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Determination of the optimum operating parameters of an axial fan used on the conventional air blast orchard sprayer

Medet Itmec[1,*] **Ali Bayat**[1]

[1]Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Çukurova University, Adana, Turkey

[*]Corresponding Author: mitmec@cu.edu.tr

Abstract

The pesticide droplets are carried to the tree canopy with the assist of the air flow which is generated by an axial fan of orchard sprayer. The designers manufacture the fan of orchard sprayer with ability of 6 different working conditions under constant PTO speed. Previous studies were related to evaluating the effectiveness of sprayers. In this study, 6 different options that presented to farmers was evaluated with view of energy consumption and air flow. A Conventional orchard sprayer having an axial fan with 36” diameter was operated at two fan revolutions (1890 and 2430 rpm) and at three blade angles (15º, 30º, 45º), and measured air capacity, the fuel consumption, variations of air velocities in air jet profile of the fan and calculated power consumption for each operating parameters potentially to be chosen by farmers. As a result, for each blade angle, if the fan speed increase, the air jet of the fan become more uniform than before. The maximum fan efficiency and system efficiency were %73,25 and %59,98 respectively which were obtained 30º blade angle and 2430 rpm fan rotation speed condition. The minimum fuel consumption and torque need was obtained under conditions of 15º blade angle and 1890 rpm fan rotation speed. However, considering maximum air capacity and the best air velocity uniformity in the profile of fan jet was established at, 45º blade angle and 2430 rpm fan rotation speed operating parameters.

Keywords: Air assisted orchard sprayers, Axial fan efficiency, Air jet velocity profile

Introduction

In recent decades there is a clear tendency to reduce the use of pesticides in agriculture (Ozluoymak et. al., 2019). For new designed field and orchard sprayers, precisely consumption of pesticide is essential for both. With this view, controlling the air volume and quantity of pesticide with technologies is milestone of the designs for air blast orchard sprayers. The axial fan of the orchard sprayer must be flexible to supply enough airflow and had variable rate technology (VRT) of pesticides to different types of trees for precisely pest application (Hołownicki et al., 2017). The efficiently usage of an axial fan can reduce tractor fuel consumption and offers more economical and environmental friendly pesticide application. To do this, the parameters that affected the air flow must be regulated. In air assisted orchard sprayers, the spray droplets produced by the nozzles are carried to the tree crown by the air flow that provided by fans. During the pest application of orchard, the airflow is needed to atomize the droplet, to carry the droplets to the target and to get better penetration (Matthews, 2000). The amount and the distribution of the pesticides on the tree crown varies depending on the characteristics of the air jet (Khot et al., 2012). The air volume flow rate of the orchard sprayer and penetration of the air flow must be set to be sufficient to different tree crowns (Panneton et al. 2001, Delele

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et al. 2005, Chen et al. 2011, Garcia et al. 2012). Beside this, the airflow need of orchard depends on the crown geometry of the tree, tractor velocity, vegetative development of the tree, foliage density, wind velocity (Chen et al. 2012). Canopy geometry, foliage density and vegetative development of a tree affects the pesticide penetration and deposition of droplets on the tree. According to Balsari et al. (2008) 5m/s air velocity was sufficient to give higher spray deposits on the leaves in vineyard.

In the real world, spraying involves a changing droplet size distribution, turbulent airflow, fluttering and wobbling objects of non-uniform size and shape, and an ever-changing canopy situation. Leaves used as targets can to some extent be regarded as ribbons or disks (Fox et al., 2008). The forced air jet transports the spray droplets throughout the target, moving and lifting the foliage to allow penetration and depositing the droplets on the plant surface including the undersides of leaves (Cross et al. 2003). There are two approaches to dealing with the problems of inefficiency and inadequate coverage associated with applying pesticide treatments: improving the dosing system and improving the application machinery. Adjusting the spray dose is useless if the application equipment is not adapted to the target canopy. Therefore, efforts have been undertaken to improve air blast sprayers (Miranda-Fuentes et al. 2017). The economically produced sufficient airflow is one of the main mission of the pest application of a orchard also for spray deposit.

