engine. The torque of the engine, emission, and fuel consumption values were also measured as a function of engine speed. Results demonstrated that the power and torque of the engine while running on canola oil were lower than with petrodiesel. Moreover, using methyl esters of oil acids, higher and similar power and torque performance could be obtained when compared to raw canola oil and petrodiesel, respectively.

Stalin and Prabhu (2007) tested B5, B10, B15, B20, B40, B60, B80, and B100 fuel mixtures. The use of B5, B10, B15, and B20 did not affect the power and torque values but did cause a reduction in the fuel consumption, while the use of B40, B60, B80, and B100 caused a reduction of the power and torque values of the engine and increased the fuel consumption.

Arapatsakos et al. (2007) tested biodiesel mixtures (B10, B20, B30, B40, and B50), derived from the methyl ester of cotton oil, on a diesel engine and determined the emission and fuel consumption. According to these test results, fuel consumption could be reduced by using biodiesel. No power measurements were conducted in this study.

Wirawan et al. (2008) conducted an experiment on an automobile engine to determine the performance and emission values of B0 (petrodiesel), B10, B20, B30, B50, and B100. Lower and higher power values were obtained in the case of B100 and biodiesel mixture fuels, respectively. It was also found that fuel consumption and torque values were reduced when the percentage of biodiesel was increased.

It appears that more scientific literature is needed addressing the PTO performance characteristics of agricultural tractors as affected by various biodiesel fuels. The studies to be conducted should report PTO performance characteristics under standard laboratory test conditions specified by OECD Test Code 2 (OECD 2008) to provide comparable test results.

The purpose of this study was to determine the effect of 4 different fuels (petrodiesel (B0), B10, B20, and B30) on PTO performance characteristics (PTO power, engine torque, fuel consumption, and specific fuel consumption) of an agricultural tractor, Massey Ferguson 3056 2WD.

Materials and methods

In this study, PTO performance tests were conducted on a Massey Ferguson 3056 2WD agricultural tractor. Technical properties of the tractor are given in Table 1.

Table 1. Properties of the tractor used in tests.

Brand - Model	Massey Ferguson - 3056 2WD
Engine	Perkins
Power (kW)	43
Fuel feeding system	Direct injection
Capacity of fuel tank	80 L
Engine speed	750-2327 min^{-1}
Nominal engine speed	2200 min^{-1}
Mass of the tractor (unweighted)	
Front	798 kg
Back	1425 kg
Total	2223 kg

Some technical properties of the petrodiesel and biodiesel fuels used in the study are given in Table 2. PTO performance tests were conducted using petrodiesel and petrodiesel blended with biodiesel at 3 different rates (10%, 20%, 30%), as shown in Table 3. Biodiesel was produced in compliance with EU specifications (TS EN 14214 2005) from canola oil, and was provided for this study by the Chamber of Alternative Energy and Biodiesel Producers Association - Turkey. The densities of the blends were measured using a densimeter to calculate specific fuel consumption.

Table 2. Some properties of petrodiesel and biodiesel (TS EN 14214 2005; EIE 2009).

Fuel properties	Petrodiesel	Biodiesel
Chemical formula	$C_{12.226}H_{23.29}S_{0.0575}$	$C_{19}H_{35.2}O_2$
Density (kg m^{-3}) (15 °C)	820-845	860-900
Viscosity (mm^2 S^{-1}) (40 °C)	2.0-4.5	3.5-5.0
Flash point (°C)	>55	≥120
Lower heating value (MJ kg^{-1})	42.7	37.1
Cetane number	44-49	51-62
Sulfur content	0.05%	0%

Table 3. Fuels used in tractor performance tests.

Fuel	Explanation	Density (g cm^{-3})
B0	100% petrodiesel	0.837
B10	10% biodiesel + 90% petrodiesel	0.840
B20	20% biodiesel + 80% petrodiesel	0.843
B30	30% biodiesel + 70% petrodiesel	0.847

Tests were performed according to OECD Standard Code 2 (OECD 2008) in a certified laboratory at the Directorate of Agricultural Equipment and Machinery Test Center (TAMTEST), Ministry of Agriculture and Rural Affairs, Ankara, Turkey. A PTO dynamometer was used to measure the PTO performance of the tractor under various load conditions. The engine of the tractor was warmed up until the measured quantities stabilized on the computer screen, and then the actual test was run for each performance characteristic to collect the data for analysis. The ambient temperature was kept at 18-22 °C, while relative humidity ranged from 23% to 29% during the experiments.

