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Research Article

Development and Performance Evaluation of a Solar Powered Lawn Mower

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ABSTRACT

The continuous increase in the cost of fuel and the effect of emission of gases from burned fuel into the atmosphere when operating engine powered lawn mower has necessitated the use of the abundant solar energy from the sun as a power source of a lawn mower. A solar powered lawn mower was designed, fabricated and assembled on the basis of the general principle of mowing. The components of the lawn mower are; direct current (DC) motor, rechargeable battery, solar panel, galvanized steel blade of various thicknesses and shapes, and a speed controller. The required torque needed to drive the galvanized steel blade was achieved through the DC motor. The speed of the DC motor was controlled by the speed controller with the resistance in the circuit and allowed the motor to drive the blade at varied speeds. The battery recharged through the solar charging circuit, which comprises of a solar panel and charge controller. Performance evaluation was conducted on the developed mower with various thicknesses (1 mm, 1.5 mm and 2 mm) and shapes of the cutting blade (two, three and four blades). It was found that the cutting efficiency of the mower ranges from 70.50% - 84.10%, also the cutting capacity ranges from 0.05 ha h^{-1} - 0.27 ha h^{-1}, the uncut area was also found to range from 15.90% - 29.50%.

RESEARCH ARTICLE

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Keywords:

- Lawn mower,
- Solar panel,
- Environmental pollution,
- Cutting efficiency,
- Cutting capacity

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INTRODUCTION

The previous technology of grass cutting was manually operated using hand tools like pruning shreds, scissors etc., these tools weren't efficient because they require more human effort and time. With the incorporation of lawn mowers into grass cutting, human effort and time was being saved (Prasanthi and Balaiah, 2017). Lawn mowers are classified based on different criteria and according to the axis of rotation of blades; reel lawn mowers (that which axis is horizontal) and rotary lawn mowers (that which axis is vertical).

The reel mower is made of a cylindrical blade, it achieves a clean cut by scissors action. Rotary mowers are often powered by gasoline or electricity (Dutta *et al*., 2016).

The sun supply viable amount of energy used for several purposes on earth. Every minute the sun radiates about 5.68x1018 calories of energy and the earth intercept only 2.55x1018 calories (NRF, 2010). This represents only 2000 millionth of the total solar energy is sent into space. The total solar energy is estimated to be 30000 times greater than the total annual energy of the world (Mgbemu, 2005). The solar powered lawn mower works on the same principle as other lawn mowers; the only difference is the energy source. It uses the photovoltaic panel to generate the energy needed to power the mower (Tanimola *et al*., 2014). In recent times, the environment has become one of the paramount global concern, especially with the surge of pollution, the depletion of natural resources and environmental degradation. As a result of this, lot of researches are ongoing to find alternative solutions that encourage environmental preservation (Fernandez and Krishnasamy, 2018). Due to the present revolution in green energy, industries are starting to change their perspective about power utilization. They now tend to lean toward the usage of green energy i.e., renewable energy which reduces effort, cost and pollution (Fernandez and Krishnasamy, 2018). A solar powered lawn mower is a lawn mower that uses solar energy as its source of power. It uses the electricity gotten from the solar energy to power the electric motor which in turn drives the blade that mows the lawn (Satwik *et al*., 2015). Solar lawn mower is a manually operated grass cutting vehicle powered by solar energy. The electric current is derived from the solar panel powers the electric motor, which then drives the blades Tanimola *et al*. (2014). The only difference between it and gas-powered lawn mowers is the application of different power sources. Satwik *et al*. (2015) researched on design and fabrication of lever operated solar lawn mower and contact stress analysis of spur gears. They worked on the adjustment of the mower's rotor blades heights with the aid of a spur gear displacement mechanism and a lever to achieve efficient cutting of grasses of different heights. The mechanism involves a pair of spur gears of different face width and the lever, which is used to adjust the rotor height in a way that the smaller spur gear slides against the face width of the larger spur gear. An Arduino board was incorporated to control the speed of the motor manually, also an ultrasonic sensor is placed in front of the machine which sends signal to the board before collision with an obstacle. A Buzzer receives a signal from the board and produces an alarm that prevents the collision. Dalal *et al*. (2016) researched on manufacturing of solar grass cutter which consists basically of direct current (D.C) motor, a rechargeable battery, solar panel, a stainless-steel blade and control switch. It was reported that solar panels were mounted in such a way that it can receive solar radiation with high intensity easily from the sun. These arranged solar panels converted solar energy into electrical energy. This electrical energy was stored in batteries through the solar charger. The motor was connected to the batteries through two mechanical circuit breaker switches, which aided the ON and OFF of the motor. The rotary power from the motor was transmitted to the blade, which resulted in the cutting of grasses. Igbokwe *et al*. (2019) worked on the development of a solar powered lawn mower which is made of a twin solar panel of 75A/130W capacity each. The purpose of this research work is to design, fabricate, assemble and evaluate a solar powered lawn mower using Design Expert software and MS Excel.

MATERIALS and METHODS

Machine Conception

The components of the solar lawn mower include; the machine frame, electric motor, solar panel, steel blades, connecting wires, tyres, battery, charging circuit and machine handle. The machine frame holds every other component of the machine together. The solar panel charges the battery while the battery powers the electric motor, which in turn rotates the attached blades at a high speed using the control switch. The machine has a handle which is used to maneuver it in the direction the handler intends it to go, with the help of the rotary wheels (Figure 1).

