AgriVoltaics World Conference 2024
Optimization and Economic Modeling
https://doi.org/10.52825/agripv.v3i.1341

Published: 24 Feb. 2025

Development of a Small Aquavoltaic System for Co-Production of Microalgae and Electricity

Hooman Pirtaj Hamedani[1], Shiva Gorjian[1,2,*], and Barat Ghobadian[2]

[1] Mechanics of Biosystems Engineering Department, Tarbiat Modares University (TMU), Tehran, Iran

[2] Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg im Breisgau, Germany

*Correspondence: Shiva Gorjian, Gorjian@modares.ac.ir; shiva.gorjian@ise-extern.fraunhofer.de

Abstract. In this study, a small aquavoltaic system was developed to simultaneously generate solar electricity and improve the conditions for the cultivation of microalgae. The key operating parameters of the system — dissolved oxygen, pH, water temperature and dead zones — were evaluated to gain insights into the dual benefits of integrating solar energy into aquaculture systems. In this context, the independent variable parameters of the rotation speed of a paddle wheel in the pond at 10, 20, and 30 rpm, the water depth at 15, 25, and 35 cm, and the reaction time at 0.5, 1 and 1.5 h were evaluated on May 9-15, 2023. The Response Surface Methodology, the Central Composite Design, and the experimental design were used to optimize the independent variables on the amount of dissolved oxygen for microalgae production in the open raceway pond. In this case, a maximum dissolved oxygen of 6.94 mg/l was achieved after 1 hour, at a water depth of 25 cm, and at a rotation speed of 20 rpm. Increasing the rotation speed from 10 to 30 rpm brought the dissolved oxygen content in the water to the desirable range of 6 to 7 mg/l and resulted in a decrease in stagnant areas from 21.05% to 9.16%. In addition, the shading effect of the photovoltaic system on the open pond was more than 80%, which led to a decrease in water temperature and dissolved oxygen.

Keywords: Aquavoltaic, Raceway Open Pond, Dissolved Oxygen

1. Introduction

While fossil fuels, diesel, and oil are common energy sources in aquaculture, it is important to note that there are sustainable alternatives that are being explored to reduce the industry's reliance on non-renewable resources. The integration of renewable energy sources is becoming increasingly important in aquaculture to promote environmental sustainability and reduce carbon emissions [1]. Agrivoltaics integrates solar energy systems with agricultural or aquacultural activities to maximize land use efficiency and promote sustainability. In this context, aquavoltaics — a subfield of agrivoltaics— pursues the dual objectives of solar energy production and aquatic resource management. Aquavoltaics, the combination of solar energy production and aquaculture can effectively meet the water, food, and energy needs of communities [2]. The integration of solar panels with water-based systems offers benefits such as efficient land use, reduced water evaporation, and potentially higher productivity in both electricity generation and aquatic product yield [3].

Research into microalgae has attracted a lot of attention due to their many potential applications, such as biofuels and food [4]. The successful productivity and growth of microalgae is highly dependent on the maintenance of suitable culture conditions [5]. The cultivation of microalgae is primarily carried out in open pond systems, i.e., in open circular channels in which a flow of liquid is generated by mechanical agitation with a paddle wheel [6]. The essential parameters for microalgae production in open raceway pond systems include water temperature, light availability, dissolved oxygen content and pH [3]. Maintaining an adequate level of dissolved oxygen (DO) in the water is crucial for successful microalgae production. Too much DO in the water can negatively affect the respiratory function of microalgae. Installing photovoltaic (PV) panels on an open pond reduces wind flow and prevents physical exchange between the aquatic environment and the atmosphere. This helps regulate oxygen levels and prevents saturation [7]. To ensure optimal oxygen levels for microalgae production in open pond systems, the implementation of mixing systems is the key factor. This mixing effectively reduces dead zones in open raceway ponds [6]. Château et al. [7] investigated a dynamic model to study the primary biochemical processes in a fish farm pond covered with floating photovoltaic (FPV) panels. The results showed that FPV arrays can have an impact on some of the essential parameters of the aquaculture environment, such as the reduction of DO content in the water. However, the electricity obtained from this integration is significant and can compensate for the losses in fish production. In another study, Kim et al. [8] proposed a FPV system for combined salt harvesting and electricity generation. They confirmed that the electrical output of the FPV system is better than that of the ground-mounted solar panels due to the cooling effect of the panels located near the water. Based on the studies conducted, contradictory results have been reported regarding DO levels in integrated aquaculture systems with PV modules. Some studies report increased DO levels in shaded systems [9], while others have found a lower DO content with increasing PV coverage [10].