The theoretical feed rate and engine speed of the tractor were automatically calculated using a computer processing the data provided by a sensor mounted on the PTO, which measures the rotational speed. Some technical properties of the sensors associated with the measurements are given in Table 4.

The automatic control of the accelerator lever of the engine and the angle of the accelerator lever of the tractor can be controlled precisely, and thus adequate loading can be applied. The test system was integrated with a computer network to collect and analyze test data using software called MOTEST, developed by TUZEKS Inc. Using the software, test procedures can be created and the system can be operated automatically. The test system includes an alarm system that can stop the system when it exceeds specified limits during the tests. The system has features of displaying instantaneous data, performing automatic tests, determining test procedure by the user, saving and reusing test results and procedures, and printing and displaying results in a prescribed format.

A new plastic fuel tank was mounted on the system to avoid potential adverse effects of diesel fuel remains from the previous tests conducted on the test system, and each biodiesel fuel blend was prepared in a separate container. The required volume of biodiesel for each blend was measured using a graduated cylinder**.** The petrodiesel and biodiesel fuels were mixed together in a plastic fuel tank to be used in the performance tests. To obtain homogeneous biodiesel mixtures in each fuel tank, fuel mixtures were prepared by adding small volumes to the tank as the mixture was being mixed continuously, instead of preparing the whole mixture at once. Before a test started, the fuel tank contents were mixed again and shaken to prevent sedimentation and precipitation.

The fuel flowed through a flowmeter (Aqua Metro VZO 4) with a precision of 0.001 to determine the volumetric flow rate before the fuel was delivered to the engine. After calibration of the flowmeter, the outlet of the fuel tank was connected to the tractor. The fuel tank of the tractor was bypassed during the test to measure the volumetric fuel consumption of the tractor.

Some tractor performance tests are compulsory while others are optional (OECD 2008). Compulsory tests include PTO tests, fuel consumption tests, hydraulic power and lift tests, drawbar power, and fuel consumption tests, while optional tests include belt performance tests, performance tests at high temperature conditions, the 10-h tractor test with

Table 4. Some properties of sensors used for data collection.

Measured parameter	Type	Brand	Model	Sensitivity
Engine speed	Photocell	TUZEKS	AVL500	0.1
PTO speed	Photocell	TUZEKS	AVL500	0.1
Temperature and pressure	-	TUZEKS	PT-100	0.01

unballasted mass, determination of axle power, turning radius of the tractor, and the position of center of gravity. Torque and fuel consumption are measured in PTO performance tests at maximum torque, standard PTO speed, and maximum engine power, and PTO power, engine torque, fuel consumption, and specific fuel consumption are also measured. Compulsory performance tests were conducted as described by OECD (2008), including the drawbar performance of the tractor. In this study, only PTO performance test results are included since the drawbar performances of different biodiesel blends have been published elsewhere (Başer and Aybek 2009).

PTO power, engine torque, and fuel consumption were determined through tractor PTO performance tests, and specific fuel consumption was calculated from the data collected during the experiments. Three measurements were recorded and the means and standard errors were calculated for each measured parameter. The following were obtained as a result of the performance tests:

- PTO power as a function of engine speed,
- Engine torque as a function of engine speed,
- Fuel and specific fuel consumption as a function of engine speed, and
- Specific fuel consumption as a function of PTO power.

Analysis of variance (Tukey's multiple mean comparison tests) was used to compare the effects of different biodiesel mixtures on measured tractor performance indicators. The percentage changes in PTO characteristics were also calculated to compare the results.

Results

In this study, PTO performance tests were conducted to determine the effect of biodiesel blends (B10, B20, and B30) and petrodiesel (B0) on PTO power, engine torque, fuel consumption, and specific fuel consumption of an agricultural tractor (Massey Ferguson 3056 2WD).