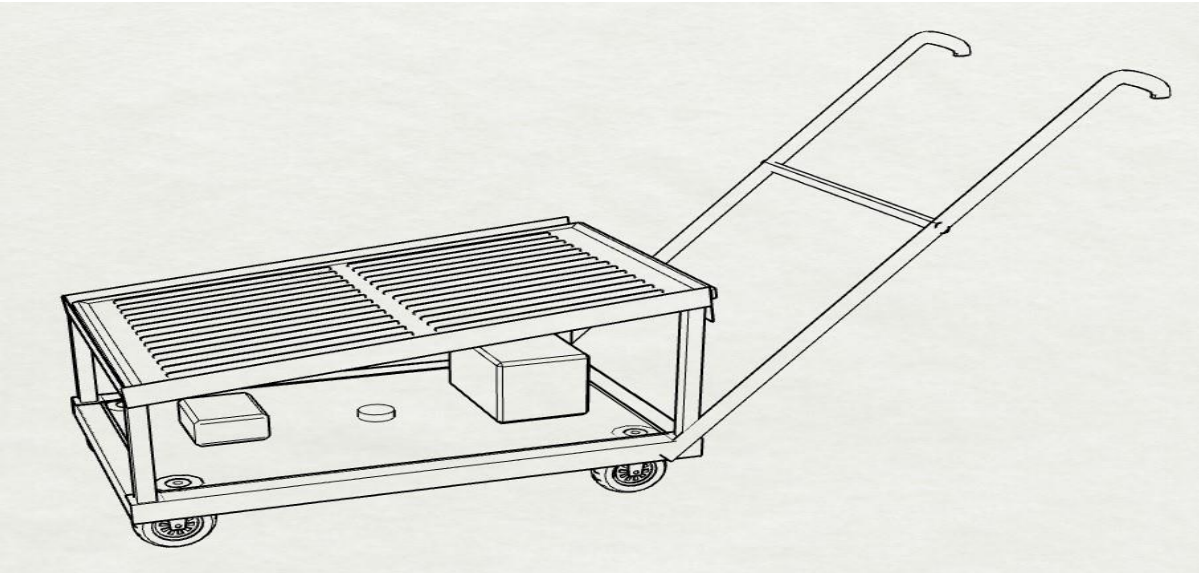

Figure 1. 3D Front view of the machine concept.

Design Analysis

The necessary components needed for the fabrication of the machine was designed following the standard design procedure used by Igbokwe *et al.* (2019).

Power selection

Mower blades are the cutting components of lawn mowers. They are usually made of sturdy metals as they must be able to withstand high-speed contact with various objects in addition to grass. The materials used (as well as size, thickness, and design of the blades) vary by manufacturer. Galvanized steel was selected with a density of 7922 kg m^{-3} in accordance with what was used by Igbokwe *et al* (2019). The shearing force of most annual and perennial grasses found on most lawns is usually between 9.20 N and 11.51 N, however, it depends on the height of the grass, type of grass as well as grass density in the area. The calculations (a to j) were done in accordance to Igbokwe *et al* (2019).

a) $Area\ of\ blade = Length \times Breadth = 300\ mm \times 50\ mm = 15000\ mm^2$

b) $Volume\ of\ blade = Area \times Thickness = 15000\ mm^2 \times 2\ mm = 30000\ mm^3$

c) $Mass\ of\ blade\ (M) = Density \times Volume = 7922 \times 30000 \times 10^{-9} = 0.238\ kg$

d) $Weight\ of\ the\ blade = Mass \times Acceleration\ due\ to\ gravity = 0.238 \times 9.81 = 2.335\ N$

e) $Torque\ produced\ by\ blade\ =\ Weight \times\ Radius = 2.335 \times \frac{0.3}{2} = 0.35\ N\ m$

f) $Where\ N\ is\ the\ rotational\ speed\ of\ the\ selected\ motor\ (1800\ rpm), then$

g) $Angular\ velocity = \frac{2\pi N}{60} = \frac{2 \times \pi \times 1800}{60} = 188.50\ rads/s$

h) $The\ power\ developed\ is\ therefore\ the\ product\ of\ torque\ and\ angular\ velocity$ $= 0.35 \times 188.50 = 66\ Watts.$

i) $Converting\ determined\ power\ to\ horsepower =\ 66 \times 0.00134 = 0.088\ HP$

Battery sizing

The design power was determined using Equation 1 (Igbokwe *et al.*, 2019);

$$\text{Design power} = \frac{I \times V}{Power\ factor\ of\ the\ machine} \tag{1}$$

Where I is the expected current to be drawn by the motor, V is the expected voltage of the battery (12 V), and the power factor is 0.8. Current used to power the motor is given as;

$$I = \frac{Design\ power \times Power\ factor\ of\ the\ machine}{V} = \frac{66 \times 0.8}{12} = 4.40\ Amps$$

The battery selected is 45 Ah at 12 volts, it is expected to discharge after; (45 Ah/4.40 A); 10.23 hours.

Solar sizing

The average sunshine in Akure, Nigeria is about 5 hours (Sinha and Mathur, 2020). The solar panel selected is 2.88 Amps rated at 50 Watts

$$Average\ battery\ charge\ per\ day\ =\ 2.88\ Amps\ \times\ 5\ hours = 14.4\ Ah$$

Battery will be fully charged in (charging rate) = 45 Ah / 14.4 A = 3.125 hours.

Component Assembly

Frame: The mower frame was fabricated from an angle iron, cut and welded with the aid of cutter, grinder and welding machine. Positions of two bearings were also provided on the metal plate at the base of the machine to prevent excessive vibration of machine while it's at work. A room is provided for the solar panel at the top of the frame in such a way that it can easily be removed and slotted in (Figure 2).

Handle: The handle is made of galvanized hollow pipe having an internal diameter of 25 mm. The pipe was cut into 100 mm on both sides spaced 46 mm, then joined together by another 45.50 mm long pipe of the same internal diameter through welding. The other open end was welded to the base of the machine frame. The handle was designed in such a way that it can be detachable for future modifications.

