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Original research article

Number of holes and blades to control the performance of aquaculture aerator

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ABSTRACT

Water quality determines the success of inland aquaculture. The factor determining water quality is the concentration of dissolved oxygen (DO). To find effective paddlewheel aerators to enhance DO concentration, nine model aerators were examined: aerator 4 blades, 6 blades and 8 blades with variations of 12 holes per blade, 16 holes per blade and 20 holes per blade. They were rotated at 80 RPM, 100 RPM, 120 RPM and 140 RPM. The results show the higher the rotation speed is, the bigger the increment of DO concentration is, but their relationship is not linier. There is a condition when increasing rotation does not affect the DO concentration meaningly. The results also indicate the greater number of blades increase more DO concentration. The results also suggest the greater number of holes per blade initially increase DO concentration increment, but after 16 holes the increment tends to reduce. It is predicted owing to that widening surface interaction due to the holes in the blade is taken over by reducing the volume of splashed water. In this research, likely the aerator with 8 blades, 16 holes per blade and rotated at 120 RPM is the optimum one to increase DO concentration. However, if the energy consumption is also the concern, the aerator with 6 blades and 16 holes per blade likely is the better choice.

1. Introduction

Aquatic animals have had a long-time history as a source of protein (Kaleem & Sabi, 2021; Kobayashi et al., 2015). As the demand grows and the wild stocks are steadily depleted, the supplies from open sources are no longer able to fulfill the demand (Yue & Shen, 2022). Since then, the aquacultures have become growing food industry (Das & Behera, 2019). Aquaculture products contribute significantly to the job creation and economic development of many countries (Cordeiro, 2019; FAO & FishStat FAO, 2017; Jayanthi et al., 2021). FAO and FishStat FAO (2017) published that the growth of aquaculture in average was about 7.8% per year.

Inland aquaculture farm yields per unit of production pond area have steadily intensified (Boyd & McNevin, 2021; Yue & Shen, 2022). The water quality highly determines the success of inland aquaculture. The essential factor that determines the water quality in an aquatic pond is the concentration of dissolved oxygen (DO) (Baylar et al., 2006; Rahmawati et al., 2021; Roy et al., 2020). The oxygen is essentially used by aquatic creatures to breath (Roy et al., 2020). Furthermore, the nutrition in an aquatic farm depends highly on DO concentration (Roy et al., 2020). Higher concentration of DO allows greater feed inputs (Boyd & McNevin, 2021). However, the DO concentration can be deteriorated by many factors, such as solar radiation, water temperature, water pH, water salinity, nutrition, and population of aquatic animals and plants (Ozaki et al., 2021; Zheng et al., 2008). Many aquatic animals, such as fish and shrimp can live comfortably in an aquatic system having DO concentration 5 mg/L or more (Boyd & Hanson, 2010; Nguyen, Matsuhashi, & Vo, 2021). If DO concentration in the aquatic pond is less than 3 mg/L for a long period, it may cause fatality to many aquatic animals. The feed consumption of aquatic animals will drop and affect the growth, if DO concentration is not sufficient. Most of the aquatic animals cannot survive in the environment having very low DO concentration, such as concentration below 0,5 mg/L (Eltawil & ElSbaay, 2016). In other words, to have good growth of aquatic life, it is necessary to keep adequate of DO concentration in an aquatic system.

Oxygen is available for free in the atmosphere, or it can be produced by water plant. There are two primary resources of oxygen in an aquatic system, which are the oxygen released by water plant as by-products of photosynthesis or oxygen in the air diffused into water. However, the oxygen production owing to photosynthesis of aquatic plant is not

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sufficient to support aquatic animals (Boyd et al., 2018). It is required suitable tools to promote air oxygen to diffuse into the water. This DO enhancement is necessary particularly during the night-time when the respiration of aquatic organisms and the accumulated leftover feed and feces during the day decaying to be organic compounds consumed a lot of oxygen (Zhang et al., 2006). Let alone, population of aquatic creatures in aquaculture farms is usually very dense due to intensification (Itano et al., 2019; Roy et al., 2021).

The DO concentration is enhanced commonly by aerators (Deng et al., 2019). An aerator allows an aeration process to transfer oxygen from the atmosphere into water (Gu & Wang, 2014). Such process is an essential part in an aquatic farm (Adel et al., 2019) to control the DO level in healthy level for aquatic animals. There are many types of aerators used for aquaculture. Paddlewheel, vertical turbine, diffuser, impeller, and venturi aerators are among others (Boyd et al., 2018). Selection of a proper model to be used depends on many factors such as the function, type and geometry of the pond, installation cost and operation and maintenance cost (Roy et al., 2020). Energy cost is big cost in an aquaculture farm (Wambua et al., 2021), because aerator system is a significant energy user (SEU). For example, currently energy used for aeration system in shrimp farming is in average 19.8 GJ/t-shrimp (Boyd & McNevin, 2021). Applying energy efficient aerator will reduce operational cost, conserve energy, and reduce emissions (Pérez et al., 2018; Zhang et al., 2016). The criteria to select an aerator are not only be able to enhance DO concentration, but also economically viable (Itano et al., 2019; Jayanthi et al., 2021). There are many opportunities available to be addressed to reduce energy consumption in aeration system. Selecting proper models and rotation speed are among others (Boyd & McNevin, 2021), as well as applying automatic system and artificial intelligent (Deng et al., 2019).

