

Development of a 3D-printed Archimedean screw turbine workflow for Pico hydropower generation at low water flow rate

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17.1 Introduction

In Sarawak, Malaysia, electricity shortage still happens in rural communities (around 20%) (Julai and Buswig, 2020), which causes the villagers to use fossil fuel-powered generators for electrification (Lee and Lee, 2021). Instead of using fossil fuel-powered generators, renewable energy technology should be adopted as it can assist in reducing pollution and improving environmental quality (Nguyen et al., 2023). In Malaysia, the potential renewable energy to be used is hydropower as it has lots of rivers, especially in Sarawak, where most of the rivers in Sarawak operate in low flow velocity (Lee and Lee, 2021). As reported by Lee and Lee (Lee and Lee, 2021), water flow rate below 100 L/min was defined as low water flow rate. Therefore Archimedean screw turbine (AST) would be one of the alternatives to develop a pico-hydro plant (generate power below 5 KW) as it has the capability to operate under low flow (YoosefDoost and Lubitz, 2020). Thus the objective of this work is to study the feasibility of small-scale AST to generate pico-hydropower energy.

17.2 Literature review

17.2.1 Archimedean screw turbine design

AST can be utilized as a pico-hydropower generator, which was able to generate power below 5 kW utilizing low head level (difference between upper water and lower water level elevation at less than 10 m) and low flow rate (below $10\text{m}^3/\text{s}$). However, the performance of the AST was influenced by its geometry (YoosefDoost and Lubitz, 2020) as shown in Fig. 17.1.

For AST designs, there is a variety of research work performed to study the performance of this turbine to harvest energy. Table 17.1 shows the summary of the AST research contributions.

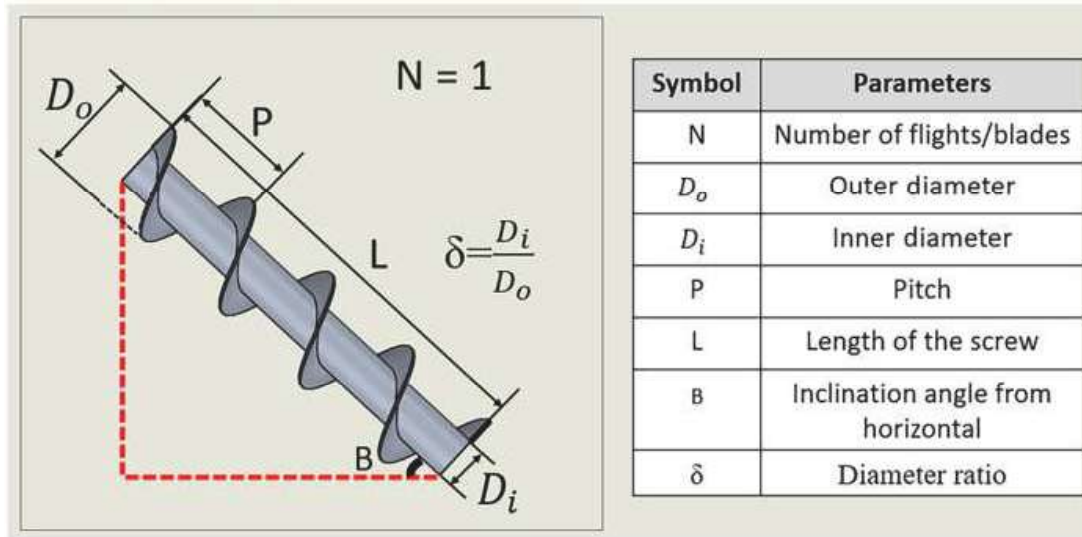


Figure 17.1 Archimedean screw turbine parameters.

17.2.2 Archimedean screw turbine fabrication methods for pico-hydro power generations

The complex geometry of AST makes fabrication difficult, which slows the adoption of this technology. Currently, the process to fabricate AST using steel (traditional manufacturing process) is complex and lengthy, as it involves a bending and welding process ([The 21st century Archimedes screw: New materials and manufacturing techniques enable the turbine's Highest-Ever Measured efficiency, n.d.](#)). Therefore the current method is not environmentally friendly as this process consumes lots of energy and has lower energy efficiency ([Yan et al., 2016](#)). Due to this, it encouraged researchers to explore different methods and materials to fabricate AST. Complex geometries are impossible or very difficult to produce using traditional manufacturing processes ([Karayel and Bozkurt, 2020](#)). Furthermore, the additive manufacturing process is environmentally friendly with low energy consumption ([Khosravani & Reinicke, 2020](#)) and less material waste generated ([Karayel and Bozkurt, 2020](#)). This process was also widely used in aerospace, automotive, and medical industries ([Karayel and Bozkurt, 2020](#)).

Generally, additive manufacturing is a process where the parts are created layer by layer deposition, which is digitally controlled. Additive manufacturing, also known as the 3D printing process or rapid prototyping process ([Karayel and Bozkurt, 2020](#)). In this manufacturing process, the common polymer materials used are polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) ([Islam et al., 2024](#)).

In AST fabrication, the 3D printing process was also used by other researchers to investigate their AST performance. As an example, [Lee et al., \(2015\)](#) utilized a 3D printing process to fabricate AST using PLA material to validate the geometry of controllable pitch AST. In conducting the experimental test, [Zitti et al., \(2019\)](#) also applied the 3D printing process in their work, and PLA was used to investigate the performance of their AST.

Table 17.1 Summary of the AST research contributions.

Reference	Main contributions	Fabrication technique
(Lee and Lee, 2021)	- Performed experimental test using 1 number of blades of AST with a fixed diameter ratio of 0.5 at a low flow rate from 0.3 to 1.7 L/s by varying the angle at high inclination angle from 30 to 90 degrees. 45 degree was an optimum inclination angle at all flow rates and generated the highest torque of 0.9 N.m at 100 L/min flow rate.	Lee and Lee do not discuss in detail the specific technique they used in fabricating their AST. However, they mentioned they used mild steel coated with paint material as their turbine.
(Erinofiardi et al., 2017).	- The conducted test used 1 blade of AST at a flow rate 1.2 L/s by varying inclination angle at 22, 30, and 40 degrees. 22 degree was an optimum inclination angle and generated the highest torque at 0.13 N.m.	Erinofiardi et al. discuss in detail the technique they used in fabricating their turbine. Generally, they used aluminium material to fabricate their blade screw and PVC Pipe as the shaft. Then, they assembled the PVC pipe and blade screw using glue.
(Syam et al., 2019).	- Conducted experimental test for AST at 30 degree inclination angle by varying flow rate at 3, 9, and 20 L/s using their AST with geometry of $N = 1$ and diameter ratio = 0.54. - Findings show that AST generated the highest torque of 4 N.m at 20 L/s.	Syam et al. do not discuss in detail the types of material and techniques they used to fabricate their AST. From their methodology process, it can be observed that they developed their turbine manually, as the turbine's pitch is not consistent.
(Maulana et al., 2019).	- Performed experimental test for AST at 30 degree inclination angle by varying flow rate at 4.4, 12.5, and 25 L/s using their AST with geometry of $N = 2$ and 0.54 diameter ratio. - Findings indicate that a high flow rate of 25 L/s generated the highest torque at 5 N.m.	Maulana et al. do not discuss in detail the specific technique they used in fabricating their AST. However, they mentioned they used stainless steel material for their turbine.

(Continued)

Table 17.1 (Continued)

Reference	Main contributions	Fabrication technique
(Nagel and Ohg, 1968)	In designing the Archimedean screw, he suggests that the dimension of the diameter ratio needs to be 0.45–0.55.	The Archimedean screw turbine is a recent technology. Currently, Nagel's research works are focusing on optimizing the Archimedean screw pump (ASP) design. However, the fundamental design of AST uses the design of ASP, but it is not necessary to use the optimum design of ASP will cause the turbine to operate optimally. This is because ASP and AST run in different mechanisms.
(Rahim et al., 2025a).	AST's optimum design was with three blades and an inclination angle of 38 degree to generate the highest torque at 0.046 Nm from a flow velocity of 0.6 m/s.	Abd Rahim, N.S. et al. mention that they utilized the Additive Manufacturing process (3D Printing) to fabricate their small-scale AST with a length of 350 mm.

From the above findings, the majority of the researchers focus on validating the geometry of the AST's model with PLA material. However, no further investigation on the strength of 3D printed AST to validate the feasibility of generating torque. Hence this work focuses on studying the strength and torque of 3D printed AST utilizing PETG material as a potential clean energy generation. Instead of using PLA material, PETG material was selected due to its water resistance characteristics (Nieto et al., 2021). Therefore the objective of this research is to develop a novel workflow to develop a 3D-printed AST utilizing a low water flow rate of a river in generating clean energy. The outcome of the research works by Rahim et al., (2024a) will be used as a benchmark to show the procedure required to develop a framework of 3D printed AST.

17.2.3 Effect of infill density on 3D-printed components' strength

The final products of 3D-printed parts not only depend on the material itself but are also influenced by the printing parameters (Mazlan et al., 2023). Infill density is defined as the percentage of volume inside the object that is filled by the extruded filament material. If there is no material filled within the inner volume, air will take this space. The value of infill density is in a range of 0%–100%. Zero percent infill

density represents that the inner volume is hollow, meanwhile the 100% infill density shows that the inner volume totally filled (Ambati and Ambatipudi, 2022).