PTO power as a function of engine speed

Test results regarding the maximum PTO power for petrodiesel and biodiesel blends are given in Table 5. The maximum PTO power (32.23 kW) was obtained at an engine speed of 2200 min^{-1} using petrodiesel, whereas the maximum PTO power was achieved at 2100 min^{-1} for all biodiesel blends.

Table 5. Mean PTO power (kW) as a function of engine speed.

Engine speed (min^{-1})	Petrodiesel	B10	B20	B30	P
	Mean ± std. error				
1000	18.06 ± 0.034 d	18.87 ± 0.042 c	19.39 ± 0.042 b	20.05 ± 0.188 a	P < 0.01
1050	19.30 ± 0.035 c	19.54 ± 0.043 b	20.11 ± 0.043 a	20.11 ± 0.035 a	P < 0.01
1102	20.04 ± 0.027d	20.22 ± 0.027 c	20.58 ± 0.022 b	20.84 ± 0.027 a	P < 0.01
1300	23.32 ± 0.029 c	23.35 ± 0.023 c	23.76 ± 0.023 b	24.06 ± 0.023 a	P < 0.01
1500	26.28 ± 0.040 b	26.00 ± 0.032 c	26.47 ± 0.040 b	26.78 ± 0.040 a	P < 0.01
1702	29.46 ± 0.044 c	29.07 ± 0.036 d	29.64 ± 0.044 b	30.00 ± 0.044 a	P < 0.01
1976	31.64 ± 0.046 a	31.27 ± 0.037 b	31.68 ± 0.037 a	31.68 ± 0.037 a	P < 0.01
2100	32.09 ± 0.073 ab	31.87 ± 0.060 b	32.35 ± 0.060 a	32.13 ± 0.073 a	P < 0.01
2200	32.23 ± 0.002 a	31.54 ± 0.002 c	32.00 ± 0.002 b	31.54 ± 0.002 c	P < 0.01
2254	28.07 ± 0.079 a	27.41 ± 0.079 b	27.73 ± 0.097 a	27.26 ± 0.097 b	P < 0.01
2278	21.27 ± 0.020 a	20.74 ± 0.016 c	21.04 ± 0.016 b	20.63 ± 0.016 c	P < 0.01
2292	14.27 ± 0.004 a	13.94 ± 0.003 c	14.10 ± 0.00 b	13.84 ± 0.003 d	P < 0.01
2310	7.19 ± 0.008 a	7.01 ± 0.008 b	7.10 ± 0.008 c	6.96 ± 0.008 c	P < 0.01

Engine torque as a function of engine speed

Engine torque as a function of engine speed is given in Table 6 for each fuel tested. Maximum engine torque (175.5 Nm) was accomplished at 1050 min^{-1} when petrodiesel was used, while maximum engine torque (180.20, 183.10, and 185.90 Nm) was achieved at 1000 min^{-1} with the use of B10, B20, and B30, respectively. The greatest engine torque (139.9 Nm) at 2200 min^{-1} was achieved with petrodiesel, while the highest torque value among all engine speeds corresponded to 2100 min^{-1} for all biodiesel blends.

Fuel consumption as a function of engine speed

The maximum fuel consumption was 11.91, 11.66, 11.50, and 11.43 L h^{-1} for petrodiesel, B10, B20, and B30, respectively (Table 7). The engine speed yielding the highest fuel consumption was 2200 min^{-1} for all 4 fuels tested in the study. Biodiesel blend B30 had the lowest fuel consumption compared to the other 3 fuels, but the average fuel consumption with B10, B20, and B30 were statistically the same while petrodiesel use caused higher fuel consumption ($P < 0.01$).

Specific fuel consumption as a function of engine speed

Specific fuel consumption at the maximum PTO power was determined to be 313.73, 293.69, 288.72, and 300.03 g kW^{-1} h^{-1} for petrodiesel, B10, B20, and B30, respectively (Table 8). The measured average specific fuel consumption was found to be the same for all fuel test samples ($P > 0.05$).

Specific fuel consumption as a function of PTO power

PTO performance test results showed that specific fuel consumption values at the maximum PTO power (32.23 kW) were 313.73 g kW^{-1} h^{-1} for petrodiesel, 293.69 g kW^{-1} h^{-1} at 31.87 kW for B10, 288.72 g kW^{-1} h^{-1} at 32.35 kW for B20, and 300.03 g kW^{-1} h^{-1} at 32.13 kW for B30 (Table 9).

