Assessing the Efficiency of a Proposed Agrivoltaic System in Bangladesh to Ensure Multiple Uses of Land and Water

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ABSTRACT: A new conceptual agrivoltaic system has been designed, developed, and tested in this study to assure multiple uses of land for energy and food production along with a Carbon Capturing Device (CCD), which is not yet practiced. Dust deposition on the solar panel of agrivoltaic system can impair power generation. As a result, regular cleaning of the solar panel is required for improved panel performance. However, dry cleaning is not always appropriate for effective cleaning when sticky materials, such as bird droppings or dirt, deposition on the panel. Depending on the size of the PV system, wet cleaning will take a large volume of water. Therefore, this study aimed to investigate the proposed agrivoltaic system to explore the potential of sustainable ways of utilizing water for multiple applications. In the outdoor experiment, the developed prototype was tested. The amount of provided and recovered water was determined. Recycled water was used to grow Napier grass, water spinach, and fish. Within one month, yields from vegetation and fish were 8 kg and 426 grams, respectively. In addition, research has been conducted using carbon sequestration techniques to construct a CCD utilizing algae and recycled water. A comparative study of water and algae scrubbing found that algae washing removed 9.10% more CO_2 from the sample gas than water scrubbing. Additional biogas scrubbing experiments demonstrated that the developed algal CCD eliminated 78% of the undesired H_2S from biogas. The study finds that deploying the combined production technique for power and food can give a mutual advantage. The effective application of the aforementioned method might help to accomplish the following Sustainable Development Goals: SDG 13- Climate Action; SDG 7-Affordable and Clean Energy. It can provide environmental and economic sustainability by producing clean energy and conserving water. It is obvious that more research in this area is necessary, and the outcomes for various crops and geographical regions of the country and further improvement scopes should be investigated to determine the potential of agrivoltaic farming in Bangladesh.

Keywords: Agrivoltaic; Wastewater Reutilization; Multiple Land use; Carbon Capture Device; SDG

INTRODUCTION

Ever since the industrial revolution, there has been a progressive increase in the strain on land for food and energy production. The huge increase in both energy and food production has enabled the world's population to triple in a decade. To provide food and power for this rising population, a considerable portion of the land has been recommended for dedication to food and energy production (Food and Agriculture Organization, 2017). Meeting the need for increased energy and food output in the next decades, on the other hand, is likely to be more challenging than it has been thus far. The second concern entangling many natural processes involved in contemporary energy and food production is global climate change. Food production is one of the primary causes that is aggravating global climate change through biodiversity loss through habitat degradation, the overexploitation of species through farming, and the pollution and extensive utilization of land and water resources. Due to extensive agricultural activities, lands undergo soil erosion and chemical contamination from chemical fertilizers. On the other hand, energy production from conventional resources is also affecting the global climate by being the major source of greenhouse gas emissions. Notwithstanding these overexploitations causing an enormous impact on the environment, the existing food and energy production system is expected to expand at a rapid pace to keep up with projected increase in population. As a solution for the above-mentioned difficulties, the integration of solar power production facilities on agricultural lands can be symbiotically beneficial in energy and food production. Many recent research efforts have thus focused on strategies to improve solar energy's environmental compatibility. The integration of solar power production with other land uses has demonstrably maximized the shared benefits of preserving ecosystem balance (Walston et al., 2018) through soil and water retention, carbon sequestration, and

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potentially improving surrounding agriculture (Walston et al., 2021). An experiment performed on an agrivoltaic system has shown increased land productivity in the range of 35-73% (Dupraz et al., 2011). It has widened the possibility to utilize the drylands for agrivoltaic system development. It offers benefits that are shared by food, energy, and water consumption in dry lands (Barron-Gafford et al., 2019). The balance of water uses shifts as a result of the reduction in solar radiation under the PV panel, leading to water savings in agricultural activities (Weselek et al., 2019).