Tyres/wheels: Two (2) Swivel caster wheels were attached to the front of the machine and two (2) fixed caster wheels were attached to the back of the machine. This is to enable easy maneuverability of the machine during operation when handled from the handle.

DC motor: A DC motor with speed of 1800 rpm was used. The shaft of the motor was fixed into the bearing and threaded at the end to screw the blades. The motor was supported by three rods screwed and welded to the top of the base frame.

Blades: The blade is made of galvanize steel, 300 mm long, 50 mm wide and 0.1 mm thick. The blade was sharpened and screwed to the end of the threaded motor shaft. The panel was connected to a charge controller before connected to the battery.

Battery and solar panel: The battery is placed beside the motor and the panel was affixed to the space provided by the frame at the top of the machine.

Painting: After the completion of the fabrication, the machine was painted to cover weld and scratch marls and enhance the beauty as shown in Figure 3.

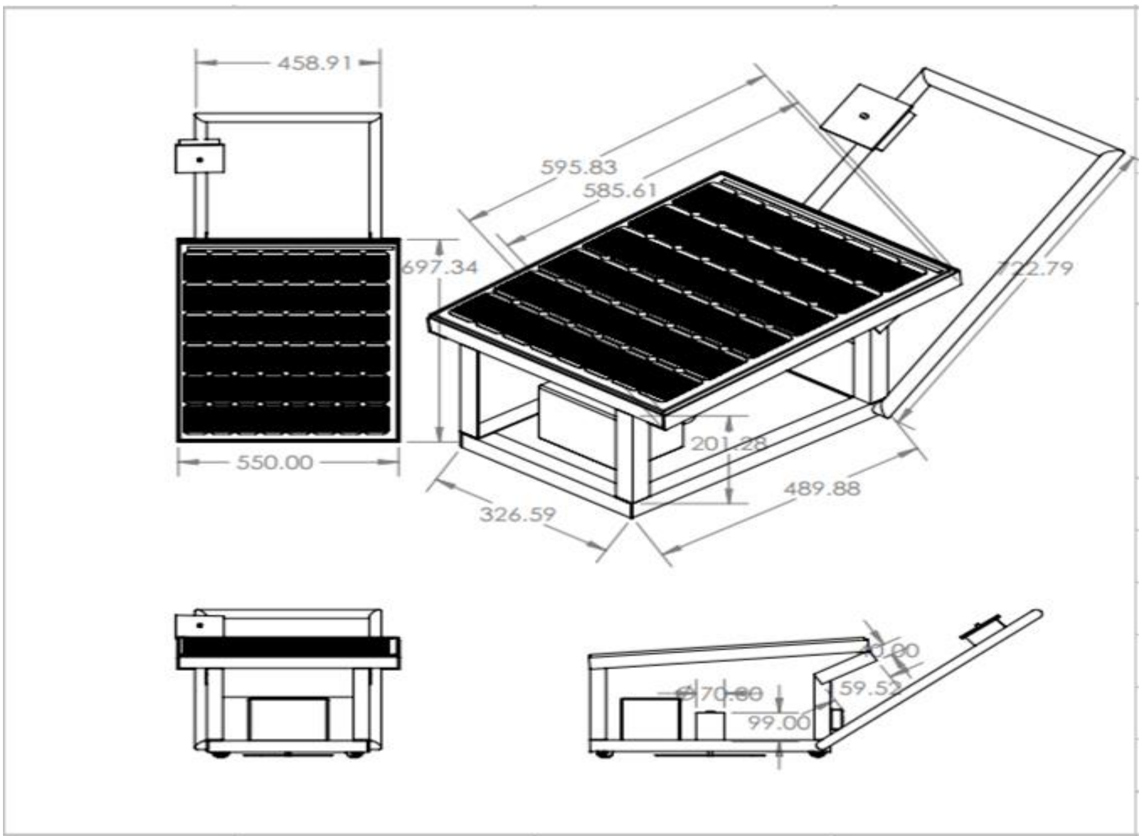

Figure 2. Orthogonal view of the designed lawn mower.

Figure 3. Assembled lawn mower.

Speed controller

The circuit used for the lawn mower uses similar PWM (Pulse Width Modulation) technique to control the motor speed and uses IC 555 to generate PWM signals. The PWM, is a modulation technique in which the width of the output pulse varies with respect to time. Therefore, changes the duty cycle of the wave, which in turn modify on and off time of this PWM signal. The heart of this circuit is an astable multivibrator built out of IC 555. This multivibrator produces a series of square wave pulses as the output of the fixed frequency. A 555 astable multivibrator output duty cycle can never fall below 50%. In order to achieve the PWM signal in the output, the duty cycle should be able to be modified to the required optimum level. This is achieved through the use of D2, D1 and RV1 (Figure 4).