Discussion

Maximum PTO power was achieved at an engine speed of 2100 min^{-1} for all biodiesel blends (Table 5). According to the multiple mean comparisons, the mean PTO power was the same for B20, B30, and biodiesel at this engine speed ($P < 0.01$). Therefore, different percentages of biodiesel did not vary the PTO power at 2100 min^{-1}. At a 2200 min^{-1} engine speed, however, the PTO power obtained with petrodiesel was not only the maximum among the 4 cases, but was statistically greater than all biodiesel blends. Thus, as long as maximum PTO power is considered, petrodiesel should be used with a 2200 min^{-1} engine speed, which is also the

Table 6. Mean engine torque (Nm) as a fun ction of engine speed.

Engine speed (min^{-1})	Petrodiesel	B10	B20	B30	P
	Mean ± std. error				
1000	172.50 ± 0.188 d	180.20 ± 0.230 c	183.10 ± 0.230 b	185.90 ± 0.230 a	P < 0.01
1050	175.50 ± 0.373 c	177.70 ± 0.456 b	182.90 ± 0.456 a	182.90 ± 0.373 a	P < 0.01
1102	173.50 ± 0.228 d	175.50 ± 0.228 c	178.70 ± 0.186 b	180.90 ± 0.228 a	P < 0.01
1300	171.30 ± 0.219 c	171.50 ± 0.179 c	174.50 ± 0.179 b	176.70 ± 0.179 a	P < 0.01
1500	167.30 ± 0.262 b	165.50 ± 0.214 c	168.50 ± 0.262 b	170.50 ± 0.214 a	P < 0.01
1702	165.30 ± 0.229 c	163.30 ± 0.187 d	166.50 ± 0.229 b	168.50 ± 0.229 a	P < 0.01
1976	152.90 ± 0.218 a	151.10 ± 0.178 b	153.10 ± 0.178 a	153.10 ± 0.178 a	P < 0.01
2100	145.90 ± 0.333 ab	144.90 ± 0.272 b	147.10 ± 0.272 a	146.10 ± 0.333 a	P < 0.01
2200	139.90 ± 0.044 a	136.90 ± 0.036 c	138.90 ± 0.036 b	136.90 ± 0.044 c	P < 0.01
2254	118.92 ± 0.335 ab	116.37 ± 0.335 c	118.07 ± 0.410 a	116.37 ± 0.410 bc	P < 0.01
2278	89.17 ± 0.058 a	87.27 ± 0.047 c	88.55 ± 0.047 b	87.27 ± 0.047 c	P < 0.01
2292	59.46 ± 0.020 a	58.19 ± 0.016 c	59.04 ± 0.016 a	58.19 ± 0.016 b	P < 0.01
2310	29.73 ± 0.033 a	29.10 ± 0.033 b	29.52 ± 0.033 b	29.10 ± 0.033 b	P < 0.01

Table 7. Mean fuel consumption (L h^{-1}) as a function of engine speed.

Engine speed (min^{-1})	Petrodiesel	B10	B20	B30	P
	Mean ± std. error				
1000	6.01 ± 0.023	6.15 ± 0.029	6.15 ± 0.029	6.14 ± 0.029	P > 0.05
1050	6.32 ± 0.050	6.41 ± 0.061	6.23 ± 0.061	6.52 ± 0.050	P > 0.05
1102	6.59 ± 0.039 b	6.49 ± 0.039 b	6.58 ± 0.032 b	6.77 ± 0.039 a	P < 0.05
1300	7.87 ± 0.056	7.76 ± 0.045	7.91 ± 0.045	7.85 ± 0.045	P > 0.05
1500	9.08 ± 0.134	9.06 ± 0.110	8.96 ± 0.134	9.00 ± 0.134	P > 0.05
1702	10.24 ± 0.112	10.44 ± 0.091	10.02 ± 0.112	10.08 ± 0.112	P > 0.05
1976	11.16 ± 0.140	10.67 ± .0115	10.72 ± 0.115	11.02 ± 0.115	P > 0.05
2100	11.60 ± 0.169	11.15 ± 0.138	11.08 ± 0.138	11.38 ± 0.169	P > 0.05
2200	11.91 ± 0.081 a	11.66 ± 0.066 b	11.50 ± 0.066 b	11.43 ± 0.081 b	P < 0.01
2254	10.44 ± 0.027 a	10.47 ± 0.027 a	10.14 ± 0.033 b	10.26 ± 0.033 b	P < 0.01
2278	7.99 ± 0.135	8.09 ± 0.111	7.81 ± 0.111	8.01 ± 0.111	P > 0.05
2292	5.84 ± 0.152	6.28 ± 0.125	6.13 ± 0.125	5.88 ± 0.125	P > 0.05
2310	4.04 ± 0.179	4.44 ± 0.179	4.86 ± 0.179	4.10 ± 0.179	P > 0.05
2325	3.08 ± 0.124	3.07 ± 0.124	2.96 ± 0.124	3.05 ± 0.124	P > 0.05