The fans are used in different areas and for each blade angle of the fan, the performance and volumetric flow rate of the fan differs (Izadi and Falahat 2008, Patel and Patel 2012, Huang and Gau 2012). The airflow that produced with axial fans can be controlled by changing the fan blade angles and fan rotation speed. The blade performance may be predicted from the aero-dynamic characteristics such as *lift* and *drag coefficients* of the chosen blade section and given by the following equations:

$$C_l = \frac{L}{\frac{1}{2}\rho V^2 A_l} \qquad (1)$$

$$C_d = \frac{L}{\frac{1}{2}\rho V^2 A_d} \qquad (2)$$

where C_l is the coefficient of lift, C_d is the coefficient of drag, *L* is the lift force, *D* is the *drag force*, ρ is the density of air, *V* is the velocity of undisturbed airflow. The related areas of the fan blades are shown in Figure 1. The top view of the fan blade is A_l *and* the side view of the fan blade is A_d (Panigrahi and Mishra 2014). As the blade angle (α) of the fan increases, the exit velocity and the volume flow rate of the fan also increase (Logan and Roy, 2003). The fuel consumption and power need also increase depending upon the blade angle increase. Therefore, to get better performance with high working efficiency, the correct fan blade must be determined for processes.

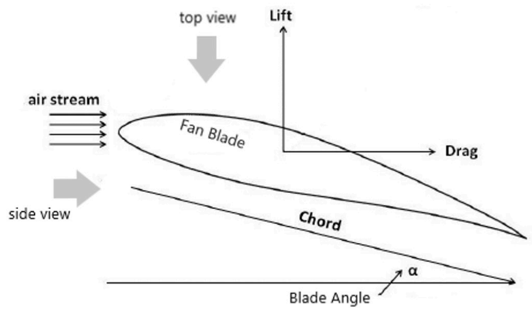

Figure 1. Lift and Drag forces acting on the blade and the blade angle change.

The branches and leaves which resist to the air flow, decreases their kinetic energy of air flow. The designers manufacture the orchard sprayer with 6 different air capacity options (1890 rpm and 2430 rpm via transmission and 15º, 30º, 45ºblade angles) under constant PTO speed. However, they did not make any advice about the correct option for related tree kind during the pesticide application for each options. The recent studies which was made according to pesticide application. In these studies, the energy consumptions was not taken into account. In this study, the axial fan which is designed for the variable airflow with the help of fan blade angle change, was used. The air velocities, the torque, fuel consumption values were measured under conditions of the two fan revolutions (1890 rpm and 2430 rpm) and three different blade angles (15º, 30º, 45º) with 540 rpm of PTO. By this way, the fan power, average air velocity, air jet velocity profile, PTO power, approximate fuel power and efficiency was calculated. Then, the axial fan of the orchard sprayer performance and efficiency was compared to determine optimum axial fan working conditions. The optimum working condition was determined according to with view of less energy consumption and high air velocity application.

Materials and Methods

Establishment of the experimental unit

The tests were carried out at the laboratory conditions with no air flow. New Holland TD 95 (Turkey) tractor which was stationary, was used to drive PTO. The maximum power of the tractor was 62,5 kW and it had diesel motor with four cylinders. To evaluate axial fan efficiency of the orchard sprayer; the pump, pressure regulator unit, and the tank were removed from the orchard sprayer. The orchard sprayer axial fan was connected to the three-point linkage system of the tractor and PTO was used to drive axial fan. Before the axial fan blades, there were flow redirecting stationary blades of 19 which were located as 55º angle according to air inlet axis. After the air passed from the fan blades, at the exit side of the fan the air flow directed to the nozzles (Figure 2a) with an air deflector. The diameter of axial fan was 900 mm (36’’) and it had 9 blades which was made of polyethylene, was arranged in an aluminum hub at angle of 40º. The Exit side of the fan area calculated as 0,31 m². The fan blades had holes to set the angle of the blade as 15º,30º,45º via the bolts on the aluminum hub (Figure 2b). The axial fan transmission system had the two stages as 1:3,5 and 1:4,5 transmission rates which corresponded 540 rpm to 1890 rpm and 2430 rpm respectively. Before the experiment started, each nozzle axis was turned perpendicular direction of the circumference of the axial fan to eliminate the turbulences at fan exit.

Measurement of the experimental results and data calculation

To calculate the PTO power () and fan efficiency, the torque sensor was connected between the transmission unit of the axial fan and the shaft. The torque and angular velocity was measured via torque sensor with data logger (Grant 2020 series) (Figure 3).