This study contributes to the agrivoltaic framework by optimizing an aquavoltaic system designed for microalgae cultivation and electricity generation and demonstrates the potential of such systems to improve food and energy security. Additionally, there are no precise results in the literature on the control and improvement of parameters such as DO, water temperature, and pH in relation to microalgae production in open raceway ponds, especially with PV cover. Therefore, in this study, a small aquavoltaic system was constructed with a solar panel over the surface of an open raceway pond. The aim was to create, develop, and study the key factors that influence the aquaculture environment for microalgae, including oxygen levels, light availability, pH, and water temperature, while simultaneously generating solar electricity. To achieve the desired DO levels, minimize dead zones in the pond, and maximize the efficiency of the system, the Response Surface Method (RSM) was used to optimize the input parameters, enhancing both microalgae production and solar power generation.

2. Material and methods

The main components of the aquavoltaic system used in this study include: (1) an open raceway pond, (2) a mechanical paddle wheel, (3) a motor and power transmission system, (4) a motor speed control loop, and (5) a photovoltaic system (see Figure 1). An off-grid PV system was integrated to generate electricity and simultaneously cover the power requirements of the aquaculture facility's electrical equipment. The PV module model EU-M100 with a maximum output of 100 watts was integrated into the system. A 12-volt battery with a capacity of 60 ampere-hours and a 10-ampere charge controller were selected to power the system. The dimensions of the modules were adapted to the open pond to investigate the effects of shading on the parameters of microalgae production. A schematic representation of the open raceway pond used in this study can be found in Figure 2a.

2.1 Dead zones in open raceway pond

Dead zones in raceway ponds have a detrimental effect on fluid dynamics and mixing. They cause stagnation and the accumulation of solids, which leads to energy wastage [11]. In these ponds, there are dead regions even with only a single central baffle, as shown in (Figure 2b). In this case, Computational Fluid Dynamics (CFD) was used to simulate flow patterns and dead zones in open ponds with a length-to-width ratio of 2.5 at different velocities.