In Indonesia, mechanical aerators are popularly used (Sofiah & Apriani, 2019), particularly impeller and paddlewheel models which are attached to the shaft on electric motors or diesel engines (Boyd et al., 2017; Boyd & McNevin, 2021). In the research reported here paddlewheel aerators were investigated. Different numbers of blades and holes per blade of aerators were tested to find good aeration performance and energy efficient model. In principle, the bigger surface interaction between water and air, the better oxygen diffusion into water (Itano et al., 2019). However, different number of holes, blades and rotation speed of impeller may affect not only the area of surface interaction between water and air, but also the volume of water splashed and the duration of water-air interaction. Different number of blades and holes per blade splash different amount water and different sizes of water droplets. Hence, various number of blades, holes per blade and rotation rate were investigated to find the optimum ones and are reported here.

2. Materials and methods

Here, the materials and tools used in this study are explained and then this section describes how the experiments were conducted.

2.1. Materials and tools

The materials and tools were used in this research as follow.

1. Nine models of mechanical paddlewheel aerators made from plastic filament PLA (Polylactic acid) were designed, fabricated, checked for stability and used for the experiment:
   i. Aerator 4 blades with 12 holes per blade;
   ii. Aerator 4 blades with 16 holes per blade;
   iii. Aerator 4 blades with 20 holes per blade;
   iv. Aerator 6 blades with 12 holes per blade;
   v. Aerator 6 blades with 16 holes per blade;
   vi. Aerator 6 blades with 20 holes per blade;
   vii. Aerator 8 blades with 12 holes per blade;
   viii. Aerator 8 blades with 16 holes per blade;
   ix. Aerator 8 blades with 20 holes per blade

   as shown in Fig. 1.

   The aerators were manufactured using 3d Printing machine, PRUSA H4 and smoothened using fine sandpapers.

2. Plastic filament PLA (Polylactic acid) was chosen as materials for these aerators because they are widely available and environmentally friendly.
3. The aerators were derived by a single-phase AC electric motor 200 W, maximum speed 2000 RPM, with variable frequency drive (variable speed drive). Variable frequency drive is important to vary the rotation speed during the experiments.
4. The experiments were conducted inside an aquatic pond shown in Fig. 2, filled with fresh water until the blades of aerators immersed. After each experiment, the water was replaced with fresh water. So, each experiment was always started from fresh water and DO concentration more or less 5.5 mg/L.
5. Rotation rate of aerator inside the pond was controlled to be constant for each experiment and measured using a tachometer.
6. The concentrations of oxygen dissolved in the water before, during and after experiments were measured by a Portable Digital Dissolved Oxygen (DO) meter JPB-70A.

2.2. Aerator wheels

The aerators, wheels, and blades were designed and drawn first using Solid Work software. As an example, Fig. 3 shows the design and drawing for the aerator 8 blades with 16 holes per blade. All aerator models were curved 45^{o} as shown in Fig. 1. Before the aerator wheels were realized, the stability of designs was first tested by simulations at different rotation speeds using computation fluid dynamics (CFD). One of examples of simulation is depicted in Fig. 4 showing velocity contour of water due to aerator rotation. After the stability of the design was tested, the designs were realized to be mechanical paddlewheel aerators, with scale 1:4, using 3-D printer. The wheels and blades of aerators were made from plastic filament PLA (Polylactic acid). The prototypes made by 3-D printers was smoothened carefully using very fine grain sandpapers. Then, the wheels and blades were constructed together to build a mechanical impeller using baked plastic glue. The manufactured mechanical impeller can be seen in Fig. 1. The mechanical impeller was then assembled onto the shaft rotor of AC electric motor to form a complete aerator system as shown in Fig. 5.

2.3. Experiments

The manufactured aerators were exercised in four different rotation speeds, 80 RPM, 100 RPM, 120 RPM and 140 RPM. The rotation speed here means the rotation speed of aerators rotated inside water of the aquatic pond. It was measured and monitored by a tachometer and regulated by a variable frequency drive electric motor to maintain constant speed when the aerators were examined for aeration process. In these studies, the water height was maintained, and the aerators were immersed until the blades inside water. Then when the aerators were turned, the blades would splash the water onto the air and the oxygen in air was expected to diffuse into water. Because the diffusion is a mass transfer process, it happens when the concentration of oxygen in the air is higher than that of in the water. It was also observed that the rotation of the blades did not disturb the sediment on the floor of the pond. The blade rotations mainly only disturbed the water that directly contacted with the blades and surrounding. During the experiments, disturbances to the water body having distance to the rotating blades were minor. This is also supported by the simulation result depicted in Fig. 4 showing velocity contour of water due to aerator rotation. The simulation shows that the water movement due to aerator rotation was mainly only due to direct contact with the blades.