The real time fuel consumption values were measured by two flow-meter (AICHI OF05ZAT Aichi Tokei Denkei Co. Ltd. Japan). One of the flow meter measured the amount of fuel passing from the fuel supply line between the fuel tank and the injection pump (Figure 4a). The other was used for measuring the amount of fuel returning line of the fuel tank from the injection pump and the injectors. By the way, the difference between the two measurements represented real time fuel consumption (Figure 4b). The both flowmeters were calibrated according to diesel fuel before the experiments.

Figure 2. (a) The axial fan of the orchard sprayer and (b) aluminum fan hub blade angle change unit.

Figure 3. Connection of the torque sensor between transmission unit PTO and data logger

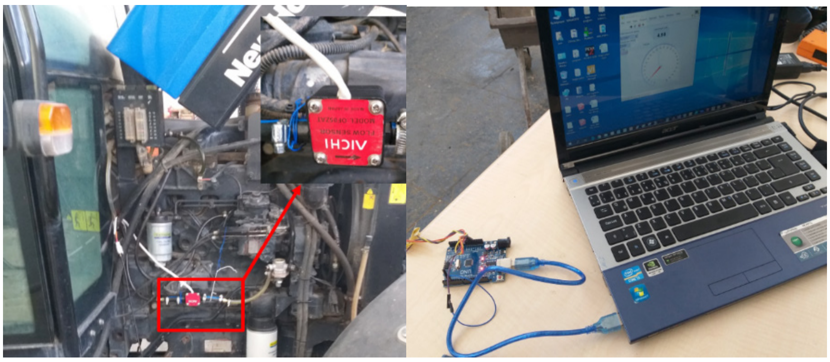

Figure 4. (a) Flowmeter of the supply line between the fuel tank and the injection pump, (b) real time gauge that show the differential difference of the two flowmeters.

To determine the fan power and air jet velocity of the axial fan, the measurement of the velocity was practiced with a hot wire anemometer. From the bottom side of the axial fan there was no air flow exit. The rest of the circumference was separated 12 regions and numeri zed to measure air velocity (Figure 5). The velocities that measured from the regions 1 to 6 are the left side of the axial fan and 7 to 12 are the right side of the axial. The air velocity measurement from each region was conducted with three replicates for each experiment to calculate the average exit velocity.

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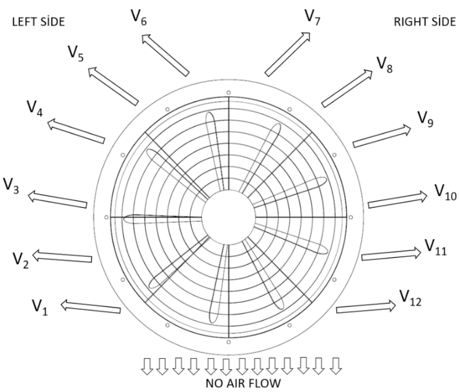

Figure 5. Air velocity measurement regions for air jet profile determination from back view of the sprayer.

The air jet velocity's uniformity of distribution was evaluated according to coefficient of variation (CV) method;

$$CV = \frac{\sigma}{\mu} \qquad (3)$$

where indicates the standard deviation and µ also means mean values of the air velocities that measured from 12 regions. The value of CV was calculated for left, right sides and totally for each experiment conditions. Reason for calculating the CV value of each experiment condition is, determining disturbance of the air jet. As the CV value increase, distribution uniformity of the jet gets worse.

The average value of each air exit velocity that measured from exit side of the axial fan was used for the Bernoulli equation to calculate fan power (N_{fan});

$$N_{fan} = \dot{m}\left(k\frac{V_2^2}{2}\right) \qquad (4)$$

Where is the mass flow rate, is kinetic energy correction factor (=1.1). P_1 is the inlet air pressure and P_2 is the exit air pressure of the air, V_1 is the inlet velocity, V_2 is the exit velocity, is air density, the g is the gravitational acceleration, z_1 and z_2 is the elevation respectively inlet and outlet side of the fan. P_1 and P_2 are equal to the atmospheric pressure P_{atm} so these two values can be neglected and there was negligible elevation difference between inlet and outlet so z_1 and z_2 were also negligible. Inlet side of the fan was large, therefore V_1 was also neglected. The mass flow rate and fan average exit velocity fan power can be calculated with these assumptions (Çengel and Cimbala 2004).