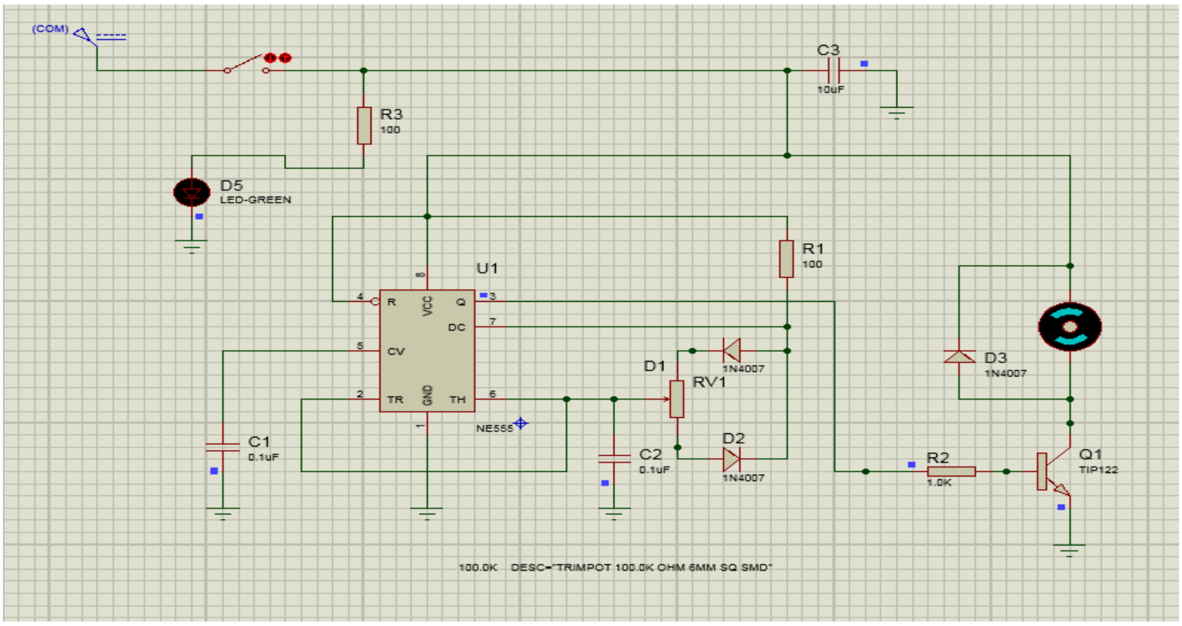

Figure 4. Circuit design of the speed controller.

Working of this astable multivibrator depends on the resistors and capacitor used with pin 7, pin 6 and pin 2. When the circuit is powered ON capacitor *C2* charges via resistor *R1* and *RV1*. But in the circuit, the current from *R1* can pass through only one terminal of the variable resistor since *D2* is reverse biased. Hence, *D1* allows current to flow through it and RV1 exhibits some resistance to the current, which depends on the position of the pot. When the capacitor is charging output of IC 555 will be in a high state. Once the capacitor charges up to 2/3 VCC (Voltage Common Collector), internal discharge transistor connected to pin 7 goes high. Now, the output of IC 555 will go low. This forces the capacitor to discharge through RV1. But this time the discharging current goes through diode *D2* since *D1* is reverse biased. The resistance exhibited by *RV1* to discharging current will be different from what exhibited to charge current of capacitor. Therefore, the discharge time of capacitor will be different from charging time. These varied charging and discharging time will modify the width of the output pulse. This results in a *PWM* output signal in the output. When *RV1* is set up, it exhibits very high resistance to charging current coming from *D1*, output pulse will have longer ON time. On the other hand, this will leave low resistance path for the discharge current going out via *D2*, therefore, capacitor discharges quickly make the OFF time shorter. Thus, a high duty cycle *PWM* pulse will be generated. If the resistance is reversed, low time will be longer and high time will be much shorter comparatively. This will make *PWM* signal much lower than 50% be generated.

Charging time and discharge time were determined using Equations 2 and 3;

$$Charging\ time\ or\ ON\ time\ =\ 0.693(R1\ +\ RV1)C2 \quad (2)$$

$$Discharge\ time\ or\ OFF\ time\ =\ 0.693\ x\ RV1\ x\ C2 \quad (3)$$

If the variable resistor was set to exhibit 10 kΩ resistance between terminals 1 and 2. Then, this will be the resistance to charging path by *RV1*. At this point terminal 2 and 3 in *RV1* will exhibit 90kΩ resistance to discharge path. Substituting the values into equation (2) and (3);

$$ON\ time\ =\ 0.693\ (100 + 10)0.1\ =\ 0.7\ ms$$

$$OFF\ time\ =\ 0.693 \times 90 \times 0.1\ =\ 6.237\ ms$$

$$T\ =\ ON\ time\ +\ OFF\ time\ =\ 0.7\ ms + 6.237\ ms\ =\ 6.937\ ms$$

$$Duty\ cycle\ =\ 0.7\ ms\ /\ 6.937\ ms\ =\ 10\%$$

Now if *RV1* is altered to make the resistance in terminal 1 and 2 as 90 kΩ and terminal 2 and 3 as 10kΩ. The duty cycle changes vastly;

$$ON\ time\ =\ 0.693\ (100 + 90)0.1 =\ 6.24\ ms$$

$$OFF\ time\ =\ 0.693 \times 10 \times 0.1\ =\ 0.693\ ms$$

$$T\ =\ 6.24\ ms + 0.693\ ms\ =\ 6.933\ ms$$

$$Duty\ cycle\ =\ 6.24\ ms\ /\ 6.933\ ms = 90\%$$

From the above calculations, providing different charging and discharging path with different resistance will give room for the production of *PWM* pulse from IC 555. Modifying the resistance value of *RV1* between its terminals will modify the duty cycle.

Motor driver

The output of the IC 555 is pretty low to drive a motor that can consume 500 mA. Therefore, a transistor TIP122, a Darlington transistor that can drive motor load up to 5A was used as a switch and a current driver. The *PWM* signal will drive the base of transistor *Q1*. This drives the motor according to the incoming signal from the output of the 555 IC. When the duty cycle of the *PWM* signal is high then the speed of the motor will be high and vice versa.

Diode *D3* is used to arrest the reverse current from motor when it is turned off. Figure 5 shows the fabricated speed controller. The 0 point on the speed controller signifies OFF while 1, 2, 3 and 4 signify the varying speeds of the blade.

Figure 5. Speed controller.

