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Full length article

Design and evaluation of a self-propelled field sprayer to be operated and controlled remotely

Abdallah E. Elwakeel [a,*], Saad F. Ahmed [b], Abdalla M. Zein Eldin [b], Loai Nasrat [c]

[a] Department of Agricultural Engineering, Faculty of agriculture and natural resources, Aswan University, Aswan, Egypt.
[b] Department of Agricultural and Biosystems Engineering, Faculty of Agriculture, Alexandria University, Alshatby, Alexandria, Egypt.
[c] Department of Electrical Engineering, Faculty of Energy Engineering, Aswan University

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ABSTRACT

Nowadays, agricultural sprayers are the most widely used equipment to carry out pesticide applications. Several kinds of sprayers have been developed from hand-operated, hydraulic sprayers to boom/speed sprayers or aircraft sprayers with the development of agricultural engineering. The objectives of this study were to design a self-propelled field sprayer to be operated and controlled remotely and evaluate the performance of the purposed machine at different forward speeds of 9.33, 8.39, 7.46, 6.48, and 6.22 km/hr and different pump pressure of 9.5, 8.5, 8, 7 and 6 bar under laboratory conditions. Also, evaluate and calibrate the performance of the spraying system. The results showed that the maximum actual field capacity was 8.66 fedd/hr at 9.33 km/hr, and the total operation cost was 60.44 EGP/hr (6.98 EGP/fedd) at 9.5 bar.

1. Introduction

The growing concern to control plant diseases, insects, and weeds for a qualitative yield of agricultural products is increasing speedily in many developing countries. Pesticides are an integral part of worldwide agriculture. Between 30 and 35% of crop losses can be prevented when harmful insects and diseases are eliminated by spraying pesticides (Cho et al., 1999). Although pesticides are needed in modern agriculture, they are poisonous and are dangerous for humans and the environment (Dasgupta et al., 2007; Rogan and Chen, 2005; Pimentel and Lehman, 1993; and Reus et al., 2002). The use of pesticides will always involve some degree of risk, because of the poisonous character of these chemicals (Damalas and Koutroubas, 2016). Farmers and their family members run the highest risks, as they can easily meet the pesticides when mixing the chemicals or when applying them to the crop. Acute poisoning with pesticides is a global public health problem, accounting for as many as 300,000 deaths worldwide every year (Goel and Aggarwal, 2007). Many of these pesticide poisonings, particularly in the developing world, are intentional. Apart from target organisms, other organisms (e.g., beneficial insects, birds, earthworms, and fish) can be affected by pesticides in or around fields, resulting in the death of wildlife, death of farm animals, and loss of biodiversity (Damalas and Eleftherohorinos, 2011). Developing a target-specific pesticide robot sprayer can reduce the amount of pesticides used in modern agriculture and potentially remove the human from the pesticide spraying process. Studies show that up to 60% of pesticide use can be reduced by using selective sprayers (Elkabetz et al., 1998; Goudy et al., 2001). Robotic

*Corresponding authors.
E-mail address: abdallah_elshawadfy@agr.aswu.edu.eg (Abdallah E. Elwakeel).

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technology is an alternative method for spraying in agriculture, which provides multiple benefits, such as safety, sustainability, and environmental impact. In terms of safety, it removes the farmer from exposure to dangerous chemicals (Horrigan et al., 2002). In addition, less pesticide means healthier food products for the consumer (Williams and Hammitt, 2001). In terms of agriculture sustainability, robotic technology can provide a way to reduce inputs (e.g. by reducing the quantity of pesticides used) and make the most efficient usage of pesticide controls (e.g. by targeted spraying). Furthermore, targeted spraying can have a significant reduction in environmental impact (Gill and Garg, 2014).

2. Materials and methods

To achieve the objectives proposed for the current research, an experimental spraying machine was designed and manufactured at a local workshop in Aswan governorate - Aswan, Egypt. This experimental machine was designed to operate inside the open field.

The experimental unit was designed for computable with a wide range of flow rate, working pressure, forward speed, and application height. The assembly unit is shown in Figs. 1-4.

2.1. Description of the experimental spraying machine

The entire experimental field sprayer was subjected to standard design methodology. The spraying machine consists of five main parts as follows:

1. Machine frame.
2. Driving system.
3. Power supply system.
4. Control system.
5. Spraying system.

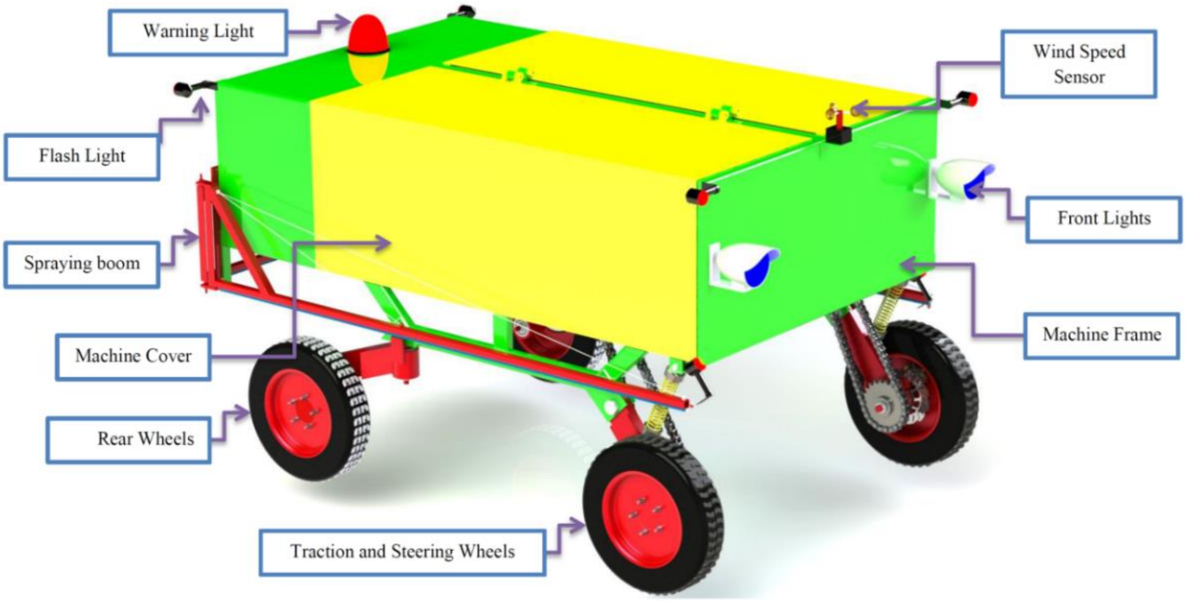

Fig. 1. Isometric view of the spraying machine shows the main components.

Fig. 2. The spraying machine with spraying position.