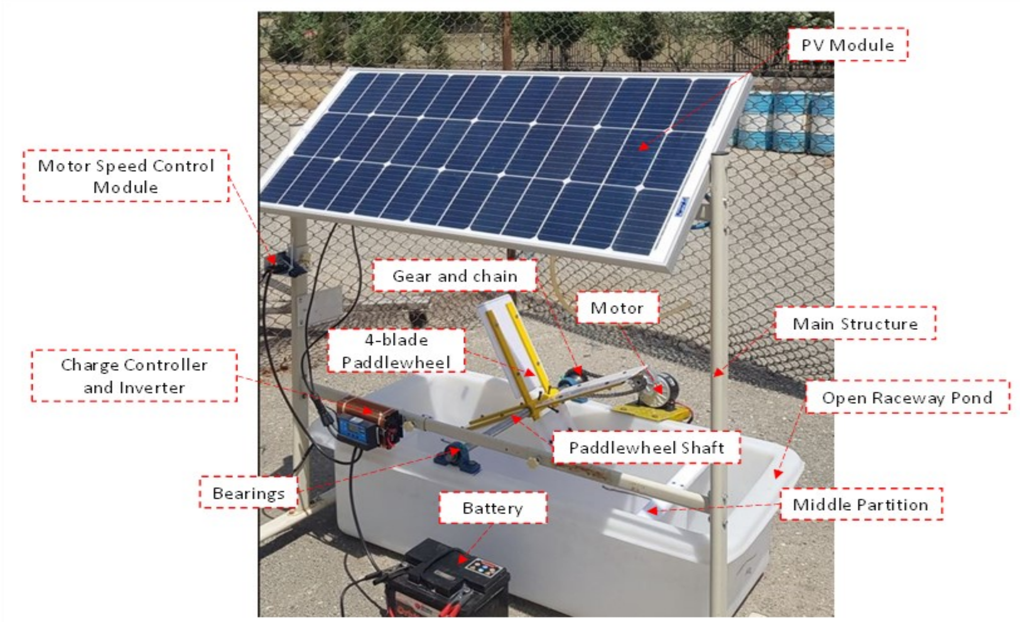

***Figure 1**. Photo of the constructed aquavoltaic system.*

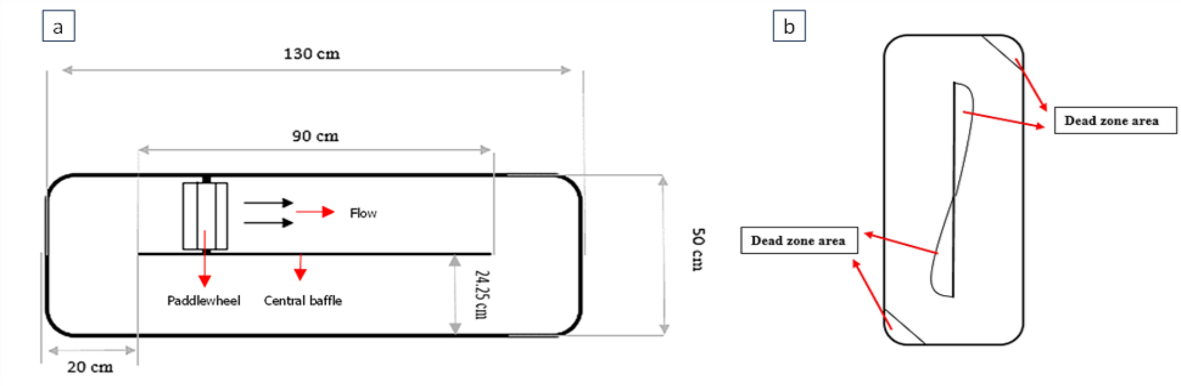

***Figure 2**. (a) Dimensions of the open raceway pond containing distinct parts, (b) Dead zones in the open raceway pond.*

2.2 Paddle wheel and power transmission system

Considering that the aquaculture system uses solar energy to power the electrical equipment of the open raceway pond for microalgae production, a DC motor with a gear ratio of 1:10 and a speed of 340 revolutions per minute (rpm) was used to provide the required power. The motor speed was controlled by pulse width modulation (PWM). In addition, a paddle wheel with four flat blades for mixing was designed and constructed. During the daily experiments, the solar radiation was measured with a solar current meter (model TES-1333). The measuring range of the device is 2000 W/m^2 and has a resolution of 1 W/m^2, it can measure solar radiation in the spectral range from 400 to 1100 nm.

Practical tests were carried out to investigate the effects of the defined variables on DO, water temperature, and pH value in the raceway pond for microalgae production. For this purpose, a Taiwanese water quality meter (model WA2017SD) was used for measurement. The measurement ranges of the water quality meter for DO is 0 to 20 mg/L with a resolution of 0.1 mg/l, for temperature from 0 to 50 °C with a resolution of 0.1 °C, and finally, for pH measurement, the range is 0 to 14 ppm. The measured environmental parameters and the corresponding measuring devices are listed in Table 1.