Cutting blades

For the purpose of performance evaluation, three pairs of blades made of galvanized steel were fabricated, each having different shapes. As shown Figure 6, the first pair is double-bladed, the second is triple-bladed, while the third is quadruple-bladed. Each pair have two different thickness, 1 mm and 1.3 mm. Designs were first made on a drawing paper, then cut out and pasted on the galvanized steel plate, the shape was then reproduced on the plate, which was then cut out with the aid of a hand grinder.

Figure 6. Blades of different shapes and thickness.

RESULTS and DISCUSSION

Cutting Efficiency

The graphical representations of the cutting efficiency of the mower at different number of blades, blade thickness and machine speed are shown in Figures 7 to 9. According to the figures, the cutting efficiency of the mower ranges from 70.50% to 84.10%. The number of blades and blade thickness has an inverse relationship with the cutting efficiency (Figure 7). The machine speed is proportional to the cutting efficiency (Figures 8 and 9). As deduced from the linear relationship in Equation 4, a unit increase in the machine speed resulted in an average increase in the cutting efficiency by 0.008%, whereas a unit increase in the number of blades and thickness resulted in an average decrease in the cutting efficiency of the solar powered lawn mower by 0.278% and 1.789%, respectively, which might be as a result of the increase in weight of the blades as the number and thickness increases.

$$E = +69.229 - 0.2778n - 1.7889t + 0.0083S \quad (4)$$

The mathematical relationship between the cutting efficiency and the input parameters (number of blades, thickness and machine speed) are shown in Equation 5 with a determination coefficient of thickness and this shows that the equation can significantly ($p<0.05$) predict the 99.01% change in the cutting efficiency as a function of number of blades, thickness and machine speed.

$$E = +57.76 + 11.37n - 3.08t + 1.27x10^{-3}S - 0.38nt - 2.90x10^{-4}nS - 2.20x10^{-5}tS - 1.78n^2 + 0.82t^2 + 2.98x10^{-6}S^2 \quad (5)$$

Where E is the machine efficiency, n is no of blades (blades), t is thickness of the blade (mm) and S is machine speed (rpm).

Table 1 shows the results of the analysis of variance (ANOVA) of the cutting efficiency. Based on the table, the number of blades do not have significant effect on the efficiency of the mower but the blade thickness and the machine speed significantly affect its efficiency. The combination of number of blades, thickness and machine speed can significantly explain the variation in the cutting efficiency at 95% probability level. However, the change in the cutting efficiency significantly ($p<0.05$) depends on the machine speed followed by blade thickness and number of blades has the least significant effect on the cutting efficiency of the Solar Powered Lawn Mower. The result has a similar trend with that reported by Sinha and Mathur (2020) when they evaluated the performance of a solar powered lawn mower, where they also experimented with various thickness of blade and the cutting efficiency obtained was 78.06%.

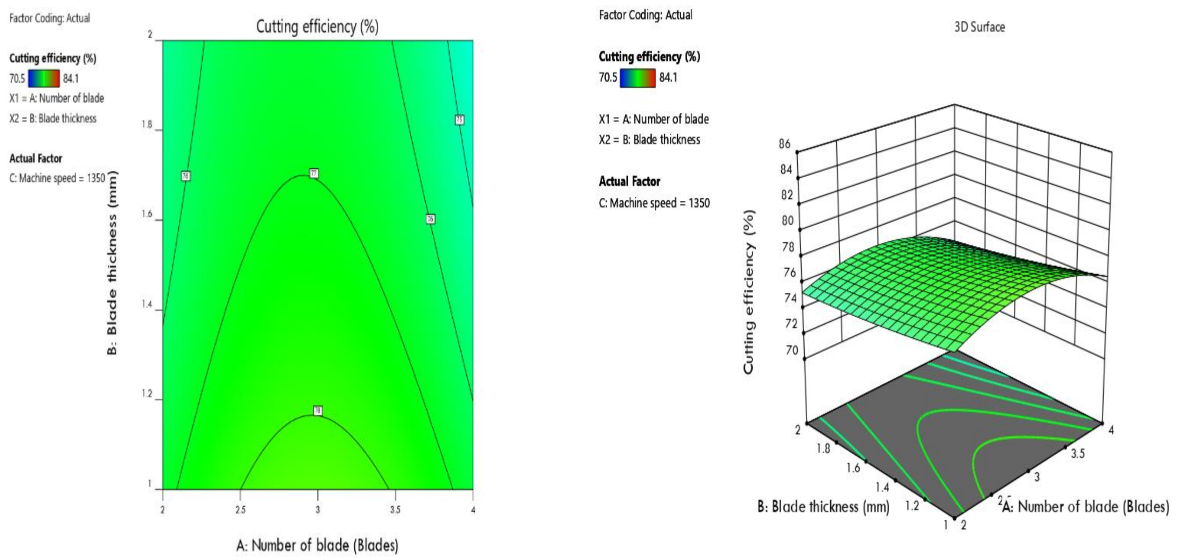

Figure 7. Contour and 3D surface plot of cutting efficiency at different blade thickness and number of blades.