Fig. 3: The spraying machine with opening machine cover.

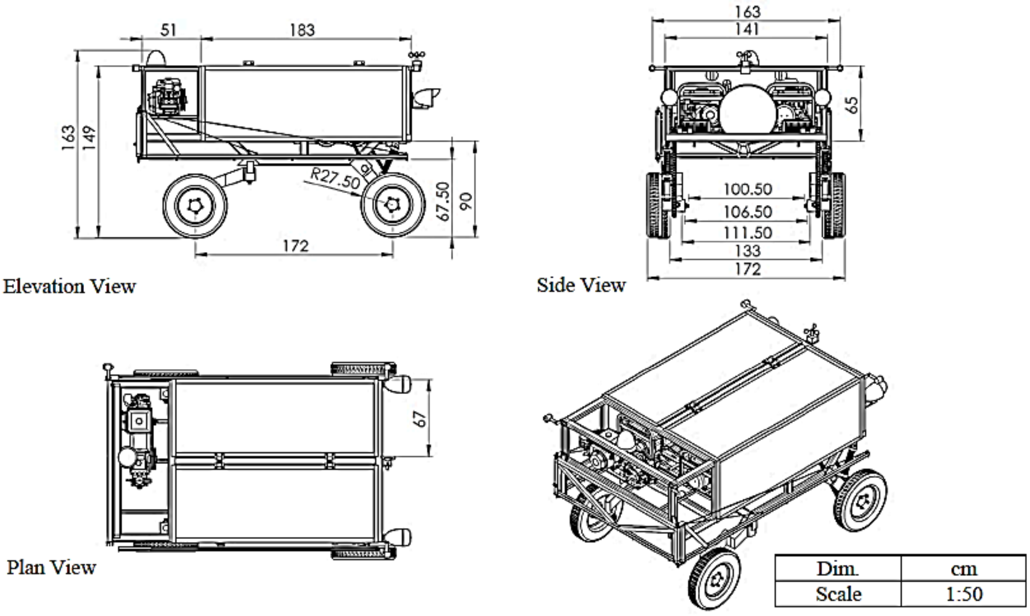

Fig. 4. Detailed views of the spraying machine.

2.1.1. Machine frame

The machine frame consists of several members most of which were constructed out of (Rectangular tube (40*70*3.2) mm, rectangular tube (40*20*1.5), Rectangular tube (15*15*1.0), Angle (30*30*1.5), And was covered with sheet metal 1.5 mm thickness as shown in Figs. 5 and 6.

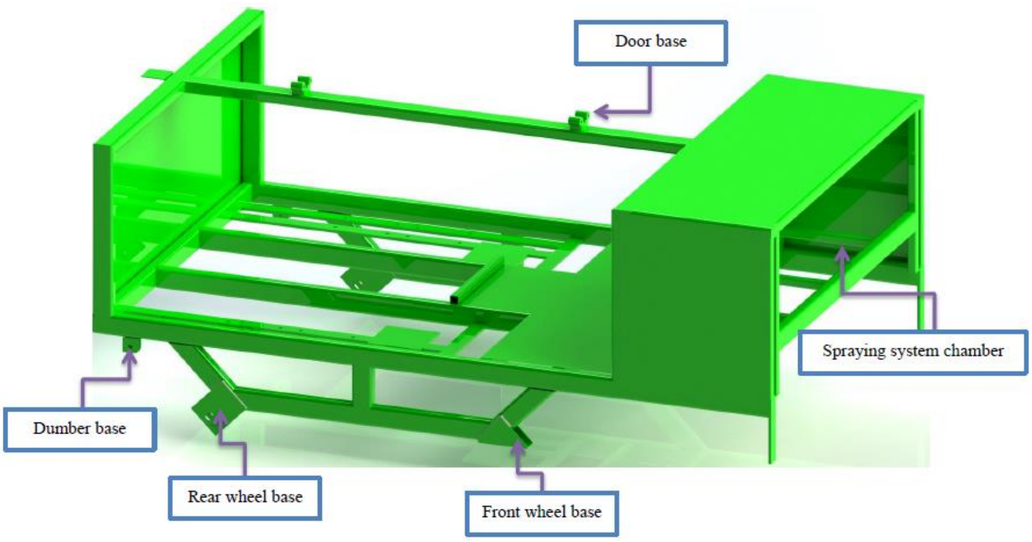

Fig. 5. Isometric view of the machine frame.

The whole spraying machine parts include (driving system, Power supply system, control system, and spraying system) were carried out in a metallic frame module of mild steel. The supporting base and entire unit need to be strong and lightweight. It was made of metal, and the other parts of the machine were mounted on the frame.

The machine frame contact with the soil surface using four wheels and consists of the main frame, front and rear suspension units, the front suspension unit as shown in Figs (7 and 8), consists of a front-wheel shaft, bearings, front-wheel arm, pins, nut, compression spring, and front-wheel arm, on the other hand, the rear wheel suspension unit consists of a rear-wheel shaft, bearings, pivot shaft, pins, nut, compression spring, and rear-wheel arm.

The machine frame dimensions are 163 cm in height, 234 cm in length, and 172 cm in width. The clearance from the ground surface is (85 - 90 cm) with both empty and full tanks respectively, as shown in Fig. 6.

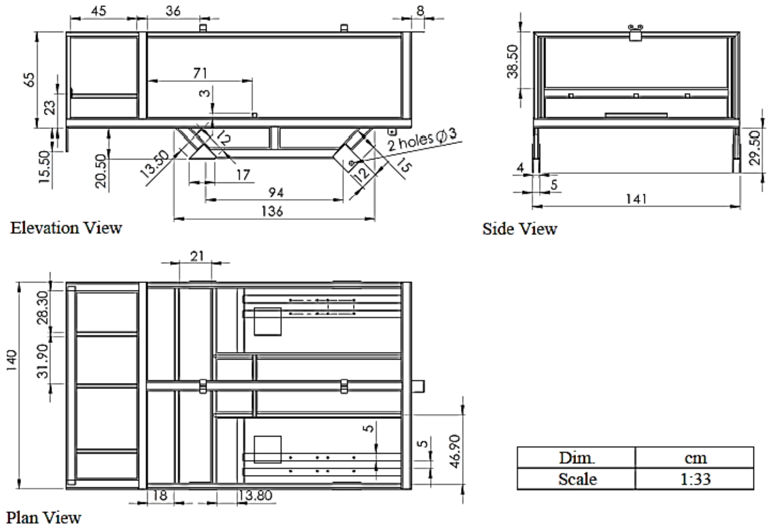

Fig. 6. Detailed views of the machine frame.