Parameters of infill density mainly affect the mechanical properties of the 3D-printed products. Ambati and Ambatipudi (2022) also conduct a study on investigating the mechanical properties of PLA polymer by varying the infill pattern and infill density. 60%, 75% and 90% infill densities have been tested in this research work. The results show that an infill density of 90% has the highest strength. In accordance with a study conducted by Maszybrocka et al. (2022), the strength properties increased as the filling density increased. According to Farbman and McCoy (2016), filling density can be altered according to the intended use of the application of product.

In this work, infill density will be employed for PETG polymer in a range of 50%–80% with steps of 10% in order to investigate how this parameter affects the strength of AST.

17.2.4 Effect of printing speed on 3D-printed components' strength

Miazio (2019) has studied the strength of PLA polymer by varying the printing speed of the 3D printer. The speed varied from 20 to 100 mm/s. The research shows that increasing the printing speed will reduce the strength of samples. To print PLA polymer, a range of 50–80 mm/s is the best printing speed value as it indicates the strength of specimens remains at a constant level. The average breaking force for printing speeds of 50, 60, 70, and 80 mm/s are 0.56KN, 0.57KN, 0.55KN, and 0.55KN, respectively. Nevertheless, printing speeds that are above 80 mm/s show that the strength of the samples declines significantly.

Hsueh et al. (2021) has performed research on the effect of two different printing parameters, which are printing speed and printing temperature, on PLA polymer and PETG polymer. The printing speed for PLA polymer was varied from 35 mm/s to 45 mm/s, while for PETG polymer it was varied from 25 mm/s to 35 mm/s. The research indicates that the strength of PLA polymer is increasing with increasing printing speed, meanwhile for PETG polymer, it indicates vice versa.

Therefore in this work, printing speed will be employed for the PETG polymer in a range of 20–60 mm/s to investigate how printing speed will influence the strength of AST.

Overall, this work developed a 3D-printed AST workflow as a Pico Hydropower generation at low water flow rate, of between 6.7 L/min and 8.8 L/min. The novelty is in the workflow that utilizes PETG material to 3D print the AST.

17.3 Methodology

Overall methodology of this work is shown in Fig. 17.2.

From Fig. 17.2, AST development work was divided into two tests, which are the strength test and the AST experimental test. This research methodology started by investigating the strength of 3D printed material, and later, an AST experimental

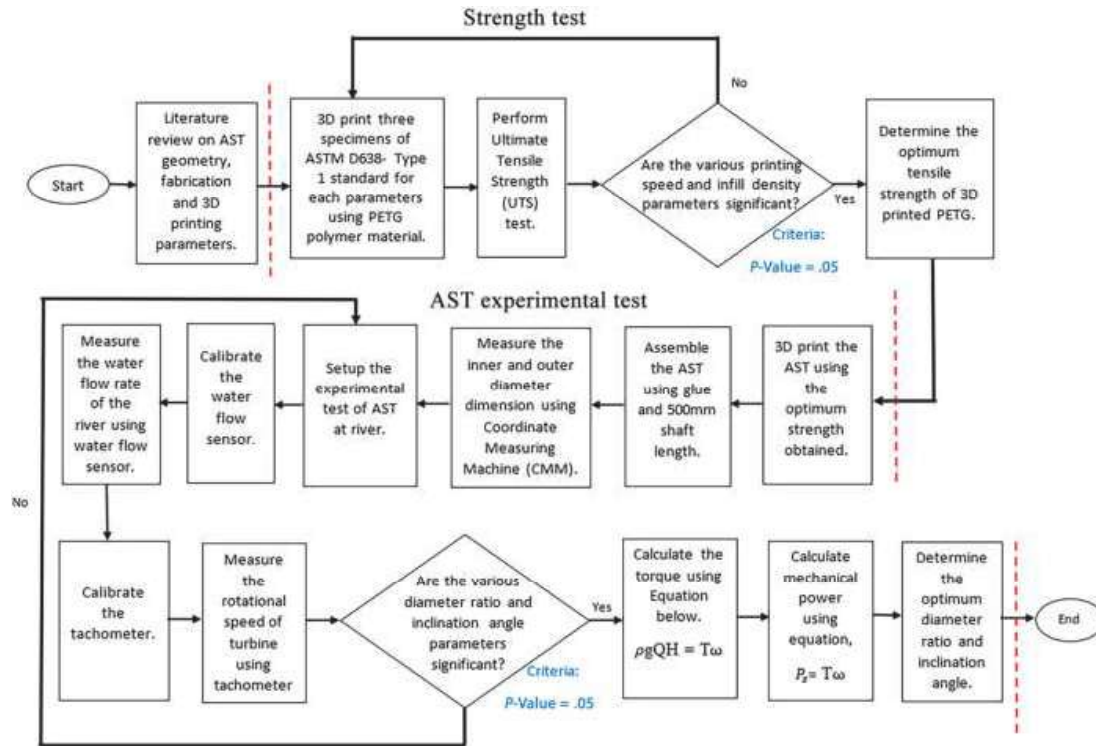


Figure 17.2 Flowchart for the development of a 3D-printed Archimedean screw turbine using PETG material.

test was carried out to investigate the feasibility of 3D printed AST in generating the torque output. Details of each test were discussed in Sections 3.1 and 3.2, respectively.

17.3.1 Strength test

Ultimate tensile strength (UTS) test was performed to study the mechanical strength of 3D printed PETG polymer. Details of the strength test for 3D-printed PETG were discussed in the section below.

17.3.1.1 Experimental setup for UTS test for 3D-printed PETG

UTS experimental test was carried out to investigate the mechanical strength of 3D-printed PETG. Draw the specimens for this test by following the ASTM D638- Type 1 standard design utilizing SolidWorks software. Then, the specimens were fabricated through a 3D printing process using different parameter settings. The parameter settings are Printing Speed (mm/s) with values of 20, 30, 40, 50, and 60, respectively, and Infill density (%) with values of 50, 60, 70, and 80, respectively. Three specimens were printed for each variable parameter. Ultimaker Cura 5.5.0 software was used to slice specimens according to the parameter settings as shown in Table 17.2.

Table 17.2 Printing parameters settings.

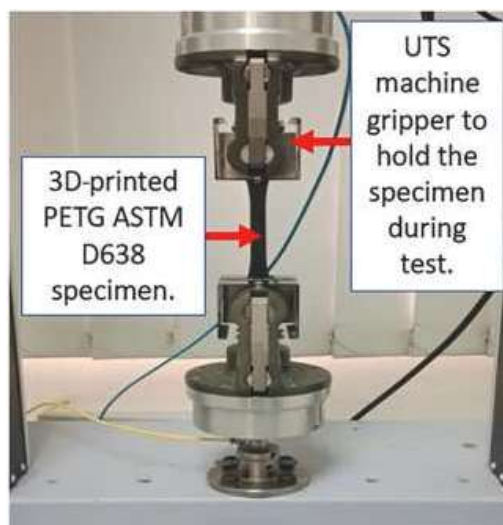
Parameters settings	Values
Nozzle temperature (°C)	240
Bed temperature (°C)	70
Infill density (%)	50, 60, 70, 80
Printing speed (mm/s)	20, 30, 40, 50, 60
Infill pattern	Cubic

Creality Ender Pro Max 3 printer, with 0.8 mm hardened steel nozzle, was used to print these specimens. PETG filament (manufactured by e-sun) with a diameter of 1.75 mm was used in this work. Next, the fabricated samples were used for the UTS test to investigate the effect of printing speed and infill density on tensile strength. Ultimate Tensile Machine was used to perform tensile strength on 3D-printed specimens as shown in Fig. 17.3.

Fig. 17.3 depicts the procedure for carrying out the UTS test, whereas the specimen has to be placed within the UTS machine gripper.

17.3.1.2 Data analysis using the two-factor analysis of variance and Tukey test for infill density and 3D printing speed parameters

To analyze the data obtained, two-factor analysis of variance (ANOVA) was performed using a confidence level = 95% to validate the significance of the output data, as there are two independent factors (infill density and printing speed

**Figure 17.3** Ultimate tensile test of ASTM D638 Type 1 for 3D-printed PETG.

parameters) in the experiment (Rahim et al., 2024b; Yang et al., 2021; Rahim et al., 2025b). The observed data were tabulated based on Table 17.3.

Then, after ANOVA was performed, a post-hoc test was performed to further investigate the interactions between the significant factors at a confidence level = 95%. The Tukey test was conducted in this experimental work using Minitab software.

17.3.1.3 Determine the optimum infill density and 3D printing speed parameters

From the data obtained through the UTS experimental test, it is important to determine which parameters need to be used to fabricate the AST. To develop the AST model, it is necessary to apply the optimum 3D printing parameters to fabricate the turbine to ensure the AST's strength is sufficient.

17.3.2 AST experimental test

AST experimental test was conducted to study the feasibility of 3D printed PETG to generate sufficient torque utilizing a low water flow rate at the Pusu River. Details of the work were discussed below.

17.3.2.1 Experimental setup for 3D-printed PETG Archimedean screw turbine test to obtain rotational speed of AST

Three different ASTs' diameter ratios were designed using Solidworks software, and later, the turbines were printed using the optimum 3D printing parameters obtained. Detailed parameters of the AST were shown in Fig. 17.4.

From Fig. 17.4, the details parameters of AST used in this experimental test. Three different AST parameters were designed each of which has different diameter ratio (0.36, 0.4, and 0.44). After the turbine was completely assembled, measurements of the inner diameter and outer diameter were taken using a Coordinate Measuring Machine (CMM) as shown in Fig. 17.5. In this work, it is necessary to take the dimensions of the inner diameter and outer diameter, as these dimensions are related to the diameter ratio. Besides, in the 3D printing process, it is expected that the design dimension will have a slight difference with the fabrication dimension due to the shrinkage (Hanon et al., 2021).