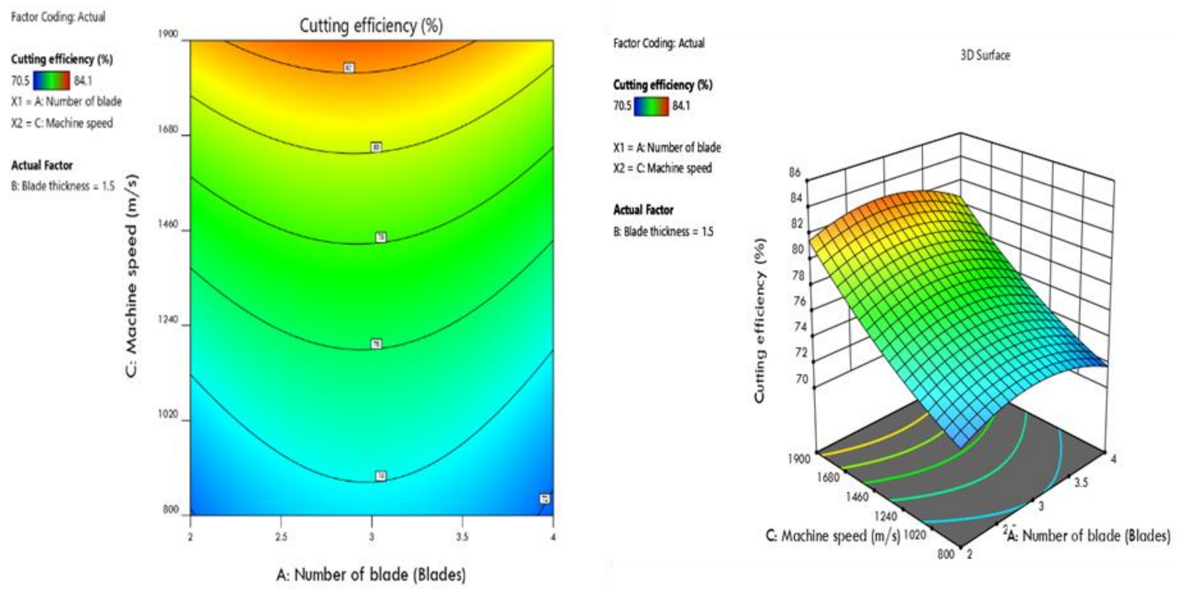

Figure 8. Contour and 3D surface plot of cutting efficiency at different machine speeds and number of blades.

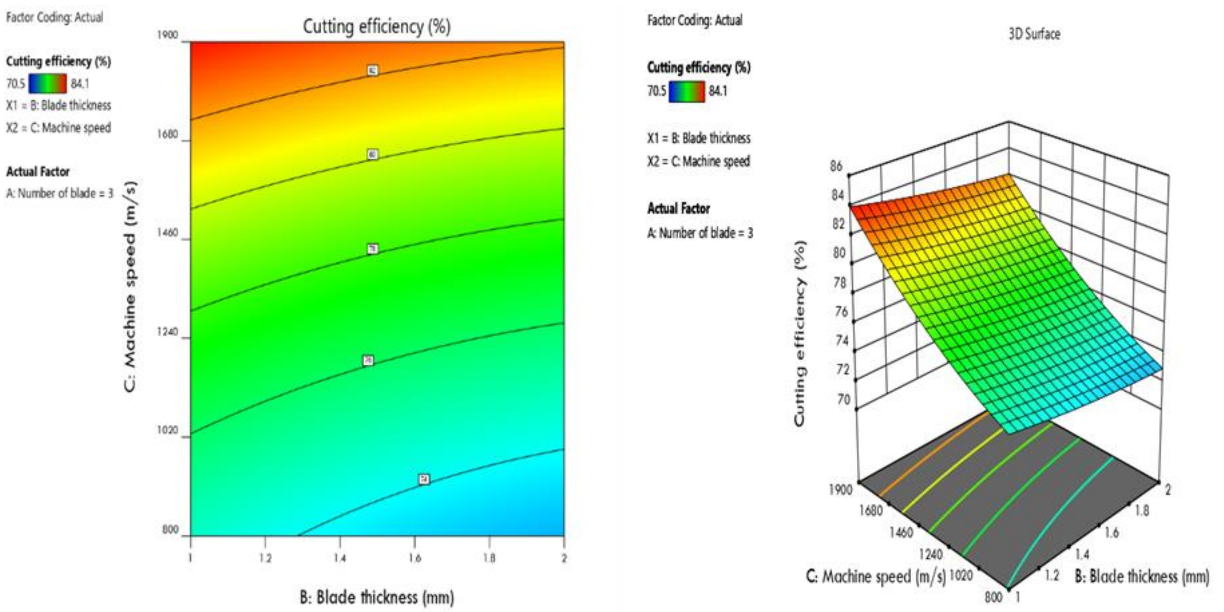

Figure 9. Contour and 3D surface plot of cutting efficiency at different machine speeds and blade thickness.

Table 1. ANOVA Table for the cutting efficiency.

Source	Sum of Squares	Df	Mean	F-value	p-value	Remark
Model	422.353	9	46.9281	189.1794029	3.04×10^{-15}	Significant
A-Number of blades	1.233	1	1.2326	4.968975514	0.039585437	
B-Blade thickness	14.211	1	14.2113	57.2896481	7.69×10^{-7}	Significant
C-Machine speed	385.494	1	385.4939	1554.027487	3.75×10^{-18}	Significant
AB	0.441	1	0.4408	1.777115376	0.200094605	
AC	0.314	1	0.3135	1.263996204	0.276521067	
BC	0.000	1	0.0004	0.001733877	0.967270957	
AÂ²	18.963	1	18.9630	76.44470257	1.07×10^{-7}	
BÂ²	0.254	1	0.2535	1.021999979	0.326218455	
CÂ²	4.076	1	4.0757	16.4303131	0.000825884	Significant
Residual	4.217	17	0.2481			
Cor Total	426.570	26				

Df = degree of freedom, F-value = F- statistics (Fisher's) value and p-value = Probability value