***Table1.** Measured environmental parameters and corresponding measuring devices.*

Parameter	Measuring device
Dissolved oxygen, mg/l	Water quality meter WA2017SD
Solar radiation, W/m²	Solar power meter TES 1333R
pH, ppm	Water quality meter WA2017SD
Wind speed, m/s	Anemometer AR856
Fluid velocity in the channel, m/s	Flow meter
Water temperature, °C	Water quality meter WA2017SD
Rotational speed of the paddlewheel, rpm	Tachometer DT2236

2.3 Response surface methodology (RSM)

The Design Expert 13 statistical software was used to optimize and analyze the experimental data using the Response Surface Method (RSM). The CCD method was used to optimize the variable factors for the input parameters in the aquavoltaic system to control the allowable DO range for microalgae production in the open pond. This model included 19 runs with 5 replicates at the central points.

3. Results and discussion

3.1 Effects of environmental factors and shading on water temperature and DO

The experiments were conducted from May 9 to May 15, 2023, from 9:00 to 16:00. During the tests, the variations in solar radiation, air temperature, and the shadow effect generated by the PV module were monitored to investigate the amount of DO, the variations in water temperature in the pond and the pH of the water. There were no significant differences between the evaluation days in the average amount of solar radiation. Therefore, the data from May 9 was used for the system evaluation in the Design Expert 13 software. The average variations in available solar radiation and air temperature on the evaluation days are shown in Figure 3. As can be seen in this figure, solar radiation has the highest values between 12:00 and 13:30. The decrease in solar radiation between 13:30 and 15:00 had no significant effect on the air temperature, and the air temperature showed a steadily increasing trend between 10:00 and 15:00.

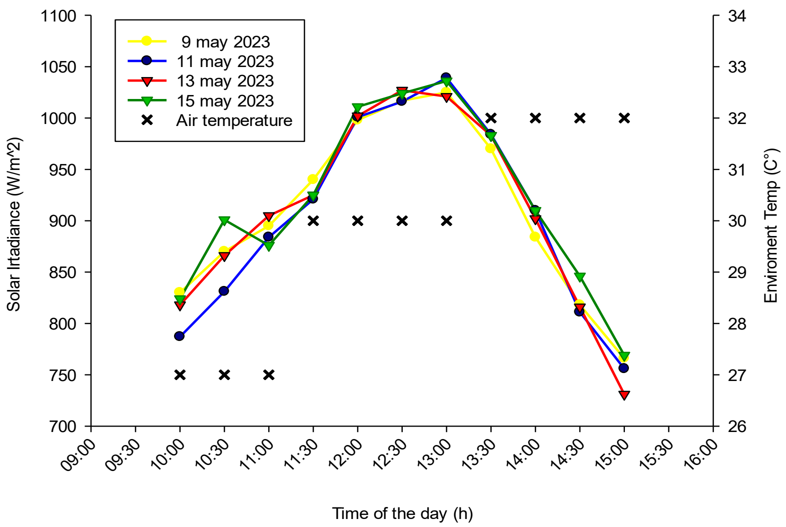

***Figure 3**. Variations in average solar radiation and air temperature on the days of the evaluation (May 9 to 15, 2023).*

As shown in Figure 3, the abrupt changes observed (+3ºC in 30 minutes) are likely the result of local atmospheric effects, such as intermittent cloud cover or fluctuations in solar radiation, which can cause rapid temperature changes. Despite these changes, the overall trend in ambient temperature remained consistent, with stable points observed during the measurement period. The installation of a PV panel on the raceway pond results in shading that contributes positively to controlling the essential parameters for microalgae production. The percentage shading of the solar panel on the raceway pond was more than 80% during the test period. The DO content in the solution was measured during the experiments without mixing due to changes in water temperature. The shade reduces the daily temperature fluctuations in the pond and under the solar PV module. The decrease in water temperature due to the shading effect of the PV module can directly affect the performance of DO and pH, as shown in Figure 4. In this figure, the DO content was measured as a function of the fluctuations in water temperature. In general, the DO content decreases when the water temperature in the raceway pond drops. The DO content is influenced by physical processes. As the PV module shadow's area increased further, the DO content showed a significant decreasing trend, as the DO was closely linked to the temperature of the water body [4]. It turns out that the PV module area can significantly reduce the surface temperature of the water, but the reduction is limited. Therefore, it is concluded that the DO content in shading tests was higher than in non-shading experiments, suggesting that appropriate shading does not adversely affect DO levels in the raceway pond.