Table 17.4 discussed the summary of the inner diameter and outer diameter measurements obtained through CMM.

Fig. 17.5 shows the process to measure the dimension of inner diameter and outer diameter using CMM, while Table 17.4 indicates the summary of measurement results for inner diameter and outer diameter. From the measurement obtained, it shows there is slight difference in dimensions of the inner diameter and outer diameter between the drawing and the physical 3D-printed screw turbine. For inner diameter, the percentage difference between dimensions of design and the physical 3D-printed screws' dimensions for the diameter ratios of 0.36, 0.40, and 0.44 3D-printed screws is 0.43%, 0.30%, and 0.01%, respectively. Next, for outer diameter, the percentage difference between drawing and physical 3D-printed screws

Table 17.3 Data for a two-factor experimental design for the ultimate tensile strength (UTS) test.

Infill density (Factor A)	Printing speed (Factor B)				
	20 rpm	30 rpm	40 rpm	50 rpm	60 rpm
50%	$y_{111}, \dots, y_{11n}$	$y_{121}, \dots, y_{12n}$	$y_{131}, \dots, y_{13n}$	$y_{141}, \dots, y_{14n}$	$y_{151}, \dots, y_{15n}$
60%	$y_{211}, \dots, y_{21n}$	$y_{221}, \dots, y_{22n}$	$y_{231}, \dots, y_{23n}$	$y_{241}, \dots, y_{24n}$	$y_{251}, \dots, y_{25n}$
70%	$y_{311}, \dots, y_{31n}$	$y_{321}, \dots, y_{32n}$	$y_{331}, \dots, y_{33n}$	$y_{341}, \dots, y_{34n}$	$y_{351}, \dots, y_{35n}$
80%	$y_{411}, \dots, y_{41n}$	$y_{421}, \dots, y_{42n}$	$y_{431}, \dots, y_{43n}$	$y_{441}, \dots, y_{44n}$	$y_{451}, \dots, y_{45n}$

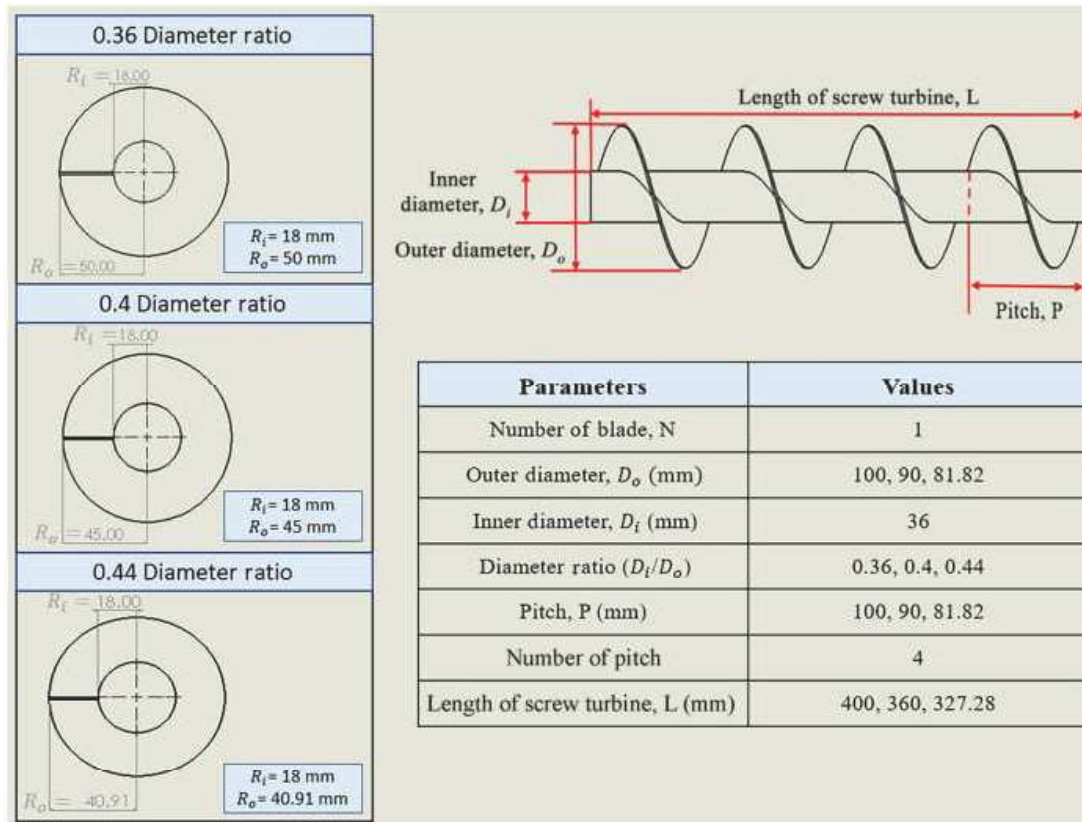


Figure 17.4 Design parameters of Archimedean screw turbine (AST) for 0.36, 0.4, and 0.44 diameter ratio.

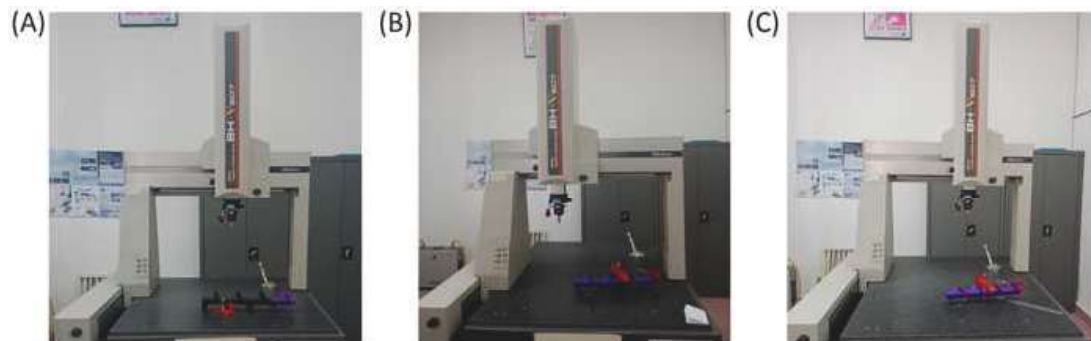


Figure 17.5 Inner and outer diameter measurement using Coordinate Measuring Machine (CMM) for screw turbines with diameter ratios of (A) 0.36, (B) 0.40, and (C) 0.44.

dimension for the diameter ratios of 0.36, 0.40, and 0.44 3D-printed screws is 0.62%, 2.02%, and 2.09%, respectively. Based on research findings, for dimensional accuracy for 3D printed parts, there is no standard range of tolerance for the dimensions of the 3D printed parts as the accuracy of the products depends on the machine process parameters (Hanon et al., 2021). It can be stated that the

Table 17.4 Summary results for the measurement of inner diameter and outer diameter utilizing Coordinate Measuring Machine (CMM).

Design of diameter ratio	Design of inner diameter dimension, D_{id} (mm)	Measured inner diameter dimension, D_{im} (mm)	Percentage error (%) error = $\frac{ D_{id} - D_{im} }{D_{id}} \times 100\%$	Design of outer diameter dimension, D_{od} (mm)	Measured outer diameter dimension, D_{om} (mm)	Percentage error (%) error = $\frac{ D_{od} - D_{om} }{D_{od}} \times 100\%$
0.36	36	35.8436	0.43	100	99.3789	0.62
0.4	36	35.8906	0.30	90	88.1804	2.02
0.44	36	36.0025	0.01	81.82	80.1093	2.09

percentage error for the dimension of AST for this work is small, as [Hanon et al. \(2021\)](#) has obtained a greater dimension error in their work, which was up to 8.25%. Therefore the error is negligible as it will not affect the performance of the turbine in generating the torque output. Later, the screw turbines were assembled with a 500 mm shaft length. Next, to conduct the AST's experimental test, the location of the experimental area was selected as shown in [Fig. 17.6](#). In this work, Pusu River was selected to carry out the AST experimental test, as currently, this river is facing sand sediment issues, which cause the depth of the river to be shallow ([Razali and Ayob, 2022](#)). Due to this issue, the flow rate of rivers is also being affected, which leads to low water flow rates of the river.

Next, before the rotational speed of the turbine data can be taken, the water flow rate of the river need to be measured. Thus, the further step was measuring the water flow rate of the river using a water flow sensor. However, before the water flow sensor was being used to measure the water flow rate of river, calibrate the water flow sensor as depicted in [Fig. 17.7](#).

After the water flow sensor calibration experimental setup was developed, as illustrated in [Fig. 17.7](#), prepare the stopwatch, weighing scales, and water jug before running this process. Then, place the water jug beside the water flow sensor. Next, start this work by turning on the water pump. At the same time, record the time needed by the water flow sensor to obtain a stable reading of the water flow rate using a stopwatch. When the water flow rate achieved a consistent reading, stop filling the water within the water jug and stop recording the time needed to fill the water in the water jug simultaneously. Next, measure the volume of the water within the water jug using a weighing scale as shown in [Fig. 17.8](#).

Next, the theoretical water flow rate can be calculated by dividing the volume by the time. Theoretical water flow rate compared with the water flow rate shown from the water flow sensor. [Table 17.5](#) indicates the summary results for the measurement of water flow rates and volumes.



Figure 17.6 Location to conduct Archimedean screw turbine's (AST) experimental test. Note: Map lines delineate study areas and do not necessarily depict accepted national boundaries.

