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Performance evaluation of a modified axial flow water Lifting pump for small to medium irrigation in Nigeria.

James David [1,*], Oyebode Muyideen Abubakar [2] and Habib Ismail [2]

[1] *National Centre for Agricultural Mechanization (NCAM), Ilorin, Nigeria.*

[2] *Department of Agricultural and Bio-Resources Engineering Ahmadu Bello University, Zaria, Nigeria.*

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Abstract

Most irrigation pumps used in Nigeria are imported. Consequently, the challenges farmers faced in using these pumps include but not limited to the following; priming before operation, relatively low-capacity delivery at low head and high price which is often time not affordable by peasant farmers. The objective of this research was to develop an axial flow pump with locally sourced materials and affordable by farmers for small to medium scale irrigation in Nigeria. The design of the pump for the study was adopted from an existing and functioning axial pumping machine, developed by Agricultural Machinery and Mechatronics Department, Kasetsart University, Thailand. The pump was fabricated at the workshop of National Centre for Agricultural Mechanization (NCAM), Ilorin, Nigeria. Diesel fuel was used in powering the pump because of higher torque deliverable. The developed pump based on its capacity can be used to irrigate one hectare in one hour at 16.2 mm depth of water using 2000 rpm at 1m head and 9.6 mm depth of water using 1000 rpm at 3 m head. The maximum water discharge of 162 m^3/h (45 l/s) was at 1m using a speed of 2000 rpm with water to fuel delivery of 124.29 l/s. The maximum water discharge of 162 m^3/h (45 l/s) was at 1m using a speed of 2000 rpm with water to fuel delivery of 119.57m^3/L. And the least water discharge of 59.30 m^3/h (28 l/s) and water delivery per fuel was 41.0m^3/L at 3 m head at 1000 rpm. Therefore, the developed pump operates best at lower head of 1m featuring a 3kW prime mover. The developed pump based on its capacity can be used to irrigate one hectare in one hour at 16.2 mm depth of water using 2000rpm at 1m head and 9.6 mm depth of water using 1000rpm at 3m head at a moisture content of 45% on a sand-loamy soil. Statistical analysis reveals relationships between pump speed, head, fuel consumption, and various performance indicators. The centrifugal pumps were found to produce lower discharge than axial flow pumps at different water heads evaluated. Comparative economic analysis demonstrates the pump's superiority over conventional centrifugal pumps in terms of water-fuel delivery efficiency and operational cost. This study introduced a locally modified axial flow pump as a practical, cost-effective, and efficient solution to irrigation challenges faced by small and medium-scale farmers in Nigeria. This pump has higher capacity delivery, spare parts are readily available at local market, it is appropriate for use where the irrigation head requirements are low and large volumes of water is required to be lifted at low pressure, it is appropriate where water can be lifted from rivers and canals and then directed to farmers' fields for irrigation. It is also applicable in rice farm flooding and flood drainage. This type of pump is good for flood (surface) irrigation system, which include furrow, border, basin irrigation and uncontrolled flooding in loamy and clay soils for rice production and sugarcane productions. The pump's adoption and economic viability positions it as a potential catalyst for increased food production, income, and food security in the country.

Keywords: Axial flow pump; Irrigation; Efficiency; Water heads; Pump speed

* Corresponding author: David James.

1. Introduction

Pump is a mechanical device or arrangement by which water (fluid) is caused to flow at increased pressure. It lifts water (fluid) from the water (fluid) source (e.g., rivers, streams, wells, etc.) to the point of use (farmlands or other places) using energy sources such as petrol, diesel, electricity, water (hydro), wind, solar or hybrid. Pumps can be classified into two (Yu, 2017) based on their operating principle and these are: Dynamic pumps or Rotodynamic pumps: These add energy continuously to the fluid to increase the fluid velocities within the machine to values that are greater than those occurring at the discharge such that the subsequent velocity reduction within or beyond the pump produces a pressure increase (Yu, 2017). These pumps increase fluid velocity and convert this kinetic (centrifugal) energy to pressure. Displacement pumps or positive displacement: These pumps add energy periodically by application of force to one more movable boundaries of desired number of enclosed fluid-containing volumes, resulting in a direct increase in pressure up to the value required to move the fluid through values or ports into the discharge line (Wilox,2000; Yu, 2017). Axial flow pumps belong to the subcategory of dynamic or rotodynamic pumps.

Axial flow pumps are pumps generate flow in axial direction and are used to lift large flow rates through a small pressure difference that is, axial flow pumps are designed to operate at low lift with high capacity delivery. The use of axial flow pump is not limited to lifting of water but also to circulate fluids in power plants, sewage digester and evaporators. The materials that are used in constructing axial flow pumps include Cast iron, ductile iron, stainless steel, etc. Unpredictable weather condition, in which rain fall is a major factor, has been a major challenge faced by farmers in Nigeria. There have been diverse methods of artificially supplementing the annual rain fall through different irrigation methods or technologies. One of these include the use of different types of pumps to supply water to the farm. Most irrigation pumps used in Nigeria are imported. Consequently, the challenges farmers faced in using these pumps include priming before operation, relatively low-capacity delivery at low head, and high operation cost which is often time not affordable by peasant farmers. The objective of this study was to develop an axial flow pump for irrigation and evaluate the performance of the developed pump.