2.1.2. Driving system

The machine uses a couple of AC induction motors for driving the spraying machine, each motor is fitting with one of the front wheels (two-wheel drive); the maximum total weight of the machine is approximately 650 kg with a full tank and 450 kg with an empty tank, Maximum vertical load acts on each wheel is approximately 162.5 kg, Driving motor power for each wheel is 2 hp (1.5 kW), the spraying machine designed to works with maximum forward speed 11 km/hr (theoretically with 15% slipping ratio).

The spraying machine uses 4 tires [5.00 * 12], a couple of tires for traction and the other wheels for steering and carrying the total weight of the machine, the spraying machine will control the direction of movement by stopping one of the front wheels in the desired direction while giving power to the other wheel.

The front wheels take the power from the AC induction motor by using belts and pulleys as well as chains and sprockets. The power transmission system reduced the AC induction motor speed from 2800 rpm to 128 rpm.

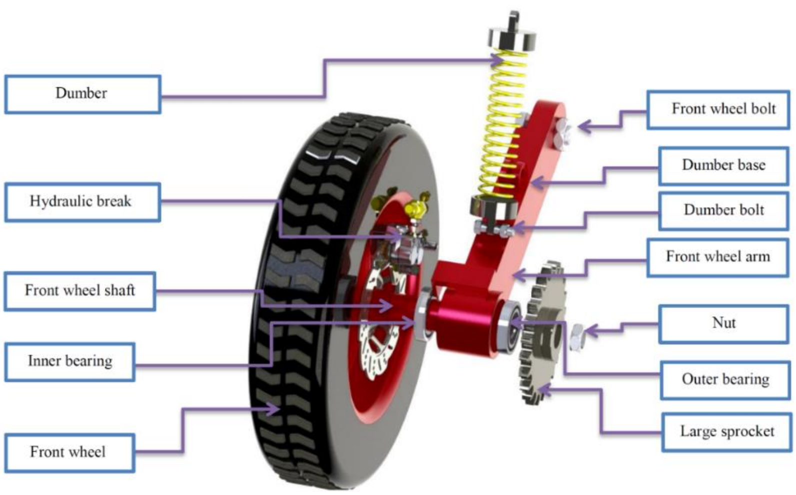

Fig. 7. Isometric view shows the front wheel components and suspension system.

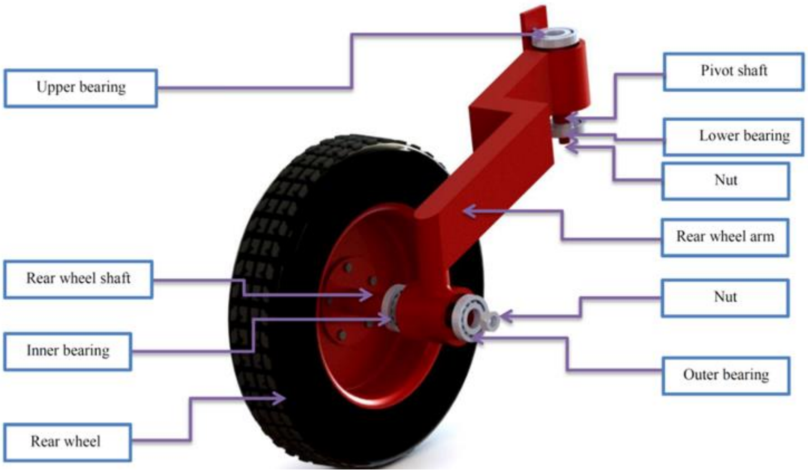

Fig. 8. Isometric view shows the rear wheel components and suspension system.

2.1.3. Power supply

2.1.3.1. Gasoline generator

The spraying machine takes the power from two gasoline generator model (Marquease OM-2000EMC), with a rated power of 2.5 kW for each one. Each generator is connected with an AC induction motor, as shown in Figs. 9 and 10.

2.1.3.2. Battery

The machine was provided with one battery, 12 V and 80 Ah sealed lead acid battery which was used as an alternative power source for the electronic circuits, servo motors, and stepper motors. The battery was charged from the gasoline generators (12 V output), as shown in Figs. 9 and 10.

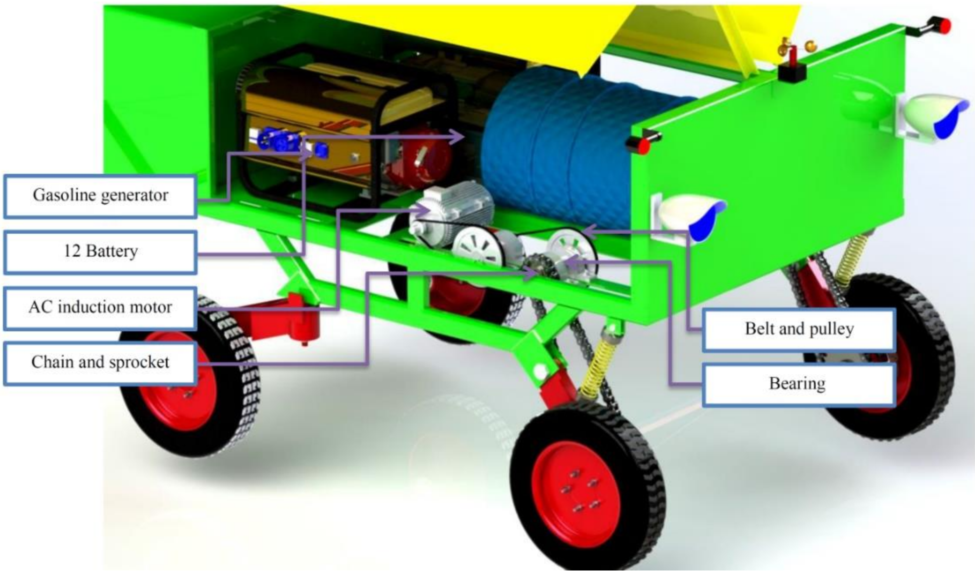

Fig. 9. The power supply system.

Fig. 10. Isometric view of the spraying machine shows the power supply system.

2.1.4. Control system

The control system consists of:

2.1.4.1. Measuring unit

This unit was designed for measuring many critical parameters that associated directly with the performance of the spraying process, and sending data immediately to laptop or PC by internet (Wi-Fi) and the delay between the frequent measurements was stated as 5 seconds, as shown in Fig. 11, this unit measuring the following parameters:

- Ambient temperature, ºC.
- Relative humidity, %.
- Air pressure, pa (N/m²).
- Altitude, m.
- Dew point temperature, ºC.
- Wind speed, m/sec.
- Liquid (pesticide) flow rate, litter/hr.
- Forward speed, km/hr.
- Light intensity, watt/m².
- Spraying height, cm.