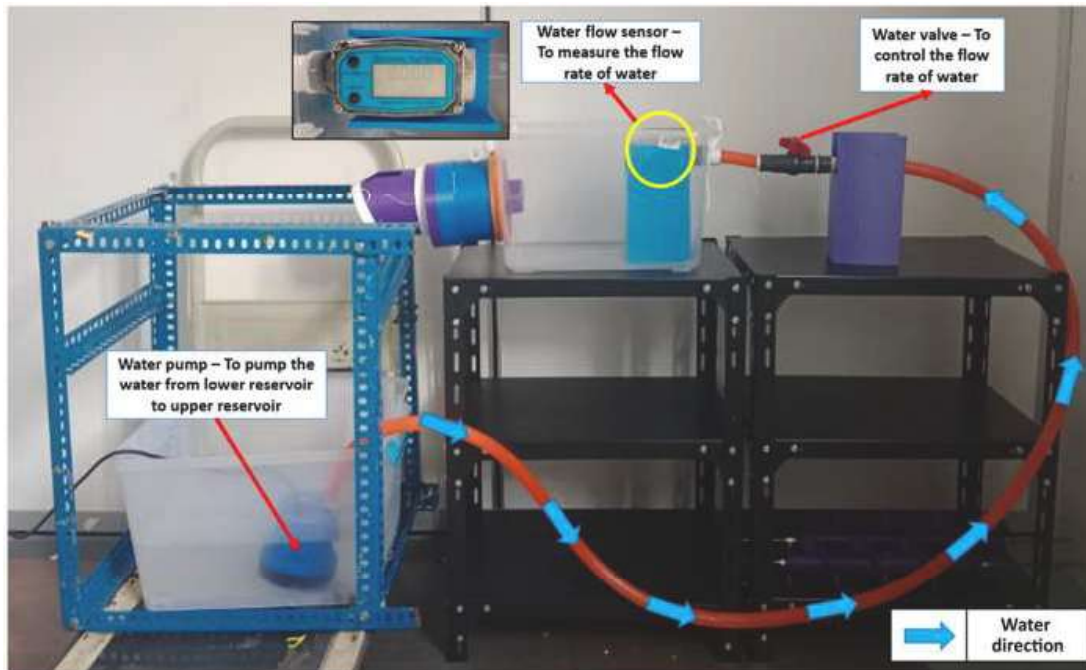


Figure 17.7 Experimental setup to calibrate the water flow sensor.

The results obtained through the calibration process, it shows that the water flow sensor used has an accuracy of 98.5%. After completing the process to calibrate the water flow sensor, measure the water flow rate of Pusu River as shown in Fig. 17.9.

Fig. 17.9A shows the process to measure the water flow rate of Pusu River using a water flow sensor, while Fig. 17.9B illustrates the result of the water flow rate of Pusu River obtained from the measurement process. From Fig. 17.9B, the results indicate that the water flow rate measurements of the Pusu River for Day 1, Day 2, and Day 3 were 8.8 L/min, 8.8 L/min, and 6.7 L/min, respectively. Through this water flow rate measurement, it can be stated that the Pusu River water flow rate has similarity with the Sarawak River, as both rivers have low water flow rates. Based on research work conducted by Lee and Lee, (2021), they tested their AST using a minimum water flow rate of the Sarawak River at 20 L/min. Since the water flow rate of the Pusu River is slightly lower than Sarawak River, it can be said that this AST model is feasible to be applied at the Sarawak River. After the flow of the water was measured, an experimental test was set up as shown in Fig. 17.10.

Fig. 17.10A illustrates the AST schematic setup to carry out the experimental test, while Fig. 17.10B shows the details parameters setup used to conduct the AST works. Then, for Fig. 17.10C, it illustrates the AST experimental setup conducted at an inclined angle, while Fig. 17.10D shows the experimental setup of AST at 0 degrees inclination angle. However, before the experimental test can be carried out, the tachometer must be calibrated as shown in Fig. 17.11.

In this calibration process, the stepper motor was being set to rotate at a known rotation speed. This rotation speed can be set and modified within the code. Table 17.6 indicates the summary results for the measurement of rotational speed by tachometer.



Figure 17.8 Mass of water and water jug in grams.

The results obtained through the calibration process, it shows that the tachometer used has an accuracy of 86.5%. After the tachometer is calibrated, the experimental test can be started by taking the rotational speed of the turbine. During the experimental test, 16 samples of AST's rotational speed data were collected. This data collection step was repeated for each turbine's diameter ratio (0.36, 0.40, & 0.44) to obtain the median of the rotational speed. To modify the inclination angle, adjust the iron angle bar position utilizing the Pythagorean theorem.

17.3.2.2 *Data analysis using the two-factor ANOVA and Tukey test for diameter ratio and inclination angle parameters*

To analyze the data obtained, two-factor ANOVA was performed using Minitab software using a confidence level = 95% to validate the significance of the output data. This test was conducted by investigating two factors, which were the diameter ratio and the inclination angle of AST. The collected data were tabulated in [Table 17.7](#).

Table 17.5 Summary results for measurements of flow rates and volumes.

Flow rate of water sensor, Q_{Ex} (L/Min)	Mass of water and water jug, $m_{WJ}(g)$	Mass of water jug, m_{Jug} (g)	Volume of water, V (L) $V=m_{WJ} - m_{Jug}$	Time taken, t (s)	Theoretical water flow rate, Q_{Cal} (L/Min) $Q_{Cal} = \frac{V}{t} \times \frac{60s}{1 min}$	Percentage error (%) $error = \frac{ Q_{Ex} - Q_{Cal} }{Q_{Ex}} \times 100\%$	Percentage accuracy (%)
5.1	439.5	91.8	0.3477	4	5.2155	2.2647	97.7
5.1	606.4	91.8	0.5146	6	5.1460	0.9020	99.1
5.1	522.9	91.8	0.4311	5	5.1732	1.4353	98.6
Average			0.4311	5	5.1782	1.5340	98.5

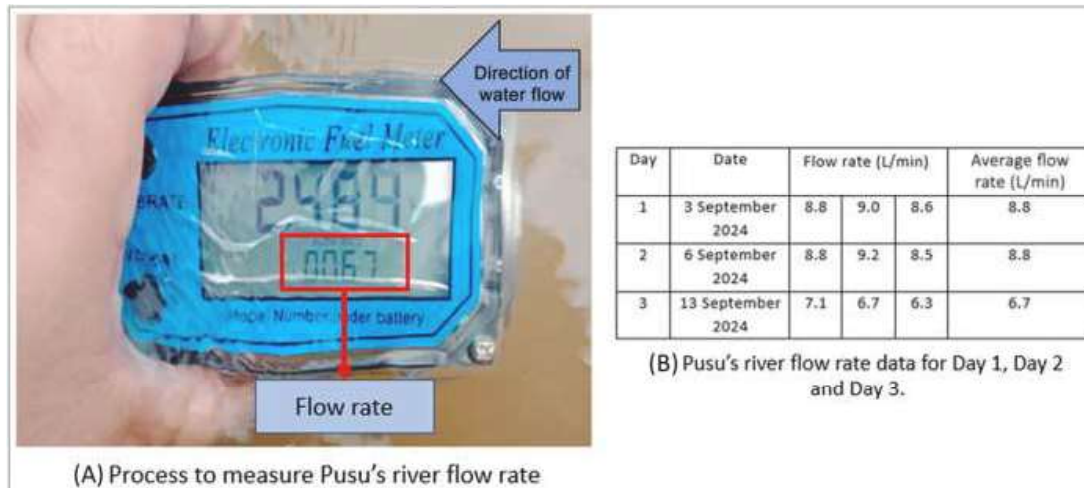


Figure 17.9 (A) Process to measure water flow rate of Pusu River using water flow sensor, and (B) water flow rate of Pusu's river data for Day 1, Day 2, and Day 3.

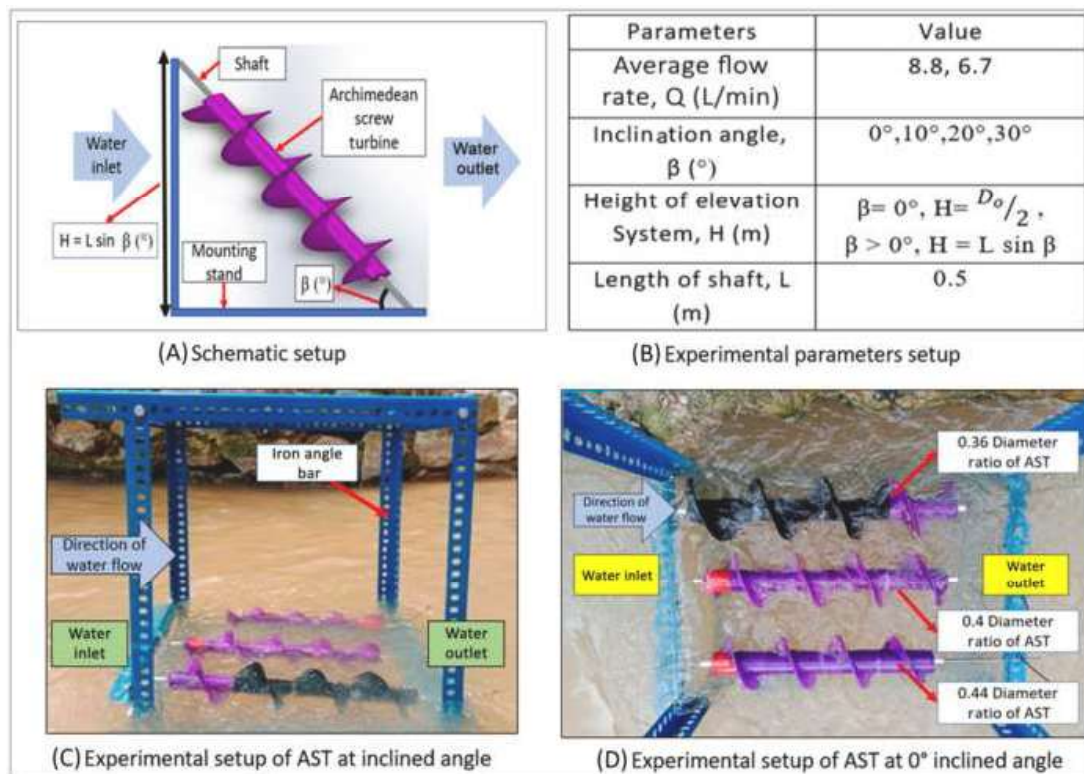


Figure 17.10 (a) Schematic setup for ast experimental test (b) AST parameters setup. (C) Experimental setup of AST at inclined angle (D) Experimental setup of AST at 0° inclination angle.