2. Materials and methods

2.1. Pump Design

The design of the axial pump for the study was adopted from an existing and functioning axial pumping machine, developed by Agricultural Machinery and Mechatronics Department, Kasetsart University, Thailand. The pump was developed in the country in 2014. The materials used in the development of the pump were replaced using galvanized steel which was locally available in Nigeria and this proved to be very effective.

2.2. Preliminary design parameters

Kathivel *et al*. (2000) and Krupnik *et al*. (2013) in separate researches discovered that the minimum discharge of an axial flow was at 3.0 m head and further increase in head will lead to decrease in discharge. Moreover, Krupnik *et al*. (2013) reported and recommended, axial flow pumps with diameter range of 146 -152 mm with pumps length ranging from 3.7 to 6.7m discharged between 42 and 68l/s (0.042 and 0.068 m^3/s) with pump speed ranging from 1,910 to 2,572 rpm which also corresponded with the reports of Abann and IRR (1985). Pauck and Cho (2018) selected 0.85 as the overall pump efficiency in their design of an axial flow pump.

2.3. Design calculations

2.3.1. Water horse power:

This is the power transferred to water per unit time (in Kilowatt) expressed as (Pauck and Cho, 2018):

$$\text{WHP} = \rho g Q h \qquad (1)$$

Where,

g= acceleration due to gravity, (9.81m/s^2)

Q= discharge (m^3/s,)

h=head (m).

2.3.2. The brake horse power

This is also called the input power deliver by motor and is expressed as (Pauck and Cho,2018):

$$BHP=\frac{WHP}{\eta} \qquad (2)$$

Where,

BHP= Brake horse power (hp), η= Pump efficiency.

2.3.3. Shaft diameter

The hollow shaft diameter of a solid shaft was obtained from the expression (Recam, et al, 2019)

$$\tau= 16T/ \pi\, d_o^3\,(1-k^4) \qquad (3)$$

Where,

d_o= Outside diameter of the shaft (mm)

d_i= inner diameter

T=Torsional moment (Nm)

π=3.142

k= d_i /d_o (ratio of inner to outside diameter)

τ= Allowable shear stress of shaft material.

$$T=\frac{60BHP}{\pi\,\tau} \qquad (4)$$

Where,

T=Torsional moment (Nm)

BHP= Break Horse Power.

The maximum shear stress for mild steel is 240 Mpa (Gope, 2012)

2.3.4. Power Transmission (Belt and Pulley)

Pulley diameter

From the equation,

$$N2\backslash N1 = D1/D2 \qquad (5)$$

(Gupta and Khurmi,2005)

Where,

N1= the machine speed

N2= the pump speed

D1= diameter of pulley on the prime mover

D2= diameter of pulley on the pump

2.3.5. Belt Selection

Because of the amount of power to be transmitted,(3kw) select type A V-Belt.

Belt length (L)=$\pi\ (r1 + r2) + 2x + (r1 + r2)\quad ^2/x$ (6)

(Gupta and Khurmi,2005)

Where,

r_1= radius of the driver pulley, r_2= radius of driven pulley, x= the center to center distance of the pulley.

2.3.6. Determination of impeller hub ratio and blade number

The ratio of impeller hub diameter to outside diameter (D_d), D_h/D_o was determined based on the specific speed. Therefore, the impeller hub ratio is expressed as (Pauck and Cho, 2018):

$D_d = 26.8\ \times\ (Ns)^{-0.603}$ (7)

$D_d = 26.8 \times (478.96)^{-0.603}$

$= 0.65$

For the calculated value of the specific speed 478.96 rpm the hub ratio, $D_{d,}$ is 0.65

The Table 3.1 presents the relationship between the specific speed versus the impeller ratio and number of blades (Pauck and Cho,2018).

Table 1 Specific Speed versus the Impeller Ratio and Number of Blades

Specific Speed (rpm)	**400**	**600**	**800**	**100**	**1200**
Impeller hub ratio	0.6	0.55	0.5	0.45	0.4
Number of blades	6	5	4	3	2

Source: Pauck and Cho (2018)

From the table above, 6 numbers of blade were selected based on rotational speed and the hub ratio.

2.4. Performance Evaluation of the Developed Pump

The key performance parameters (Water discharge, Hydraulic Power, Fuel efficiency and water delivery) were evaluated at three varying heads of 1.0, 2.0 and 3.0 m at three varying pump speeds of 1,000, 1500 and 2000 rpm in six replications,. In each treatment, volume of fuel consumed, volume of water discharged and time taken were measured and recorded.

2.5. Experimental design and layout

The two blocking factors were the depth of water and speed of the pump. These were independent factors. The experimental is 3 x 3 factorial design. That is, three different pump speeds of 1000, 1500 and 2000 rpm for each water depth of 1, 2 and 3 m were replicated six times. This was laid in a completely randomized design (CRD). The treatment combinations and their definition are as presented in Table 3.2 while the statistical analysis software (SAS) application was used to analyze the data obtained.

2.6. Statistical Analysis

Tables 2 to 8 showed the effects some pump operations on the indicators, which include fuel consumption, pump discharge, water horse power, System Fuel Efficiency and water delivery

3. Results and Discussion

3.1. Hydraulic Performance

The hydraulic performances of the developed axial flow pump were evaluated using indicators, which are: the quantity of fuel consumption in a given time, discharge, Water Horse Power and water delivery. The results showed an inverse relationship between discharge and delivery head. The maximum water discharge of 162 m^3/h (45 l/s) was at 1m using a speed of 2000 rpm with water to fuel delivery of 119.57m^3/L. And the least water discharge of 59.30 m^3/h (28 l/s) and water delivery per fuel was 41.0m^3/L at 3 m head at 1000 rpm. Also, Santos et al., (2014) discovered the same trend. The hydraulic performance of Axial flow pump was found to be higher at low lifts (i.e., 1m to 2m), although it dropped significantly as head increases. This indicates that the hydraulic efficiency of the developed pump is higher at lower heads. This might be due to high energy dissipation at higher lifts, which can increase the fuel consumption (fuel efficiency) and reduce the water delivery rate.

