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DEVELOPING AND EVALUATING A MULTI NOZZLE SPRAYING MACHINE POWERED BY SOLAR ENERGY FOR AGRICULTURAL SMALLHOLDINGS

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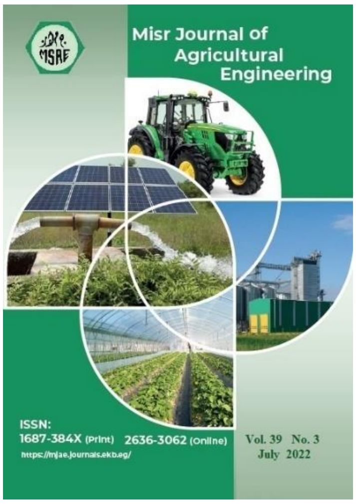


Keywords:
Solar energy; Spraying machine; Smallholdings; Machinery.

ABSTRACT

The general objective of this study is to develop and assess the performance of a moving machine, energy battery, and pumping mechanism intended for a solar energy-powered spraying machine. To achieve this aim, a spraying machine was developed and evaluated powered by solar energy via a flexible solar panel system. The development and evaluation process of the spraying machine was done in different steps. The first step was to build and develop the portable unit with remote control unit and the power system. In the second step, the spraying system was hydraulically evaluated under different nozzle types (the full-cone and the Hollow-cone), and nozzle heights by measuring the nozzle distribution efficiency and CV. The third step was to evaluate the spraying machine unit under field conditions. The results of hydraulic evaluation affirmed that, the greatest worth of distribution efficiency was 68.09% with CV% of 3.7% under 60 cm nozzle height and the Hollow-cone single nozzle. The obtained results from the solar panel system showed that, the maximum irradiance was 7783 W $m^{-2}day^{-1}$ in the summer. The theoretical performance rate was 0.25 (ha h^{-1}) with the operation width of 0.75m and machine velocity of one m s^{-1}. The daily theoretical performance rate was 1.82, 1.5, and 1.1 ha day^{-1}. The actual daily performance rate in the spring season was 1.2 ha day^{-1} with 80% of the machine field efficiency. Therefore, the energy produced from solar panels could a good alternative source for the energy consumption in the smallholding's agricultural machines.

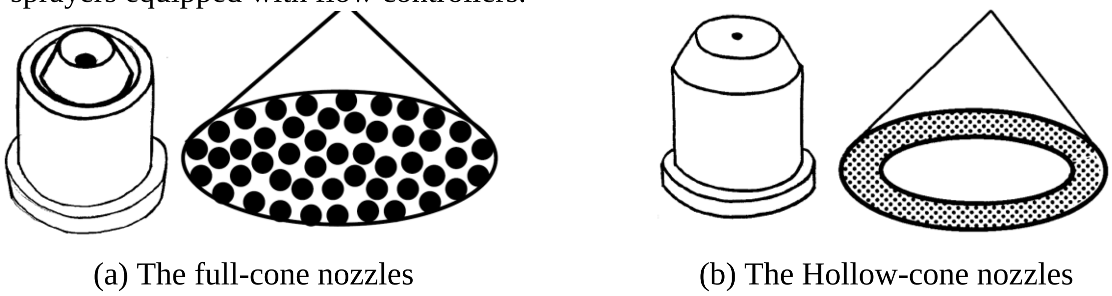
1. INTRODUCTION

Solar energy applications in agriculture, as one of the renewable energies, are firstly greenhouse heating and cooling, then lighting, product drying, solarization, and on-farm irrigation. Egypt has an advantage over the duration of sunshine; it is mostly sunny. The mechanical conversion of solar energy is possible either via photovoltaic generation of electricity or via the thermodynamic process of producing steam to generate kinetic energy directly (**Cuadros et al. 2004**).

There are applications of irrigation by solar energy in Turkey. One of those is drilling water from the ground by using only energy gained from solar panels by the Union of the Chambers of Turkish Engineers and Architects (UCTEA) Agricultural Engineers Association Konya Branch Office (**UCTEA, 2011**). According to **Pratt et al. (2018)**, the percentage of households in lower and upper Egypt per quintile of farm area is presented and distributed as follows. Most households in Egypt work in very small farm areas of less than a 0.42 ha. This is the case for 60% of households in lower Egypt and more than 70% of households in upper Egypt. Clearly explain that the maximum percentage of farm distribution belonged to small and marginal categories. The current backpack sprayer has a lot of limitations, and it required more energy to operate. The farmers who use these types of conventional backpack sprayer faces many types of problems like fatigue, tiredness, pain in the spinal cord and muscles, etc. Following problems can take place by use of this conventional type of sprayers: Heavyweight causes difficulty in lifting manually; Fatigue to the operator due to heavyweight; Due to heavyweight during spraying, operator feel very tiredness and fatigue which reduces his efficiency. These problems combined with a lack of awareness and technical knowledge and inadequate; maintenance and poor field use of equipment have led to unacceptable risks to the environment and human health. **Dhete et al. (2015)** reported that mechanization in spraying devices is distributed equally on the farm and reduces the quantity of waste, which results in the prevention of losses of input applied to the farm and reduces the cost of production. Where mechanization gives higher productivity in minimum input. Also, they found that farmers are using the same traditional methods for spraying fertilizers and pesticides and the equipment is also the same for ages. Conventionally the spraying is done by farmers carrying backpack sprayers and fertilizers are sprayed manually. Therefore, the efforts required are more beneficial for farmers having small farming land. **Joshua et al. (2010)** has designed and developed a solar sprayer for agriculture implements energy demand and according to the authors, the application of non-conventional energy is the only alternate solution for the conventional energy demand. **Samuel and Matthews, (2012)** have developed a sprayer for the application of bio-pesticides. The transition from the optimized conditions of a laboratory experiment to the field conditions has so far proved more difficult for the application due to a lack of investment in the development of effective formulations and delivery systems. **Poratkar and Raut, (2013)** developed a multi-nozzle pesticide sprayer pump, they suggested the model has removed the problem of back pain since there is no need to carry the tank on the back. The developed model has a greater number of nozzles which will spray the maximum area of spraying in minimum time and the maximum rate. Muscular problems are removed and there is no need of operating the lever. **Sanjay et al. (2015)** designed and developed a mechanical pest sprayer with a low cost manually operated machine and in terms of work and using energy reduction. **Akshay and Waghmare, (2016)** designed and developed a solar-operated sprayer for agricultural pesticide sprayers, which uses solar energy as the source of power for spraying. **Gaodi et al. (2016)** and **Vipul et al. (2016)** developed an automatic pesticide spraying machine, to reduce the time and operating costs of the process by the electric components like motor, pump, and spraying nozzles the process of spraying comes economically. They found that the developed automatic pesticide spraying machine covers more area than conventional machines. **Ahalya et al. (2017)** designed and developed a solar-powered semi-automatic sprayer to use in vineyards fields. They reported that the performance of the designed prototype was satisfactory under laboratory conditions, and it gave a good coverage and cost of operation. **Krishna et al. (2017)** developed a solar-pesticide sprayer, where they build a solar-powered pesticides pumping system with cost-effective compared to an electrically operated hydraulic pump. They reported that the developed machine covers the maximum area of spraying in minimum time with the maximum rate. Also, they found that the hollow-cone nozzle should be used in the field for better performance. **Kumar et al. (2019)** and **Kumar et al. (2020)** designed and fabricated a portable solar-operated chemical sprayer. Where in agriculture, pesticides spraying is important to protect the crop from insects using a non-conventional source of energy. Nowadays energy is the basic need for all human beings. Therefore, the main objective of this work is to develop and evaluate a movable multi-nozzles sprayer powered by solar energy via Solar photovoltaic for small-holding farmers to reduce the human efforts due to the constant pumping action and provide a suitable environment for the user reducing the fatigue load acting on the body.