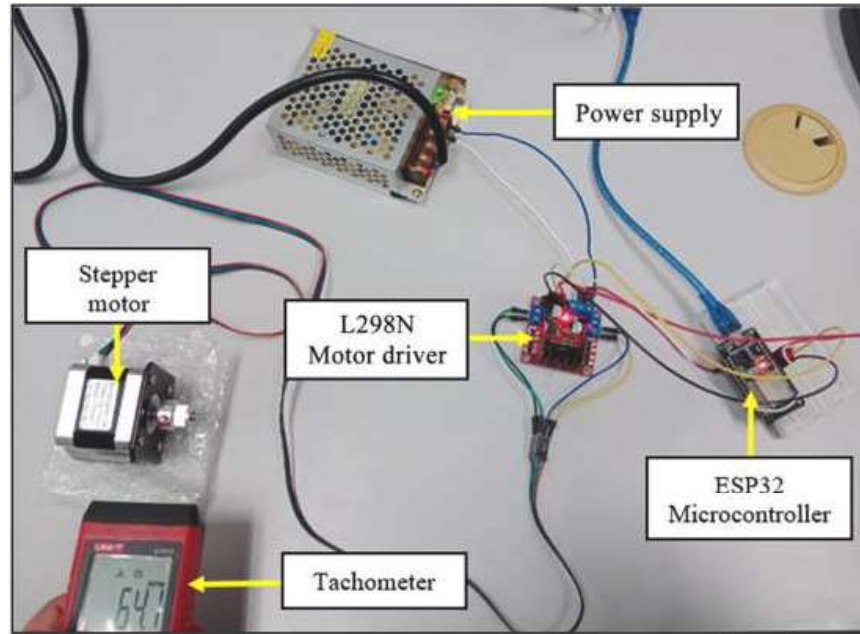


Figure 17.11 Stepper motor calibration experimental setup.

Table 17.6 Summary results for the measurement of rotational speed by the tachometer.

Motor's speed in code settings, RPM_M (RPM)	Tachometer measurement, RPM_T (RPM)	Percentage error (%) $error = \frac{ RPM_T - RPM_M }{RPM_M} \times 100\%$	Percentage accuracy (%)
50	64.1	28.2	71.8
50	48.6	2.8	97.2
50	54.7	9.4	90.6
Average	55.8	13.5	86.5

After ANOVA was performed, a post-hoc test was performed to further investigate the interactions between the significant factors at a level = 95%. The Tukey test was conducted in this experimental work using Minitab software.

17.3.2.3 Torque calculation

From the AST experimental result, the readings that display on the tachometer are the rotational speed in rotations per minute (rpm) unit. Hence the calculation of torque using rotational speed output can be calculated using Eq. (17.1) (Lee and Lee, 2021).

$$\rho g Q H = T \omega \quad (17.1)$$

Table 17.7 Data for two-factor experimental design for the Archimedean screw turbine (AST) experimental test.

Diameter ratio(Factor A)	Inclination angle (Factor B)			
	0°	10°	20°	30°
0.36	$y_{111}, \dots, y_{11n}$	$y_{121}, \dots, y_{12n}$	$y_{131}, \dots, y_{13n}$	$y_{141}, \dots, y_{14n}$
0.4	$y_{211}, \dots, y_{21n}$	$y_{221}, \dots, y_{22n}$	$y_{231}, \dots, y_{23n}$	$y_{241}, \dots, y_{24n}$
0.44	$y_{311}, \dots, y_{31n}$	$y_{321}, \dots, y_{32n}$	$y_{331}, \dots, y_{33n}$	$y_{341}, \dots, y_{34n}$

WHERE P = DENSITY OF WATER (998 KG/M^3), G = GRAVITATIONAL ACCELERATION (9.81 M/S^2), Q = VOLUME FLOW RATE (M^3/S) AND H = ELEVATION OF THE SYSTEM (M), T = TORQUE GENERATED (N/M) AND Ω = ROTATION OF THE TURBINE SHAFT (RAD/S).

17.3.2.4 Mechanical power calculation

From the data (rotational speed obtained and torque calculated), power generated by AST, P_{mech} in Watts units can be determined using Eq. (17.2) (Lee and Lee, 2021).

$$P_{mech} = T\omega \quad (17.2)$$

WHERE, T = TORQUE GENERATED ($\frac{N}{m}$) AND ω = ROTATION OF TURBINE SHAFT ($\frac{rad}{s}$)

17.3.2.5 Determine the optimum diameter ratio and inclination angle parameters

From the data obtained through the AST experimental test, it is important to determine which parameters need to be used to obtain high torque to generate sufficient clean energy.

17.3.3 Assumption toward limitation encountered during experimental test

During the experimental test, the following assumption was taken.

- Overall, the water flow rate of the river is assumed to be consistent during the whole time of the experiment, after the data flow rate of water was taken.

17.4 Results and discussion

17.4.1 Strength test results and discussion

UTS test was performed to investigate the tensile strength of the PETG polymer material. Fig. 17.12 shows the outcome of 3D-printed PETG after the UTS experiment.

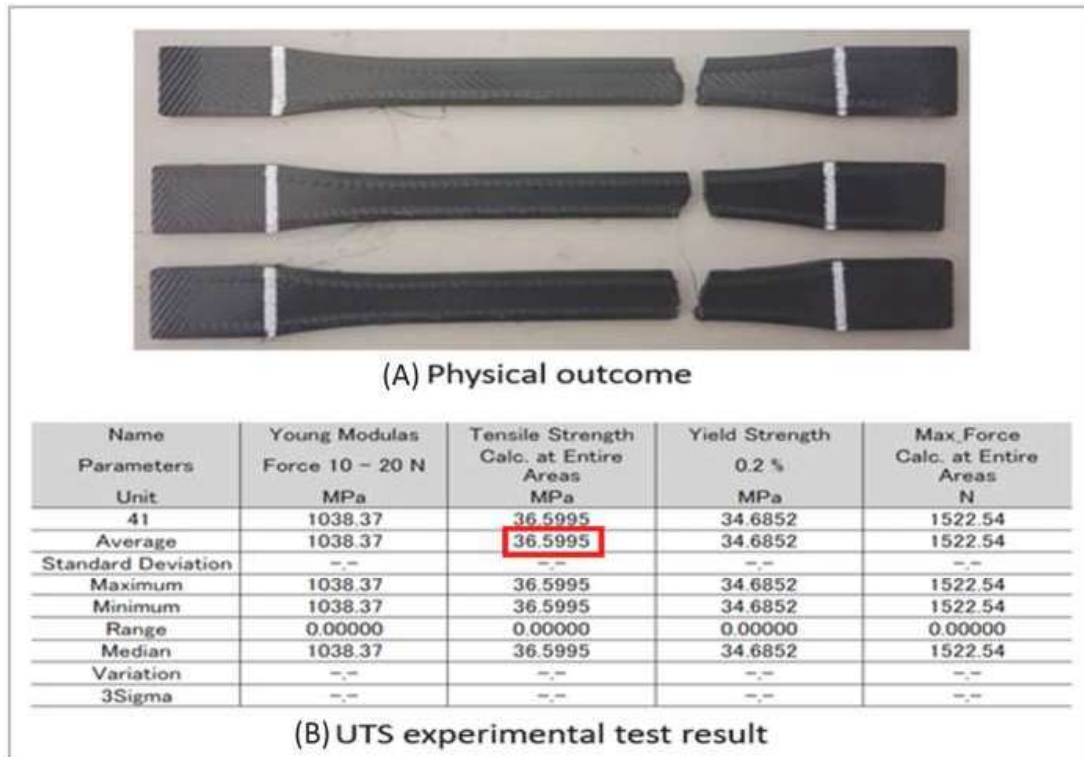


Figure 17.12 Outcome of the ultimate tensile strength (UTS) experimental test.

Fig. 17.12A shows the fractured 3D printed PETG tensile specimens (physical outcome from UTS test experiment), while Fig. 17.12B illustrates UTS experimental test results for printing parameters of 80% infill density and 20 mm/s printing speed. From Fig. 12B, the average tensile strength of the specimen is 36.5995 MPa.

Fig. 17.13 illustrates the trend of the graph of tensile strength of 3D-printed PETG (MPa) by varying infill density (%) and printing speed (mm/s). From the graph, the optimum tensile strength is 37.10 MPa, which was achieved using parameters of infill density of 80% and printing speed of 20 mm/s. This tensile strength using 3D-printed PETG polymer, is sufficient for turbine applications. This is because in wind turbine applications, 3D-printed PLA polymer (A et al., 2024) has a minimum tensile strength of 26.989 MPa (Sukindar et al., 2022).