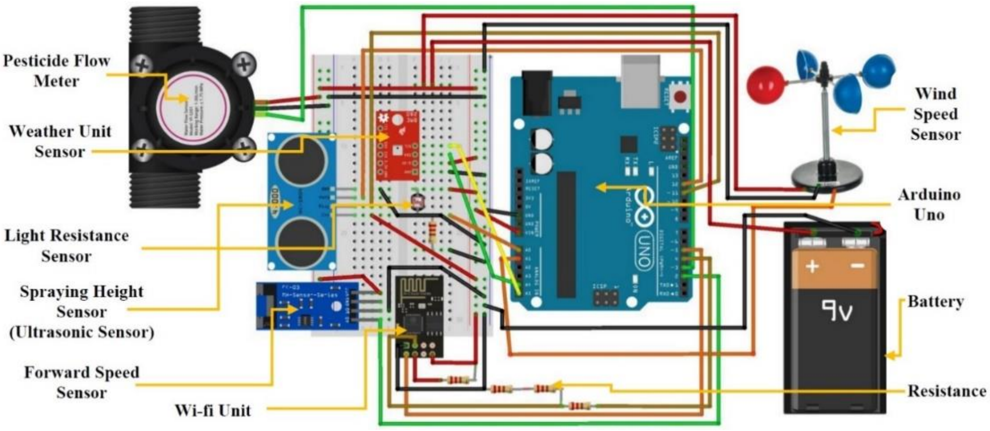

Fig. 11. The main components of the measuring unit.

2.1.4.2. Remote control unit

The processes that can be controlled remotely are divided into two main groups:

1) Remote control unit (Manual)

This unit consists of many parts included (three solenoid valves, two voice alarms, a manual remote-control unit, Arduino UNO shield, relay Kit, and battery). The spraying boom was divided into three parts and each part contains a solenoid valve, the main aim of dividing the spraying boom into three parts is to control the operation or closure of any of the three parts to be in line with the operating conditions.In addition to the voice alarm unit, which is used during the movement of the machine on the road so as not to cause accidents. The previous components, which include 3 solenoid valves and an alarm unit, were connected to remote control and controlled by a manual control unit, as shown in Fig. 12.

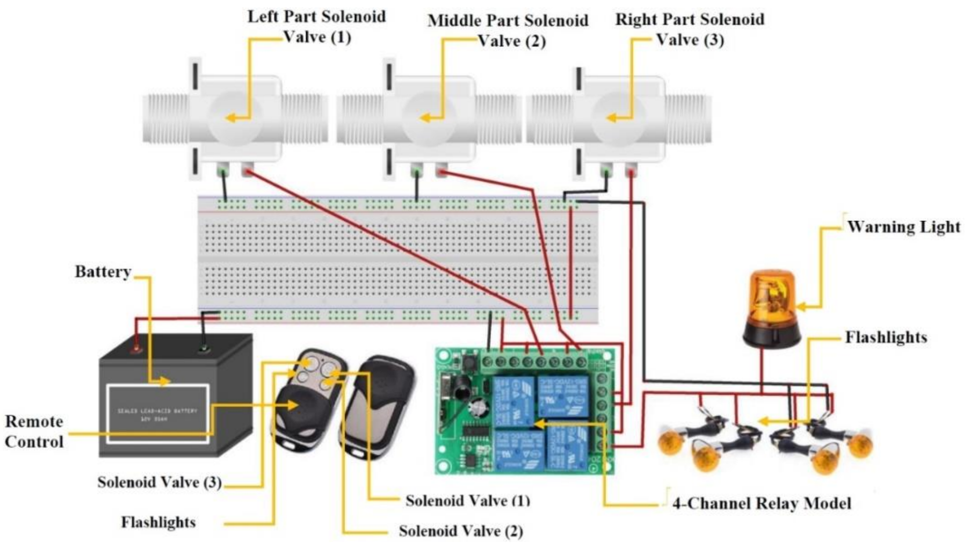

Fig. 12. The main components of the Remote-control unit (Manual).

2) Remote control unit (Smart Phone)

The movement of the machine can be controlled remotely using the Smart Mobile App. specially designed to operate the machine remotely via Bluetooth, as shown in Figs. 13 and 14, and this unit consists of:

- Bluetooth module (HC-06).
- Smartphone.
- Smartphone application.
- 2 - Servo motor (for hydraulic brake system).
- 2- Voltage regulator dimmer thermostat.
- 2- Relay.

Due to the high prices of DC motors and unavailability in the local markets with the desired power, and to solve this problem a new control circuit was created, consisting of the components shown in Fig. 15.

The movement of the machine is controlled as follows:

1. Sending a signal from smartphone mobile application via Bluetooth to Arduino units, (includes speed value and direction of moving).
2. The Servo motor will rotate with the desired angle associated with the forward speed.
3. The relay controls the direction of machine movement by cutting the current from one of the two motors in the direction of movement and connecting the current to the other motor, as well as connecting the current to both motors when the machine is moving forward or cutting the current from both motors for stopping the machine and running the servo motors to operate the hydraulic brakes.

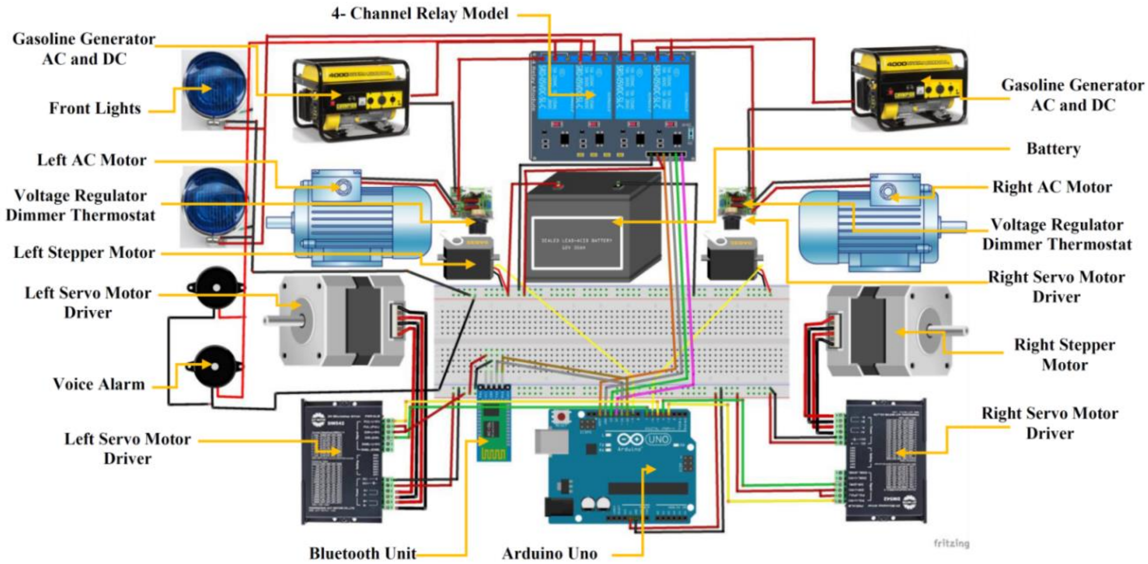

Fig. 13. The main components of the Remote-control unit (Smart Phone).

