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PERFORMANCE OF AN AGRICULTURAL ENGINE USING TURBOCHARGER AND INTERCOOLER

Marcelo Silveira de Farias*[1], José Fernando Schlosser[2], Giácomo Müller Negri[2], Leonardo Casali[2], Gilvan Moisés Bertollo[3] & Lucas Simon da Rosa[2]

1 - Federal University of Santa Maria, Frederico Westphalen Campus, Frederico Westphalen, RS, Brazil

2 - Federal University of Santa Maria, Santa Maria, RS, Brazil

3 - Federal Technological University of Paraná, Santa Helena Campus, Santa Helena, PR, Brazil

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ABSTRACT

This paper aimed to evaluate the effects of air and fuel supercharging in an agricultural engine. The analyzed variables consisted of torque, power, and specific fuel consumption. Tests were carried out using a dynamometer through the power take-off of an agricultural tractor. The experiment was carried out at a laboratory in a completely randomized design arranged under a two-factorial scheme, with three replications. Six engine configurations (natural aspiration, natural aspiration + service, turbocharger, turbocharger + service, turbocharger + intercooler, and turbocharger + service + intercooler) and 10 engine speeds (1,200, 1,300, 1,400, 1,500, 1,600, 1,700, 1,800, 1,900, 2,000, and 2,100 rpm) were evaluated. The turbocharger alone did not increase engine torque and power. The increase in fuel flow enhanced engine performance for the evaluated configurations. Turbocharger + service and turbocharger + service + intercooler configurations reduced specific fuel consumption by up to 10% and increased torque and power by approximately 30% compared to the original configuration (natural aspiration).

Palavras-chave:
Mecanização agrícola
Eficiência
Ciclo Diesel
Sobrealimentação

DESEMPENHO DE UM MOTOR AGRÍCOLA UTILIZANDO TURBOCOMPRESSOR E INTERCOOLER

RESUMO

Este trabalho teve como objetivo avaliar os efeitos da sobrealimentação de ar e combustível em um motor agrícola. As variáveis analisadas foram torque, potência e consumo específico de combustível. Foram realizados testes utilizando dinamômetro, por meio da tomada de potência de um trator agrícola. O experimento foi realizado em laboratório, com delineamento inteiramente casualizado, em esquema bifatorial, com três repetições, sendo avaliadas seis configurações do motor (Aspiração natural; Aspiração natural + Serviço; Turbocompressor; Turbocompressor + Serviço; Turbocompressor + *Intercooler*; Turbocompressor + Serviço + *Intercooler*) e 10 velocidades angulares do motor (1.200; 1.300; 1.400; 1.500; 1.600; 1.700; 1.800; 1.900; 2.000 e 2.100 rpm). Os resultados indicam que, apenas a adição do turbocompressor não aumenta o torque e a potência do motor. O acréscimo de débito do combustível aumenta o desempenho do motor, para qualquer uma das configurações avaliadas. As configurações Turbocompressor + Serviço e Turbocompressor + Serviço + *Intercooler* reduziram em até 10% o consumo específico e incrementaram próximo de 30% o torque e a potência, em relação à configuração original (Aspiração natural).

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Email (corresponding author)*: silveira_farias@hotmail.com

INTRODUCTION

Engines can transform chemical energy from fuel mixed with oxygen into mechanical energy through movement, which is transferred to the crankshaft, resulting from combustion. The constant search for improving combustion and making the engine more efficient gives rise to alternatives, such as supercharging.

Air supercharging seeks to increase the volume of air admitted inside the combustion chamber in the same space of time, without changing the swept internal volume of the engine. Increasing the admission pressure through the use of a turbocharger combined with the engine is necessary for this to occur (GONÇALVES *et al.*, 2018). In this case, air and fuel supercharging, that is, an increase in the injection of diesel and air into the combustion chamber, increases engine torque and power, without changing its physical structure, that is, an increase in the swept internal volume (PEÇA, 2019).

Turbocharger uses energy from gases resulting from the combustion to drive a turbine, which has its axis shared with a compressor. The latter is responsible for increasing the air density inside the combustion chamber in the same space of time compared to the natural aspiration. Thus, the air is compressed by pistons, generating heating to start combustion (LOPES, 2014; BENITES, 2016).