Fig. 1. Various mechanical impeller used in the research: (a) aerator 4 blades with 12 holes per blade, (b) aerator 4 blades with 16 holes per blade, (c) aerator 4 blades with 20 holes per blade; (d) aerator 6 blades with 12 holes per blade, (e) aerator 6 blades with 16 holes per blade, (f) aerator 6 blades with 20 holes per blade, (g) aerator 8 blades with 12 holes per blade, (h) aerator 8 blades with 16 holes per blade and (i) aerator 8 blades with 20 holes per blade.

Fig. 2. The aquatic pond where the experiments were conducted.

The DO concentration and temperature in the water, as well as power consumption of aerator were measured at the beginning and every minute during 20 min of each experiment. Hence, the increasing of DO concentration due to aerator operations could be calculated. Each experiment always started with fresh water with DO concentration about 5.5 mg/L. The data taken for comparison were the data after 10 min of rotation because the experiments showed that the DOs were stable after 10 min of rotation, as an example shown in Fig. 6 for six blades rotated at 100 RPM. Similar trends also happened to other numbers of blades and rotation speeds.

3. Results and discussion

3.1. Effects of different models of aerators

When the aerators were rotated inside the aquatic pond, they splashed water to the atmosphere forming various size water droplets and bubbles as displayed in Fig. 7. The volume of the splashed water, the sizes of water droplets and the sizes of bubbles depend on the number of blades, the number of holes per blade and the rotation speed. However,

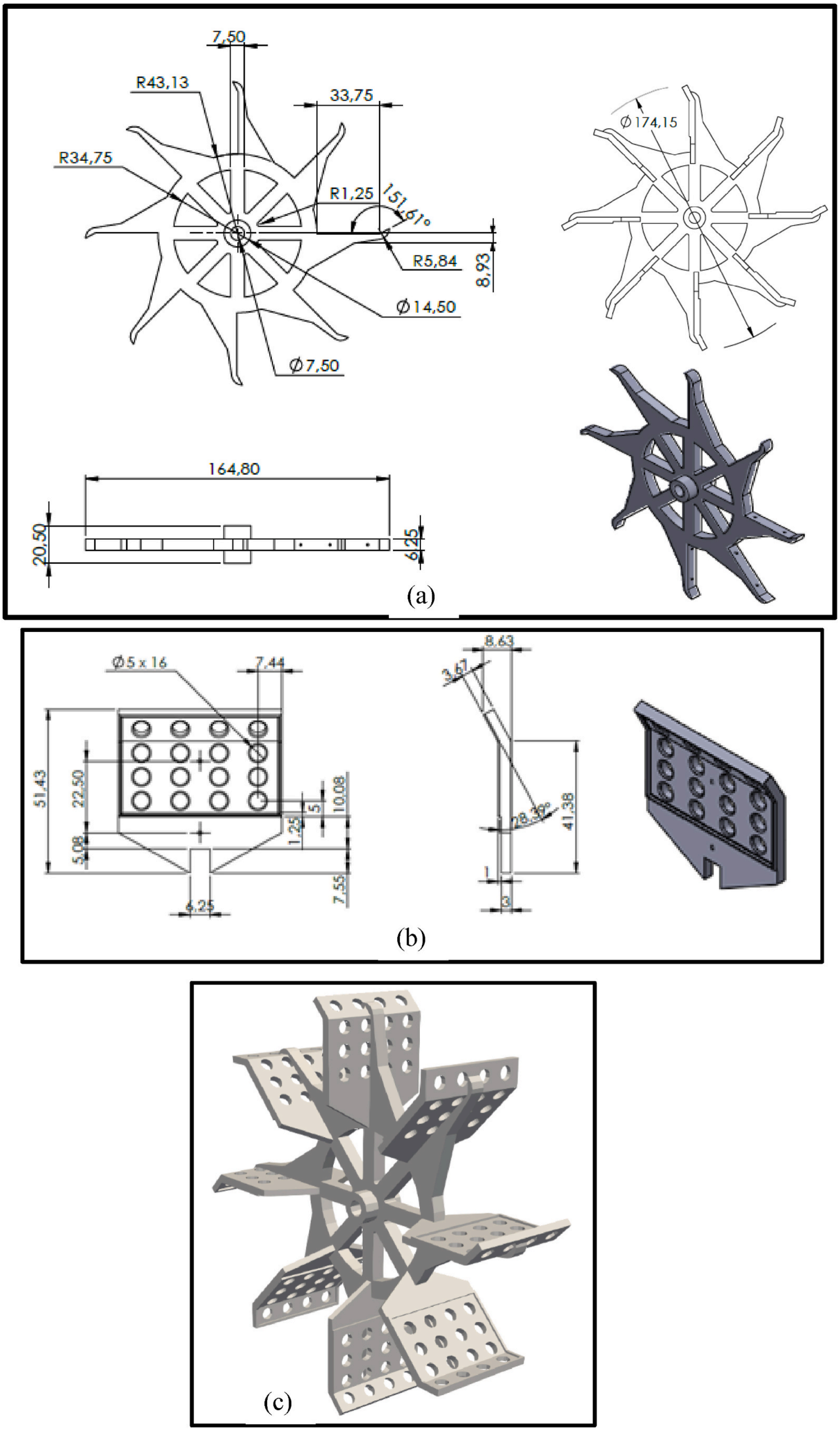

Fig. 3. An example of the design drawing of aerator 8-blades and 16-holes per blade: (a) aerator frame and wheel; (b) blades; (c) complete drawing.