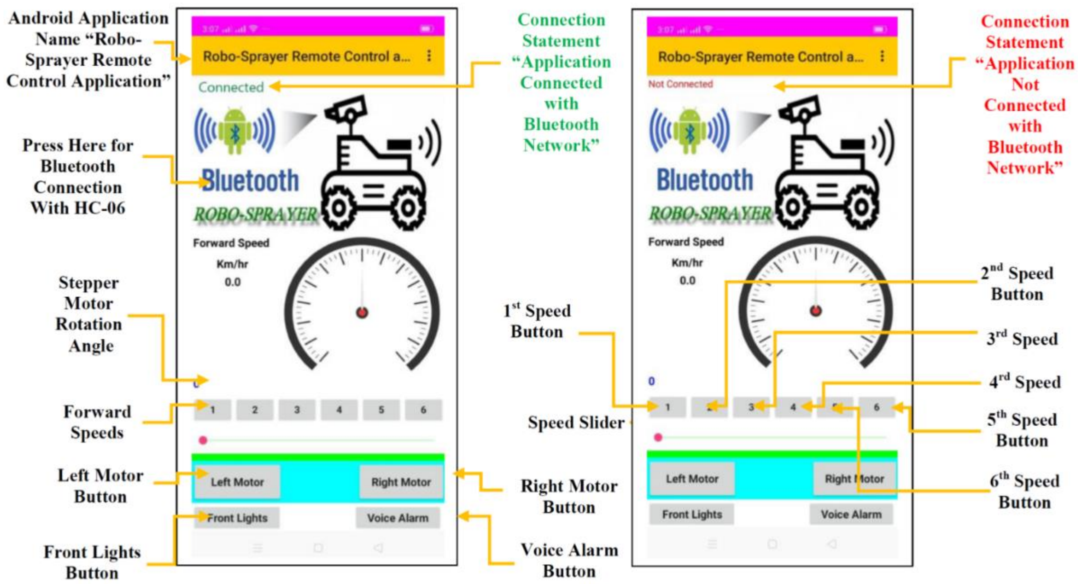

Fig. 14. Interface of the smartphone mobile app.

2.1.5. Spraying system

The spraying system frame consists of several parts most of them made of light steel because it has lightweight and easy to manufacture, all dimensions and specifications, shown in the following Figs. 15-27.

The spraying system consists of several parts such as, spray boom, injection pump, i.e. engine, nozzles, solenoid valves, manual ball valves, chemical (pesticide) tank, flowmeter sensor, pressure gauge, pressure relief valve, pressure regulator.

The equipment has three horizontal spraying booms in the rear, and the spraying boom consists of several parts most of them made of metal with lightweight to reduce the overall weight of the spraying boom and reduce the manufacturing costs, all dimensions and specifications, shown in Figs. 15-17.

The theoretical length of the spray boom is 6.25 m while the applied working width of the machine was approximately 6.40 m, the spraying boom was divided into three sections (2.25 m, 1.75 m, and 2.25 m) and mounted behind the machine at 90 cm above the ground surface, as shown in Figs. 15 and 16.

The spraying frame consists of the following parts:

1) Connecting base: connecting the spraying system with the machine.
2) Connecting arm: connecting the boom with the connecting base.
3) Boom: hold and carry the sprinklers and the connecting pipes.
4) Suspension wires: connecting the higher fixing arm with the lower fixing arm, to make the boom in a horizontal state and to reduce the defection.

The spraying system designed in such a way makes the sprinklers always in the vertical position, and the sprinkler system height can be adjusted manually depending on the soil profile and plants height. The spraying height will be measured accurately by using an ultrasonic sensor and sending data automatically Via Wi-Fi to the laptop computer.

Three solenoid valves were connected with the three boom spraying parts and controlled by an android application; the solenoid valves were assisted by three manual ball valves in case of the solenoid valves failure. 13 nozzles were mounted on the boom with a uniform (50 cm) interval between them. The nozzles were using a series of (T) joints; the line connecting the distribution valve to each section was then connected to each solenoid valve to which the nozzles were fitted as closely as possible. The (1/2 in) solenoid valve was operated with 12 V. The feed line from the pump went through a flow valve and flow meter then separated into three lines, each line feeding one section of the boom. The pump was operated by a Honda gas engine.