The air density decreases as the altitude relative to the average sea level increases, that is, the air becomes more rarefied. Consequently, combustion is affected due to the air/fuel mixture being influenced by a significant reduction in oxygen concentration. Thus, the turbocharger is used to avoid loss of engine efficiency in these places (AGUDELO *et al.*, 2009).

The turbocharger provides a higher amount of oxygen in the combustion chamber, allowing increasing the amount of injected diesel to keep the air/fuel mixture balanced aiming to increase the engine efficiency. However, excess fuel increases pollutant gas emissions and energy waste, as there is not enough oxygen to burn the excess fuel (ASSIS *et al.*, 2016; FARIAS *et al.*, 2017).

In addition, the turbocharger leads to a reduction in emissions of particulate matter and carbon monoxide, but there is an increase in the levels of nitrogen oxides emitted by the engine (FARIAS *et al.*, 2018). In this case, some engines have a recirculation system of the air in the combustion chamber, which increases the amount of air in the mixture and does not alter the proportion of injected fuel, resulting in decreased emissions and meeting the requirements imposed by the Brazilian legislation on pollutant emissions.

Moreover, the temperature of the compressed air increases when using the turbocharger, resulting in a decrease in its density due to its compression (LIMA, 2018). One way to improve the quality of the air admission in the combustion chamber is to reduce the temperature of the compressed air. In this sense, installing a cooling system, known as an intercooler, is necessary. The cooled air has an increase in mass for the same volume, and a higher amount of air, that is, oxygen, can be admitted to the combustion chamber (PEÇA, 2019).

Scientific investigations of the performance of the diesel cycle engine, with alteration of the air and fuel supply system, are still not very significant in Brazil. In this sense, this study aimed to evaluate the effects of air and fuel supercharging in an agricultural engine, fragmenting the supercharging into two stages using the turbocharger associated with the intercooler.

MATERIAL AND METHODS

A Case-IH Farmall 80 tractor (Case-IH, São José dos Pinhais, Brazil), equipped with an FPT Iveco four-stroke diesel cycle engine, with four cylinders, swept volume of 3,908 cm3, and natural aspiration. The engine had nine hours of use and presented a torque of 358.40 Nm at 1,400 rpm and a maximum power of 60.13 kW (81.75 hp) at 2,000 rpm in previous dynamometric tests under the ISO TR 14396 standard. The fuel supply system uses a Delphi mechanical rotary injection pump supplied with S500 diesel with a density of 0.845 kg L^{-1} at 19.5 °C purchased from a local gas station network.

The torque and angular velocity data of the engine were obtained using an EGGERS PT 301 MES electric dynamometer. Fuel consumption was measured using an EGGERS FM3-100 flow meter. These data allowed the calculation of power and specific fuel consumption using the software EGGERS Power Control. The schematic representation of the experiment is shown in Figure 1.

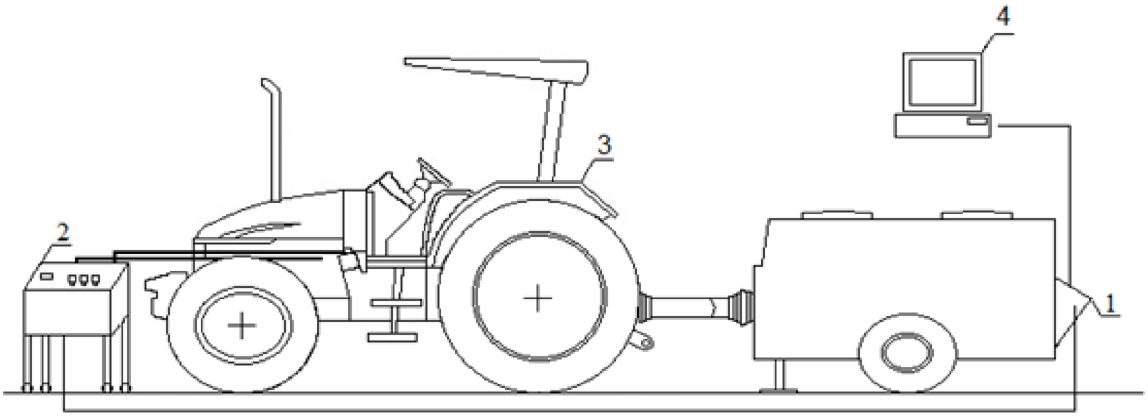

Figure 1. Schematic representation of the experiment to obtain the parameters of engine performance, through the power take-off of the tractor (1. electric dynamometer; 2. flowmeter; 3. agricultural tractor; 4. EGGERS Power Control software)