3.2. Effects of pump speed (rpm) and water head (m) on fuel consumption (l/h)

Tables 2 and 3 present the results of effects of speeds (rpm) and heads (m) on fuel consumption (l/h) of the developed pump. The fuel consumption increased with increase in head (from 1m to 3m) and also increase in speed (Figure 4.1). The highest fuel consumption was at 3m at 2000rpm while the least fuel consumption was at 1m head and at 1000rpm. Because at higher heads more power will be required to pump water which in turn translate to more fuel consumption and this was also observed by Santos et al. (2014).There was a significant interaction between pump speed and water head (Table 4.2), using speed at 1000 rpm and increase water head from 1-3m significantly increase fuel consumption of the machine. A similar trend was also observed when the speed of 1500 and 2000 rpm were held constant. At different levels of water heads while increasing the pump speed significantly increased fuel consumption.

Table 2 Effect of Speed and Head on Fuel consumption of developed Axial pump

Treatment	Fuel Consumption (l/h)
Speed (rpm) S	
1000	1.41c
1500	1.42b
2000	1.45a
SE±	0.002
Head (m) H	
1	1.36c
2	1.45b
3	1.47a
SE±	0.002
Interaction	
S*H	**

Means followed by same letter(s) are not different statistically at *P=0.05* level of probability using DMRT**= F-value significant at ($P \leq 0.01$)

Table 3 Interaction of speed and head on fuel consumption of developed axial pump

Treatment	Head (m)		
Speed(rpm)	1	2	3
1000	1.34g	1.42d	1.46c
1500	1.35f	1.46c	1.47b
2000	1.40e	1.47b	1.48a
SE±	0.004		

Means followed by same letter(s) within same column and row are not different statistically at *P=0.05* level of probability using DMRT.

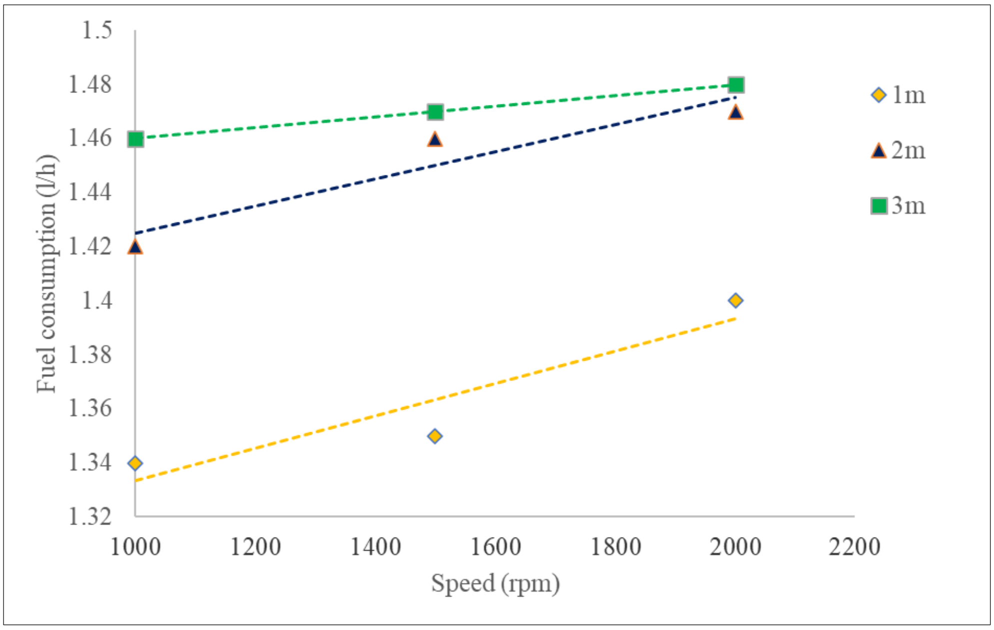

Figure 1 Regression of fuel consumption against speed of axial pump at various head.

Regression equations

At 1m

y=1.2733+6E-05x
R^2 = 0.871

At 2m

y=1.375+5E-05x
R^2 = 0.892

At 3m

y=1.44+2E-05x
R^2 = 0.997

3.3. Effects of pump speeds (rpm) and heads (m) on pump discharge (m^3/h)

Tables 4 and 5 present the results of effects of speeds (rpm) and heads (m) on pump discharge (m^3/h) of the developed pump. The discharge increases with speed of rotation and decreased with increase in head as also shown in Figure 2. The maximum discharge was observed at 1m head and 2000rpm while the least discharge was observed at 1000rpm at 3m head. This indicates that the hydraulic efficiency of the developed pump is higher at lower heads. This might be due to high energy dissipation at higher lifts, which can increase the fuel consumption (fuel efficiency) and reduce the water delivery rate.