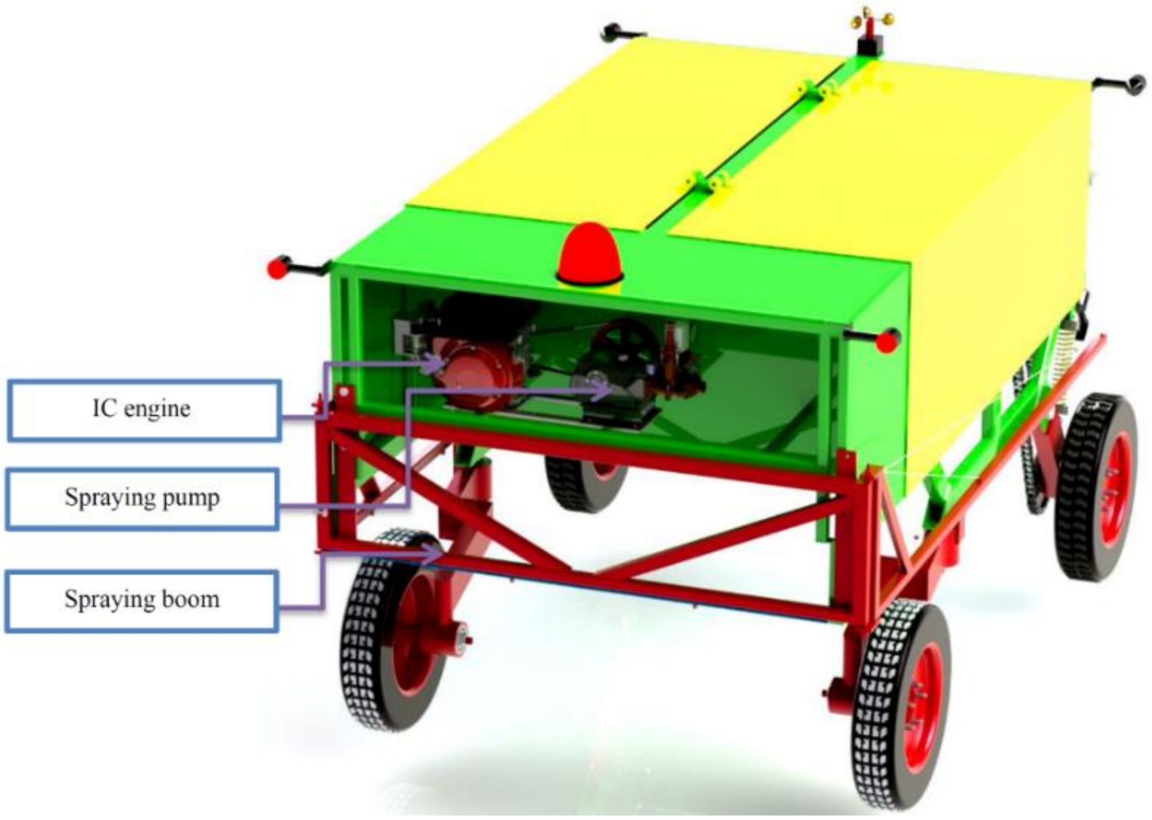

Fig. 15. Isometric view shows the spraying system components.

Fig. 16. Rear view shows the spraying system.

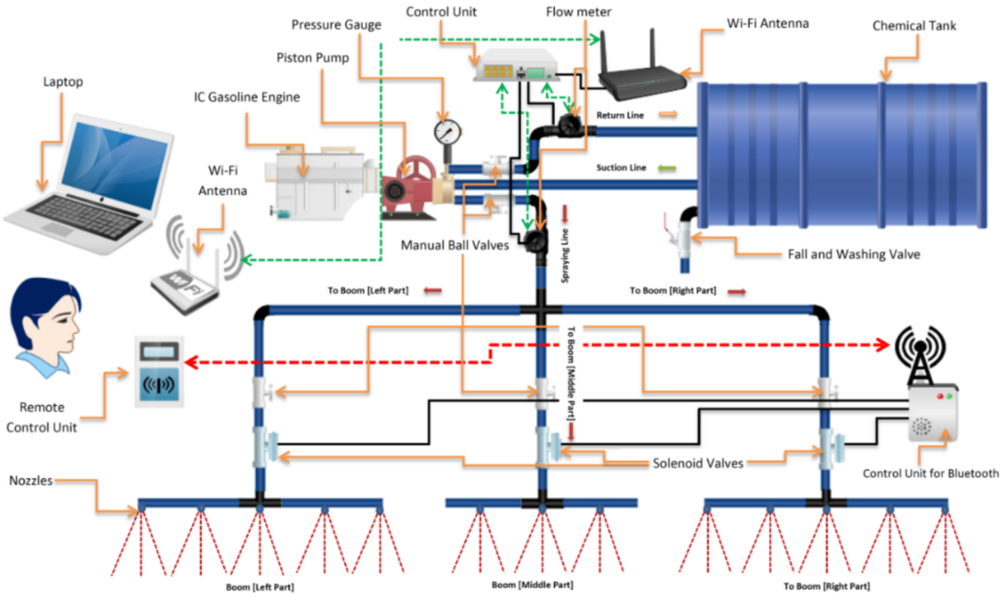

Fig. 17. Simplified schematic diagram of the fundamental spraying system components.

2.2. *Performance tests and evaluation of spraying machine*

2.2.1. *Testing of the pesticide flow meters*

Extensive testing of the pesticide flow meters was conducted. Primarily this testing was performed using water as a test fluid.

One of the tests performed was a closed-loop test. When the manual or solenoid valves are closed no fluid can flow through the nozzle meaning that the fluid exiting the tank through the boom must also flow back through the other boom to the tank. Thus, the flow rate from one flow meter should be the same as the flow from the other meter (Hall, 2016).

2.2.2. *Actual flow rate evaluation and calibration of the pesticide flow rate sensor:*

An experiment was conducted to evaluate the performance accuracy of the flow rate sensor for flow rate measurements from the nozzles mounted on the sprayer boom. The volume of water from the pump was measured manually with graduated cylinders for comparison. The experiment was replicated three times and volume measurement readings were recorded. The differences between flow rate sensor volumes and manually measured volumes were used to characterize the performance of the flow rate sensor (Hall, 2016).

2.2.3. *Theoretical field capacity*

Theoretical Field Capacity is the area covered by implement at its rated width and rated speed. Theoretical field capacity was determined by the formula,

$$T.F.c = \frac{A \times W}{4.2}$$

where:

T.F.C. = Theoretical Field Capacity, Fedd/hr

W =Effective working width, m

S = Travel Speed, km/hr

2.2.4. *Fuel consumption*

A volume of fuel consumed (cm^3) was measured during each test run at the operation speed. Consumption time for each test was measured and volumetric fuel consumption rate was calculated for each speed as follow:

$$FC = \frac{V \times 3600}{t \times 1000}$$

where:

F_C = Volumetric fuel consumption, l/h

V = Volume of consumed fuel, cm^3

t = Time of running the test, s.

2.2.5. *Cost estimation of owning and operating of the proposed machine*

Machinery operating and ownership costs are often more than half of total crop production costs. Formulas developed by the American Society of Agricultural and Biological Engineers (ASABE) are used to calculate costs. All costs are based on buying a new proposed prototype of the spraying machine, owning the machine for 5 years, and using it 1200 hours per year. The classification of costs is indicated as a following:

2.2.6. *Statistical analysis*

The Statistical analysis was carried out using IBM SPSS Statistics 25, PC statistical software. Each experiment in triplicate was repeated at least twice and the values were presented in terms of coefficient of variance (Padhee *et al.,* 2019).

3. Results and discussions

This chapter deals with the results and discussion of the experiments conducted to fulfill the objectives of the study. The experimental prototype spraying machine was fabricated and assembled in the workshop of the Agricultural and Bio-system Engineering department - faculty of Agriculture and Natural Sources – Aswan University – Aswan - Egypt. The performance evaluation of the spraying machine was conducted as per standard procedures and results are discussed in the following sections.

Experience design

The tests were carried out in the Agricultural and Bio-System Engineering Department – Faculty of Agriculture and Natural Resources – Aswan University – Aswan - Egypt, during the period from 1 to 8 October 2020.

3.1. *Testing of the pesticide flow meters*

In this test, the manifold pressure was set to 9.5 bar by adjusting the throttle on the I.C engine at the maximum position.

Table 1.

Relation between flow rate incoming and flow rate outgoing close loop, using water at 9.5 bar.