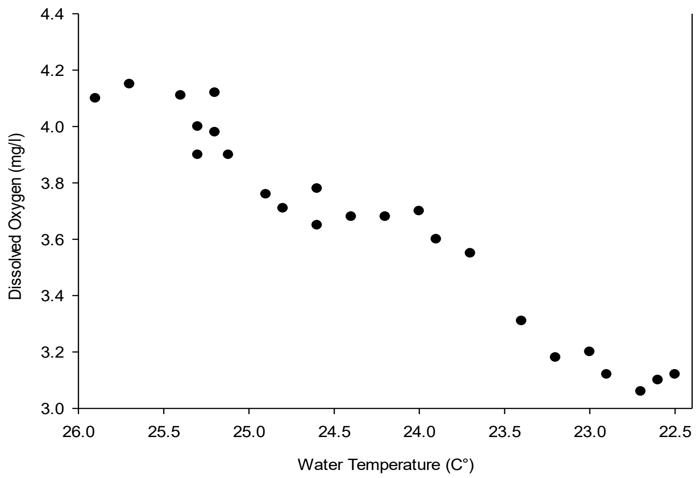

Figure 4. *Fluctuations in the water temperature in the raceway pond and their effect on the DO content during the day, without mechanical mixing by the paddle wheel.*

3.2 Results of RSM analysis based on experimental data

The RSM analysis is crucial for optimizing the operating conditions of the aquavoltaic system. By determining the relationship between the input variables (such as water depth and paddle-wheel speed) and DO content, this analysis guides the design of the system to maximize both microalgae productivity and energy efficiency. Table 2 shows an RSM design for the coded factors for the input parameters. DO content was measured in response to the input parameters. The same Design Expert 13 software was used to generate the analysis of variance (ANOVA) and response plots illustrating the relationship between the input parameters and the output response. The ANOVA table with values for the variables R^2, adjusted $R^{2,}$ and projected R^2 of 0.9355, 0.8839, and 0.6775, respectively, illustrates the effects of the input responses and the significance of the model. In addition, the signal-to-noise ratio should ideally be greater than 4. A reasonable signal was achieved by a reasonable accuracy of 14.511 for the DO content.

Table 2. *Designed and coded values of input parameters for RSM analysis.*

Variable	Units	Levels		
		-1	0	1
Depth of water	cm	15	25	35
Rotational speed	rpm	10	20	30
Reaction time	h	0.5	1	1.5

Equation (1) shows the final relation between the experimental parameters and real factors provided by the software:

$$DO\ (mg/l) = 6.61 - 0.1340\ A + 0.2050\ B + 0.1330\ C + 0.41\ AB - 0.1175\ AC + 0.1850\ BC - 0.5421\ A^2 - 0.2071\ B^2 \quad (1)$$

According to the ANOVA, there are interaction terms, namely water depth, paddlewheel rotation speed, and time response, which have a significant effect on DO content. It was also found that DO content is controlled with increasing flow rate and optimum depth within the allowable range of microalgae production in open ponds. The allowable range of DO content in water for microalgae production in an open space is 6 to 7 mg/l [12]. According to Figure 5, 3D diagrams of RSM for DO content, the highest DO content in water was obtained at a rotational speed of 20 rpm, a depth of 25 cm, and a reaction time of 1 hour. Increasing the speed of the mechanical paddle wheel in the 25 cm water depth range and 1.5 h reaction time increased the DO content of the water.