Table 8. Mean specific fuel consumption (g kW^{-1} h^{-1}) as a function of engine speed.

Engine speed (min^{-1})	Petrodiesel	B10	B20	B30	P
	Mean ± std. error				
1000	278.52 ± 0.018 a	273.98 ± 0.022 c	267.15 ± 0.022 b	259.35 ± 0.022 b	P < 0.01
1050	274.09 ± 0.043	275.33 ± 0.053	261.56 ± 0.053	274.49 ± 0.043	P > 0.05
1102	275.40 ± 0.033 a	269.54 ± 0.033 b	269.19 ± 0.027 b	275.43 ± 0.033 a	P < 0.05
1300	282.59 ± 0.045	278.80 ± 0.037	280.72 ± 0.037	276.39 ± 0.037	P > 0.05
1500	289.19 ± 0.112	292.69 ± 0.092	285.61 ± 0.112	284.54 ± 0.112	P > 0.05
1702	290.97 ± 0.093	301.69 ± 0.076	285.09 ± 0.093	284.67 ± 0.093	P > 0.05
1976	295.20 ± 0.121	286.54 ± 0.099	285.04 ± 0.099	294.51 ± 0.099	P > 0.05
2100	302.59 ± 0.142	293.69 ± 0.116	288.72 ± 0.116	300.03 ± 0.142	P > 0.05
2200	313.73 ± 0.069 a	310.40 ± 0.056 ab	303.12 ± 0.056 b	306.91 ± 0.069 ab	P < 0.05
2254	311.36 ± 0.023 ab	320.69 ± 0.023 a	308.33 ± 0.028 b	318.78 ± 0.028 a	P < 0.01
2278	314.53 ± 0.115	341.37 ± 0.094	312.74 ± 0.094	329.13 ± 0.094	P > 0.05
2292	342.68 ± 0.129	378.05 ± 0.105	366.67 ± 0.105	359.83 ± 0.105	P > 0.05
2310	470.10 ± 0.168	534.95 ± 0.168	576.06 ± 0.168	498.56 ± 0.168	P > 0.05

nominal engine speed of the tractor. However, if biodiesel use is to be preferred for the tractor, the engine should be operated at 2100 min^{-1} with B20, B30, or petrodiesel to obtain the maximum power. Another interpretation of the results could be that the nominal engine speed should be considered 2100 min^{-1} as long as biodiesel blends B20 and B30 are to be utilized.

Table 9. Mean specific fuel consumption as a function of PTO power.