Cutting Capacity

Figures 10 to 12 show the graphical representation of the cutting capacity of the developed solar powered lawn mower in different number of blades, thickness and machine speed. According to the figure, the cutting capacity of the mower ranges from 0.05 ha h^{-1} - 0.27 ha h^{-1}. As deduced from the linear relationship in the Figures (10 to 12) and Equation 6, a unit increase in the thickness resulted in an average increase in the cutting capacity by 0.027%, whereas a unit increase in the number of blades and machine speed resulted in an average decrease in the cutting capacity of the solar powered lawn mower by 0.01% and 0%, respectively, this is due to the increase in weight of the blades.

$$C = +0.3443 - 0.0102n + 0.0269t - 0.0002S \quad (6)$$

The mathematical relationship between the cutting capacity and the input parameters (number of blades, thickness and machine speed) is shown in Equation 7 with a determination coefficient of thickness and this shows that the equation can significantly ($p<0.05$) predict the 99.70% change in the cutting capacity as a function of number of blades, thickness and machine speed.

$$C = +57.76 + 11.37n - 3.08t + 1.27x10^{-3}S - 0.38nt - 2.90x10^{-4}nS - 2.20x10^{-5}tS - 1.78n^2 + 0.82t^2 + 2.98x10^{-6}S^2 \quad (7)$$

Where C is the machine capacity, n is no of blades (blades), t is thickness of blade (mm) and S is machine speed (rpm).

Table 2 shows the result of the analysis of variance (ANOVA) of the cutting capacity. Based on the table, all the considered parameters (number of blades, thickness and machine speed) significantly affect the cutting capacity of the mower and this can significantly explain the variation in the cutting capacity at 95% probability level. However, the change in the cutting capacity significantly ($p<0.05$) depends on the machine speed followed by blade thickness and number of blades has the least significant effect on the cutting efficiency of the solar powered lawn mower.

Tanimola *et al.* (2014) reported in their research that the effective field capacity of the solar powered lawn mower was 0.000111 ha h^{-1}. Sinha and Mathur (2020) also reported that the maximum and minimum field capacity of the mower was 0.0306 ha h^{-1} and 0.0282 ha h^{-1}, respectively.

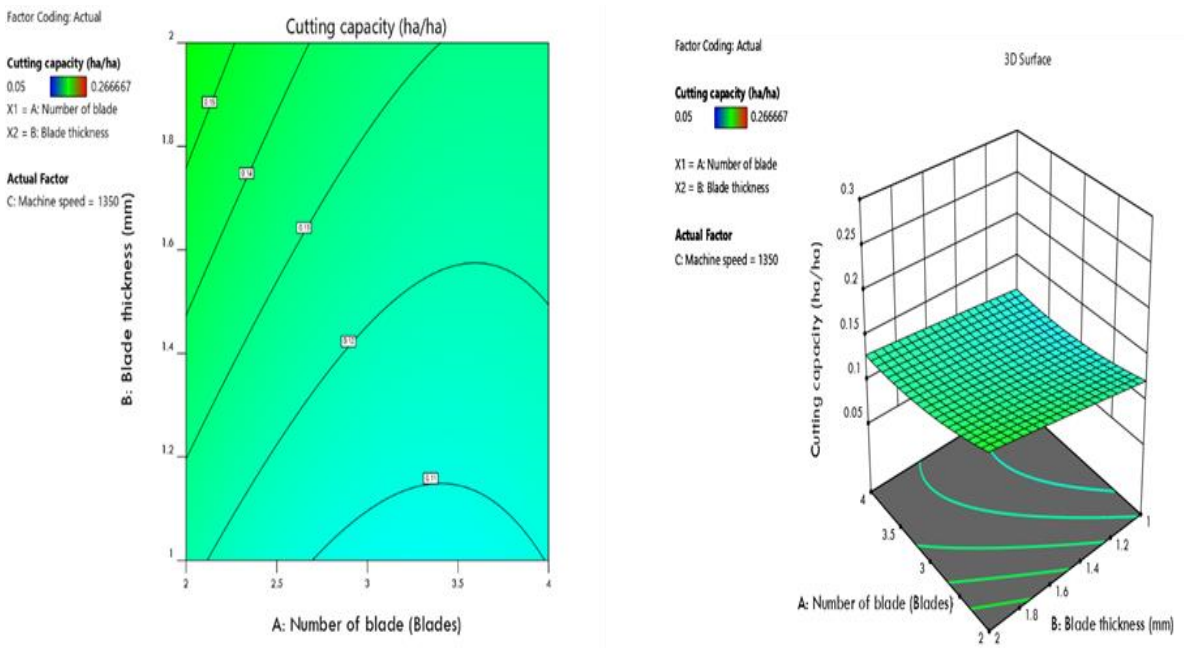

Figure 10. Contour and 3D surface plot of the cutting capacity at different blade thickness and number of blades.