Time, (sec)	Flow rate incoming, (l/hr)	Flow rate outgoing, (l/hr)	SD	CV, %
0	21.25	22.87	1.15	5.19
20	24.37	22.25	1.50	6.43
40	22.37	21.12	0.88	4.06
60	21.00	23.25	1.59	7.19
80	22.25	22.12	0.09	0.41
100	22.12	21.75	0.26	1.19
120	20.87	20.50	0.26	1.26
140	20.62	19.62	0.71	3.51
160	20.12	19.87	0.18	0.88
200	21.00	21.37	0.26	1.23
220	19.87	20.25	0.27	1.34
240	18.00	19.00	0.71	3.82
260	19.00	20.75	1.24	6.22
280	19.87	20.75	0.62	3.06
300	21.75	20.62	0.80	3.77

During the test, the butterfly on the return to the tank was slowly opened. This increased the flow rate of fluid through the output pipe and therefore flow meter sensors. Fig. 18, shows a plot of the raw flow data obtained from both the flow meters. During operation, the meter reported total transit times around 300 seconds and the Arduino board was programmed for taken the flow meter's reading every 20 seconds. The difference in the two flow rates (which ideally should be zero) had a range of around 22.5 L/min, and there are large noises on the flow meters reading. This would not be suitable for measuring the flow rate let alone controlling the flow rate of the machine. Several similar tests were conducted under various conditions. This test was indicative of the results of all the tests that were performed.

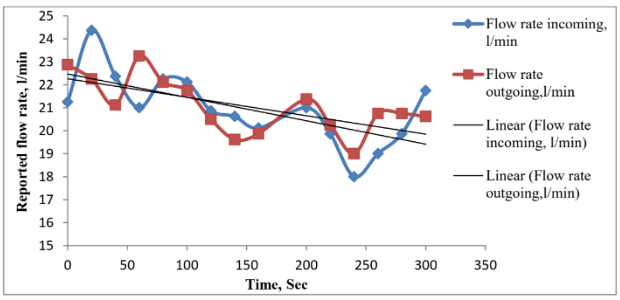

Fig. 18. The pesticide flow meters data - closed-loop testing.

3.2. *Testing and calibration of the output pesticide flow meter*

The results comparing the output flow meter sensor data to the bucket test data are shown in Table 2 and Fig 19. These tests show that the calibration of the flow meter is good. There is the little coefficient of variance between the manually measured flow rate and the flow rate reported by the output pesticide flow meter sensor.

Table 2.

The output pesticide flow meter sensor calibration test data.

Tank capacity 20 litter				
Time to fill, (sec)	Actual (manual) average flow rate, (l/min)	Flow meter average flow rate, (l/min)	SD	CV, %
48.74	24.62	24.5	0.085	0.35
48.98	24.5	24.37	0.092	0.38
50.27	23.87	24.87	0.707	2.90
52.75	22.75	22.37	0.269	1.19
55.81	21.5	22.87	0.969	4.37
53.31	22.51	21.12	0.983	4.51
58.20	20.62	21.87	0.884	4.16
62.34	19.25	20.12	0.615	3.13
58.91	20.37	20.75	0.269	1.31
69.57	17.25	16.37	0.622	3.70
69.08	17.37	16.25	0.792	4.71
71.64	16.75	17.5	0.530	3.10
84.99	14.12	13.12	0.707	5.19
88.89	13.5	12.37	0.799	6.18
88.11	13.62	14.5	0.622	4.43

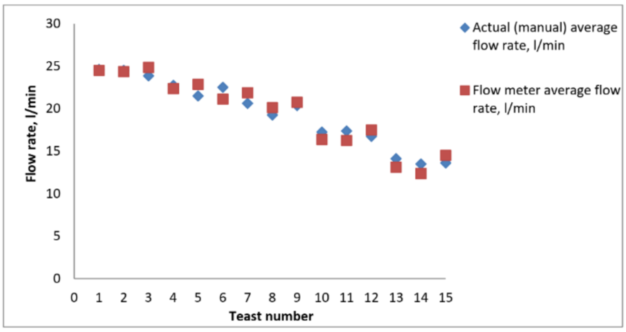

Fig. 19. The output pesticide flow meter sensor calibration test data.

3.3. Effect of pump pressure and IC engine speed on flow characteristics

To determine the effect of the manifold pressure on flow tests were performed. These tests involved setting the pressure at the manifold by adjusting the throttle of the IC engine. The flow controller was then used to slowly close the butterfly control valve increasing the nozzle flow rate. During these tests, a return hose was used to return the pump flow rate into the tank.

Table 3

Effect of I.C engine speed on pump pressure and flow characteristics.

IC engine speed, (rpm)	Average pump pressure, (bar)	Average pump flow rate, (l/min)
1146	9.5	24.58
1038	8.5	22.12
960	8	20.91
822	7	16.71
684	6	13.33

Fig. 20 represent the effect of I.C engine speed on pump pressure and flow characteristics. A result shows that increasing the I.C engine speed increases the pump pressure from (6.00 to 9.5 bar), the data also indicated that the flow rate increased from (13.33 to 24.58 l/min).

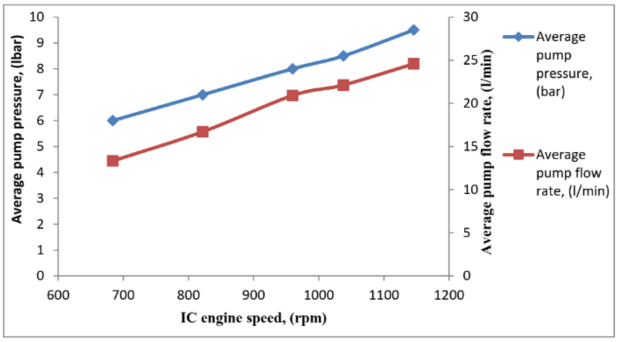

Fig. 20. Effect of I.C engine speed on pump pressure and flow characteristics.

3.4. Effect of travel speed and pump pressure on-field capacity, fuel consumption, and total operating costs

3.4.1. Field capacity

The field capacity depends upon the working width of the spraying machine. It is a function of the speed of operation. The maximum actual field capacity of the spraying machine was observed to be 8.66 fedd/hr at 9.33 km/hr, as shown in Fig. 21. The minimum field capacity obtained was 5.1 fedd/hr at 5.49 km/hr. During the field operation, many factors influence the field capacity of the sprayer i.e. turning losses, filling losses, etc. so we assumed that the field efficiency was 60%.

3.4.2. Fuel consumption

Fig. 22 shows the effect of travel speed and pump pressure on the fuel consumption rate, Results showed that the fuel consumption of the spraying machine was seen to vary from 1.8 to 1.04 1/hr as a change in forwarding speeds of 9.33 to 5.49 km/hr and change in pump pressure of 9.5 to 6 bar. Fuel demand increased as a change in forwarding speed due to increasing speed of operation and increased as a change in pump pressure due to increasing speed of the IC engine.