Petrodiesel		B10		B20		B30		
PTO power (kW)	Specific fuel consumption (g k^{-1} W^{-1} h^{-1})	PTO power (kW)	Specific fuel consumption (g k^{-1} W^{-1} h^{-1})	PTO power (kW)	Specific fuel consumption (g k^{-1} W^{-1} h^{-1})	PTO power (kW)	Specific fuel consumption (g k^{-1} W^{-1} h^{-1})	P
18.06	278.52 ± 0.018 a	18.87	273.98 ± 0.022 ab	19.39	267.15 ± 0.022 ab	20.05	259.35 ± 0.022 b	P < 0.05
19.30	274.09 ± 0.043	19.54	275.33 ± 0.053	20.11	261.56 ± 0.053	20.11	274.49 ± 0.043	P > 0.05
20.04	275.40 ± 0.033	20.22	269.54 ± 0.033	20.58	269.19 ± 0.027	20.84	275.43 ± 0.033	P > 0.05
23.32	282.59 ± 0.045	23.35	278.80 ± 0.037	23.76	280.72 ± 0.037	24.06	276.39 ± 0.037	P > 0.05
26.28	289.19 ± 0.112	26.00	292.69 ± 0.092	26.47	285.61 ± 0.112	26.78	284.54 ± 0.112	P > 0.05
29.46	290.97 ± 0.093	29.07	301.69 ± 0.076	29.64	285.09 ± 0.093	30.00	284.67 ± 0.093	P > 0.05
31.64	295.20 ± 0.12	31.27	286.54 ± 0.099	31.68	285.04 ± 0.099	31.68	294.51 ± 0.099	P > 0.05
32.09	302.59 ± 0.142	31.87	293.69 ± 0.116	32.35	288.72 ± 0.116	32.13	300.03 ± 0.142	P > 0.05
32.23	313.73 ± 0.069 a	31.54	310.40 ± 0.056 a	32.00	303.12 ± 0.056 b	31.54	306.91 ± 0.069 ab	P < 0.05
28.07	311.36 ± 0.023 bc	27.41	320.69 ± 0.023 a	27.73	308.33 ± 0.028 b	27.26	318.78 ± 0.028 ac	P < 0.05
21.27	314.53 ± 0.115	20.74	341.37 ± 0.094	21.04	312.74 ± 0.094	20.63	329.13 ± 0.094	P > 0.05
14.27	342.68 ± 0.129	13.94	378.05 ± 0.105	14.10	366.67 ± 0.105	13.84	359.83 ± 0.105	P > 0.05
7.19	470.10 ± 0.168 b	7.01	534.95 ± 0.168 ab	7.10	576.06 ± 0.168 a	6.96	498.56 ± 0.168 b	P < 0.05

PTO power increased until 2200 min^{-1} (nominal rotational speed) and then decreased rapidly. The rate of increase was almost linear up to about 1800 min^{-1} and kept increasing linearly at a lower rate up to the nominal engine speed. The linearity was expected, since engine power is proportional to engine speed.

Since engine torque increases with decreasing rotational speed at a specified engine power, the highest torque was obtained at 1000 min^{-1} with all biodiesel blends and at 1050 min^{-1} with the use of petrodiesel. Higher mixture rates of biodiesel blend resulted in greater torque at a given engine speed. For instance, 180.2 and 185.9 Nm were obtained with B10 and B30, respectively, at 1000 at min^{-1} (Table 6). At nominal engine speed (2200 min^{-1}), petrodiesel is favorable since the average measured torque was the greatest (139.9 Nm) compared to any biodiesel fuel. For all fuel types measured, torques gradually decreased with increasing engine speed up to 2200 min^{-1} and then sharply decreased with further increase in engine speed. The occurrence of such behavior is in accordance with the variation of PTO power as a function of engine rotational speed.

The statistical test suggests that B20 is more favorable with 147.1 Nm among biodiesel blends in terms of achievable torque at the nominal engine speed ($P < 0.01$). The engine torque was approximately 2% less for biodiesel blends at the nominal engine speed. Öztürk and Bilen (2009) found 2.6% and 5.3% less torque for B50 and B100, suggesting less torque with increasing biodiesel blend rates. The reduction in torque with increasing blend rate was attributed to the higher viscosity and lower heating value of canola oil's methyl ester. Emiroğlu (2007) found the maximum engine torque values to be 340, 337.2, and 332.6 Nm with petrodiesel, B10, and B20 at 1198 min^{-1}, respectively. Therefore, previous studies agree that the maximum engine torque can be accomplished by using petrodiesel at nominal engine speed.