2. MATERIALS AND METHODS

The overall goal of this study is to develop and evaluate the performance of a moving machine, energy battery, and pumping mechanism intended for a solar energy-powered spraying machine. To achieve this aim, a spraying machine was developed and evaluated powered by solar energy via a portable solar panel system. The development and evaluation process of the spraying machine was carried out in different steps. The first step was to build and develop the movable unit with remote control unit and the power system. In the second step, the spraying system was hydraulically evaluated under different nozzle types of the Full-cone and the Hollow-cone (Plastic and Copper), nozzle height (40, 60, and 80 cm), and horizontal distance between the nozzles (50, 70, 90 cm) by measuring the nozzle distribution efficiency and CV. The third step was to evaluate the spraying machine unit under field conditions. According to **Vern Hofman and Elton Solseng, (2018)**, the Hollow-cone nozzles (Fig. 1) generally are used to apply insecticides or fungicides to field crops when foliage penetration and complete coverage of the leaf surface is required. These nozzles operate in a pressure range from 40 to 100 psi. Spray drift potential is higher from hollow-cone nozzles than from other nozzles due to the small droplets produced. The wide-angle, full-cone nozzles (Fig. 1) are a good choice if drift is a concern because they produce larger droplets than flood nozzles. Full-cone nozzles usually are recommended over flood nozzles for soil-incorporated herbicides. Full-cone nozzles operate between a pressure range of 15 to 40 psi and are ideal for sprayers equipped with flow controllers.



(a) The full-cone nozzles (b) The Hollow-cone nozzles

Fig. 1: The full-cone and the Hollow-cone nozzles spray pattern
(Vern Hofman and Elton Solseng, (2018))

2.1. Developing of multi-nozzles Solar operated Spraying machine

Solar-operated sprayer machine is developed to meet the demands of small-holdings farmers such as reduced maintenance costs, and shortage of electricity and fuel. The main parts of the solar-operated sprayer machine consist of the main machine frame, Solar panel, battery, chemical tank with DC pump, and spraying nozzles frame as shown in the following Fig. 2. The machine is moved and powered via solar photovoltaic as shown in the figure. The forward movement system of the machine comprises an electric motor powered by solar energy and two gear units (drive and driven gear units) connected by a chain as shown in the Fig 2. Each drive and driven unit contain six different gears with a different number of teeth. The combination between the dive and the driven gear units results in a different 36 forward and back speeds. The backward and forward movements and speed are controlled using a remote-control system.

Fig. 2: The layout and main parts of developed spraying machine with solar photovoltaic

2.2. Working principle

The system consists of a solar panel, charging unit, battery, pump, and spray nozzles. The solar panel delivers an output in the order of 12 volts and 100 W of power to the charging unit. The charging unit is used to strengthen the signal from the solar panel. The charging unit delivers the signal which charges the battery. According to the charged unit, the pump operates, such that the sprayer works. Here, the required liquid can be stored in a tank. When the sun rays are falling on the solar panel electricity will be generated through the solar cells and stored in the battery. With the electric power in the battery the pump operates and therefore liquid from the tank is sprayed out through the sprayer's nozzles. The layout of solar spraying system is shown in the following figure. The main advantages of the developed machine are no maintenance cost and operating cost where the developed machine is using solar energy therefore no pollution problem. The working principle of the developed machine is very easy, and it is economical for the small-holdings farmers. Also, the developed machine has one more advantage that it can also generate power which is saved in the battery, and it can be used during the nighttime.

2.3. Solar spraying system

Egypt enjoys the fall of large amounts of solar radiation on its lands during the summer (at maximum 900:1100 W m^{-2}), medium during the spring and autumn (at maximum 700:850 W m^{-2}), and relatively less during the winter (at maximum 500:700 W m^{-2}) **Omar et al. (2021)**.

For this change in these rates, it was necessary to evaluate the performance rates for the solar prototype throughout the year, affected by the change in solar radiation. Solar spraying is a new application for the use of renewable energy to overcome most of the spraying problems from costs or carbon emissions (when using engines to operate the sprinkler) or the worker being affected by toxic spray materials. Solar radiation is used as energy source to operate the solar-spray pump. Solar panels are used to generate electrical energy directly from sunlight and charge a storage battery. The solar energy stored in the battery is utilized to operate the spray pump and move the machine. Due to the instability of the fall solar radiation throughout the day and to stable use during the operating period solar energy can be stored. As shown in Fig. 2, all the parts of the small machine (prototype) powered by the solar panel was designed and fabricated in a special factory. The proposed model includes the components of the solar system shown in Fig. 3.

2.3.1. The solar remote control spraying components

To operate the proposed model with solar energy, the components of the solar system are fully used, and its use is evaluated as an energy source for operating the machine. The solar spraying was comprised a solar system, a DC motor type, a battery, remote control, and the sprayer.

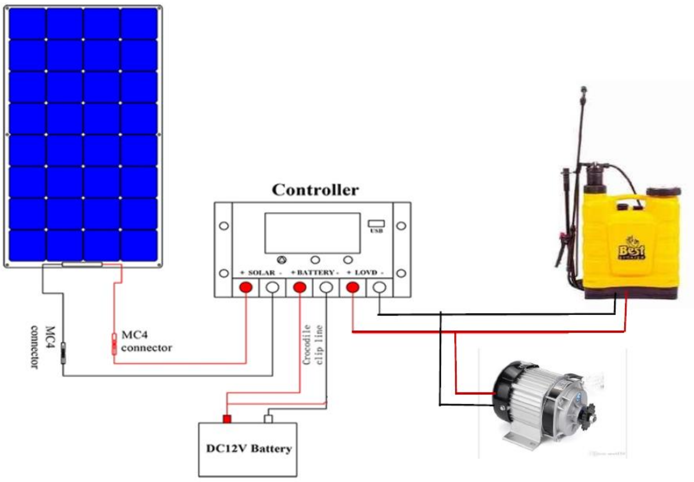


Fig. 3: The solar spraying, solar system, DC motor type and a battery

2.3.2. Solar system characteristic.

Electrical energy is generated from solar radiation by the photovoltaic panel and stored in a solar battery. The photovoltaic panel system is composed of solar cells, batteries, and charge controller (as shown in fig. 4). For the present study, a photovoltaic flexible panel (mono-crystalline PV type) with 100 W, weight 1.8 kg, size 1050*540*3 mm and 0.567 m^2 area with 18% catalog efficiency is used to produce electrical energy which is related to operating the pump and moved the machine. It was installed to always keep the direction into the south, and in a variable position to achieve the most amount of the solar radiation by making the rays fall perpendicular to the solar panel. In summer season, the better inclination angle (15^o) is equal to the location latitude angle (-15). In winter season, the better inclination angle (45^o) is equal to the location latitude angle (+15). Decreasing the electricity production from solar PV panels was significant when the temperature of the ambient air is raised. The ambient air temperature (T_a) and the temperature coefficient (C_v) affect the actual electrical energy produced from the solar panel. The temperature coefficient (C_v) is not a constant and it may change a little from 0.35% to 0.5% (**Kumar et al. 2018**) for different cell manufacturers and the ambient air temperature is the present atmospheric temperature at the panel. Eq. (1) **Kumar et al. (2018)** give the relation between the solar panel output and the ambient air temperature.

$$\text{Actual efficiency } = \eta_{panel} - [C_v \times (T_a - 25)] \quad (1)$$

Where: η_{panel} is the maximum panel efficiency, C_v is the temperature coefficient which was taken −0.35 %/°C in the theoretical calculations of the actual efficiency.