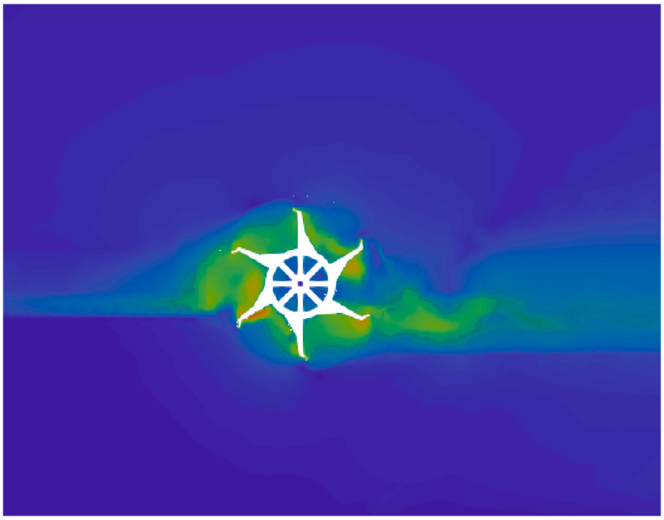

Fig. 4. An example of simulation of the design to test the stability, six blades, at rotation speed 90 RPM.

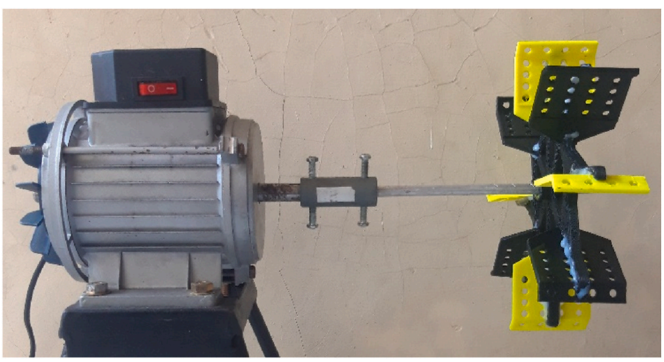

Fig. 5. A complete aerator, mechanical impeller attached at the shaft of electric motor AC.

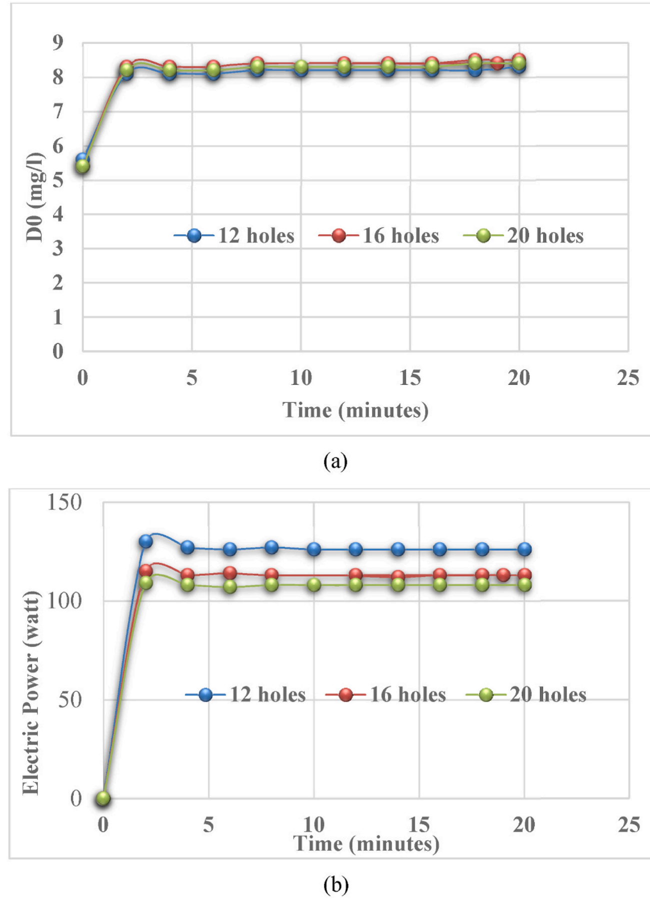

Fig. 6. When the aerator of six blades was run at rotation speed 100 RPM: (a) the progress of DO concentrations in the pond; and (b) the power consumption of aerator.

it is rather difficult to precisely measure the sizes of water droplets due to quite random and broad range of the size. During the experiments, it was observed in general the sizes of water droplets produced by the aerator with 20 holes per blade are approximately less than 75% of the sizes of water droplets produced by the aerator with 12 holes per blade are. The volume of splashed water, the sizes of water droplets and the sizes of bubbles determine surface interaction areas between air and water. The bigger surface area of interaction between water and air, the better oxygen diffusion into the water which results in higher DO concentration in the pond (FAO & FishStat FAO, 2017; Itano et al., 2019). Diffusion of oxygen into water is mass transfer process (Dai et al., 2020) which will occur as long as DO concentration in the water less than that of air. Hence, the process not only depends on surface interaction, but also duration of interaction. The following paragraphs will discuss the effects of number of blades, number holes per blade and rotation speed to the DO concentration of pond and the power consumption of an aerator.