The experimental methodology was similar to that used by Farias *et al.* (2018) and recommended for this type of evaluation. A two-factorial arrangement was used for the configuration of the experimental treatments. The factors consisted of the configuration of the engine air and fuel supply system (C1, C2, C3, C4, C5, and C6) and the engine speed (1,200, 1,300, 1,400, 1,500, 1,600, 1,700, 1,800, 1,900, 2,000, and 2,100 rpm) in a completely randomized experimental design, with three replications. The following procedures were used to establish the levels of the engine fuel and air supply system configuration factor:

• **C1 (natural aspiration):** Initially, the tractor engine was evaluated in its original manufacturing configuration, with no intervention in the air and fuel injection system.

• **C2 (natural aspiration + service):** The diesel volume supplied by the injection pump to the engine was increased by 10% in the second level. This modification, called service, was performed on a test bench by changing the original fuel volume from 76 to 84 mL at 800 rpm of the injection pump.

• **C3 (turbocharger):** A Master Power APL 240 kit with an air admission pressure of 1.0 bar was installed to assess the effect of air supercharging on engine performance. The injector pump returned to its original condition (76 mL of Diesel at 800 rpm) with the turbocharger installed.

• **C4 (turbocharger + service):** The performance was analyzed together with the increase in the fuel flow in the injection pump with the turbocharger installed.

• **C5 (turbocharger + intercooler):** A cooling kit for the admission air mass (intercooler) was installed for the last two configurations. At this level, the supercharged air-cooled with the fuel injection in the original manufacturing configuration can be evaluated.

• **C6 (turbocharger + service + intercooler):** The two turbocharger and air mass cooling kits were maintained, setting again the original fuel volume from 76 to 84 mL at 800 rpm of the injection pump.

The engine was previously warmed up before the beginning of the data collection until reaching the optimum operating temperature, using a load imposed using the dynamometer for 30 minutes. This procedure was performed after each change of configuration of the engine air and fuel supply system.

The dynamometer was configured to take readings at each imposition of loads that would cause a reduction of 100 rpm in the engine speed, starting from the first collection, at 2,100, until the last one, at 1,200 rpm. The speeds of power and maximum torque were obtained in this range for all evaluated configurations. The data were collected every two seconds with 45 readings for each configuration and engine speed. A 10% loss of power due to its transmission from the engine to the PTO was considered because the measurements were made on the tractor PTO (Figure 1) (MÁRQUEZ, 2012).

The response variables analyzed in each experimental treatment were torque, power, and specific fuel consumption of the engine. The statistical analysis was carried out using the statistical software Sisvar version 5.3 (FERREIRA, 2014). The variables torque, power, and specific fuel consumption were subjected to analysis of variance ($p \leq 0.05$). In case of significance, the means were analyzed by the Tukey test ($p \leq 0.05$).

RESULTS AND DISCUSSION

An interaction was found between the configurations of the air and fuel supply system (Factor A) and engine speeds (Factor B) for all the studied response variables. The means shown in Table 1 allow defining the speeds of the engine in its original configuration of 1,300 rpm as the maximum torque and 2,000 rpm as the maximum power. However, the air and fuel supercharging of the configurations C4 and C6, which presented the best results for these variables, changed the points of torque (Table 1) and maximum power (Table 2) to 1,400 and 2,100 rpm, respectively.

The means of specific fuel consumption of the engine shown in Table 3 indicate that the lowest consumption was obtained at an engine speed of 1,400 rpm. However, the configuration C6 (turbocharger + service + intercooler), which presented the lowest consumption in the entire evaluated range, had the lowest engine consumption (242.64 g kWh^{-1}) at 1,600 rpm.