The solar system contains solar batteries to store the generated electricity and supply the required energy needed for the operation of the pump and the motor included in the system. The battery was used to store energy. The surplus electricity of the consumed amount is stocked in the solar batteries when the energy output is greater than the required.

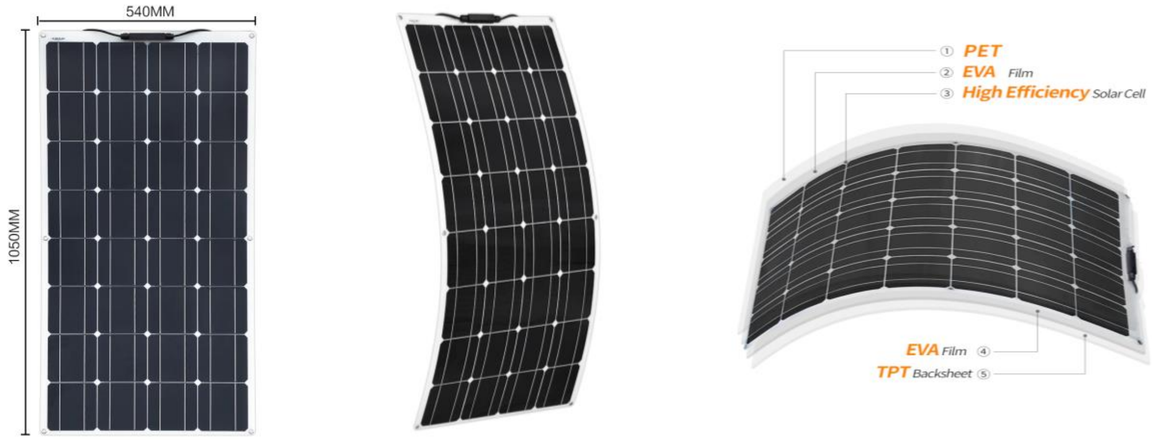


Fig. 4: Photo and isometric view of solar panel system applied in the empirical study

2.3.3. Motor and battery

DC motors are the electrical machine that converts electrical energy to mechanical energy. Three DC motors are required to operate the solar sprayer, one is responsible for moving the machine the second operating the sprinkler pump and the third is responsible for changing machine direction.

2.3.4. DC Battery

DC battery is a powerhouse of the system composed of electrochemical cells charged by solar panel. It stores energy through electrochemical reactions. A controller is provided between the solar panels, battery, and motors to control the current flow. a battery Specification with a capacity of 100 amps and 12 volts in addition to the internal battery for the sprayer with a capacity of 10 amps and 12 volts.

2.4. The sprayer

Fig. 5 shows the used sprayer in the developed machine. The sprayer consists of a barrel, a base, a battery, a mini pump, a charger, a spraying system (rubber tubes, switch, spraying rod, and nozzles), a strip, and castors. The total size is 380 * 207 * 495 mm, and the total weight is 7.4 kg. The barrel capacity is 20 L. The pump type is a mini diaphragm pump with a maximum pressure of 0.15 – 0.4 Mpa and a flow rate of 1.2 – 2.2 L min^{-1} as shown in Fig. 5.

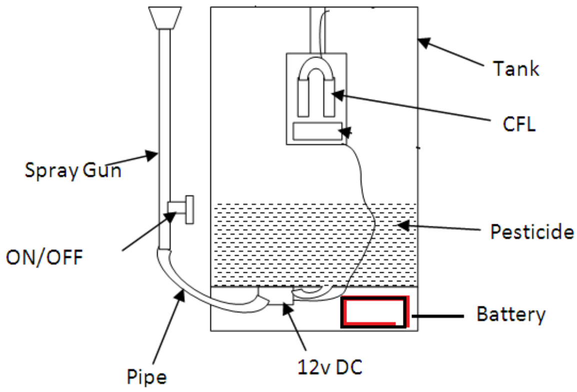


Fig. 5: The photo of the sprayer used in the developed machine

2.5. The power required to operate the machine

The consumed electrical power in the equipment of the machine system (pt) per W was calculated to determine the solar spraying (prototype) performance rate per day year-round. The energy consumption comprises the pump power and the motor in hour. The consumed power of the prototype was obtained as Eq. (2).

$$pt = pcs_{mot} + pcs_{pump} \quad (2)$$

Where to calculate the power required to move the machine, we need to determine the total weight of its component. a solar sprayer has one flexible solar PV panel of about 2 kg, a 20-L spraying tank having about 20 kg weight and its other accessories with 5 kg weight, one battery having 16 kg weight, three Dc moors having 2.5 kg weight each and the machine frame having 20 kg weight. Therefore, the total weight of the machine is 68 kg.

The power required to pull the spray vehicle may be calculated as follows according to **Vinay et al. (2016),** and **Poratkar and Raut (2013):**

$$P = FT \times v/\eta \quad (3)$$

Where, p is the engine power (W) required to pull the spray vehicle, FT is the total force required (N), v is the velocity of the vehicle (m s^{-1}), η is the efficiency of the pulling,75%.

The total forces required to move an object are as follows:

$$FT = FR + FD + FA \quad (4)$$

Where: FR is the rolling resistance force, FD is the aerodynamic dragging force, FA is the force required for acceleration

$$FR = CR \times W \quad (5)$$

Where: FR is the rolling resistance or rolling friction (N), CR = rolling resistance coefficient, which is dimensionless, coefficient of rolling resistance CR=0.017 according to **Poratkar and Raut (2013)**. The weight of any substances is realized due to gravitational force, mg, where m is the mass of the substances and g is the acceleration due to gravity.

$$FG = mg \sin\theta \quad (6)$$

Where: Fg is the gradient force, m is the mass of the object, g is the acceleration due to gravity, and θ is the tilting angle or slope of the surface.

$$FA = m \times a \quad (7)$$

Where, FA is the forces required for acceleration, m is the mass of the object and a is the acceleration (m s^{-2}).

2.6. Slip calculation

Slippage in the machines leads to a loss part of the power and excessive consumption of energy, as well as irregularity in the performance of the machine. It results from the failure of the machine to travel a distance equal to the circumferential distance traveled by the rear wheel. The slip is expressed as a percentage and can be calculated based on the following equation

$$S = \frac{L_1 - L_2}{L_1} \times 100 \tag{8}$$

Where: S is the slippage percentage %, L_1 is the calculated distance after the number of rotations of the rear wheel of the machine during a select time, m, L_2 is the distance the machine moved on the ground at the same set time, m.

2.7. Machine performance rate

The field efficiency of the machine depends on the theoretical performance rate (TPR) and actual performance rate **Issa, (2020)**. The theoretical performance rate of the machine is determined during three periods of the year due to the change in the intensity of the solar radiation falling on this region, which is during the summer, autumn, spring, and winter seasons. The number of possible hours to operate the machine depends on the total power required to operate the machine, W h^{-1} according to **Malatesh et al. (2017)**, as well as the total solar radiation falling during the day, and then the amount of electricity that can be produced through the used solar panel.

$$N_H = \frac{solar\ radiation}{p_t} \tag{9}$$

Where: N_H is the number of possible hours to operate the machine, h day^{-1}, solar radiation is the total solar radiation falling during the day, W day^{-1}, p_t is the total power required to operate the machine, W h^{-1}.

$$TPR = LV \tag{10}$$

Where: TPR is the theoretical performance rate, hectare h^{-1}, L is the operation width (spray), m and V is the velocity of the vehicle (m s^{-1}).

$$TPR_d = \frac{TPR}{10000 N_H} \tag{11}$$

Where: TPR_d is the daily theoretical performance rate, hectare per day.

$$\eta_f = \frac{TPR_d}{APR_d} \times 100 \tag{12}$$

Where: η_f is the field efficiency %, APR_d is the daily actual performance rate, hectare per day.