Fig. 8 shows that the rotation of aerator increases the concentration of DO in the water of pond. The results are consistent because the trend happens to all models of aerator tested here, aerator 4, 6 and 8 blades with 12, 16 and 20 holes per blade. Fig. 8 clearly displays that the higher the rotation speed is, the bigger the increment of water DO concentration is. The results are predicted due to that higher rotation speed means greater amount of water volume splashed onto the atmosphere which increases probable surface interaction between water and air. The surface interaction between air dan water plays significant role in oxygen diffusion from atmosphere into water (Hanotu et al., 2017; Itano et al., 2019; Zhu et al., 2019), because it is a mass transfer process. However, the relationship between rotation speed and increment of water DO concentration is not linier. The graphs show that at higher rotation speed, the DO concentration increments are less compared to that of lower rotation speed. It means there is a condition when increasing rotation speed does not affect the DO concentration meaningly. It is predicted owing to that the diffusion of oxygen into water is also affected by the duration of interaction between water and air (Adel et al., 2019; Itano et al., 2019). Increasing rotation speed of aerator wheels may shorten the interaction between water and air, because it also posters the angular momentum of splashed water.

Fig. 8 also shows that the number of blades affects an aerator to help controlling the DO concentration in the aquatic pond. In this study the number of blades 4, 6 and 8 blades were examined because they are commonly available aerators in market and widely used in an aquatic farm. The graphs illustrated in Fig. 8 indicate that the rotation of aerator of eight-blades resulted in higher DO concentration than that of the aerator of six-blades, and the rotation of aerator of six-blades resulted in higher DO concentration than that of the aerator of four-blades. These results are predicted due to that the aerator which has a greater number of blades splashes more water to the atmosphere than that of the aerator which has less ones. Each blade splashes water to the atmosphere. Hence, the aerator having more blades splashes greater amount of water compared to the less ones if the rotation speed is similar. These phenomena were also observed by eyes during the experiments conducted. Therefore, it can be concluded that in this research the aerator with 8-blades resulted in the most effective one to increase DO concentration among the aerator models examined.

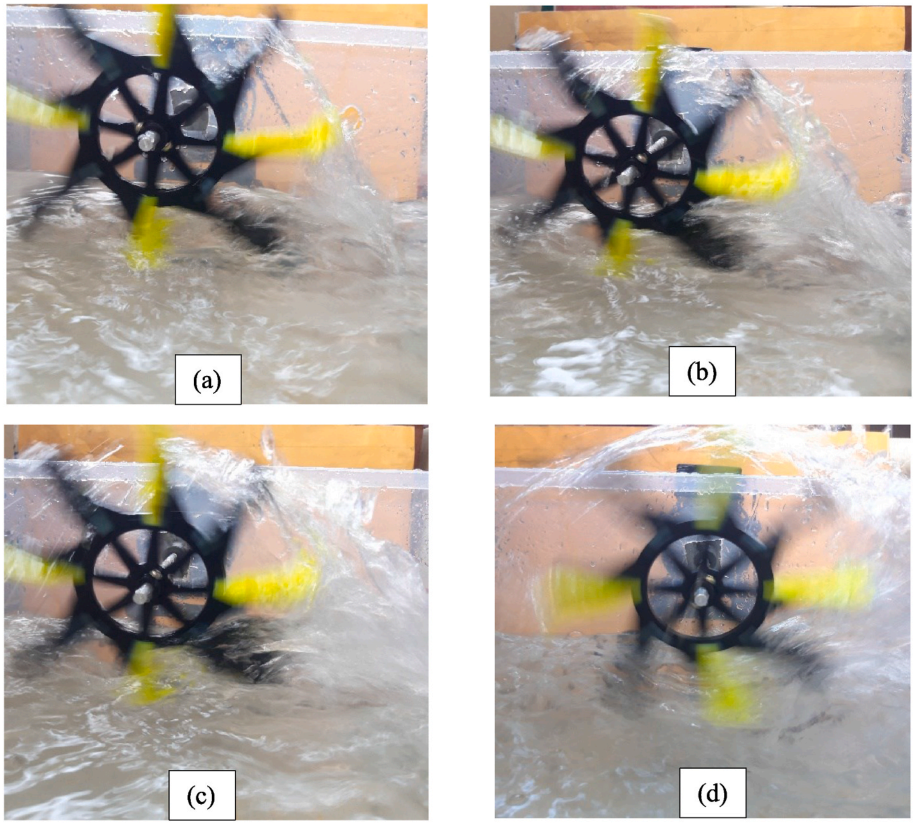

Fig. 7. Examples of experiment. Four different rotation rates: (a) 80 RPM, (b) 100 RPM, (c) 120 RPM, and (d) 140 RPM, of 8-blades aerator.