The torque and power data (Table 4) show an increase of 92.85 Nm (28.29%) of torque and 16.23 kW (29.26%) of power for the configuration C6 compared to C1. However, the configuration C4 did not differ from C6 and, therefore, the

Table 1. Parameters of torque, at different engine speeds, for the six configurations evaluated

	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,100
					Torque (N.m)*					
C1	355.42^{f}	358.40^{f}	355.49^{f}	349.58^{f}	346.46^{e}	336.15^{f}	320.50^{e}	302.14^{e}	287.16^{f}	269.84^{d}
C2	381.16^{e}	376.08^{e}	370.91^{e}	361.44^{e}	351.71^{d}	339.15^{e}	332.81^{d}	318.49^{d}	308.15^{c}	301.54^{b}
C3	383.58^{d}	381.23^{d}	380.88^{d}	375.16^{d}	366.73^{c}	363.78^{d}	345.45^{c}	318.72^{cd}	296.97^{d}	272.24^{c}
C4	433.52^{b}	438.89^{b}	441.50^{b}	439.85^{a}	433.78^{a}	424.92^{a}	417.55^{a}	405.87^{a}	393.55^{b}	379.87^{a}
C5	389.40^{c}	385.20^{c}	384.93^{c}	377.61^{c}	369.98^{b}	365.57^{c}	344.63^{c}	319.52^{c}	295.93^{e}	271.63^{c}
C6	436.67^{a}	441.27^{a}	442.48^{a}	438.26^{b}	434.01^{a}	423.84^{b}	415.09^{b}	403.81^{b}	394.53^{a}	379.87^{a}
Mean	396.63	396.85	396.03	390.32	383.78	375.57	362.67	344.76	329.38	312.15
CV (%)	8.07	8.75	9.35	10.01	10.37	10.57	11.73	13.63	15.34	17.12

*Means followed by the same letter in the column do not differ by Tukey test, at 5% significance level.

Table 2. Parameters of power, at different engine speeds, for the six configurations evaluated

	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,100
					Power (kW)*					
C1	44.41^{f}	48.58^{f}	51.82^{f}	54.68^{f}	57.74^{e}	59.58^{f}	60.13^{f}	59.89^{e}	59.82^{f}	59.11^{e}
C2	47.63^{e}	50.98^{e}	54.06^{e}	56.53^{e}	58.61^{d}	60.11^{e}	62.44^{e}	63.13^{d}	64.20^{c}	66.06^{b}
C3	47.93^{d}	51.68^{d}	55.52^{d}	58.68^{d}	61.11^{c}	64.48^{d}	64.81^{c}	63.17^{d}	61.87^{d}	59.64^{c}
C4	54.17^{b}	59.49^{b}	64.35^{b}	68.80^{a}	72.29^{a}	75.31^{a}	78.33^{a}	80.45^{a}	81.99^{b}	83.22^{a}
C5	48.66^{c}	52.21^{c}	56.11^{c}	59.06^{c}	61.66^{b}	64.80^{c}	64.66^{d}	63.33^{c}	61.65^{e}	59.50^{d}
C6	54.57^{a}	59.81^{a}	64.50^{a}	68.55^{b}	72.33^{a}	75.12^{b}	77.87^{b}	80.04^{b}	82.19^{a}	83.16^{a}
Mean	49.56	53.79	57.73	61.05	63.96	66.57	58.04	68.34	68.62	68.45
CV (%)	8.07	8.75	9.35	10.01	10.38	10.57	11.73	13.63	15.34	17.10

*Means followed by the same letter in the column do not differ by Tukey test, at 5% significance level.

Table 3. Parameters of specific fuel consumption, at different engine speeds, for the six configurations evaluated

	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,100
	Specific fuel consumption (g kWh^{-1})*									
C1	275.97^{b}	267.72^{b}	262.21^{b}	267.35^{b}	269.10^{b}	270.96^{b}	271.52^{b}	279.70^{b}	295.39^{b}	302.21^{b}
C2	291.11^{a}	294.84^{a}	293.88^{a}	298.25^{a}	300.03^{a}	306.81^{a}	308.68^{a}	319.05^{a}	326.42^{a}	330.09^{a}
C3	255.71^{c}	251.69^{c}	249.10^{c}	249.97^{c}	247.49^{c}	251.71^{c}	256.25^{c}	263.07^{c}	271.95^{c}	281.70^{c}
C4	257.07^{c}	252.03^{c}	247.09^{c}	245.45^{cd}	243.76^{d}	243.91^{d}	245.72^{d}	249.47^{d}	253.33^{d}	259.84^{d}
C5	251.91^{c}	250.69^{c}	249.04^{c}	249.97^{c}	251.20^{cd}	254.25^{c}	257.79^{c}	264.70^{c}	273.51^{c}	283.14^{c}
C6	255.21^{c}	249.47^{c}	245.59^{c}	244.05^{c}	242.64^{d}	243.42^{d}	244.50^{d}	249.22^{d}	252.13^{d}	259.13^{d}
Média	264.50	261.07	257.82	259.17	259.04	261.84	264.08	270.87	278.79	286.02
CV (%)	5.90	6.84	7.23	8.06	8.60	9.24	9.07	9.66	10.12	9.43