The mass flow rate of the axial flow also calculated as;

$$\dot{m} = \rho.A.V_{ave} \qquad (5)$$

In equation; is air density (kg/m^3), A is the exit area (m^2) of the axial fan and is (m/s) the average velocity of the exit side.

After measuring the torque and angular velocity data of the experiment the PTO Power (N_{PTO}) can be calculated as:

$$N_{PTO} = \frac{M_d x n}{9550} \qquad (6)$$

Where is the torque (Nm) and n is the angular velocity (rpm). Then fan efficiency of the experiment can be calculated:

$$N_{fan,eff} = \frac{N_{fan}}{N_{PTO}} \qquad (7)$$

The fuel power (can be calculated according to the fuel consumption of the each experiment data;

$$N_F = \frac{BxH}{3600} \qquad (8)$$

Where the B is the fuel consumption per hour (kg/h) and the H is the energy value of the fuel (kg/kj) which can be 42.000 kj/kg and diesel engine operates approximately %32 efficiency, hence it was used as multiplier factor (Erzurumlu, 2018). The efficiency of the whole system which meaned ratio of the fan power to the fuel power can be calculated as;

$$N_{sys,eff} = \frac{N_{fan}}{N_F} \qquad (9)$$

In recent studies, it can be clearly seen that effect of air volume, air jet capacity, air exit velocity were studied. However, energy consumption and energy components (blade angle, fan revolution speed, torque etc.) were not evaluated (Pai et.al. 2009; Khot et. al., 2012). In the study, the energy consumption and air jet was evaluated. The axial fan of the orchard sparayer was worked at 540 rpm PTO with two different revolutions (transmission rates1:3,5 and 1:4,5 which corresponds to 1890 rpm and 2430 rpm). The fan blade angle was changed to 15º,30º,45º angles to measure fuel consumptions, torque, and local velocities (from 12 regions) with three replicates. Then the fan power, the fan efficiency, PTO power, fuel power and system efficiency were calculated. According to these values the optimum operation condition was determined according to these experimental conditions. To show operation conditions effect on air velocity The air velocity data was evaluated in SPSS 20 program, with One Way Anova Test with Duncan Post HocTest.

Results and Discussion

Air Jet Profile

To present effect of the blade angle and fan rotation speed (rpm) on the axial fan average velocity, each operation velocity data that was measured from related region (Figure 3), and evaluated statistically with One Way Anova and examined by Post Hoc Duncan Test (Figure 6). The operation conditions were statistically significant which means each operations differed. For instances, with 45º blade angle with 2430 rpm experiment condition the maximum average velocity was obtained and the 15 º blade angle with 1890 rpm was the minimum average velocity statistically. In this study, maximum average value of the velocity was 48,367 m/s. Endalew et al. (2010), used 800 mm diameter axial fan with flow regulator on deflector unit, to prevent turbulences at exit side and measured the maximum velocity at 30 m/s at exit side. The air velocity which enters the tree canopy and the exit at the other side of tree canopy must be between 5 m/s as explained before. However, it depends on vegetation, foliage density.

It was obvious that for the same blade angle, if the fan rotation speed was chosen as 2430 rpm instead of 1890 rpm, the CV (%) of the left side, right side and total CV (%) became less which means more stable velocity characteristic (Table 1). As the blade angle was increased, the velocities that measured from each region were increased. Because of transmission unit, the impeller of the fan (counter clockwise) turned reverse side of the PTO. By the way the axial fan vacuumed air firstly discharged from right side of the axial fan. Because of this reason, the turbulence occurred at the right side of the axial fan. Therefore, at V_{11} as lowest velocity of the whole air jet and V_{12} as maximum velocity of the air jet. Due to the irregularity of the right side of the axial fan, CV_{right} was larger than the CV_{left} for all experiment conditions. As the both blade angle and fan rotation speed increased, CV_{total} value became less than before. It was clear that rise of the blade angle caused the velocity increase for each region. In this study, the fan blade angle was changed to 15º, 30º, 45º. However, fan's stationary blade angles (as said before 55º) were not able to change. Because of construction, the flow redirecting blades was constant. Therefore, the flow redirecting blades must be also set according to fan blade angle. According to Liu et al. (2011), the difference between the flow regulator blade angle and fan blade angle must be 10º to get better performance.