2.8. Measurements and measuring tools

2.8.1. Solar radiation

The solar radiation was estimated inside and outside the greenhouse using a TES 1333 solar power meter that was fixed on a top stand at an inclination angle of 30 º 54'. The data were recorded every hour (W m^{-2}).

2.8.2. Temperatures

With each painting material, the internal and external air temperatures in the two greenhouse models were estimated. The external test greenhouse air temperature, internal air temperature and soil temperature were measured. IC (LM35) sensors were utilized to estimate all the temperatures (surrounding air, internal air). The data collecting and frequency recording were registered every one minute and one hour average of each estimation by using a LabJacks data logger

2.8.3. Electricity energy productivity

Voltage and current measurements: Panel's voltage (Voc, VL) and current (Isc, IL) are sensed by using a current sensor ACS714 module and voltage divider which are coupled with a controller for Maximum Power Point Tracking (MPPT)

Fig. 6: Layout of multi-nozzles solar-operated spraying machine

2.9. Hydraulic evaluation of spraying nozzles system

A hydraulic experiment was carried out to evaluate the spraying machine under a single spraying nozzle and double nozzles of the full-cone and the Hollow-cone nozzles. The single nozzle was evaluated under three heights (40, 60, and 80 cm), and the double nozzles spraying system was evaluated under the same different heights and three different horizontal distances between the nozzles. The evaluation was carried out using the Catch-cans experiment. The following parameters were measured and calculated to evaluate the spraying system. The CV is a standardized measure of data point dispersion and provides a relative estimate of the extent of variability in relation to the average flow rate across the spray pattern. Greater CV values indicate greater dispersion and variability within the spray pattern. A CV below 10% indicates a desirable spray pattern uniformity, while a CV greater than 15% is unacceptable for an application. The coefficient of variation (CV) for Spraying Nozzles can be calculated using the following formula (**Krishnan et al. (1988); Ozkan et al. (1992); Siebe and Luck, (2016); Forney et al. (2017)**).

$$CV = \frac{\sqrt{\sum_{i=1}^{N}(X-M)^2}}{M\sqrt{N-1}} \qquad (13)$$

The uniformity coefficient (UC) can be measured as follows:

$$UC = 1 - \frac{\sum_{i=1}^{N}|X-M|}{NM} = 1 - 0.798CV \qquad (14)$$

Where: M is the mean water depth in all catch cans (mm min^{-1}), X is the water depth collected by each catch can (mm min^{-1}), N is the total number of catch cans, and CV is the coefficient of variation.

The distribution efficiency (DU) can be calculated as follows:

$$DU = \frac{LQ}{N_{LQ}M} = 1 - 1.27CV \qquad (15)$$

Where: LQ is the sum of the low quarter, and N_{LQ} is the Nozzles number of the low quarter.

2.10. Field evaluation of spraying nozzles

An experiment was carried out to evaluate the spraying machine under field conditions. The field evaluation was carried out under the treatments of the best results under hydraulic evaluation. Therefore, the single spraying nozzle was evaluated under a nozzle height of 60 cm for both nozzles type. While the double nozzles were evaluated under 60 cm nozzle height and 90 cm horizontal distance for the full-cone and (plastic nozzle). Meanwhile, under 80 cm nozzle height and 70 cm horizontal distance for the second nozzle type of the Hollow-cone (copper nozzle). The field evaluation was carried out under a machine forward speed of 0.5 km h^{-1}. The field evaluation was carried out using the Catch-cans experiment and the same parameters of hydraulic evaluation were measured and calculated to evaluate the spraying system under field conditions.

3. RESULTS AND DISCUSSION

3.1. Results of single nozzle Hydraulic evaluation

Table 1 presents the results of average value, maximum value, minimum value, CV%, UC%, and DU% of water distribution depth (mm) under the full-cone and the Hollow-cone (plastic and copper) single nozzle for different nozzle heights of 40, 60, and 80cm experimental treatments. The reported data confirmed in general that, there were a clearly affected to nozzle types (the full-cone and the Hollow-cone) for all measured parameters.

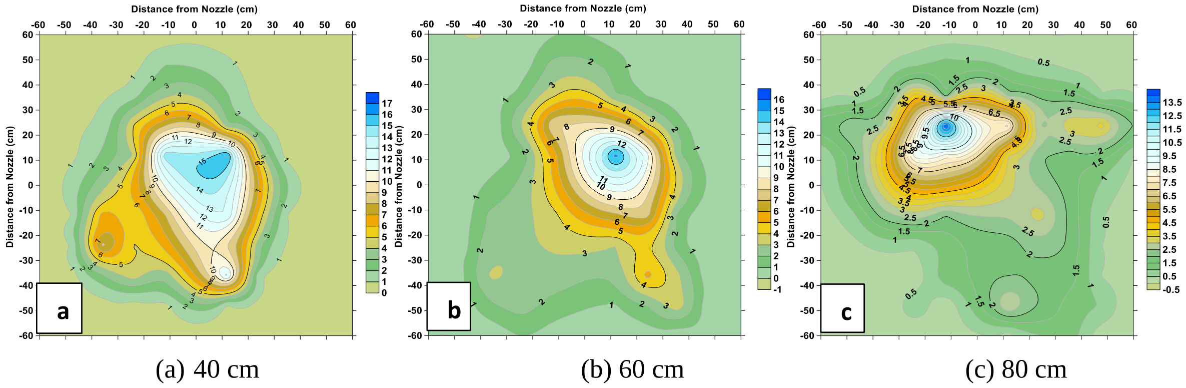
Table 1: Results of average value, maximum value, minimum value, CV%, UC% and DU% for the single Nozzle spraying system

Nozzle type		Nozzle height (cm)		
		40	60	80
The full-cone (Plastic)	Average (mm min^{-1})	2.32	1.80	1.52
	Max. (mm min^{-1})	8.09	7.73	7.17
	Min. (mm min^{-1})	0.15	0.19	0.02
	CV %	9.10	8.60	9.50
	UC %	31.18	40.16	36.18
	DU %	14.52	9.28	21.21
The Hollow-cone (Copper)	Average (mm min^{-1})	3.58	2.43	2.24
	Max. (mm min^{-1})	6.80	4.05	4.97
	Min. (mm min^{-1})	0.98	1.05	0.67
	CV %	4.4	3.7	4.30
	UC %	62.84	68.09	64.90
	DU %	43.49	52.70	45.31

The reported results showed that, the CV% value was 9.10%, 8.60%, and 9.50% for the full-cone (plastic) single nozzle under 40, 60, and 80cm of nozzle heights, respectively. While the CV% value was 4.4%, 3.7%, and 4.30% for the Hollow-cone (copper) single nozzle under 40, 60, and 80cm of nozzle heights, respectively. But the reported results demonstrated that, the UC% value was 31.18%, 40.16%, and 36.18% for the full-cone (plastic) single nozzle under