*Means followed by the same letter in the column do not differ by Tukey test, at 5% significance level.

Table 4. Averages of engine performance variables and their variations (Δ), with respect to the C1 configuration (Natural aspiration)

	Torque (N.m)	Δ (%)	Power (kW)	Δ (%)	Specific fuel consumption (g kWh^{-1})	Δ (%)
C1	328.11^{e}	0.00	55.58^{e}	0.00	276.21^{b}	0.00
C2	344.14^{d}	4.89	58.38^{d}	5.04	306.92^{a}	11.12
C3	348.47^{c}	6.21	58.89^{c}	5.96	257.86^{c}	-6.64
C4	420.93^{a}	28.29	71.84^{a}	29.26	249.77^{d}	-9.57
C5	350.44^{b}	6.81	59.16^{b}	6.44	258.62^{c}	-6.37
C6	420.96^{a}	28.30	71.81^{a}	29.20	248.54^{d}	-10.02

*Means followed by the same letter in the column do not differ by Tukey test, at 5% significance level.

intercooler was not efficient in its functionality (Table 4). According to Assis *et al.* (2016), the engine can have an increase of up to 20% in torque and power when undergoing supercharging, with no need to be redesigned or have its dimensions increased.

The lack of difference between treatments with and without the intercooler (C4 and C6) may be attributed to the construction characteristics of the intercooler fixation system and the limitations of physical space, as it is installed above the tractor air filter, which reduces the airflow over it. Lima (2018) studied a turbo internal combustion engine with and without an intercooler and obtained higher torque and power in the engine from the intercooler installation.

The curves shown in Figures 2a and 2b showed higher values of torque and power in the entire range of engine speed for the two configurations that had the Diesel volume increased by 10% (C4 and C6), associated with the turbocharger. The engine has a higher capacity to generate work when injecting a higher amount of fuel and a higher air admission, at the same time, through the cylinders.

Figure 2b also shows a reduction in the engine speed of maximum power, with values ranging from 2,100 to 1,700 rpm for configurations that show an increase in air mass only in the cylinders (C3: turbocharger and C5: turbocharger + intercooler). It is due to an increase in the pressure of the turbocharger only at high engine speeds, as the installed equipment does not have a relief valve, known as wastegate.

Most turbochargers have a wastegate valve, which limits the pressure produced by the compressor to relieve any overload that could damage the engine (PEÇA, 2019). The increased pressure due to the absence of this valve resulted in the highest volume of air admitted, making the