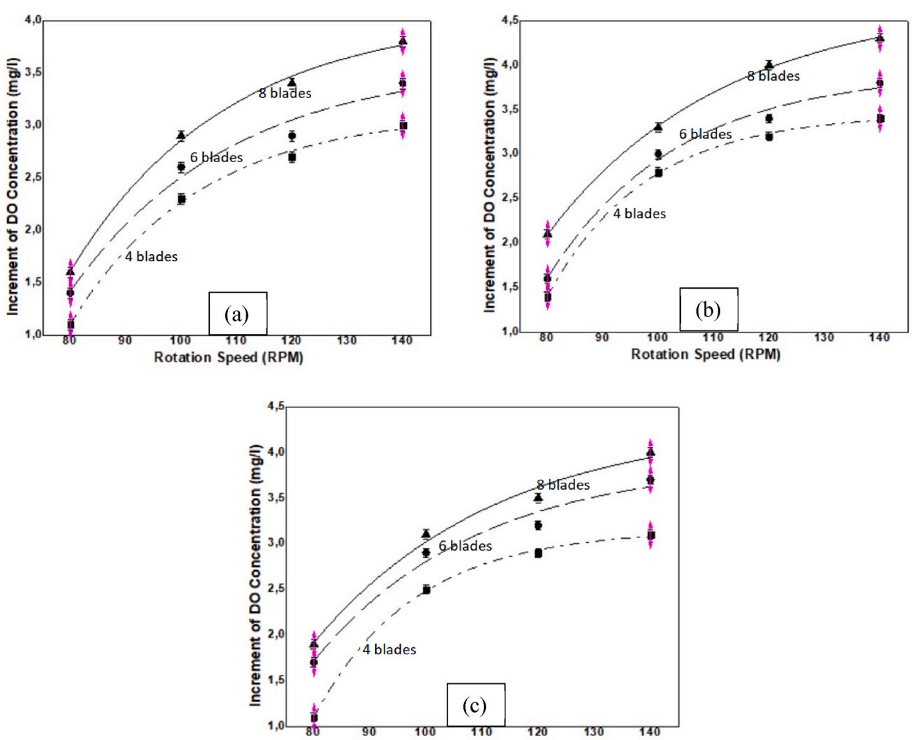

Fig. 8. Increment of DO concentration due to rotation of aerator for various aerator models: (a) aerator 12 holes per blade, (b) aerator 16 holes per blade, and (c) aerator 20 holes per blade.

The effectiveness of oxygen diffusion from atmosphere into water is also affected by number of holes per blade. Holes in the blades help to smaller the size of water drops and bubbles. If a volume of water is divided into several water droplets and bubbles, the area of surface interaction between air and water is widened. It results in better diffusion of air into water, and so oxygen. It was predicted that the greater number of holes per blades, the smaller size of water droplets and bubbles produced. If these water droplets and bubbles come from the same volume of water, the interaction area between water and air is widened, so it will increase the effectiveness of oxygen transfer from air into water. However, Fig. 9 shows that all graphs consistently indicate that after 16 holes the increment of DO concentration tend to reduce. It suggests that the greater number of holes per blade, the smaller sizes of water droplets and bubbles produced, but concurrently the holes in the blades also reduced the volume of water splashed. At certain condition, widening surface interaction owing to holes in the blade is taken over by reducing the volume of splashed water which is also due to the holes in the blade. In this study, it happened when the number of holes per blade was 16 holes. This prediction is supported by the power consumption data shown in Fig. 10 which shows that the greater number of holes per blade is, the less amount of power consumption is. An aerator consumes less power because its rotation has less load and less resistance, and it happens because it splashes less volume of water. Hence, the aerators which have greater number of holes per blade consumed less power depicted by Fig. 10 because they splashed less amount of water into the atmosphere, so the blade rotation has less resistance. This conclusion is supported by Fig. 11 that shows that more holes mean less effective area of blade surface, which is blade area minus total area of holes, to throw water into the atmosphere. Therefore, it must have a tradeoff between increasing the number holes per blade, and volume of water splashed. Fig. 9 suggests that likely about 16 holes is the optimum one.

If the concern is only enhancing DO concentration, Fig. 8 dan Fig. 9 suggest that the aerator with 8-blades and 16-holes is the most effective one to increase the DO concentration, However, sometimes the energy efficiency needs also to be considered. Particularly, now people highly concern about energy cost, energy conservation and green-house gas emission. It has been stated earlier that energy cost is significant cost in an aquaculture farm (Wambua et al., 2021). Let alone, many electrical power plants still use fossil fuels that emit greenhouse gas emission. Hence, sometimes it is necessary to find which one the most energy efficient is. Fig. 12 indicates that the aerator with 6-blades and 16-holes per blade and rotated at the rotation speeds of 120 or 140 RPM is the most energy efficient one.

Generally, the most available paddlewheel aerators in Indonesian market are aerator with 8 blades. Obtaining six-blades aerator may need to make a request to the suppliers and it may cause the six-blades aerator is higher price than the eight-blades one is. Meanwhile, the blade with 16 holes is widely available in the market. If increasing DO concentration is the main concern, the model of eight-blades and 16 holes per blade is the suggested choice. However, if the energy efficiency is also a big concern, the model of six-blades and 16 holes per blade may be better choice. The PLA material is durable enough for this model. It was observed during experiments that the blades showed robustness even until high rotation speed. PLA is environmentally friendly plastic material (biodegradable) because it is made from renewable resources. The price is relatively cheap too because it is the most widely used plastic filament in 3D printing. It also has properties, high strength, and low thermal expansion.