Fuel Consumption and Power

The torque and fuel consumption values for each experimental conditions were measured as shown Table 2. It can be seen that as the rotation speed of fan increased from 1890 rpm to 2430 rpm, the torque need of the system and fuel consumption increased. If the *blade angle* increase for constant Fan Rotation Speed, both Torque and Fuel Consumption values also increased because of the resistance of the air. The maximum torque need and fuel consumption values were measured at 2430 rpm and 45º blade angle. Comparing the data that obtained from the experiments and previous studies (Işıktepe and Sümer (2010)) were similar in results of torque, power, and fuel consumption data for 540 rpm PTO. At first view, for low fuel consumption and torque, the condition of 1890 rpm and 15º blade angle was appropriate but the produced air velocity was another parameter to decide.

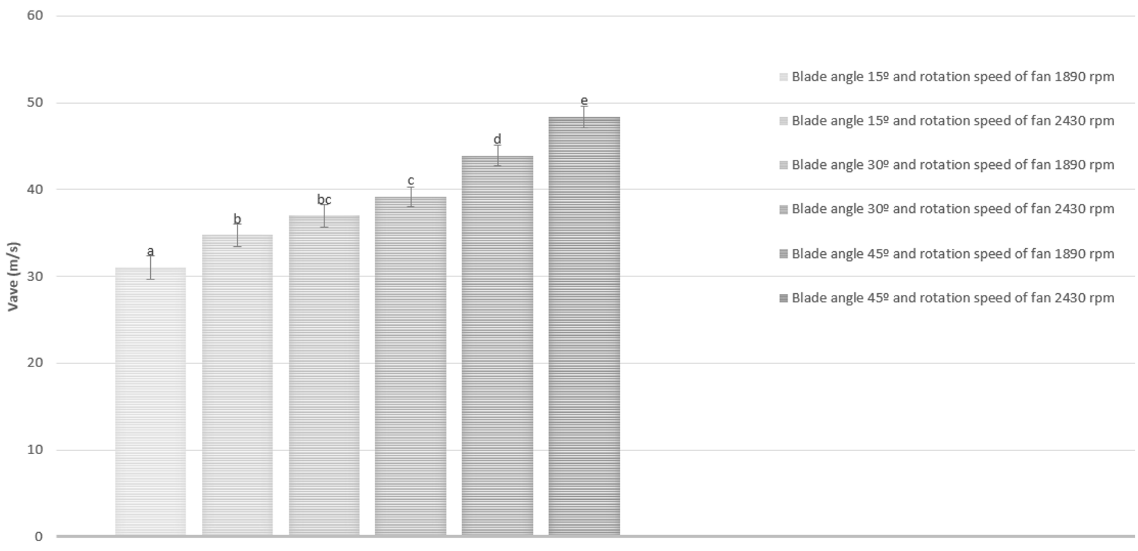

Figure 6. Statistical results of result of average fan velocity of each operation conditions.

Table 1. Measured velocity from 12 regions and distribution values under different conditions

Stage	Blade Angle (º)	V1 (m/s)	V2 (m/s)	V3 (m/s)	V4 (m/s)	V5 (m/s)	V6 (m/s)	CVleft (%)	V7 (m/s)	V8 (m/s)	V9 (m/s)	V10 (m/s)	V11 (m/s)	V12 (m/s)	CVright (%)	CVtotal (%)	Vave
3,5	15	28,96	30,8	32,6	31,03	29,9	32,23	4,45	32,23	31,2	33,8	30,5	24,8	33,87	10,80	7,89	30,99
4,5	15	35,47	36,5	37,6	39,17	36,9	37,69	3,36	38,67	39,9	37,2	35,76	29,4	39,57	10,67	7,53	36,99
3,5	30	31,46	32,2	32,8	34,8	36,4	35,2	5,73	37,2	36,8	35,2	33,88	31,8	39,2	7,36	6,92	34,74
4,5	30	41	42,9	45,4	46,93	42,5	44,2	4,87	45,93	45	45,3	42,9	38,1	46,63	7,14	5,83	43,90
3,5	45	37,97	37,9	37,4	41,5	38,4	41,43	4,74	41,63	43,3	36,5	33,93	34	45,67	12,83	9,23	39,15
4,5	45	45,5	41,3	44,7	46,73	45,1	46,7	4,44	51,15	52,6	50,1	51,57	47,9	57,13	5,95	8,89	48,37