Nevertheless, the comparison just made for the nominal engine speed may not be sufficient to conclude that petrodiesel fuel provides the best performance. The greatest power generation occurred at 2100 min^{-1} with the use of biodiesel blends, as explained previously, which is slightly lower than the nominal engine speed. Thus, one needs to evaluate the torque results corresponding to an engine speed of 2100 min^{-1} in the case of biodiesel blends. Any torque value obtained from biodiesel use (144.9, 147.1, and 146.1 Nm for B10, B20, and B30, respectively) at 2100 min^{-1} was greater than the torque (139.9 Nm) resulting from petrodiesel use at 2200 min^{-1}. Furthermore, B20 and B30 provided greater torque at 2100 min^{-1} compared to petrodiesel at 2100 min^{-1}, as well. The increase in torque is more obvious when torque with B20 and B30 at 2100 min^{-1} is compared to petrodiesel at 2200 min^{-1}, corresponding to 4.5% and 5% differences in favor of biodiesel blends B20 and B30.

Based on the results, it may be generalized that measured PTO power values were somewhat close at about nominal engine speed for all fuels tested in this study, whereas torque measurements showed slightly more apparent differences at low engine speeds. The differences in measured average quantities, however, were statistically significant in the case of both PTO power and torque. Since the highest PTO power and engine torque were obtained by using biodiesel fuel blends (B20 and B30) at 2100 min^{-1}, the nominal engine speed should be considered 2100 min^{-1} when biodiesel blends are used on the tractor.

Fuel consumption varied proportionally with the engine speed up to the nominal engine speed, but the rate of increase in fuel consumption slightly decreased at about 1700 min^{-1}. The greatest fuel consumption (11.91 L h^{-1}) was found at 2200 min^{-1} with petrodiesel, followed by B10 (11.66 L h^{-1}), B20 (11.50 L h^{-1}), and B30 (11.43 L h^{-1}), respectively. The differences in average measured fuel consumption at 2100 min^{-1} was insignificant ($P > 0.05$) for all fuels tested, suggesting that any biodiesel fuel use at 2100 min^{-1} could be favorable compared to petrodiesel use at 2200 min^{-1} (Table 7).

As discussed previously, biodiesel blends B20 and B30 were found to be more advantageous in enhancing PTO power and torque performance. Furthermore, it was suggested that the engine should be operated at 2100 min^{-1} to attain the best performance in terms of PTO power and torque. Mean fuel consumption at 2100 min^{-1} conflicted with measurements at 2200 min^{-1} and showed that fuel consumption was the same for all fuels tested in this study at 2100 min^{-1} ($P > 0.05$). As a conclusion, although no fuel is more favorable in terms of fuel consumption at 2100 min^{-1}, B20 or B30 should be preferred over other fuels to obtain the best PTO power and/or engine torque performance. However, biodiesel use decreased the mean fuel consumption compared to B0 at 2200 min^{-1}.

Stalin and Prabhu (2007) and Arapatsakos et al. (2007) found reduction in fuel consumption with the use of different biodiesel blends. Emiroğlu (2007) stated that there were no apparent differences in fuel consumption, but that petrodiesel use resulted in slightly higher fuel consumption compared to B2, B5.75, B10, and B20. The percentage of the reduction of fuel consumption as a result of biodiesel use was calculated for our tests conducted at 2100 and 2200 min^{-1}. It was found that 2% (B30) and 4% (B10 and B20) reductions at 2100 min^{-1} and 2% (B30), 3% (B20), and 2% (B10) reductions at 2200 min^{-1} were accomplished by using biodiesel blends. Öztürk and Bilen (2009), however, tested B0, B50, and B100 and found an increase of 8% for B50 compared to B0. Furthermore, 12% more fuel was consumed when biofuel (B100) was used in the form of canola oil's methyl ester. It appears that biodiesel use increases fuel consumption as the blend rate of biodiesel keeps increasing.

The variation of specific fuel consumption with engine speed matches previous observations relevant to fuel consumption. There was a gradual increase in specific fuel consumption from 1000 to 1700 min^{-1}, and a declining rate of increase between 1700 and 2100 min^{-1}, followed by a sudden rise after 2200 min^{-1}.