From Fig. 17.13, the trends of the graph indicate that increasing infill density will also increase the strength. This is because there is a direct correlation between an increase infill density and a decrease in the porosity level within the specimen (Karad et al., 2023). According to Karad et al., (2023). The main cause of failure in the Fused Deposition Modeling is porosity. Thus the greater the porosity, the higher the chance of failure that can be formed from large pores and pore clusters. Due to this, at an infill density of 80%, fewer pores have been created compared to the infill density of 40 % which causes the high strength of the specimen.

Besides, from the graph (Fig. 17.13), decreasing printing speed leads to increasing the strength of the 3D printed PETG. This is because at the higher printing speed, porosity and void is expected to be increased within the material (Kim et al., 2020).

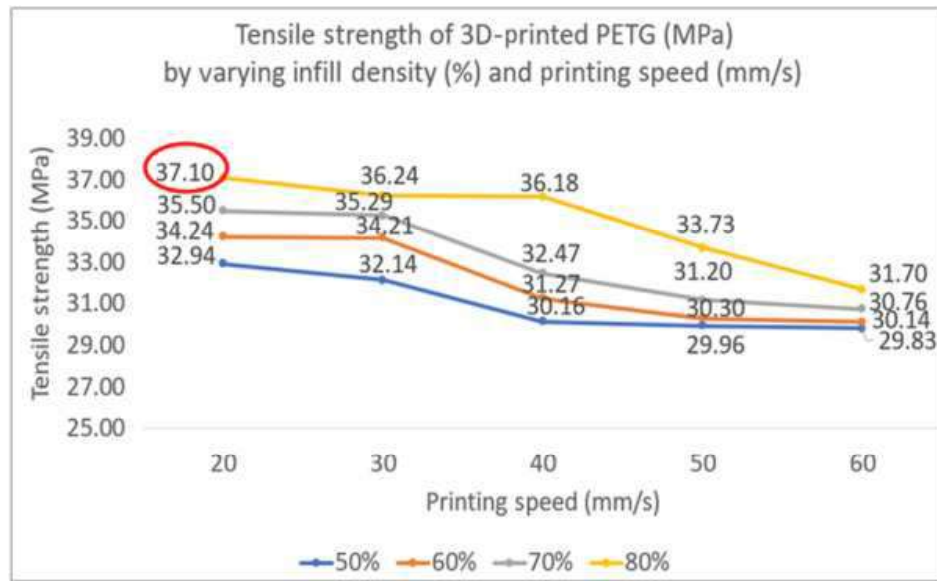


Figure 17.13 Tensile strength of 3D-printed PETG (MPa) by varying infill density (%) and printing speed (mm/s).

As reported by [Loskot et al., \(2023\)](#), the possible reason is that at the higher speed, insufficient material has been supplied through the nozzle. Therefore the extruded path is thinner, which causes the molten material at the extruded path not to overlap. Due to this, porosity and void are induced at the higher speed. [Kim et al., \(2020\)](#), mentions that voids can adversely affect the interfacial strength between the neighboring paths, which could have a negative impact on the mechanical properties of the finished product, which comprises ultimate tensile stress/Young's modulus. Similar findings were reported in the work of [Pazhamannil et al., \(2021\)](#), which correlated large voids induced at rapid printing speed to a reduction in the printed PLA's mechanical strength. The ANOVA test was carried out to validate the significance of the infill density and printing speed parameters on tensile strength output.

[Fig. 17.14](#) illustrates the results of two-factors ANOVA analysis for the tensile strength of 3D-printed PETG. The calculation was carried out at the significance level of P -value = .05 using Minitab software. From [Fig. 17.14](#), it can be stated that infill density and printing speed parameters are significant towards the tensile strength output as the P -value for infill density and printing speed are 0.000. Since the parameters are significant, further investigation into the infill density and printing speed factors was performed using the Post Hoc Tukey test using Minitab software. [Fig. 17.15](#) illustrates the post hoc Tukey test results for infill density and printing speed.

[Fig. 15A](#) illustrates Tukey test results for infill density, while [Fig. 15B](#) shows Tukey test results for printing speed. From [Fig. 15A](#), all the pairwise comparisons are significant except the interaction pairwise of infill density (%) of 60.00-50.00 and 70.00-60.00. This is because both the parameters have a P -value above .05. Subsequently, in [Figure 15B](#), Tukey test results show that all the interactions are

Analysis of variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Infill density	3	129.76	43.254	32.14	0.000
Printing speed	4	174.43	43.609	32.41	0.000
Infill density*printing speed	12	20.27	1.689	1.26	0.282
Error	40	53.82	1.346		
Total	59	378.29			

Figure 17.14 Results of two-factor ANOVA analysis for tensile strength of 3D printed PETG.

(A) Tukey Simultaneous Tests for Differences of Means					
Difference of Infill Density Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
60.00% - 50.00%	1.025	0.424	(-0.110, 2.160)	2.42	0.090
70.00% - 50.00%	2.038	0.424	(0.903, 3.173)	4.81	0.000
80.00% - 50.00%	3.982	0.424	(2.846, 5.117)	9.40	0.000
70.00% - 60.00%	1.013	0.424	(-0.122, 2.148)	2.39	0.095
80.00% - 60.00%	2.957	0.424	(1.822, 4.092)	6.98	0.000
80.00% - 70.00%	1.944	0.424	(0.809, 3.079)	4.59	0.000
Individual confidence level = 95.94%					

(B) Tukey Simultaneous Tests for Differences of Means					
Difference of Printing Speed Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
30 - 20	-0.476	0.474	(-1.829, 0.877)	-1.00	0.852
40 - 20	-2.424	0.474	(-3.777, -1.071)	-5.12	0.000
50 - 20	-3.647	0.474	(-5.000, -2.294)	-7.70	0.000
60 - 20	-4.340	0.474	(-5.693, -2.988)	-9.17	0.000
40 - 30	-1.948	0.474	(-3.301, -0.595)	-4.11	0.002
50 - 30	-3.171	0.474	(-4.524, -1.819)	-6.70	0.000
60 - 30	-3.865	0.474	(-5.217, -2.512)	-8.16	0.000
50 - 40	-1.224	0.474	(-2.576, 0.129)	-2.58	0.093
60 - 40	-1.917	0.474	(-3.270, -0.564)	-4.05	0.002
60 - 50	-0.693	0.474	(-2.046, 0.660)	-1.46	0.591
Individual confidence level = 99.32%					

Figure 17.15 Tukey test results (A) infill density, (B) printing speed.

significant except for interactions of printing speed (mm/s) for pairwise 30-20, 50-40, and 60-50. This is because the *P*-value of the above printing speed is more than .05.

17.4.2 AST experimental test results and discussion

Further investigation of the 3D-printed models was studied through the AST's capability to generate torque using a low water flow rate of Pusu River. Fig. 17.16A–C show rotational speed of the turbine at different diameter ratios (0.36, 0.4, and 0.44) and inclination angles (0, 10, 20, and 30 degrees) at Day 1, Day 2, and Day 3, respectively. From Fig. 17.16, it shows that the high water flow rate will have high turbines' rotational speed at the three diameter ratios investigated. Furthermore, the maximum rotational speed of the turbine at different diameter ratios was summarized in Table 17.8.

From Table 17.8, it can be stated that at all diameter ratios, at 8.8 L/min water flow rate, the turbine rotates at high speed compared to the water flow rate of 6.7 L/min. This is because an increase in the water flow rate will lead to an increase in the kinetic energy, which causes the turbine to rotate faster. The result is aligned with Lee and Lee, (2021) research, which reported that an increase in water flow rate causes an increase in the rotational speed of the turbine.