An agrivoltaic system may suffer from efficiency loss due to dust deposition and the efficiency of PV modules may reduce by 10 to 15% due to this external cause. Investigations on the effect of dust deposition on solar modules at several locations have suggested that there were significant efficiency reductions. A loss of 20% efficiency in Germany (Christian et al., 2015), and 32% of efficiency reduction in the Algerian Sahara Desert in only 6 months of no cleaning (Mostefaoui et al., 2019) was recorded. Natural means for cleaning solar panels (Rainfall, wind) cannot be controlled (Hachicha et al., 2019; Gholami et al., 2018) and it offers only 1% of performance improvement (Şevik and Aktaş, 2022). Some other dry-cleaning methods i.e., mechanical methods, electrostatic removal of dust, and self-cleaning nanofilm coating methods cannot clean sticky objects like bird droppings or muddy substances from the panels (Jamil et al., 2017; He et al., 2011, Alagoz and Apak, 2020, Said et al., 2018; Park et al., 2011).

Therefore, this study proposes an approach to the improvement of the overall efficiency of the agrivoltaic system with a solution for above mentioned situations. A combination of dry and wet cleaning methods has been applied for proper cleaning of solar panels. For water conservation, wastewater generated from wet cleaning has been planned to utilize for fish and crop production. Additionally, an algae-based carbon sequestration device (CCD) has been experimented with the developed system, which could be further utilized for attaining environmental sustainability through carbon sequestration from the surrounding air.

METHODOLOGY

To evaluate the effect of the agrivoltaic system, a model of solar photovoltaic system was designed. Photovoltaic systems were installed on a mounting structure above the ground. A water catchment was attached to the solar panels. With this arrangement, wash water from the solar panel can be collected for further use. According to the proposed model, the solar PV system is combined with an integrated system to facilitate vegetable production and fish farming. For this, two water tanks of 30-liter capacity are attached to the system. The first tank placed underneath the panel was used for cultivating fish and conserving the solar panel wash water. The second tank that was kept aside was used to reserve the excess water. Besides the system, a place was chosen for vegetable plantation.

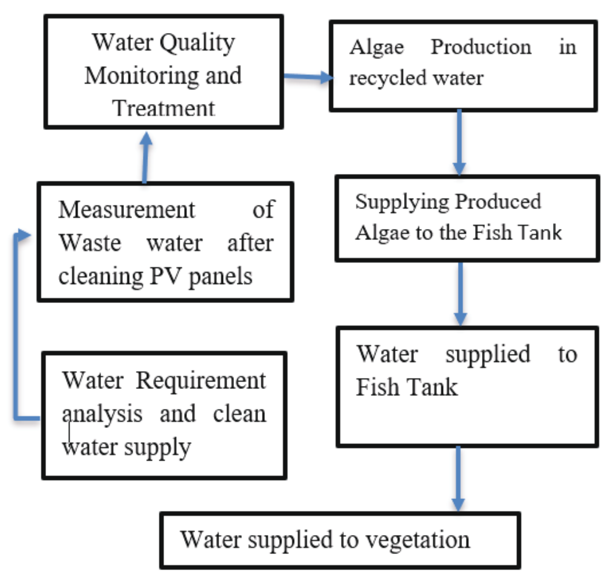

Figure 1: Overview of Research Methodology

The water supplied for solar panel cleaning and the collected amount of water are measured. Collected water is supplied to the fish tank and vegetation areas were measured. For fish cultivation underneath, the solar panels, recirculating aquaculture system (RAS) is chosen (Fig. 2).