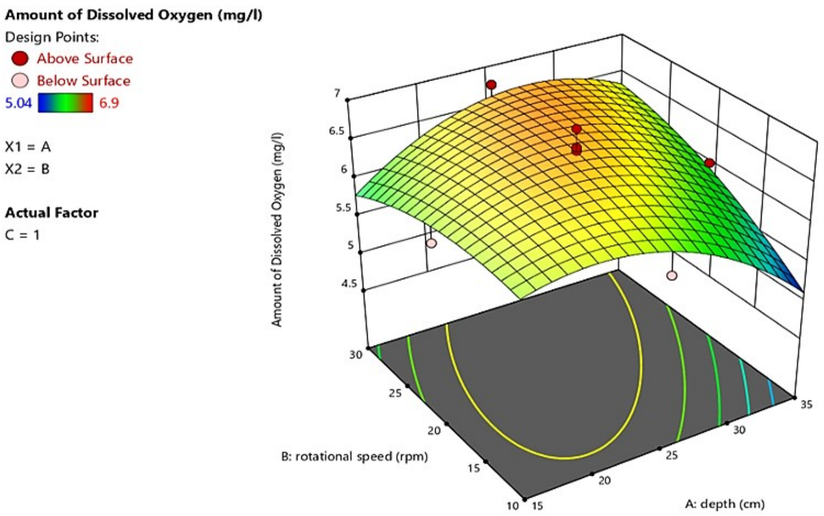

Figure 5. *3D diagram of the response surface showing the relationship between the rotational speed of the paddle wheel, the water depth, and the DO content.*

The results of the RSM analysis illustrate the potential of aquavoltaic systems to meet the dual challenge of optimizing aquatic productivity while maintaining compatibility with solar energy generation in an agrivoltaic system. By fine-tuning parameters such as water depth and paddlewheel speed, the system not only supports the cultivation of microalgae, but also demonstrates a scalable approach to agrivoltaics.

3.3 RSM results regarding DO content in dead zones

Dead zones in open raceway ponds have a direct impact on the cultivation of microalgae as they reduce oxygen distribution and mixing efficiency. This section examines how the aquavoltaic system minimizes these dead zones and thereby improves the overall performance of the system. ANOVA was used to examine the variables affecting DO content in the dead zones.

The lack of fit is not significant. Furthermore, the "Predicted R^2" of 0.7023 agrees well with the "Adjusted R^2" of 0.7948, i.e., the difference is less than 0.2, indicating that the modeling by the software is valid and that the model accurately predicts the actual data. The final equation resulting from the analysis is as follows:

$$\text{Dead Zone DO (mg/l)} = 5.14 - 0.1220\,A + 0.2160\,B - 0.0120\,C - 0.1150\,AB - 0.1404\,B^2 \quad (2)$$

Figure 6 shows that with a response time of 1 hour, a rotation speed of 30 rpm, and a water depth of 15 cm and 35 cm, the DO content in the dead zones decreased from 5.45 to 4.99. Increasing the rotation speed from 10 to 30 rpm caused the DO content in the water to fall into the acceptable range of 6 to 7 mg/l, resulting in a reduction in dead zones from 21.05% to 9.16%. These results show how the integration of an optimized mixing system into the aquavoltaic system improves the hydrodynamics of the pond and the oxygen distribution. This optimization helps to create favorable conditions for the cultivation of microalgae within the aquavoltaic system.

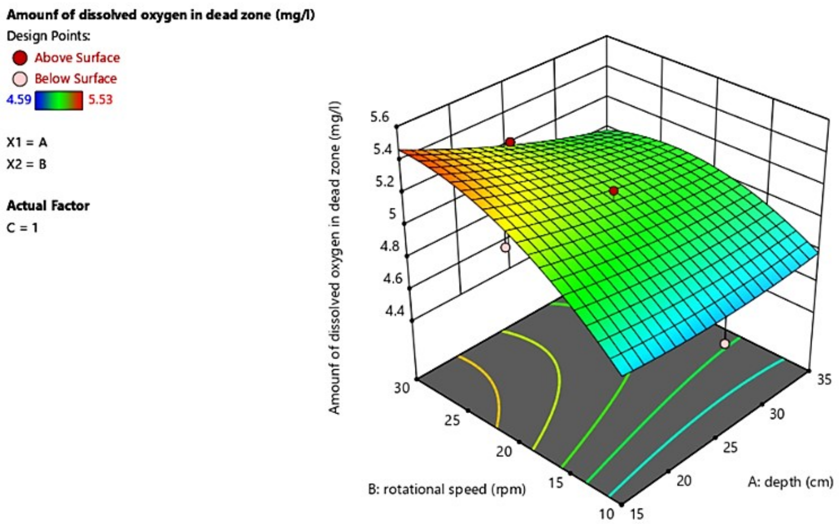

Figure 6. *3D diagram of the response surface plot for the rotational speed of the paddle wheel and the water depth for the DO value in dead zones.*