4. Conclusion

The rotations of paddlewheel aerators inside the aquatic pond splash water to the atmosphere forming various size water droplets and bubbles. The volume of water splashed, the sizes of water droplets and the sizes of bubbles depend highly on the number of blades, the number of holes per blade and the rotation speed. The volume of splashed water, the sizes of water droplets, and the sizes of bubbles govern surface interaction areas between air and water. The wider surface interaction

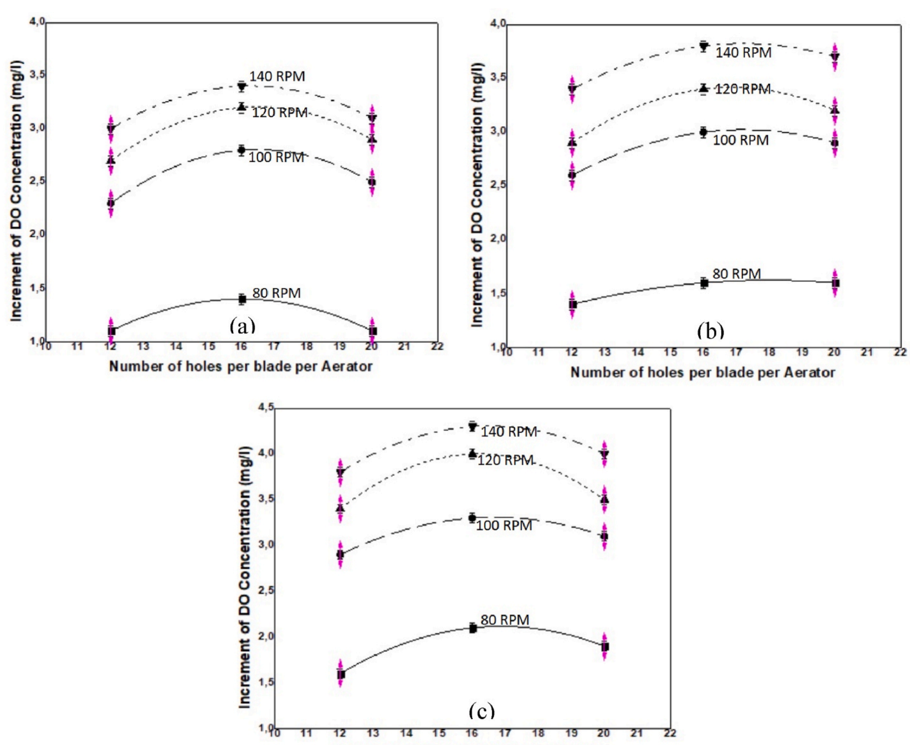

Fig. 9. Effect of number of holes per blade on the effectiveness of oxygen diffusion into water: (a) aerator four-blades, (b) aerator six-blades, and (c) aerator eight-blades.

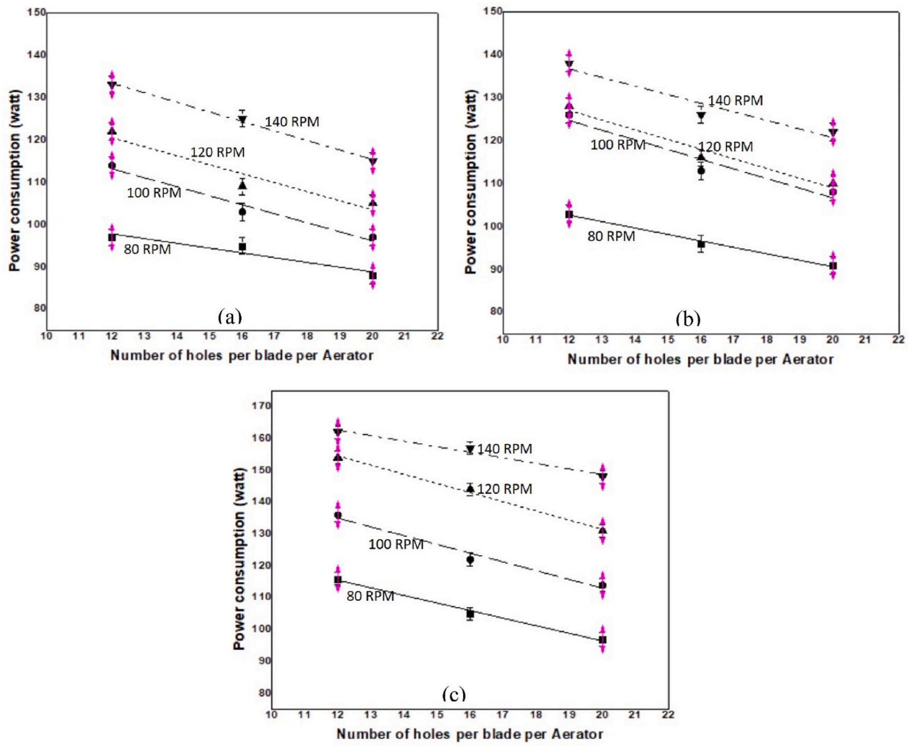

Fig. 10. Electric power consumption: (a) aerator four-blades, (b) aerator six-blades, and (c) aerator eight-blades.