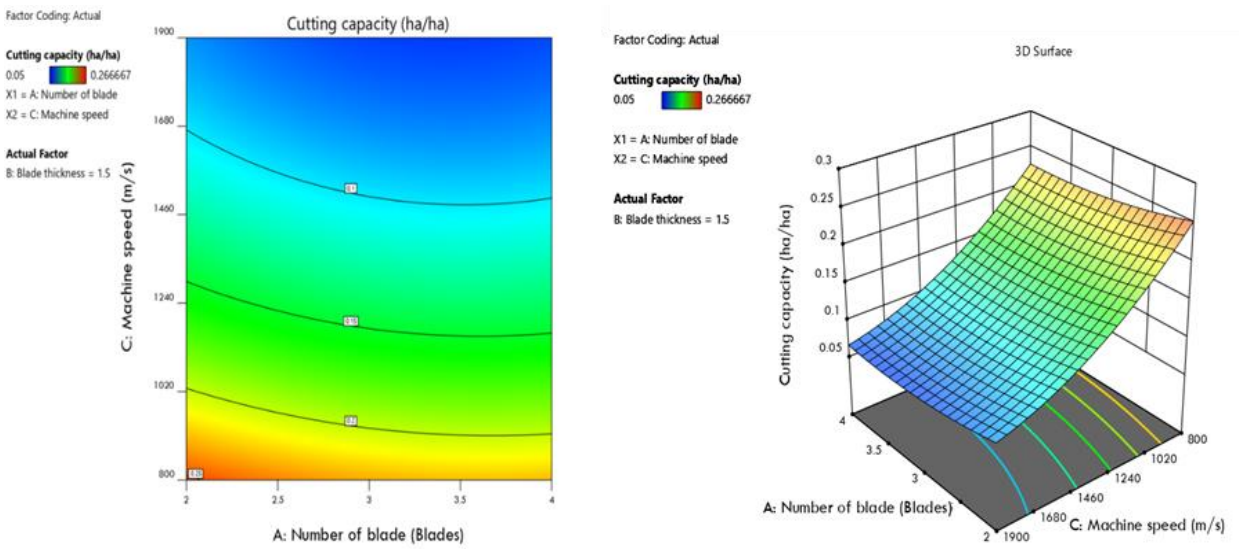

Figure 11. Contour and 3D surface plot of the cutting capacity at different machine speeds and number of blades.

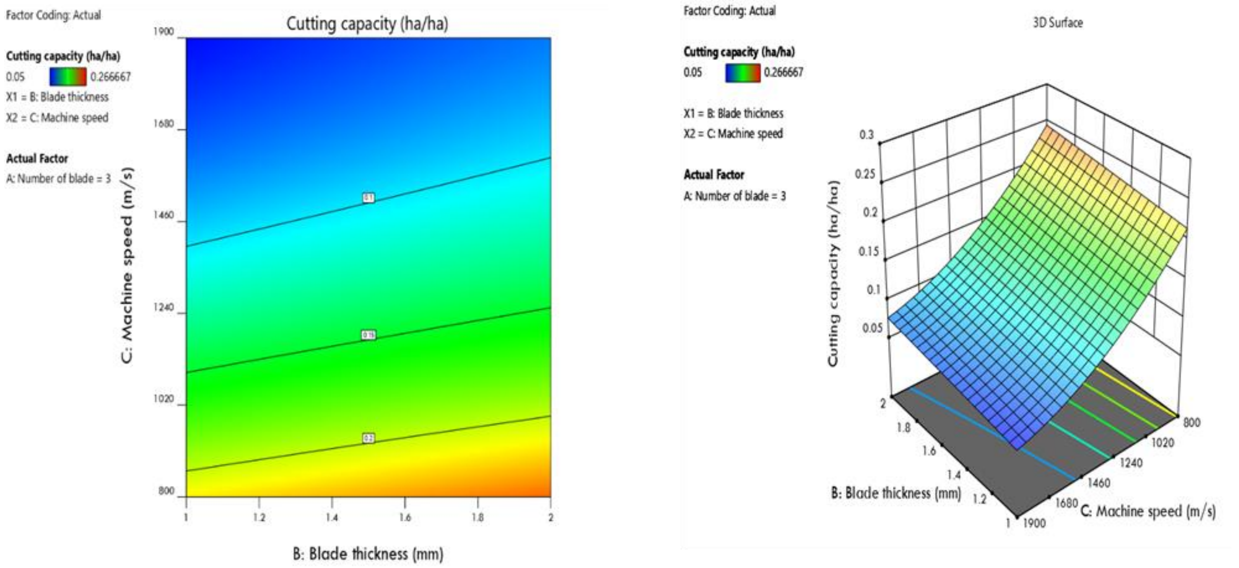

Figure 12. Contour and 3D surface plot of the cutting capacity at different machine speeds and blade thickness.

Table 2. ANOVA Table for the cutting capacity.

Source	Sum of Squares	Df	Mean Square	F-value	p-value	Remark
Model	0.1427	9	0.0159	629.18	< 0.0001	Significant
A-Number of blades	0.0019	1	0.0019	76.64	< 0.0001	Significant
B-Blade thickness	0.0033	1	0.0033	129.79	< 0.0001	Significant
C-Machine speed	0.1236	1	0.1236	4905.99	< 0.0001	Significant
AB	0.0002	1	0.0002	8.27	0.0105	
AC	0.0001	1	0.0001	3.27	0.0884	
BC	0	1	0	1.07	0.3161	
A^2	0.0005	1	0.0005	20.42	0.0003	Significant
B^2	1.29E-06	1	1.29E-06	0.051	0.824	
C^2	0.0034	1	0.0034	135.61	< 0.0001	Significant
Residual	0.0004	17	0			
Cor Total	0.1431	26				

Df = degree of freedom, F-value = F- statistics (Fisher's) value and p-value = Probability value

CONCLUSION

In recent times, machines are designed with the aim of reducing or eliminating greenhouse gas emissions, which are the major causes of climate change. This project has met the challenges of environmental pollution and high cost of operation by producing a solar powered lawn mower from locally sorted materials. The cutting efficiency and cutting capacity were evaluated using Design-Expert software and MS Excel and found to range from 70.5% to 84.10% and 0.05 ha/h to 0.27 ha h^{-1} respectively. The following conclusions can be drawn from this study:

a) Utilization of solar energy in lawn mowing is more efficient compared to other means.
b) Light weighted materials used in construction aids easy movement of the operator.
c) The machine's capacity is adequate for its purpose.
d) The machine has proved to be a possible replacement for the gasoline powered lawn mowers.

DECLARATION OF COMPETING INTEREST

The author of this manuscript declare that there is no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

The author would like to declare that he solely developed all the sections in this manuscript.

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