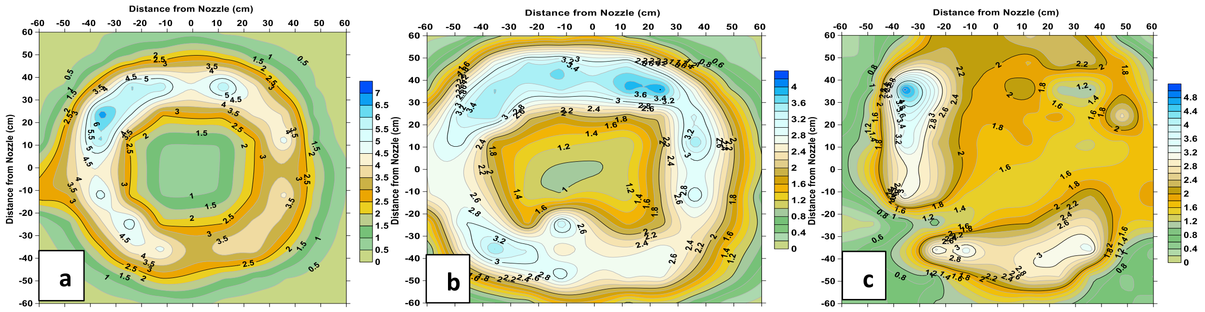
40, 60, and 80cm of nozzle heights, respectively. While the UC% value was 62.84%, 68.09%, and 64.90% for the Hollow-cone (copper) single nozzle under 40, 60, and 80cm of nozzle heights, respectively. On other hand, the DU% value was 14.52%, 9.28%, and 21.21% for the full-cone (plastic) single nozzle under 40, 60, and 80cm of nozzle heights, respectively. While the DC% value was 43.49%, 52.70%, and 45.31% for the Hollow-cone (copper) single nozzle under 40, 60, and 80cm of nozzle heights, respectively. The reported results confirmed that, the highest results values were found with the Hollow-cone (copper) nozzle under 60 cm nozzle height.

Fig. 7 represents the contour map of water distribution depth (mm) under the full-cone and the Hollow-cone (plastic and copper) single nozzle for different nozzle heights of 40, 60, and 80cm experimental treatments. Under the full-cone (plastic) nozzle, the maximum water depths were 8.09, 7.73, and 7.17 mm under 40, 60, and 80 cm of nozzle heights, respectively. Also, the maximum values have occurred approximately beneath the spraying nozzle. While, under the Hollow-cone (copper) nozzle as shown in Fig. 8, the maximum water depths were 6.80, 4.05, and 4.97 mm under 40, 60, and 80 cm of nozzle heights, respectively. But the maximum values have occurred approximately at a circle of 25, 35, and 45cm from the spraying nozzle under 40 and 60 cm of nozzle heights. While the results of minimum values showed that under the full-cone (plastic) nozzle, the minimum water depths were 0.15, 0.19, and 0.02 mm under 40, 60, and 80 cm of nozzle heights, respectively. Additionally, the minimum values have occurred far away from the spraying nozzle under all nozzle heights of 40 and 60 cm. While, under the Hollow-cone (copper) nozzle, the minimum water depths were 0.98, 1.05, and 0.67 mm under 40, 60, and 80 cm of nozzle heights, respectively. But the minimum values have occurred approximately beneath the spraying nozzle, and faraway of the spraying nozzle under 40 and 60 cm of nozzle heights. But the reported results showed that under the full-cone (plastic) nozzle, the average water depths were 2.32, 1.80, and 1.52 mm under 40, 60, and 80 cm of nozzle heights, respectively. While, under the Hollow-cone (copper) nozzle, the average water depths were 3.58, 2.43, and 2.24 mm under 40, 60, and 80 cm of nozzle heights, respectively. The reported results clarified that the best water distribution of the full-cone (plastic) nozzle was done under 60cm nozzle height with CV% of 8.60% and UC% of 40.16%. Also, under the second nozzle type of the Hollow-cone (copper), the best water distribution was done under 60cm nozzle height with CV% of 3.7% and UC% of 68.09%.



(a) 40 cm (b) 60 cm (c) 80 cm

Fig. 7: Water distribution depth (mm) under the full-cone (plastic) single nozzle for different nozzle heights of 40, 60, and 80cm (operation time 2 minutes)



(a) 40 cm (b) 60 cm (c) 80 cm

Fig. 8: Water distribution depth (mm) under the Hollow-cone (copper) single nozzle for different nozzle heights of 40, 60, and 80cm (operation time one minute)

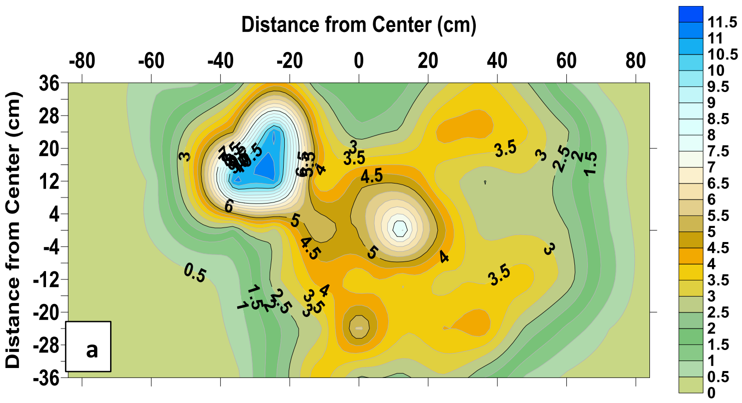
3.2. Results of double nozzles hydraulic evaluation

Table 2 and Figs. 9 and 10 show the results of average value, maximum value, minimum value, CV%, UC%, and DU% of water distribution depth (mm) under the full-cone and the Hollow-cone (plastic and copper) double nozzles for different nozzle heights of 40, 60, and 80cm and different horizontal distances of 50, 70, and 90 cm experimental treatments. The reported data confirmed in general that, there were a clearly affected to nozzle types (the full-cone and the Hollow-cone) for all measured parameters.

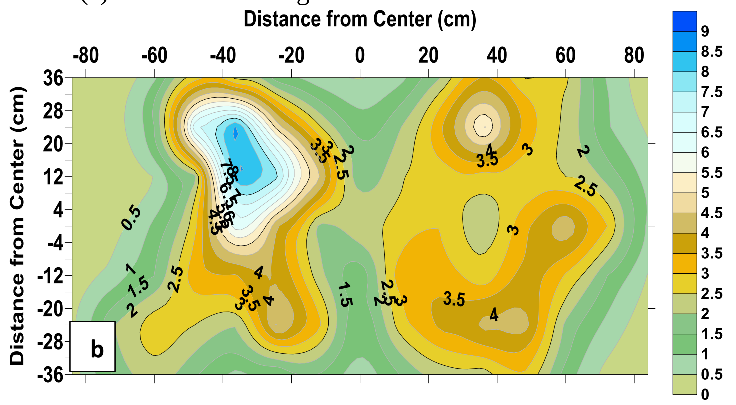
Table 2: Results of average value, maximum value, minimum value, CV%, UC% and DU% for the double nozzles spraying system under different horizontal distances

Nozzle type	Nozzle height (cm)	40			60			80		
	Horizontal distance (cm)	50	70	90	50	70	90	50	70	90
The full-cone (Plastic)	Average (mm min^{-1})	1.23	1.08	1.25	1.13	1.12	1.05	1.05	1.07	1.10
	Max. (mm min^{-1})	7.05	5.38	6.50	5.70	4.33	4.12	4.81	5.99	5.36
	Min. (mm min^{-1})	0.04	0.04	0.08	0.03	0.04	0.04	0.04	0.04	0.03
	CV %	1.26	1.14	1.01	1.02	0.79	0.70	0.91	0.87	0.86
	UC %	7.22	10.06	23.81	24.29	40.87	45.87	32.98	41.23	40.32
	DU %	59.69	44.61	28.35	29.93	0.51	10.90	15.21	10.39	8.81
The Hollow-cone (Copper)	Average (mm min^{-1})	1.22	1.20	1.16	1.13	1.25	1.26	1.13	1.12	1.18
	Max. (mm min^{-1})	6.05	4.27	5.77	4.78	3.39	2.94	3.70	2.73	9.51
	Min. (mm min^{-1})	0.03	0.08	0.03	0.01	0.12	0.07	0.05	0.15	0.15
	CV %	1.18	0.98	1.18	0.88	0.62	0.60	0.75	0.49	0.80
	UC %	0.57	18.42	2.41	28.01	47.42	48.44	37.26	61.87	62.25
	DU %	49.78	23.99	49.34	11.51	21.53	23.65	4.64	37.70	1.05