There was a significant interaction between pump speed and pump discharge (Table 4). using speed at 1000 rpm and increase water head from 1-3m significantly decrease in discharge of the machine. A similar trend was also observed when the speed of 1500 and 2000 rpm were held constant. At different levels of water heads while increasing the pump speed significantly increased water discharge.

Table 4 Effect of Speed and Head on Pump Discharge of developed Axial pump

Treatment	Pump Discharge (m^3/h)
Speed (rpm) S	
1000	78.2c
1500	110.9b
2000	134.6a
SE±	0.422
Head (m) H	
1	131.2a
2	109.5b
3	83.0c
SE±	0.422
Interaction	
S*H	**

Means followed by same letter(s) are not different statistically at *P=0.05* level of probability using DMRT; **= F-value significant at (P≤0.01)

Table 5 Interaction of speed and head on pump discharge of developed axial pump

Treatment	Head (m)		
Speed(rpm)	1	2	3
1000	96.5f	78.5h	59.5i
1500	133.5c	115.0d	84.3g
2000	163.5a	135.0b	105.3e
SE±	0.731		

Means followed by same letter(s) within same column and row are not different statistically at *P=0.05* level of probability using DMRT.

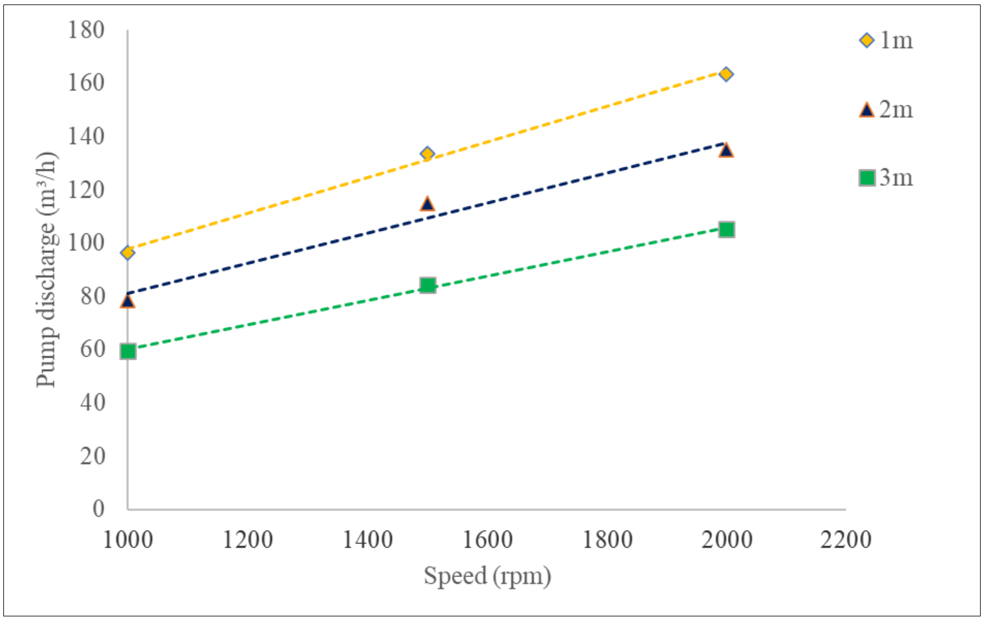

Figure 2 Regression of pump discharge against speed of axial pump at various head.

Regression equations

At 1m

$y=30.667+0.067x$
$R^2 = 0.996$

At 2m

$y=24.75+0.0565x$
$R^2 = 0.972$

At 3m

$y=14.333+0.0458x$
$R^2 = 0.997$

3.4. Effects of pump speeds (rpm) and heads (m) on water horsepower (W)

Table 5 Effect of Speed and Head on Water Horse Power of developed Axial pump

Treatment	**Water Horse Power (W)**
Speed (rpm) S	
1000	338.7c
1500	476.6b
2000	574.8a
SE±	0.450
Head (m) H	
1	360.3c
2	589.3a
3	440.7b
SE±	0.450
Interaction	
S*H	**

Means followed by same letter(s) are not different statistically at *P=0.05* level of probability using DMRT; **= F-value significant at ($P \leq 0.01$)

Table 6 Interaction of speed and head on water horse power of developed axial pump

Treatment	**Head (m)**		
Speed(rpm)	1	2	3
1000	262.7i	430.1f	323.5h
1500	376.4g	601.8b	451.8d
2000	441.8e	736.0a	546.8c
SE±	0.779		

Means followed by same letter(s) within same column and row are not different statistically at *P=0.05* level of probability using DMRT.

Tables 5 and 6 present the results of effects of speeds (rpm) and heads (m) on water horsepower (W) of the developed pump. The Water Horsepower increased with increase in speed and head (from 1-2m) while a decrease was observed at 3m head (Figure 3). Further increase in head will lead to further decrease in water horse power. The highest water horse power was at 2m head with 2000rpm while the least was at 1m head at 1000rpm. There was a significant interaction between pump speed and water horsepower (Table 5) using speed at 1000 rpm and increase water head from 1-2m significantly increase the water horsepower. However a decrease in water horse power was observed at 3m head. At different levels of water heads while increasing the pump speed significantly increased water horsepower.