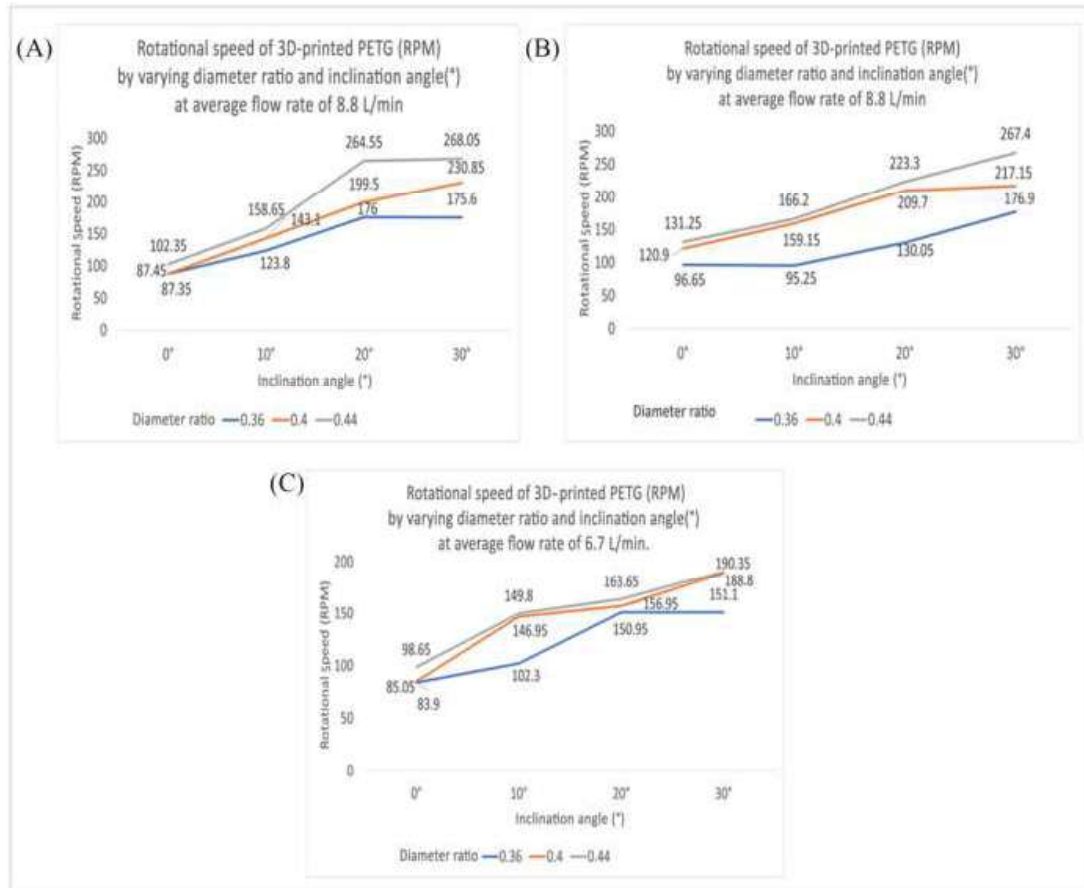


Figure 17.16 Rotational speed of 3D-printed PETG for various diameter ratios at average water flow rate of 8.8L/min (A), 8.8 L/min (B), and 6.7 L/min (C).

Table 17.8 Maximum rotational speed of the turbine at 0.36, 0.4, and 0.44 diameter ratios.

Day	Flow rate (L/min)	RPM of 0.36 diameter ratio at $\beta = 30$ degrees	RPM of 0.40 diameter ratio at $\beta = 30$ degrees	RPM of 0.44 diameter ratio at $\beta = 30$ degrees
1	8.8	175.6	230.85	268.05
2	8.8	176.9	217.15	267.4
3	6.7	151.1	188.8	190.35

From [Table 17.8](#) also, increasing in diameter ratio led to an increase in the rotational speed. At all water flow rates, 0.44 diameter ratio rotates at high speed, followed by 0.4 and 0.36 diameter ratios, respectively. Therefore an increase in the diameter ratio will decrease the outer diameter blade surface. Thus it will cause a decrease in the volume of the water trapped between the blades ([Dragomirescu, 2021](#)). Hence, the turbine can

rotate faster due to the less volume of water trapped between the blades. However, a decrease in the diameter ratio, the outer diameter blade surface will increase, resulting in an increase in the volume of water trapped between the blades (Dragomirescu, 2021). Due to this, the turbine rotates slowly as the heavier weight of the water trapped between the blades.

From Fig. 17.16A–C at all water flow rates and diameter ratios of the turbine, it indicates that at 0 degrees inclination angle, the turbine rotated at the slowest rotation speed, while at 30 degrees inclination angle, the turbine rotated at the highest rotation speed. This is because at the inclination angle of 0 degrees, there is an absence of hydrostatic force. Therefore the rotations of the screw turbine only depend on the kinetic force from the flowing water (Waters and Aggidis, 2015). At the 10, 20, and 30 degrees angle inclination, the turbine rotated faster than 0 degrees due to the occurrence of hydrostatic force. Hydrostatic force occurs when there is a difference in head level between the water inlet (higher elevation) and the water outlet (lower elevation) due to the assistance of gravity to push the water trapped between the blades to the water outlet.

Two factors: ANOVA was used to validate the significance of the two variable parameters (diameter ratio and inclination angle). The summary of results of two-factor ANOVA using Minitab software is illustrated in Fig. 17.17.

Based on Fig. 17.17A–C, the results show that the *P*-value for diameter ratio and inclination angle are 0.000 and 0.000, respectively for all water flow rates. Thus it indicates that the diameter ratio and inclination angle are significant parameters in this work, as the *P*-value is less than .05. Since the diameter ratio and inclination angle are significant towards the rotational speed output, further analysis was carried out using the Tukey test. The results of the Tukey test for diameter ratio and inclination angle for water flow rate of 8.8 L/min (Day 1), 8.8 L/min (Day 2), and 6.7 L/min (Day 3) are shown in Fig. 17.18.

(A) Analysis of variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Diameter ratio	2	96888	48444	76.16	0.000
Inclination angle	3	578021	192674	302.92	0.000
Diameter ratio*inclination angle	6	30497	5083	7.99	0.000
Error	180	114491	636		
Total	191	819897			

(B) Analysis of variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Diameter ratio	2	186561	93281	176.03	0.000
Inclination angle	3	317567	105856	199.76	0.000
Diameter ratio*inclination angle	6	26771	4462	8.42	0.000
Error	180	95385	530		
Total	191	626285			

(C) Analysis of variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Diameter ratio	2	41443	20722	20.36	0.000
Inclination angle	3	219530	73177	71.89	0.000
Diameter ratio*inclination angle	6	18813	3135	3.08	0.009
Error	180	183228	1018		
Total	191	463014			

Figure 17.17 Summary of ANOVA results for water flow rate of Pusu River at (A) 8.8 L/Min, (B) 8.8 L/min, and (C) 6.7 L/min.

Day	Flow rate (L/min)	Tukey test result for diameter ratio	Tukey test result for inclination angle																																																																		
1	8.8	Tukey simultaneous tests for differences of means <table><thead><tr><th>Difference of diameter ratio levels</th><th>Difference of means</th><th>SE of Difference</th><th>Simultaneous 95% CI</th><th>T-Value</th><th>Adjusted P-Value</th></tr></thead><tbody><tr><td>0.40 - 0.36</td><td>21.73</td><td>4.45</td><td>(11.32, 32.28)</td><td>4.88</td><td>.000</td></tr><tr><td>0.44 - 0.36</td><td>34.63</td><td>4.45</td><td>(44.12, 55.18)</td><td>12.26</td><td>.000</td></tr><tr><td>0.44 - 0.40</td><td>32.90</td><td>4.46</td><td>(22.37, 43.43)</td><td>7.38</td><td>.000</td></tr></tbody></table> Individual confidence level = 30.07%	Difference of diameter ratio levels	Difference of means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value	0.40 - 0.36	21.73	4.45	(11.32, 32.28)	4.88	.000	0.44 - 0.36	34.63	4.45	(44.12, 55.18)	12.26	.000	0.44 - 0.40	32.90	4.46	(22.37, 43.43)	7.38	.000	Tukey simultaneous tests for differences of means <table><thead><tr><th>Difference of inclination Angle Levels</th><th>Difference of means</th><th>SE of Difference</th><th>Simultaneous 95% CI</th><th>T-Value</th><th>Adjusted P-Value</th></tr></thead><tbody><tr><td>10 - 0</td><td>53.74</td><td>3.15</td><td>(40.38, 67.10)</td><td>10.44</td><td>.000</td></tr><tr><td>20 - 0</td><td>134.87</td><td>3.15</td><td>(111.61, 138.13)</td><td>24.27</td><td>.000</td></tr><tr><td>30 - 0</td><td>134.25</td><td>3.15</td><td>(120.89, 147.61)</td><td>26.08</td><td>.000</td></tr><tr><td>20 - 10</td><td>73.23</td><td>3.15</td><td>(57.67, 84.39)</td><td>12.94</td><td>.000</td></tr><tr><td>30 - 10</td><td>60.51</td><td>3.15</td><td>(47.33, 53.67)</td><td>15.54</td><td>.000</td></tr><tr><td>30 - 20</td><td>9.28</td><td>3.15</td><td>(-4.06, 22.64)</td><td>1.80</td><td>.276</td></tr></tbody></table> Individual confidence level = 98.98%	Difference of inclination Angle Levels	Difference of means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value	10 - 0	53.74	3.15	(40.38, 67.10)	10.44	.000	20 - 0	134.87	3.15	(111.61, 138.13)	24.27	.000	30 - 0	134.25	3.15	(120.89, 147.61)	26.08	.000	20 - 10	73.23	3.15	(57.67, 84.39)	12.94	.000	30 - 10	60.51	3.15	(47.33, 53.67)	15.54	.000	30 - 20	9.28	3.15	(-4.06, 22.64)	1.80	.276
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Figure 17.18 Tukey test results for diameter ratio and inclination angle for flow rate of 8.8 L/min (Day 1), 8.8 L/min (Day 2), and 6.7 L/min (Day 3).

From Fig. 17.18, all the pairwise comparisons for all water flow rates are significant except for the interaction pairwise of inclination angle ($^{\circ}$) of 30-20 for Day 1 and the interaction pairwise of inclination angle ($^{\circ}$) of 20-10 for Day 3. This is because the P -values of the above pair-wise are .276 and .126, which are larger than the P -value of .05.

By using Eq. 17.1, the torque value can be calculated by substituting the data within Fig. 17.16A–C. Torque data for river water flow rate 8.8 L/min/ 8.8 L/min and 6.7 L/min are shown in Fig. 19A–C, respectively.

From Fig. 17.19A–C, it can be observed that a decrease in the diameter ratio led to an increase in the torque value. From this graph, at all water flow rates and inclination angles, it can be concluded that a 0.36 diameter ratio generated the highest torque, while a 0.44 generated the lowest torque. Results from this research work are similar to the research outcome by Erinofardi et al., (2017), which stated that increasing the rotational speed of the turbine causes a decrease in torque. From Fig. 19A–C, it can be stated that a 30° inclination angle is the optimum inclination angle as it generated the highest torque. The result is aligned with research (Syam et al., 2019; Maulana et al., 2019), which reported that 30 degrees is the common angle used to install the turbine. Based on the experimental results data of Lee and Lee, (2021), they varied the inclination at high inclination angles, which are 30, 45, 60, 75, and 90 degrees in their work, and the finding indicates that 30 degrees angle generates the second-highest torque output.