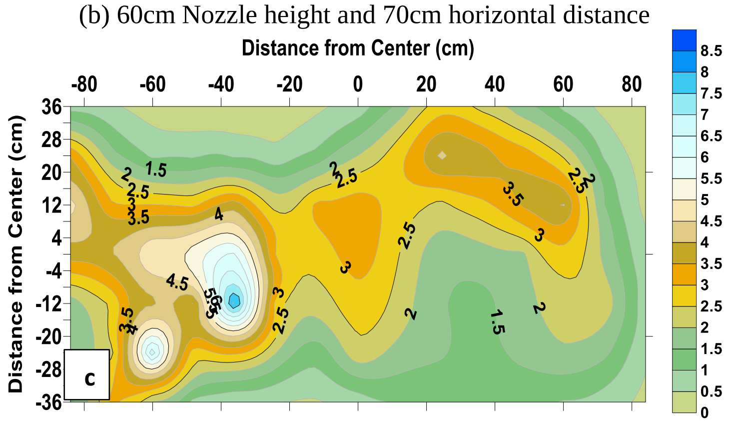
The reported results of the full-cone (plastic) nozzle showed that, the CV% value was 1.26%, 1.14%, and 1.01% for the first nozzle height of 40 cm under 50, 70, and 90cm of nozzle horizontal distances, respectively. While under the second nozzle height of 60 cm, the CV% value was 1.02%, 0.79%, and 0.70% under 50, 70, and 90cm of nozzle horizontal distances, respectively. And finally, under the third nozzle height of 80 cm, the CV% value was 0.91%, 0.87%, and 0.86% under 50, 70, and 90cm of nozzle horizontal distances, respectively. While the reported results of the second nozzle type the of the Hollow-cone (copper nozzle) showed that, the CV% value was 1.18%, 0.98%, and 1.18% for the first nozzle height of 40 cm under 50, 70, and 90cm of the nozzle horizontal distances, respectively. While under the second nozzle height of 60 cm, the CV% value was 0.88%, 0.62%, and 0.60% under 50, 70, and 90cm of nozzle horizontal distances, respectively. And finally, under the third nozzle height of 80 cm, the CV% value was 0.75%, 0.49%, and 0.80% under 50, 70, and 90cm of nozzle horizontal distances, respectively.



(a) 60cm Nozzle height and 50cm horizontal distance

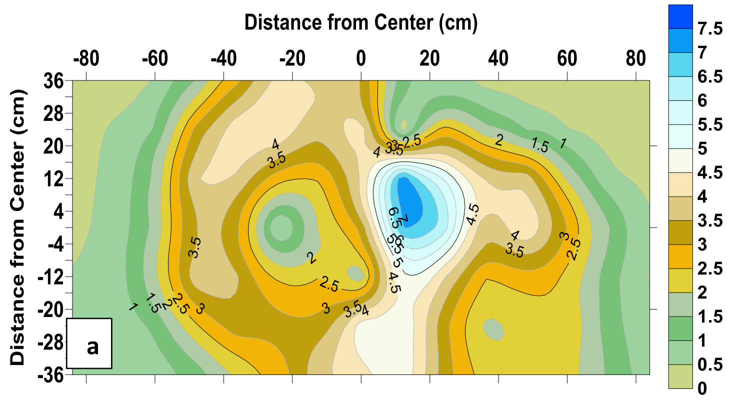


(b) 60cm Nozzle height and 70cm horizontal distance

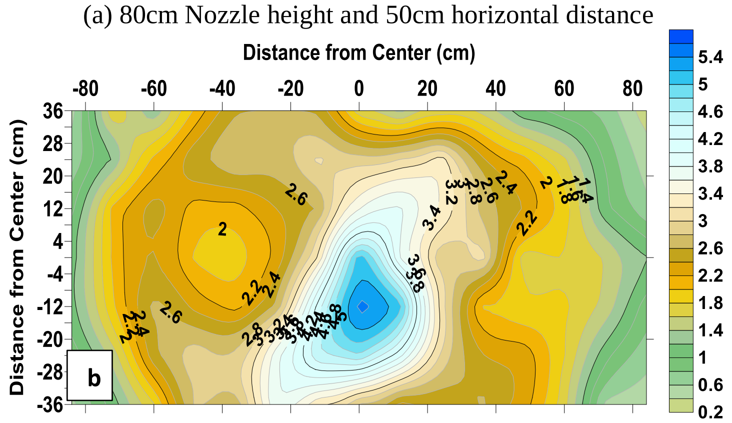


(c) 60cm Nozzle height and 90cm horizontal distance

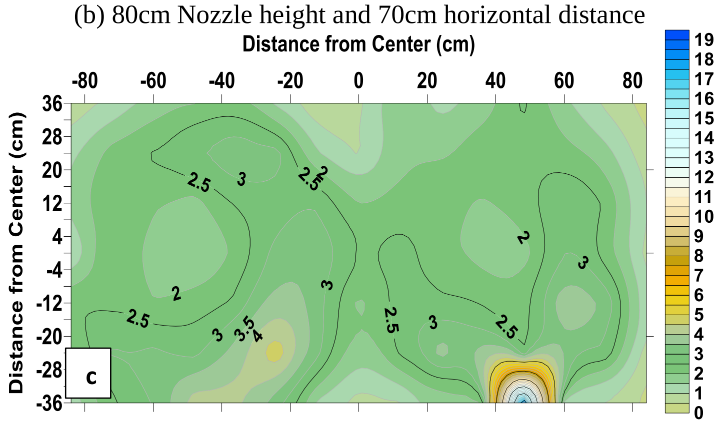
Fig. 9: Water distribution depth (mm) under the full-cone (plastic) double nozzles and 60 cm nozzle height for different nozzle horizontal distances of 50, 70, and 90 cm (operation time 2 minutes)



(a) 80cm Nozzle height and 50cm horizontal distance



(b) 80cm Nozzle height and 70cm horizontal distance



(c) 80cm Nozzle height and 90cm horizontal distance

Fig. 10: Water distribution depth (mm) under the Hollow-cone (copper) double nozzles and 80 cm nozzle height for different nozzle horizontal distances of 50, 70, and 90 cm (operation time 2 minutes)

But the reported results of the full-cone (plastic) nozzle in the table demonstrated that, the UC% value was 7.22%, 10.06, and 23.81% for the first nozzle height of 40 cm under 50, 70, and 90cm of nozzle horizontal distances, respectively. While under the second nozzle height of 60 cm, the UC% value was 24.29%, 40.87%, and 45.87% under 50, 70, and 90cm of nozzle horizontal distances, respectively. And finally, under the third nozzle height of 80 cm, the UC% value was 32.98%, 41.23%, and 40.32% under 50, 70, and 90cm of nozzle horizontal distances, respectively. While the reported results of the Hollow-cone (copper) nozzle showed that, the UC% value was 0.57%, 18.42%, and 2.41% for the first nozzle height of 40 cm under 50, 70, and 90cm of nozzle horizontal distances, respectively. While under the second nozzle height of 60 cm, the UC% value was 28.01%, 47.42%, and 48.44% under 50, 70, and 90cm of nozzle horizontal distances, respectively. And finally, under the third nozzle height of 80 cm, the UC% value was 37.26%, 61.87%, and 62.25% under 50, 70, and 90cm of nozzle horizontal distances, respectively. On the other hand, the results of the full-cone (plastic) nozzle demonstrated that, the DU% value was 59.69%, 44.61%, and 28.35% for first nozzle height of 40 cm under 50, 70, and 90cm of nozzle horizontal distances, respectively. While under the second nozzle height of 60 cm, the UC% value was 29.93%, 0.51%, and 10.90% under 50, 70, and 90cm of nozzle horizontal distances, respectively.