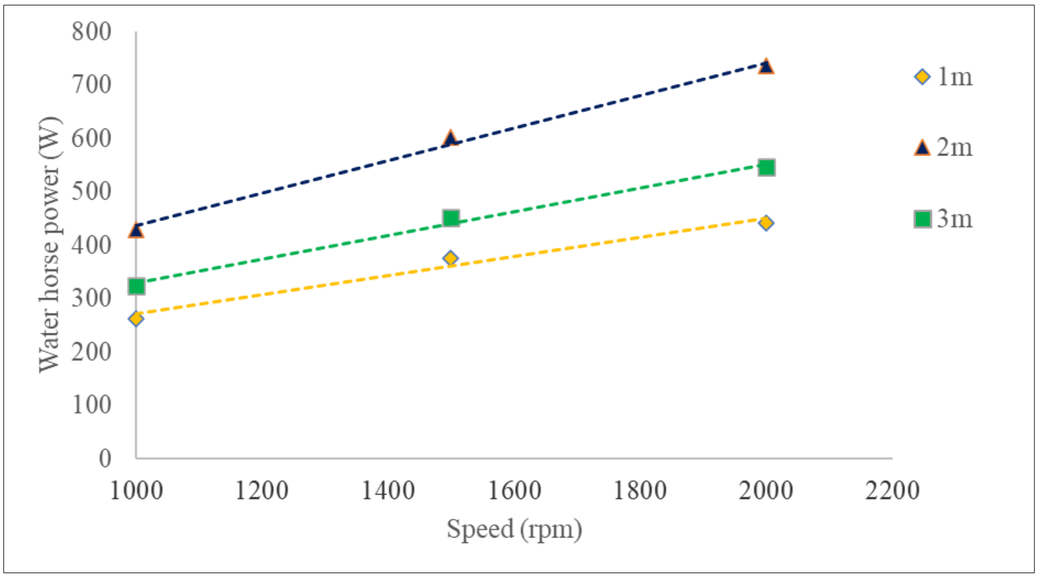

Figure 3 Regression of water horse power against speed of axial pump at various head.

Regression equations

At 1m

y=91.65+0.1791x
$R^2 = 0.976$

At 2m

y=130.45+0.3059x
$R^2 = 0.995$

At 3m

y=105.75+0.2233x
$R^2 = 0.992$

3.5. Effects of pump speeds (rpm) and heads (m) on System Fuel Efficiency

Table 7 and Table 8 present the results of effects of speeds (rpm) and heads (m) on system fuel efficiency (%) of the developed pump. The system fuel efficiency is higher at a lower head of 1m (Figure 4.4). However, the system fuel efficiency of this pump is generally low at higher speeds irrespective of the heads. This was due to high energy dissipation at higher lifts, which will increase the fuel consumption and reduce the water delivery rate.

There was a significant interaction between pump speed and water head (Table 4.4) using speed at 1000 rpm and increase water head from 1-3m significantly decrease in system fuel efficiency. A similar trend was also observed when the speed of 1500 and 2000 rpm were held constant. At different levels of water heads while increasing the pump speed significantly decrease in system fuel efficiency.

Table 7 Effect of Speed and Head on System Fuel Efficiency of developed Axial pump

Treatment	**System Fuel Efficiency (%)**
Speed (rpm) S	
1000	58.3b
1500	59.8a
2000	58.3b
SE±	0.405
Head (m) H	
1	59.1
2	58.6
3	58.8
SE±	0.405
Interaction	
S*H	NS

Means followed by same letter(s) are not different statistically at *P=0.05* level of probability using DMRT; NS = F-value not significant

Table 8 Interaction of speed and head on water delivery of developed axial pump

Treatment	**Head (m)**		
Speed(rpm)	1	2	3
1000	72.4e	55.2h	40.9i
1500	98.9b	77.0d	57.5g
2000	116.8a	92.3c	71.4f
SE±	0.407		

Means followed by same letter(s) within same column and row are not different statistically at *P=0.05* level of probability using DMRT.

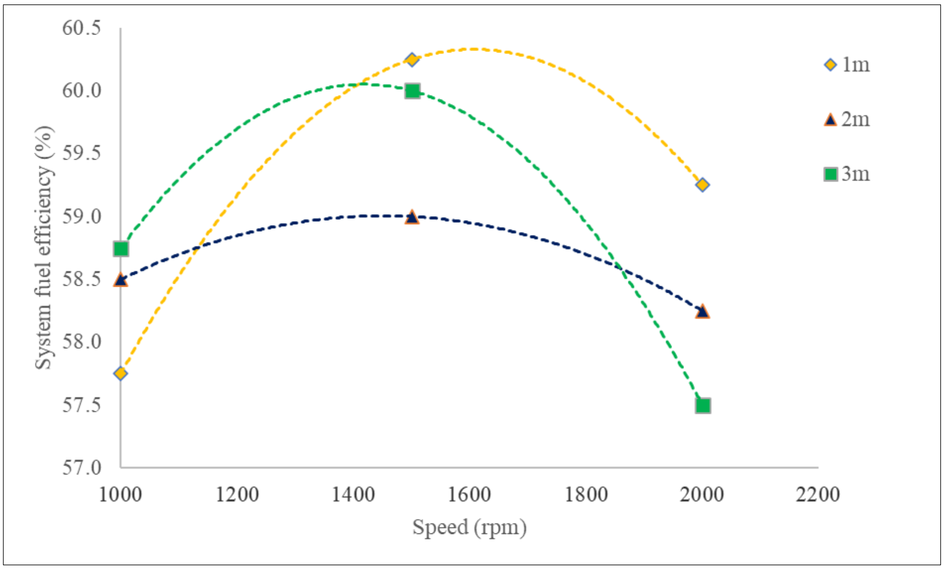

Figure 4 Regression of system fuel efficiency against speed of axial pump at various head

Regression equations

At 1m

$y=2.25+0.0225x-7E\text{-}06x^2$
$R^2 = 0.997$

At 2m

$y=53.75+0.0072x-2E\text{-}06x^2$
$R^2 = 0.998$

At 3m

$y=45+0.0212x-7E\text{-}06x^2$
$R^2 = 0.995$.