3.4 Electric performance evaluation of the aquavoltaic system

The system was simulated using PVsyst 7.1 software to predict the annual power generation of the modules installed in the aquavoltaic system. Figure 7 shows the diagram of the ratio between the energy supplied and the energy required based on the energy generated under STC conditions (solar radiation of 1000 W/m^2 and panel temperature of 25 ^{o}C). According to the power ratio diagram, the amount of energy produced under STC conditions during the year, i.e., in each month, represents 58.2% of the load required by the consumer. Simulations were carried out using PVsyst software to predict the annual power generation of the PV module integrated into the aquavoltaic system. The meteorological data used for the simulation was taken from METEONORM 7.3 to ensure an accurate representation of the local climatic conditions. The PV system, which consists of a 100 Wp solar module and three 60 Ah batteries connected in series, was calculated to generate a total annual energy yield of 249 kWh, covering 98.6% of the energy required to operate the system.

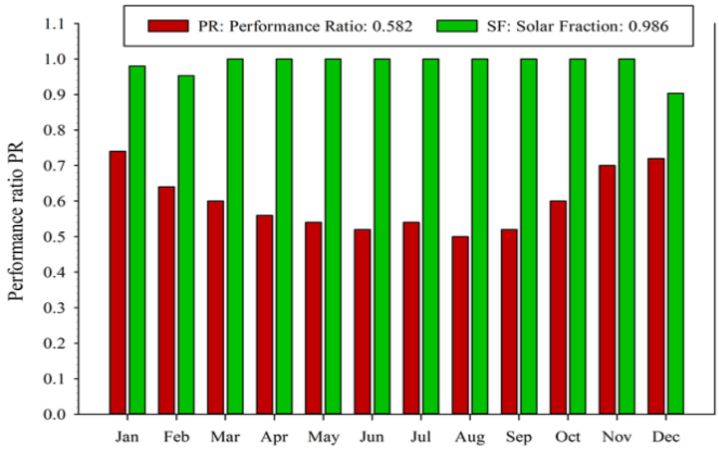

Figure 7. *Results of power generation simulations "Solar fraction and power ratio".*

The percentage error in predicting the output of the PV modules was found to be 4.71%, indicating a high reliability of the simulation results. The presence of water in the open race-course ponds had a positive effect on the long-term performance of the PV modules, as it provided a cooling effect, particularly in the summer months. This effect led to the highest increases in output in July, August, and September, which coincided with the peaks in solar radiation. Figure 7 shows the monthly trends in energy production and the solar fraction graph, illustrating the system's ability to meet its energy needs throughout the year.

4. Conclusion

In this study, an aquavoltaic system consisting of an off-grid photovoltaic system and an open raceway pond was designed and constructed to simultaneously generate solar power and meet the energy needs of the small microalgae cultivation system. The results showed that a significant reduction in water temperature prevents the values from dropping and keeps the pH value in the range of 6.5 to 7.5 ppm. The results also indicated that shading has a significant impact on controlling the temperature and pH range in the pond for microalgae production. Using the response surface method (RSM), a rotation speed of 30 rpm, a water depth of 31 cm, and a response time of 1.5 hours were determined to be the optimum conditions for DO content, resulting in a desirable percentage of 93.9%.