And finally, under the third nozzle height of 80 cm, the DU% value was 15.21%, 10.39%, and 8.81% under 50, 70, and 90cm of nozzle horizontal distances, respectively. While the reported results of the Hollow-cone (copper) nozzle showed that, the DU% value was 49.78%, 23.99%, and 49.34% for the first nozzle height of 40 cm under 50, 70, and 90cm of nozzle horizontal distances, respectively. While under the second nozzle height of 60 cm, the DU% value was 11.51%, 21.53%, and 23.65% under 50, 70, and 90cm of nozzle horizontal distances, respectively. And finally, under the third nozzle height of 80 cm, the DU% value was 4.64%, 37.70%, and 1.05% under 50, 70, and 90cm of nozzle horizontal distances, respectively. The reported results clarified that the best water distribution of the full-cone (plastic) double nozzles was done under 60cm nozzle height and 90 cm horizontal distance with CV% of 0.70% and UC% of 45.87%. Also, under the second nozzle type of the Hollow-cone (copper) double nozzles, the best water distribution was done under 80cm nozzle height and 70 cm horizontal distance with CV% of 0.49% and UC% of 61.87%.

3.3. Results of spraying system evaluation under field conditions

Tables 3 and 4 represent the results of the field evaluation of the spraying machine. The field evaluation was carried out under a nozzle height of 60 cm for both nozzles type with a single spraying nozzle. While the double nozzles were evaluated under a 60 cm nozzle height and 90 cm horizontal distance for the full-cone (plastic) nozzle. Meanwhile, under 80 cm nozzle height and 70 cm horizontal distance for the second nozzle type of the Hollow-cone (copper nozzle). The field evaluation was carried out under a machine forward speed of 0.5 km h^{-1}.

Table 3: Results of average value, maximum value, minimum value, CV%, UC% and DU% for the single nozzle spraying system under field conditions evaluation

Nozzle type		Nozzle height (60 cm)	
		Hydraulic conditions	Field conditions
The full-cone (Plastic)	Average (mm)	0.11	0.12
	Max. (mm)	0.46	0.50
	Min. (mm)	0.01	0.01
	CV %	8.60	8.67
	UC %	40.16	39.88
	DU %	9.28	15.08
The Hollow-cone (Copper)	Average (mm)	0.15	0.16
	Max. (mm)	0.24	0.26
	Min. (mm)	0.06	0.07
	CV %	3.7	3.85
	UC %	68.09	66.77
	DU %	52.70	50.68

The field evaluation was carried out using the Catch-cans experiment and the same parameters of hydraulic evaluation were measured and calculated to evaluate the spraying system under field conditions. The reported results of single the full-cone (plastic) nozzle in the Table 5 demonstrated that, the CV%, UC%, and DU% values were 8.67%, 39.88%, and 15.08% under field conditions in comparison to 8.60%, 40.16%, and 9.28% respectively, under hydraulic evaluation. While the results of the Hollow-cone (copper) nozzle showed that, the CV%, UC%, and DU% values were 3.85%, 66.77%, and 50.68% under field conditions in comparison to 3.7%, 68.09%, and 52.70% respectively, under hydraulic evaluation. In addition, the average value, maximum value, and minimum value of the full-cone (plastic) nozzle were 0.12, 0.50, and 0.01 mm under field conditions in comparison to 0.11, 0.46, and 0.01 mm respectively, under hydraulic evaluation. Meanwhile, the average value, maximum value, and minimum value of the Hollow-cone (copper) nozzle were 0.16, 0.26, and 0.07 mm under field conditions in comparison to 0.15, 0.24, and 0.06 mm respectively, under hydraulic evaluation. The reported results of double the full-cone (plastic) nozzles under 60 cm nozzle height and 90 cm horizontal distance in the Table 4 showed that, the CV%, UC%, and DU% values were 1.20%, 43.94%, and 16.55% under field conditions in comparison to 0.70%, 45.87%, and 10.90% respectively, under hydraulic evaluation.

Table 4: Results of average value, maximum value, minimum value, CV%, UC% and DU% for the double Nozzles spraying system under field conditions evaluation

Nozzle type	Nozzle height (cm)	60		80	
	Horizontal distance (cm)	90		70	
		Hydraulic conditions	Field conditions	Hydraulic conditions	Field conditions
The full-cone (Plastic)	Average (mm)	0.06	0.07	-	-
	Max. (mm)	0.25	0.27	-	-
	Min. (mm)	0.01	0.01	-	-
	CV %	0.70	1.20	-	-
	UC %	45.87	43.94	-	-
	DU %	10.90	16.55	-	-
The Hollow-cone (Copper)	Average (mm)	-	-	0.07	0.09
	Max. (mm)	-	-	0.16	0.19
	Min. (mm)	-	-	0.01	0.01
	CV %	-	-	0.49	1.55
	UC %	-	-	61.87	58.82
	DU %	-	-	37.70	39.33

While the results of double the Hollow-cone (copper) nozzles under 80 cm nozzle height and 70 cm horizontal distance showed that, the CV%, UC%, and DU% values were 1.55%, 58.82%, and 39.33% under field conditions in comparison to 0.49%, 61.87%, and 37.70% respectively, under hydraulic evaluation. In addition, the average, maximum, and minimum value of double the Hollow-cone (plastic) nozzles were 0.07, 0.27, and 0.01 mm under field conditions in comparison to 0.06, 0.25, and 0.01 mm respectively, under hydraulic evaluation. Meanwhile, the average, maximum, and minimum value of double the Hollow-cone (copper) nozzles were 0.09, 0.19, and 0.01 mm under field conditions in comparison to 0.07, 0.16, and 0.01 mm respectively, under hydraulic evaluation. The reported results showed that the average, maximum, and minimum values under field conditions were lower than the similar results of hydraulic conditions. These results are due to the slipping of the machine during field working and wind effecting.

3.4. Electrical productivity from PV and Energy consumption of machine

Table 5 gives the daily total electrical productivity from PV during the summer, spring and autumn and winter for the experimental day. The data shows that the irradiance was 7783, 5108 and 3660 W m^{-2}.day in the summer, the spring or autumn and winter respectively. The value of Electrical energy productivity from PV has different values throughout the day and the total value was 552, 460 and 330 W day^{-1} in the summer, the spring or autumn and winter respectively. This result is in agreement with **Ruiz et al. (2020)**. The actual efficiency changed between 13 to 16.6 %, affected by high temperatures in the summer more than 25°C, but it did not change during the spring and winter, because the temperature did not affect during those periods. The energy consumption for the machine is obtained from electrical energy productivity from PV. The excess electricity of the amount required is stored in the battery to regain it at times of poor production from PV.

3.5. The power required to operate the machine

The power required for operating the sprinkler pump is 33.3 W h^{-1}. it can be operated continuously for up to 9 hours after one full charging which consumes only 0.3 kWh of electricity obtained from electrical energy productivity from PV. The power required to pull the spray vehicle may be calculated according to equations from 2 to 6 and 1 m s^{-1} forward speed. It was found 38 W h^{-1} we assumed it was 40 W h^{-1}. The machine has 36 forward speeds and can be changed to suit the spray rate required to be achieved. Consequently, the power required, and performance rate will change. The total power required is 75 W h^{-1}.