The quadratic equation implies that at a particular point if the speed is increased the fuel efficiency will drop. From the graph it indicates that the fuel efficiency will start dropping after 1500rpm. It implies that more fuel was used and less watery delivery was obtained. This was due to high energy dissipation at higher lifts, which will increase the fuel consumption and reduce the water delivery rate. This was also observed by Santos et al. (2014).

3.6. Effects of Pump speeds (rpm) and heads (m) on water delivery (m^3/l)

Tables 9 presents the results of effects of speeds (rpm) and heads (m) on water delivery (m^3/l) of the developed pump. The water delivery decreased with increase in head but increased with increase in speed (Figure 5). The highest water delivery was at 1m head at 2000rpm and the least water delivery was at 3m with 1000rpm.There was a significant interaction between pump speed and water delivery (Table 9) using speed at 1000 rpm and increase water head from 1-3m significantly decrease the water delivery. A similar trend was also observed when the speed of 1500 and 2000 rpm were held constant. At different levels of water heads while increasing the pump speed significantly increased in water delivery.

Table 9 Effect of Speed and Head on Water Delivery of developed Axial pump

Treatment	**Water Delivery (m^3/l)**
Speed (rpm) S	
1000	56.2c
1500	77.8b
2000	93.5a
SE±	0.235
Head (m) H	
1	96.0a
2	74.8b
3	56.6c
SE±	0.235
Interaction	
S*H	**

Means followed by same letter(s) are not different statistically at *P=0.05* level of probability using DMRT **= F-value significant at (P≤0.01).

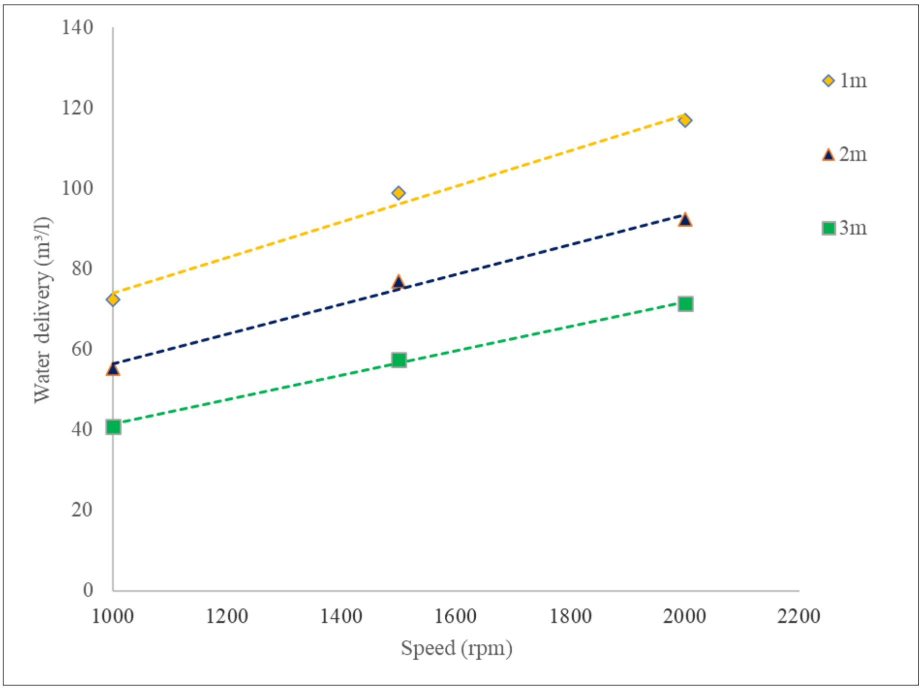

Figure 5 Regression of water delivery against speed of axial pump at various head.

Regression equations

At 1m

$y=29.433+0.0444x$
$R^2 = 0.987$

At 2m

$y=19.183+0.0371x$
$R^2 = 0.989$

At 3m

$y=10.85+0.0305x$
$R^2 = 0.997$

Table 10 Correlation matrix of mechanical parameters of developed axial pump as affected by speed and head

Var	1	2	3	4	5
1	1.0000				
2	-0.2575NS	1.0000			
3	0.6467**	0.3968*	1.0000		
4	-0.0628NS	0.0999NS	-0.0852NS	1.0000	
5	-0.3776*	0.9903**	0.2841NS	0.1203NS	1.0000

1 = Fuel consumption 2 = Pump discharge 3 = Water horse power 4 = System fuel efficiency 5 = Water delivery NS = r-value not significant *= r-value significant at ($P\leq0.05$) **= r-value significant at ($P\leq0.01$) N = 36 Df = N-2 = 36-2 = 34

Table 11 Mechanical properties of the developed axial pump as affected by speed and head

Properties	Unit	No. of observation	Min. value	Max. value	Mean value	Coefficient of variation
Fuel consumption	l/h	36	1.33	1.49	1.43	0.035
Pump discharge	m^3/h	36	59.4	165.0	107.9	0.288
Water horse power	W	36	262.3	740.0	463.4	0.300
System fuel efficiency	%	36	56.0	61.0	58.8	0.025
Water delivery	m^3/l	36	40.8	117.9	75.8	0.299