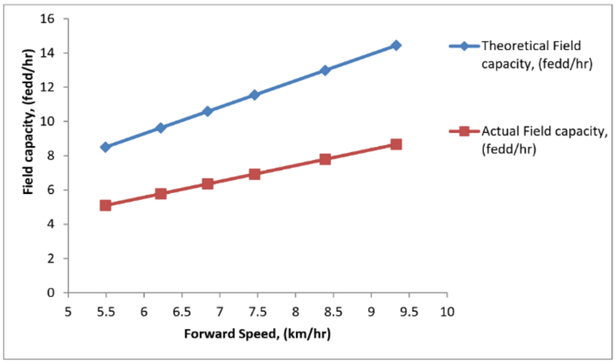

Fig. 21. Effect of forward speed on field capacity for the developed sprayer.

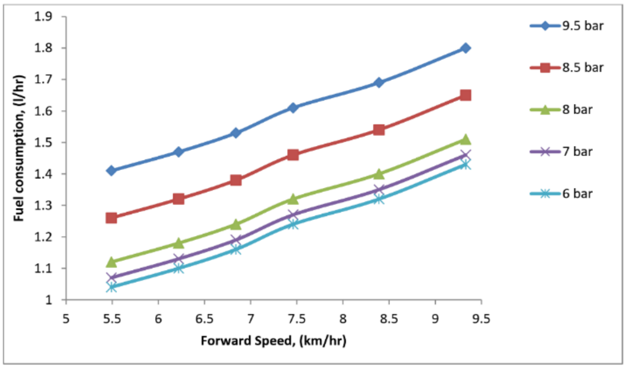

Fig. 22. Effect of forward speed on fuel consumption rate for the developed sprayer.

3.4.3. Operating costs of the proposed unit

Fig. 23, indicate that the total operating cost was calculated at all forward speeds and pump pressures as shown in the previous tables, and we found that the least total operating cost was 59.57 EGP/hr when the forward speed was (5.10) km/h, and the pump pressure was (6) bar.

Also, we found that the largest total operating cost was 60.44 EGP/hr when the forward speed was (9.33) km/h, and the pump pressure was (9.5) bar.

3.4.4. Labor costs

Labor charges should be based upon prevailing wage rates. The labor cost per Feddan is inversely proportional to the field capacity of the machine. Selecting the optimum width or size of a machine minimizes the total cost per Feddan for performing the spraying operation.

The proposed spraying machine unit needs only one skill operator for the machine which costs (20 EGP/h).

4. Conclusions

The selection of the appropriate field sprayer is one of the most important factors leading to the success of the controlling process, and therefore during the design of this machine, many critical points that affect the efficiency and quality of the pesticide spraying process, as well as the health aspects associated with the operator based on the spray process, have been observed. This machine can be controlled remotely via laptop or mobile phone with a Bluetooth system. The front speed of this machine is 6.22 to 9.33 km/hr and the actual field capacity is 5.1 to 9.33 fedd/hr.

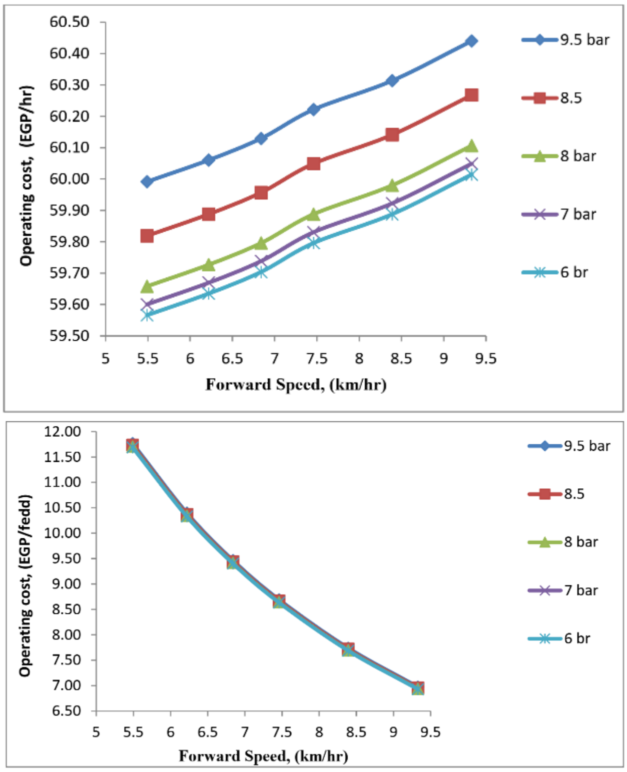

Fig. 23. Effect of forward speed on operating costs.

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تصميم وتقييم آلة رش مبيدات ذاتية الحركة يتم تشغيلها والتحكم فيها عن بعد

عبدالله الشوادفى الوكيل [١]، سعد فتح الله أحمد [٢]، عبدالله مسعد زين الدين [٢]، لؤى سعد الدين نصرت [٣]

[١] قسم الهندسة الزراعية، كلية الزراعة والموارد الطبيعية، جامعة أسوان، أسوان، مصر.
[٢] قسم الهندسة الزراعية والنظم الحيوية، كلية الزراعة، جامعة الأسكندرية، الشاطبي، الأسكندرية، مصر.
[٣] قسم الهندسة الكهربائية، كلية الهندسة، جامعة أسوان، أسوان، مصر.

الملخص العربي

في الوقت الحاضر، تعتبر الرشاشات الزراعية أكثر المعدات استخداما لرش مبيدات الآفات. مع تطور الهندسة الزراعية تم تطوير عدة أنواع من الرشاشات من الرشاشات الهيدروليكية التي تعمل يدوياً إلى الرشاشات الهيدروليكية التي تعمل عند السرعات العالية والتي تتميز بعرض الرش الكبير أو الرش بالطائرات. كانت أهداف هذه الدراسة هي تصميم رشاشة حقلية ذاتية الحركة ليتم تشغيلها والتحكم فيها عن بعد وتقييم أداء الآلة عند سرعات أمامية مختلفة تبلغ ٩,٣٣ و٨,٣٩ و٧,٤٦ و٦,٤٨ و٦,٢٢ كم / ساعة وضغط مضخة مختلف. ٩,٥ و٨,٥ و٨ و٧ و٦ بار تحت الظروف المعملية. أيضاً، تقييم ومعايرة أداء نظام الرش. أظهرت النتائج أن أقصى سعة حقلية فعلية للآلة كانت ٨,٦٦ فدان / ساعة عند ٩,٣٣ كم / ساعة، وبلغت التكلفة الإجمالية للتشغيل ٦٠,٤٤ جنيه / ساعة (٦,٩٨ جنيه / فدان) عند ضغط تشغيل ٩,٥ بار.