Table 5: The daily solar irradiance, PV efficiency and electrical productivity from PV

Item	Total income power (Solar irradiance, Wm^{-2} day^{-1})	Mean solar panel efficiency (%)	Electrical productivity from the used PV system (W) by PV of 0.567 m^2
During the summer	7783	13.1 - 16.6	552
During the spring and autumn	5108	18	460
During the winter	3660	18	330

3.6. Machine performance rate

The theoretical performance rate (TPR) was determined according to equations from 9 to 12. Table 2 shows the total solar radiation falling during the day in the summer season, the spring and autumn season and the winter season, it was 7783, 5108 and 3660 W day^{-1}. The electrical productivity of the PV system in three periods was 552, 460 and 330 W day^{-1}. The total power required to operate the machine was 75 W h^{-1}. The number of possible hours to operate the machine was 7.3, 6.1 and 4.4 hour. The theoretical performance rate (TPR) was 0.25 ha h^{-1} with the operation width being 0.75 m (spray) and the velocity of the machine being 1 m s^{-1}. The daily theoretical performance rate TPR_d was 1.82, 1.5, and 1.1 ha day^{-1}. The actual daily performance rate APR_d in the spring season (test period) was 1.2 ha day^{-1}. The decline in the performance rate is due to the slip rate, which was about 9%, as well as the decrease in the electrical energy generated by about 12% the calculated during the same period. The field efficiency of the machine was 80 %.

4. CONCLUSION

Egypt has a large scale of renewable energies, although less conventional energy sources. Also, agricultural activities need energy to perform production. Based on Egypt's renewable potential, using them as energy resources in agriculture would help economically, and environmentally. Nowadays, spraying with simple tools like manual sprayers is labour-intensive and time-consuming. Thus, there is a need for developing and evaluating a multi-nozzle spraying machine powered by solar energy for an intensive and commercial farming system especially with the smallholdings farms. As a solution to solve these problems, the solar energy-powered sprayer was developed and evaluated. The general objective of this study is to develop and assess the performance of a moving machine, energy battery, and pumping mechanism intended for a solar energy-powered spraying machine. To achieve this aim, a spraying machine was developed and evaluated powered by solar energy via a flexible solar panel system. The development and evaluation process of the spraying machine was carried out in different steps. The first step was to build and develop the portable unit with remote control unit and the power system. In the second step, the spraying system was hydraulically evaluated under different nozzle types (the full-cone and the Hollow-cone), nozzle height, and horizontal distance between the nozzles by measuring the nozzle distribution efficiency and CV. The third step was to evaluate the spraying machine unit under field conditions. The found results of this work could be summarized as follows:

- The reported data of hydraulic evaluation confirmed that, there were a clearly affected to nozzle type (the full-cone and the Hollow-cone) for all measured evaluation parameters.
- The highest results values were found with the Hollow-cone (copper) nozzle under 60 cm nozzle height. Also, the maximum values have occurred approximately beneath the spraying nozzle.
- The minimum values have occurred approximately beneath the spraying nozzle, and faraway from the spraying nozzle under 40, 60 and 80 cm of nozzle heights.
- The best water distribution of plastic nozzle was done under 60cm nozzle height with CV% of 8.60% and UC% of 40.16%.
- The best water distribution under the Hollow-cone (copper) nozzle was done under 60cm nozzle height with CV% of 3.7% and UC% of 68.09%.
- The maximum irradiance was 7783 W m^{-2} day^{-1} in the summer season. And the value of Electrical energy productivity from PV has different values throughout the day and the total value was 8.75 MJ day^{-1}.

- The electrical productivity from the PV system was 552, 460 and 330 W day^{-1} for the summer season, the spring and autumn season and the winter season, respectively.
- The theoretical performance rate (TPR) was 0.25 ha h^{-1} with the operation width being 0.75 m and the velocity of the machine being one m s^{-1}. And the daily theoretical performance rate TPR_d was 1.82, 1.5, and 1.1 ha day^{-1}.
- The actual daily performance rate (APR_d) in the spring season (the test period) was 1.2 ha day^{-1} with 80% of the machine field efficiency.
- Therefore, the energy produced from solar panels could a good alternative source for the energy consumption in the smallholding's agricultural machines.

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تطوير وتقييم آلة رش متعددة الفوهات تعمل بالطاقة الشمسية للحيازات الزراعية الصغيرة

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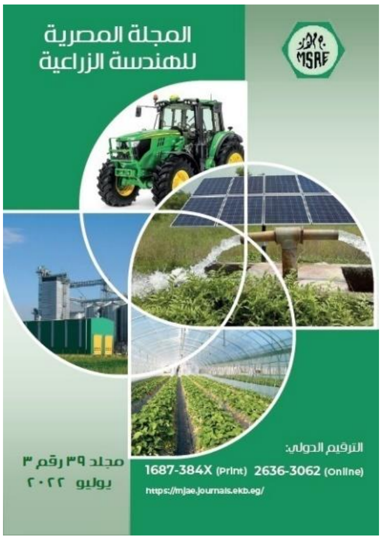

الملخص العربي

الهدف الرئيسي من هذه الدراسة هو تطوير وتقييم أداء آلة رش متحركة تعمل بالطاقة الشمسية. ولتحقيق هذا الهدف تم تطوير وتقييم آلة رش تعمل بالطاقة الشمسية باستخدام نظام الألواح الشمسية المرنة. حيث تم تنفيذ عملية التطوير والتقييم لآلة الرش من خلال مراحل مختلفة. حيث كانت المرحلة الأولى هي بناء وتطوير الوحدة المتحركة مع وحدة التحكم عن بعد ونظام الطاقة. وفي المرحلة الثانية تم تقييم نظام الرش هيدروليكيًا تحت أنواع مختلفة من الفوهات (المخروطي الكامل والمخروطي المجوف)، وارتفاع الفوهة، والمسافة الأفقية بين الفوهات عن طريق قياس كفاءة التوزيع ومعامل الاختلاف. وفي المرحلة الثالثة تم تقييم آلة الرش تحت الظروف الحقلية. أكدت نتائج التقييم الهيدروليكي أن القيمة القصوى لكفاءة التوزيع كانت ٦٨,٠٩% مع معامل اختلاف CV مقداره ٣,٧% تحت ارتفاع الفوهة ٦٠ سم وذلك للفوهة المخروطي المجوفة المفردة. وأظهرت النتائج المتحصل عليها من نظام الألواح الشمسية أن أقصى إشعاع شمسي كان مقداره ٧٧٨٣ وات / متر^{٢} في الصيف. وان قيمة إنتاجية الطاقة الكهربائية من الخلايا الكهروضوئية كانت قيم مختلفة على مدار اليوم وكانت القيم الإجمالية هي ٥٥٢، ٤٦٠، ٣٣٠ وات / يوم خلال فصل الصيف، فصل الربيع والخريف، فصل الشتاء على الترتيب. وكان معدل الأداء النظري 0.25 هكتار/ ساعة مع عرض تشغيل مقداره ٠,٧٥ م وسرعة الآلة واحد متر/ ث. وكان معدل الأداء النظري اليومي هو ١,٨٢، ١,٥، ١,١ هكتار/ يوم. وان معدل الأداء اليومي الفعلي في فصل الربيع هو ١,٢ هكتار/ يوم مع كفاءة حقلية مقدارها ٨٠%. لذلك يمكن للطاقة المنتجة من الألواح الشمسية أن تكون مصدرًا بديلاً جيدًا لاستهلاك الطاقة في الآلات الزراعية للحيازات الصغيرة.

الكلمات المفتاحية:
الطاقة الشمسية؛ آلة الرش؛ الحيازات الصغيرة.