The DO in the dead zones was measured under optimal conditions. The percentage of dead zones at a water depth of 31 cm decreased from 21% to 9.16% when the rotation speeds of 10 and 30 rpm were increased. The DO content was measured to be 6.841 under optimal conditions, an increase of 61% compared to the same temperature conditions and optimal constant depth in a non-mixed aquatic environment. According to the results of the PVsyst simulation, the PV system with a 100 Wp solar module and three 60 Ah batteries connected in series would cover 98.6 % of the electricity required for the annual operation of the aquavoltaic system.

Data availability statement

The authors can make data available to publishers and readers upon request.

Author contributions

Hooman Pirtaj Hamedani: Methodology, Software, Writing - Original Draft **Shiva Gorjian:** Conceptualization, Writing - Review & Editing, Supervision **Barat Ghobadian:** Writing - Review & Editing, Supervision

Competing interests

The authors declare that they have no competing interests.

References

[1] S. S. Bautista-Monroy *et al.*, "Insights of Raceway Bioreactor Scale-Up: Effect of Agitation on Microalgae Culture and Reduction of the Liquid Medium Speed," *Applied Sciences (Switzerland)*, vol. 12, no. 3, 2022, doi: 10.3390/app12031513.

[2] S. Gorjian, R. Singh, A. Shukla, and A. R. Mazhar, "Chapter 6 - On-farm applications of solar PV systems," S. Gorjian and A. B. T.-P. S. E. C. Shukla, Eds., Academic Press, 2020, pp. 147–190. doi: https://doi.org/10.1016/B978-0-12-819610-6.00006-5.

[3] C. Hermann, F. Dahlke, U. Focken, and M. Trommsdorff, "Aquavoltaics: dual use of natural and artificial water bodies for aquaculture and solar power generation," in *Solar Energy Advancements in Agriculture and Food Production Systems*, Elsevier, 2022, pp. 211–236.

[4] J. C. M. Pires, M. C. M. Alvim-Ferraz, and F. G. Martins, "Photobioreactor design for microalgae production through computational fluid dynamics: A review," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 248–254, 2017.

[5] F. G. Acién *et al.*, *Photobioreactors for the production of microalgae*. 2017. doi: 10.1016/B978-0-08-101023-5.00001-7.

[6] F. Bux and Y. Chisti, "Algae biotechnology. Products and processes," *Green Energy and Technology*, no. March, p. 344, 2016, doi: 10.1007/978-3-319-12334-9.

[7] P.-A. Château, R. F. Wunderlich, T.-W. Wang, H.-T. Lai, C.-C. Chen, and F.-J. Chang, "Mathematical modeling suggests high potential for the deployment of floating photovoltaic on fish ponds," *Science of The Total Environment*, vol. 687, pp. 654–666, 2019, doi: https://doi.org/10.1016/j.scitotenv.2019.05.420.

[8] B. Kim *et al.*, "Aquavoltaic system for harvesting salt and electricity at the salt farm floor: Concept and field test," *Solar Energy Materials and Solar Cells*, vol. 204, p. 110234, 2020, doi: https://doi.org/10.1016/j.solmat.2019.110234.

[9] Y.-C. Cheng, T. S. Li, H. L. Su, P. C. Lee, and H.-M. D. Wang, "Transdermal delivery systems of natural products applied to skin therapy and care," *Molecules*, vol. 25, no. 21, p. 5051, 2020.

[10] P. Château, R. F. Wunderlich, T. Wang, H. Lai, C. Chen, and F. Chang, "Science of the Total Environment Mathematical modeling suggests high potential for the deployment of fl oating photovoltaic on fi sh ponds," *Science of the Total Environment*, vol. 687, pp. 654–666, 2019, doi: 10.1016/j.scitotenv.2019.05.420.

[11] Y. Chisti, "Raceways-based production of algal crude oil," *Green*, vol. 3, no. 3–4, pp. 195–216, 2013, doi: 10.1515/green-2013-0018.

[12] K. V. Supraja, B. Behera, and P. Balasubramanian, "Performance evaluation of hydroponic system for co-cultivation of microalgae and tomato plant," *Journal of Cleaner Production*, vol. 272, p. 122823, 2020, doi: 10.1016/j.jclepro.2020.122823.