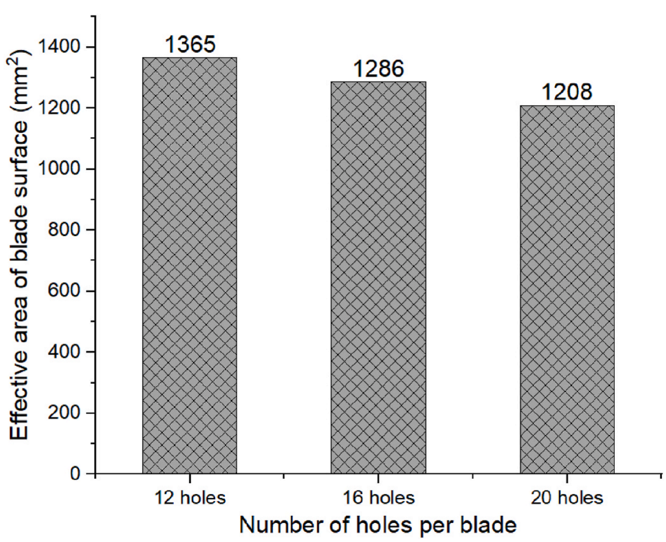

Fig. 11. Reduction of effective area of blade surface due to holes at the blades.

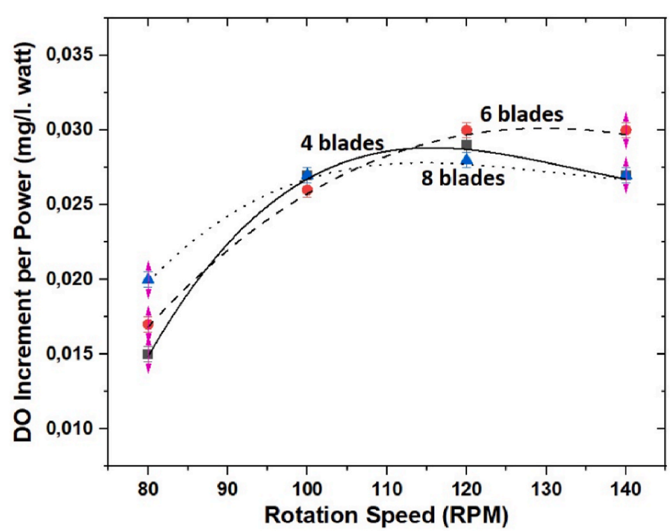

Fig. 12. Comparison of DO concentration increment per watt power consumption for the design of 16 holes per blade in the aerator four-blades, aerator six-blade and aerator eight-blades.

between water and air, the better oxygen diffusion into the water which results in higher DO concentration in the pond. Because diffusion of oxygen into water is mass transfer process, the process not only depends on surface interaction, but also duration of interaction.

The rotation of aerator increases the concentration of DO in the water of pond. The results of study display that the higher the rotation speed is, the bigger the increment of water DO concentration is. However, the relationship between rotation speed and increment of water DO concentration is not linier. At higher rotation speed, the DO concentration increments are less compared to that of lower rotation speed. It means there is a condition when increasing rotation speed does not affect the DO concentration meaningly. The study also found that the aerator which has a greater number of blades splashes more water to the atmosphere than that of the aerator which has less one. Hence, it can be concluded that the aerator with 8-blades in this study is the most effective one to increase DO concentration.

The number of holes per blade also affect the effectiveness of oxygen diffusion into water. Holes in the blades help to smaller the size of water drops and bubbles. If a volume of water is divided into several water droplets and bubbles, the area of surface interaction between air and water is widened. It results in better diffusion of air into water, and so oxygen. However, the results here indicate that after 16 holes the increment of DO concentration tend to reduce. It suggests that after certain condition, widening surface interaction owing to holes in the blade is taken over by reducing the volume water which is also due to the holes in the blade. In this study, it happened when the number of holes per blade was 16 holes. This claim is supported by the power consumption showing that the greater number of holes per blade is, the less amount of power consumption is, because it splashes less volume of water. Therefore, it must have a tradeoff between increasing the number holes per blade, and the volume of water splashed. In this research, likely the aerator with 8 blades, 16 holes per blade and rotated at 120 RPM is the most optimum one to enhance the DO concentration. However, if the concern is not only DO concentration enhancement but also energy efficiency, the aerator with 6 blades and 16 holes per blade and rotated at the rotation speeds of 120 or 140 RPM is likely better choice one.

Data availability

The data used support the findings of this paper are available from the corresponding author upon request.

CRediT authorship contribution statement

Ridwan: Conceptualization, Methodology, Validation, Resources, Supervision, Investigation, Data curation, Writing – review & editing, Project administration. **Rudi Irawan:** Conceptualization, Methodology, Validation, Resources, Supervision, Formal analysis, Visualization, Writing – original draft. **M. Alvin Mubarok:** Software, Investigation, Data curation, Visualization, Project administration.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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