Table 2. Comparison of the measured torque and fuel consumption values

Blade Angle (º)	Fan Rotation Speed (rpm)	Torque (Nm)	Fuel Consumption (l/h)
15	1890	207	8,56
15	2430	342	10,16
30	1890	318	10,04
30	2430	467	11,48
45	1890	426	12,03
45	2430	633	14,83

According to the results of the experiments for each angle, if the fan rotation speed was increased via shifting the stage, the volume and mass flow rate, fan power, PTO Power, Fuel Power increased. The maximum Fan Power, PTO Power, and Fuel Power were obtained at 2430 rpm and 45º blade angle (Table 4). The maximum air volume flow rate was obtained as 59040 m^3/h. According to Bayat et. al. (2020) to get better penetration, the volumetric flow rate of axial fan must be between 70000 m^3/h and 90000 m^3/h for citrus with 6 m canopy height. However, the excessive torque increase caused decline of the efficiencies. It was obvious that maximum efficiency of fan and system were obtained at 2430 rpm and 30º blade angle because of producing high average velocity, low torque need and fuel consumption.

Table 3. Calculated Fan power, PTO power Approximate Fuel Power and efficiencies of the experiment

Blade Angle(º)	Average Exit Velocity (m/s)	Volume flow rate*10^3 (m^3/h)	Mass flow rate (kg/s)	Fan Power (kW)	PTO Power (kW)	Fuel Power (kW)	Fan Efficiency (%)	System Efficiency(%)
15	30,99	34,67	11,80	6,23	11,70	24,05	53,26	25,92
15	36,99	37,62	12,81	9,64	19,34	28,54	49,83	33,76
30	34,73	42,41	14,43	9,57	17,98	28,21	53,23	33,93
30	43,91	53,60	18,24	19,34	26,41	32,25	73,25	59,98
45	39,16	47,81	16,27	13,72	24,09	33,80	56,96	40,60
45	48,36	59,04	20,09	25,84	35,79	50,09	72,20	51,59

Conclusion

To provide flexibility for spraying in orchard, the axial fan of orchard sprayer was designed with 6 different conditions (three blade angles and two different revolutions of fan). However, in user guide there was no explanation about, which condition was most efficient for general purpose and for different tree kind. According to vegetative development and leaf density, proper fan speed and blade angle must be determined for each tree kind. However, 6 different conditions were not sufficient for general purpose orchard sprayer. The air velocity must be changed instantaneously depending upon the tree canopy. Via ultrasonic sensor, LİDAR technology, stereovision technologies etc. flexibility of spraying for each tree can be provided precisely. With these technologies, energy and pesticide consumption savings also increase.

The most efficient of the average air velocity of 2430 rpm and 30º blade angle. The maximum average air velocity was calculated for 2430 rpm and 45º blade angle as 48,37 m/s. The uniformity of air jet velocity was changed depending upon the fan rotation speed. Because of fan turning side, there was turbulence at right side and the velocity of the V_{11} and V_{12} were not stable. However, the disorders of the air started to decrease with fan rotation speed increase. As the blade angle or stage increased, the rotating of the fan got resistance. Therefore, the fuel consumption and torque need of the fan increased. The fan and system efficiencies were decreased depending upon the excessive torque rise for 2430 rpm and 45º blade angle, because the resistance of the blades were changed. The maximum fan and system efficiencies were obtained as 2430 rpm and 30º blade angle 73,25% and 59,98% respectively. However, 2430 rpm and 30º blade angle can be default value which is optimum condition for efficiency. However, the air flow need for the sufficient pest application differs according to vegetative development, tree crown geometry, foliage density. Therefore, tree kind-air volume flow rate relationship must be determined before application depending upon foliage density.

Compliance with Ethical Standards

Conflict of interest

The authors declared that for this research article, they have no actual, potential or perceived conflict of interest.

Author contribution

The contribution of the authors to the present study is equal. All the authors read and approved the final manuscript. All the authors verify that the Text, Figures, and Tables are original and that they have not been published before.

Ethical approval

Ethics committee approval is not required.

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Data availability

Not applicable.

Consent for publication

Not applicable.

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