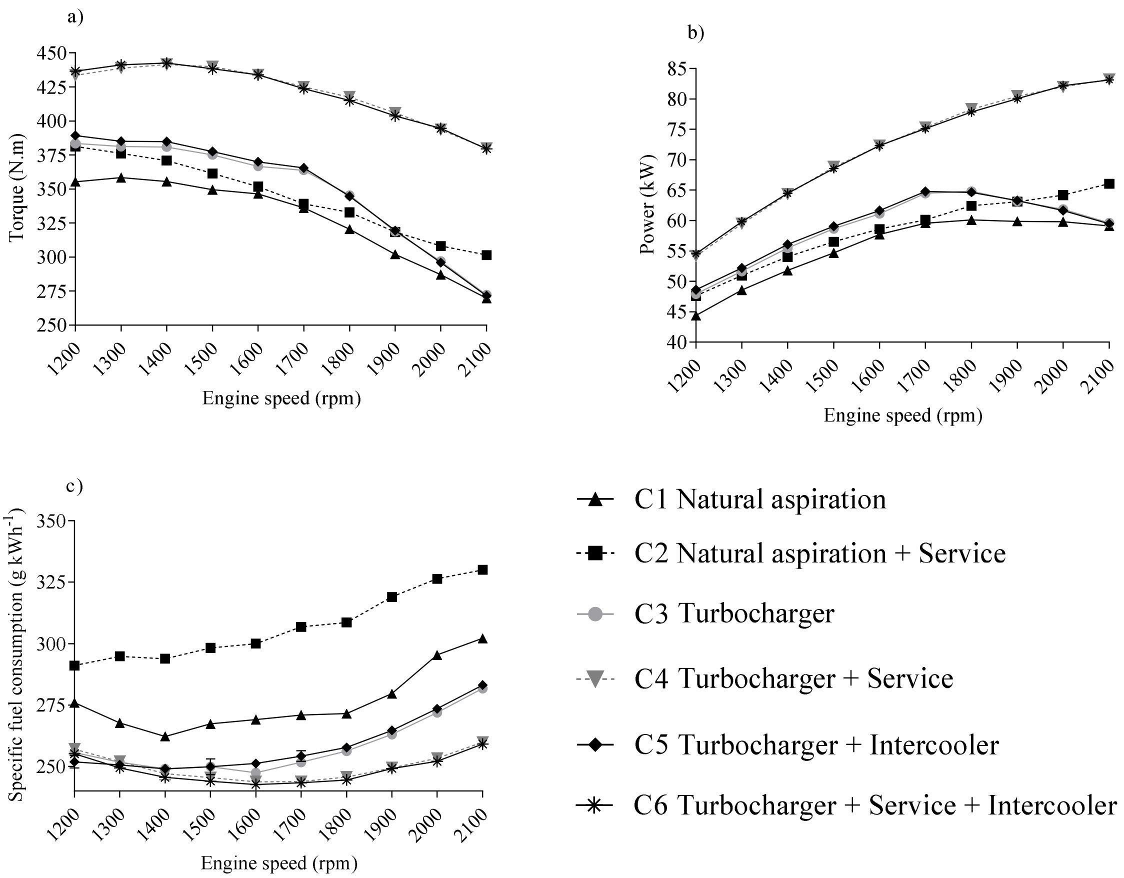

Figure 2. Characteristic curves of engine performance: a) torque; b) power and c) specific fuel consumption, as a function on the engine speed, for the six configurations evaluated

mixture poorer and adversely affecting the power curve.

In addition, the increased volume of air admitted due to the use of the turbocharger leads to a lower compression rate at the start of combustion compared to the engine in the original condition. It also explains the displacement of the entire torque curve and, consequently, the power curve because the ignition point changes the useful working ratio of the crankshaft.

The configuration turbocharger + service + intercooler had the lowest specific fuel consumption (Figure 2c), indicating an improvement in combustion in the cylinders (MIALHE, 1996). The better burning of the air/fuel mixture favors an increase in the engine power, thus reducing the specific fuel consumption (FARIAS *et al.,* 2017).

The thermal efficiency of the engine is simply the inverse of the product of the specific fuel consumption and its calorific value (RAKOPOULOS *et al.,* 2008). In this sense, even indirectly, the configuration natural aspiration + service provides the lowest thermal efficiency for the engine, as it has the highest specific fuel consumption.

On the other hand, the configurations C4 and C6 presented the lowest results regarding specific fuel consumption. Thus, these configurations provided the highest thermal efficiency to the engine when compared to the others.

CONCLUSIONS

- Installing only the turbocharger, or its association with the intercooler, without increasing the volume of injected Diesel does not increase the engine torque and power.
- The increased fuel flow provided by the injection pump significantly increased the engine performance for the evaluated configurations.
- The configurations turbocharger + service and turbocharger + service + intercooler reduced

the specific fuel consumption by up to 10% and increased the engine torque and power by approximately 30%, compared to the configuration natural aspiration.

AUTHORSHIP CONTRIBUTION STATEMENT

FARIAS, M.S.: Investigation, Supervision, Visualization, Writing – review & editing; SCHLOSSER, J.F.: Funding acquisition, Investigation, Resources, Supervision, Visualization, Writing – original draft; NEGRI, G.M.: Conceptualization, Data curation, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing; CASALI, L.: Investigation, Methodology, Writing – review & editing; BERTOLLO, M.: Formal Analysis, Investigation, Validation, Writing – review & editing; ROSA, L.S.: Investigation; Methodology, Software, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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