4. Conclusion

The maximum water discharge of 162 m^3/h (45 l/s) was at 1m using a speed of 2000 rpm with water to fuel delivery of 119.57m^3/L. And the least water discharge of 59.30 m^3/h (28 l/s) and water delivery per fuel was 41.0m^3/L at 3 m head at 1000 rpm. The developed pump based on its capacity can be used to irrigate one hectare in one hour at 16.2 mm depth of water using 2000rpm at 1m head and 9.6 mm depth of water using 1000rpm at 3m head at a moisture content of 45% on a sand-loamy soil. Axial flow pump can achieve fuel savings as the system fuel efficiency is high relatively compared to centrifugal pump. The use of this technology, the axial flow pump, can be an effective tool to mitigate the increasing energy costs of irrigation and encourage the wise use of surface water irrigation for sustainable intensification at low depth.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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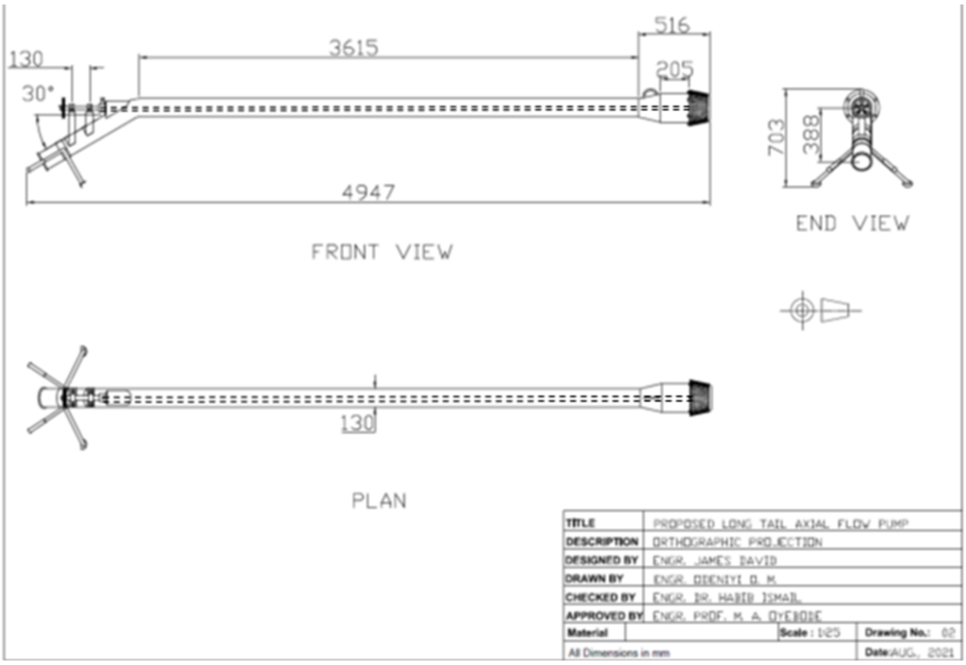
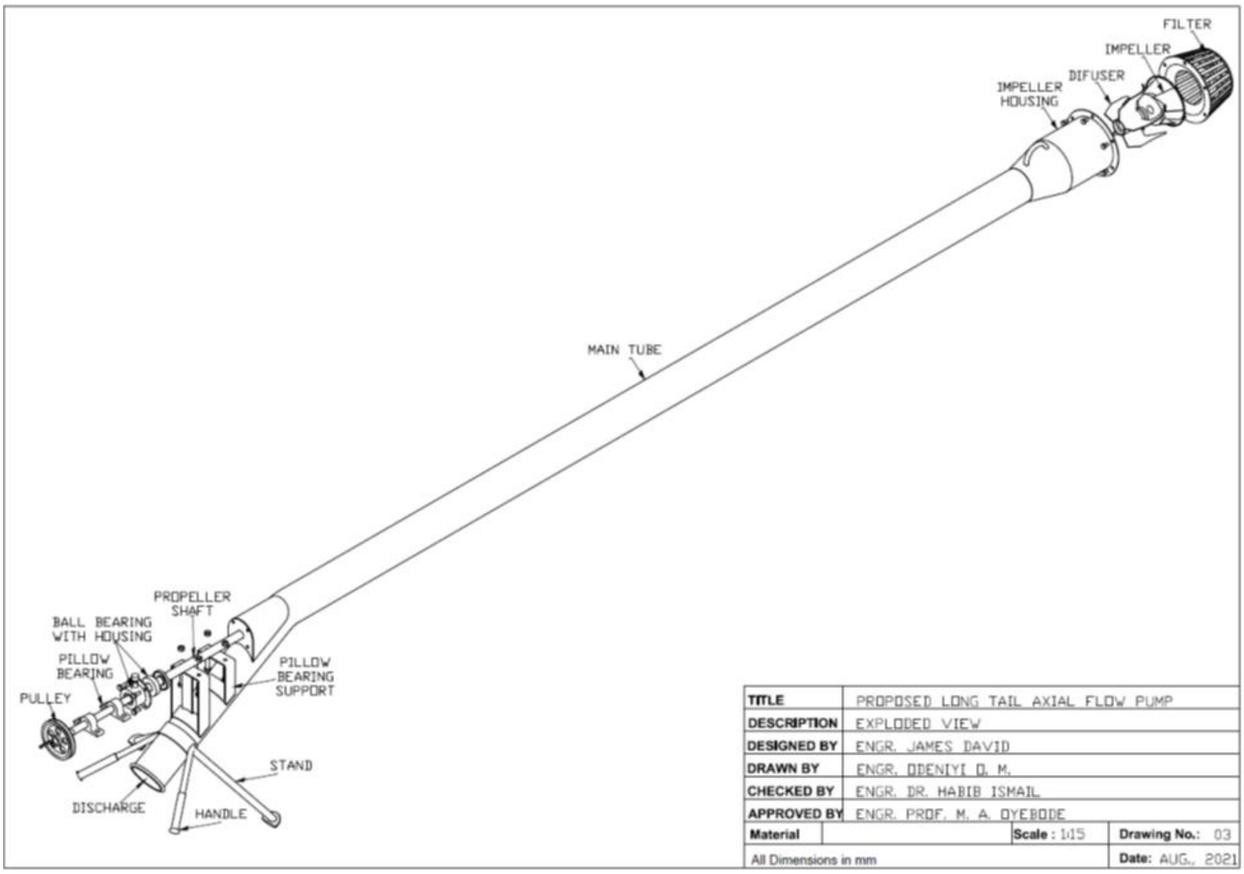
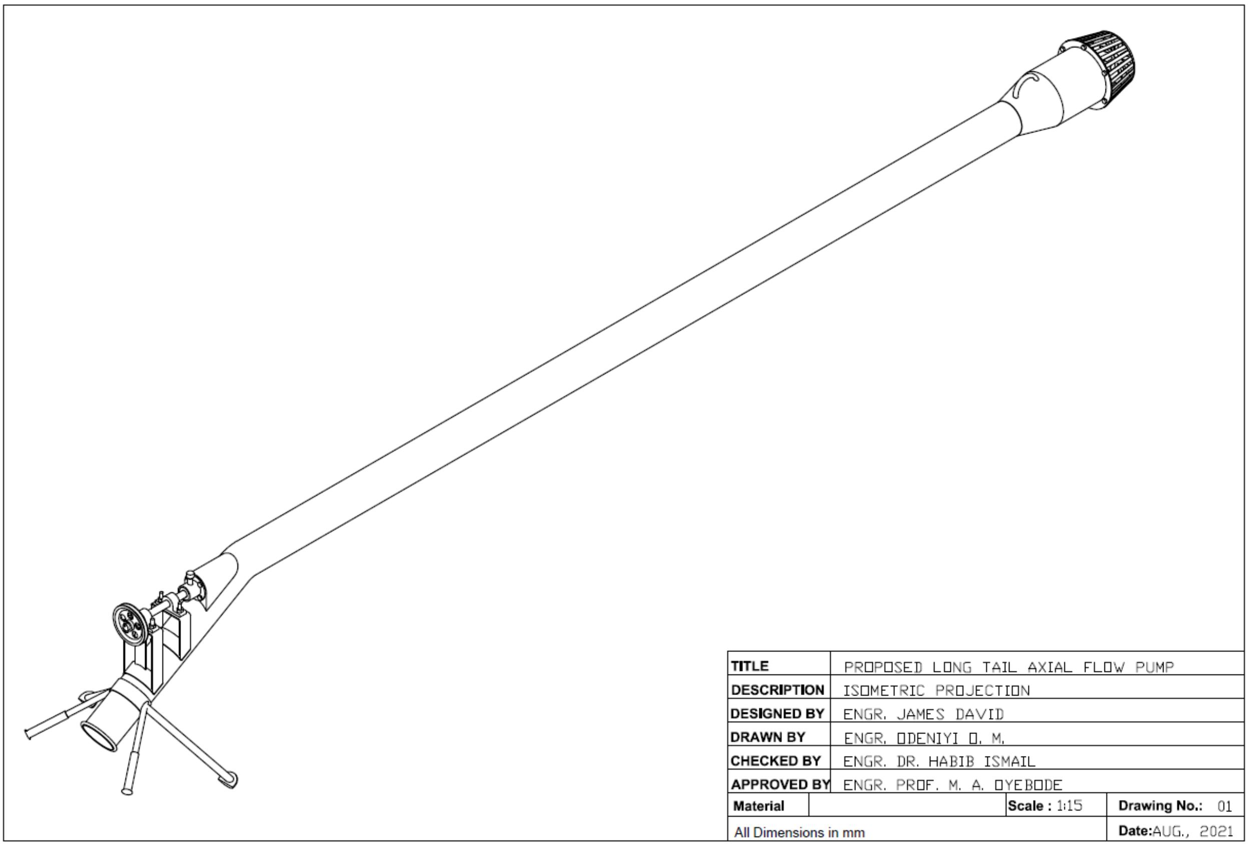
Appendix

Engineering Drawing. Below are the engineering drawings of the axial flow pump.






TITLE
PROPOSED LONG TAIL AXIAL FLOW PUMP
DESCRIPTION
ISOMETRIC PROJECTION
DESIGNED BY
ENGR. JAMES DAVID
DRAWN BY
ENGR. ODENIYI O. M.
CHECKED BY
ENGR. DR. HABIB ISMAIL
APPROVED BY
ENGR. PROF. M. A. OYEBODE
Material
Scale : 1:15
Drawing No.: 01
All Dimensions in mm
Date:AUG., 2021