By using Eq. 17.2, the mechanical power can be determined by substituting the data within Fig. 17.16A–C and Fig. 17.19A–C.

From Fig. 17.20A–C at all water flow rate and diameter ratio of the turbine, it indicates that at 0 degrees inclination angle, the turbine generated the lowest

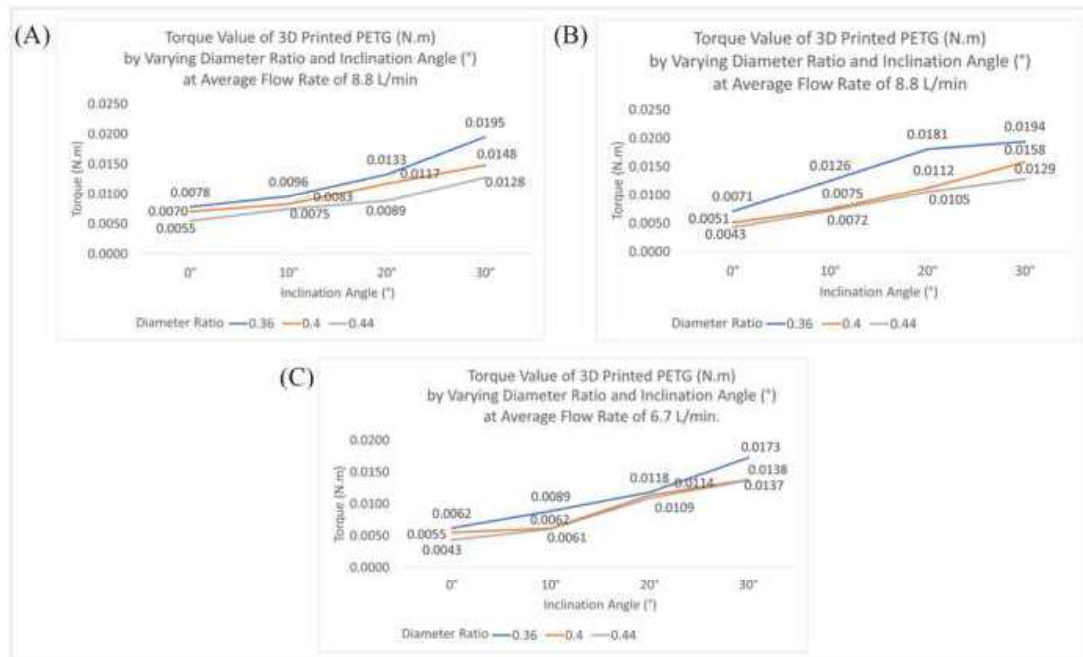


Figure 17.19 Torque of 3D-printed PETG for various diameter ratios at average water flow rate of 8.8 L/min (A), 8.8 L/min (B), and 6.7 L/min (C).

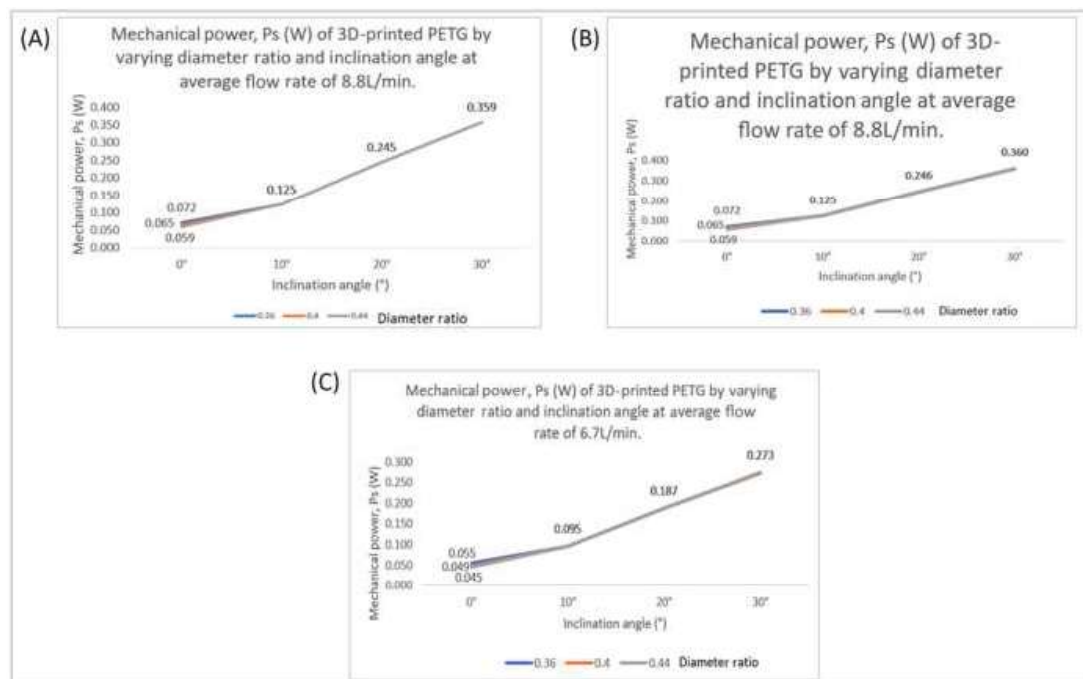


Figure 17.20 Mechanical power of 3D-printed PETG for various diameter ratios at average water flow rate of 8.8 L/min (A), 8.8 L/min (B), and 6.7 L/min (C).

mechanical power at minimum of 0.045 W while at 30 degrees inclination angle, the turbine generated the highest mechanical power at minimum of 0.273 W. This is because at the inclination angle of 0 degrees, torque generated is low while at the 30 degrees inclination angle, torque generated is the highest. From the trend of the graph in Fig. 17.20A–C, it shows that the diameter ratios 0.36, 0.4, and 0.44 generated the same mechanical power at all inclination angles except at 0 degrees inclination angle. At 0° inclination angle, diameter ratio 0.36 harvested the highest mechanical power at a maximum of 0.072 W, followed by diameter ratios 0.40 and 0.44 at maximum of 0.065 W and 0.059 W, respectively. From Fig. 17.20A–C, at flow rate 8.8 L/min, 3D-printed AST generated the highest mechanical power which is maximum at 0.360 W while at flow rate 6.7 L/min, the turbine generated the least mechanical power which maximum at 0.273 W. This result is aligned with research findings by Purece and Corlan (2021) which is increasing in flow rate led to increasing in mechanical power.

17.5 Conclusion

In conclusion, a pico-hydro power turbine (3D-printed AST) was developed to operate at a low water flow rate river for sustainable green energy generation. This AST development process was started by finding a suitable tensile strength for the turbine. Therefore UTS test was performed to investigate the tensile strength of the 3D-printed PETG polymer material. Two different parameters, which were infill density and printing speed, were varied. The results obtained, it shows that an infill density of 80% and a printing speed of 20 mm/s were the optimum parameters as these parameters give the highest tensile strength at 37.10 MPa. Later, SolidWorks software was used to design three ASTs with different diameter ratios (0.36, 0.4, and 0.44), which were then fabricated utilizing the optimum 3D printing parameters obtained. A CMM was used to measure the dimensions of the inner and outer diameters of the printed turbine. Measurement results indicate that the maximum variation between the printed turbine and the drawing dimension is 2.09%. In the 3D printing process, this issue is already expected to happen due to the heat shrinkage, which causes a difference between printed parts and drawing parts. Nevertheless, this variation is considered small and still within an acceptable range as it does not have impact on the turbine performance. Further experimental test was performed to validate the feasibility of 3D-printed AST to generate sufficient torque using the river flow rate. This work was carried out at the Pusu Tiver, Selangor, Malaysia, as this river flows at low water flow rate. From the water flow rate data taken, the average water flow rates are 8.8 L/min, 8.8 L/min, and 6.7 L/min, respectively, for each day. Experimental outcome shows that at an 8.8 L/min water flow rate, AST generated a high rotational speed at all the diameter ratios in comparison with a 6.7 L/min flow rate. The results further show that the turbine rotates at the highest speed at 30 degrees inclination angle, while at 0 degrees inclination angle, the turbine rotates at the slowest speed for all water flow rates and diameter ratios. Findings indicate that the 0.44 diameter ratio AST rotated

at its maximum rotational speed of 268.05 rpm while the 0.36 diameter ratio AST rotated at its maximum rotational speed of 176.9 rpm. Nevertheless, according to the torque calculation, AST produced the highest torque at 0.0195 N.m. at a 0.36 diameter ratio and 0.0128 N.m. at a 0.44 diameter ratio. It can be observed that the 0.36 diameter ratio generated more torque compared to the 0.44 diameter ratio. This is because torque and rotational speed are inversely proportional to each other which increase in the rotational speed of the turbine will cause a decrease in torque. Findings in this work indicate that 3D-printed AST utilizing PETG material can generate maximum mechanical power around 0.36 W. Therefore 3D-printed AST can be utilized for pico-hydro energy generation for rural electrification in Malaysia. It is recommended to use 3D printing technology in fabricating AST as it has high precision in dimension and produces minimal material waste, which is favorable for the environment. Overall, a novel workflow to develop a 3D printed AST utilizing a low water flow rate of the river in generating clean energy was achieved.

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