Mean specific fuel consumption for B20 was lower than for the rest of the fuels, and the means for petrodiesel, B10, and B30 were the same at the nominal engine speed (Table 8). Thus, at 2200 min^{-1}, B20 provided the best specific fuel consumption ($P < 0.05$). However, the mean specific fuel consumptions at 2100 min^{-1} showed no significant differences among the 4 fuels ($P > 0.05$). Specific fuel consumption is known to be an important parameter in comparing tractor performances. Based on these results, mean specific fuel consumption for all fuels was found to be the same if the best PTO power and torque were targeted by operating the engine at a rotational speed of 2100 min^{-1}. Even though the mean differences were insignificant at 2100 min^{-1}, specific fuel consumption was less in the case of biodiesel blends by 3% for B10, 1% for B20, and 5% for B30. The reductions in specific fuel consumption at 2200 min^{-1} were about 1%, 3%, 2% for B10, B20, and B30 respectively.

The greatest specific fuel consumption corresponded to the smallest PTO power obtained at the highest engine test speed for all fuels (Table 9). The differences in mean quantities at low PTO power values were generally insignificant ($P > 0.05$). At 2100 min^{-1}, which seemed to be the most appropriate engine speed for biodiesel blends, the difference in average specific fuel consumption was not significant in any case ($P > 0.05$). Measured engine powers corresponding to these cases were also quite similar. The differences in mean specific fuel consumption, however, were significant ($P < 0.05$) in favor of B20 at an engine speed of 2200 min^{-1}.

Considering all tests conducted under laboratory test conditions in this study, the most appropriate biodiesel-diesel mixture rate for the tractor among the tested fuels was found to be B20.

Conclusions

The results of the PTO performance tests conducted using 4 different fuels (petrodiesel, B10, B20, and B30) on a Massey Ferguson 3056 2WD agricultural tractor can be summarized as follows.

Maximum PTO power was achieved at 2100 min^{-1} for all biodiesel blends (31.87 kW for B10, 32.35 kW for B20, and 32.13 kW for B30), whereas the maximum PTO power using petrodiesel (32.23 kW) was achieved at 2200 min^{-1}. The engine should be operated at 2200 min^{-1} with petrodiesel to obtain the greatest mean PTO power ($P < 0.01$). In the case of biodiesel use, either B20 or B30 should be used at 2100 min^{-1} to obtain the highest mean PTO power ($P < 0.01$).

The maximum engine torque can be accomplished at an engine speed of 2200 min^{-1} ($P < 0.01$) using petrodiesel fuel, which should be considered the nominal engine speed as long as petrodiesel is used on the tractor. However, the engine torques (147.1 and 146.1 Nm for B20 and B30, respectively) were greater at 2100 min^{-1} than the engine torque (139.9 Nm) found at the nominal engine speed (2200 min^{-1}) recommended for petrodiesel (B0). These quantities correspond to 4.5%-5% more engine torque for B20 and B30. The measured mean engine torques found with B20 and B30 were significantly greater than those of the other fuels at 2100 min^{-1} ($P < 0.01$). Therefore, the nominal engine speed is 2100 min^{-1} when biodiesel is used on the tractor.

Although 2%-4% reduction in fuel consumption was measured when using biodiesel blends at 2100 min^{-1}, the mean fuel consumption was not statistically significant at ($P > 0.05$), whereas the average fuel consumption was higher with petrodiesel at 2200 min^{-1} ($P < 0.05$).

No significant differences were found in average specific fuel consumptions among the 4 fuels at 2100 min^{-1} ($P > 0.05$), whereas average specific fuel consumption at 2200 min^{-1} was greater for petrodiesel compared to biodiesel blends ($P < 0.05$). The decrease in specific fuel consumption, albeit insignificant, varied from 1% to 5% when using biodiesel blends.

The maximum PTO power (32.23 kW) was obtained at 2200 min^{-1} for petrodiesel use. In order to obtain this maximum PTO power, specific fuel consumption needs to be 313.73 g kW^{-1} h^{-1}. At the same engine speed, B20 and B30 had lower specific fuel consumptions to achieve the same performance in terms of PTO power ($P < 0.05$). By operating at 2100 min^{-1}, the specific fuel consumption can be further reduced to 288.72 and 300.03 g kW^{-1} h^{-1} using B20 and B30, respectively.

Based on the findings of these laboratory tests, it was concluded that the most appropriate biodiesel-diesel mixture rate for the tractor was 20% (B20) for maximizing PTO power and minimizing specific fuel consumption by operating the tractor engine at a rotational speed of 2100 min^{-1}.

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