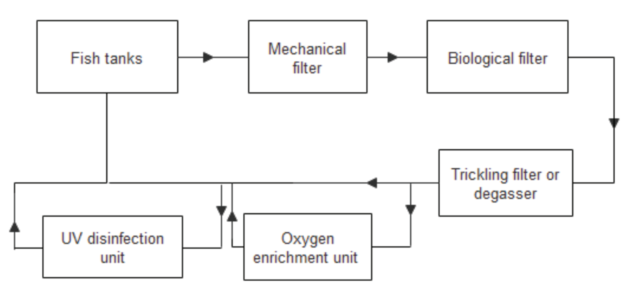

Figure 2: Basic Line of Action Diagram of RAS Fish Farming

Water from the fish tank was drained to the second tank and supplied to vegetation when required. The proposed system also includes a carbon-capturing device (CCD). It was made from abundantly available algae. Algae have some unique features. The external supply of carbon-di-oxide can multiply its growth up to ten times. A device was developed that uses solar energy to pump atmospheric carbon-dioxide into algae culture tubes and at the output the device will provide cleaner air. In algae, photosynthesis releases oxygen and can be called "oxygenic photosynthesis". CO_2 is converted into lipids and other hydrocarbons in this process, explaining the designation of "CO_2 capturing process". In oxygenic photosynthesis, water is the electron donor, and oxygen is released after hydrolysis. The equation for photosynthesis can be written as follows:

$$H_2O + CO_2 + Photons\ (light) \rightarrow [CH_2O]_n + O_2$$

Microalgae do not require a vascular system for nutrient transport, as every cell is photoautotrophic directly absorbing nutrients. All microalgal cells act like sunlight-driven cell factories. This explains the massive and rapid CO_2 consumption of algae. The setups were reutilized to conduct an experiment on biogas to reduce the amount of Hydrogen Sulphide present in the sample biogas.

$$(\mathrm{H_2s} + \mathrm{o_2} \Rightarrow \mathrm{so_4^{2-}}).$$

Experimental Setup

Figure 3 shows the proposed model of the system that combines solar power production, crop cultivation in the space between panels, and fish production underneath the panels.

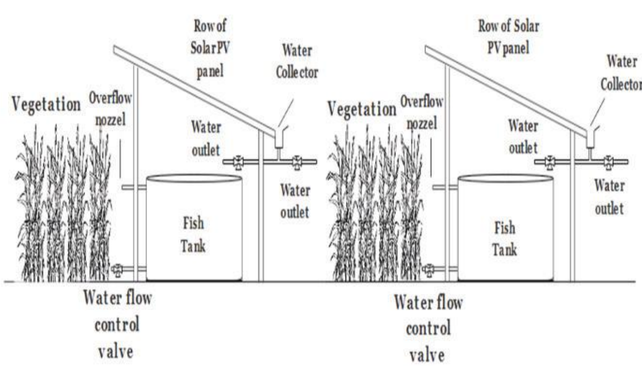

Figure 3: Overall Illustration According to the Proposed Model

Fish Tank and Vegetation Area: Figure 4 shows a practical model of the proposed system developed in the premise of the Institute of Energy, University of Dhaka. A water conservator has been installed under the panels. A system has been installed with the solar panel to collect all the water used for cleaning so that the wash water can be utilized later for both crop and fish production. The RAS method has been applied to the system for fish production. In RAS, a collection of biological and mechanical filtration devices recirculates more than 90% of the water. A mechanical filtration chamber is attached in between the water collector and reservoir to filter the washout dust from the top of the solar panel, fish residue, and leftover fish food. The biological filtration chamber is designed to facilitate a continuous flow of water. It consists of lava rocks or ceramic rings to ensure perfect abidance of denitrifying bacteria. These denitrifying bacteria were utilized in the formation of nitrates from ammonia produced from the leftover foods and fish residue. It is an aerobic treatment method that uses microorganisms to extract organic matter stuck to a medium. One of the most critical metrics of water quality is the dissolved oxygen level of the water of fish tanks since oxygen is an essential condition for all species that live in the water and have an aerobic form of respiration. To ensure the proper level of dissolved oxygen in water, an oxygen enrichment unit is added. A UV sterilizer or UV disinfection unit is used to control infections by preventing microorganisms from passing through the water from one fish to another. Microorganisms that are free-floating can be disrupted by UV light. The vegetation which needs low to medium sunlight can be grown easily in the inner space between two solar arrays. The solar panel was placed a few feet above from ground level to provide space for plant growth. There are two valves acting as the overflow valve and the water restoration valve respectively.

Figure 4: Practical Model of the Proposed System

Measurement of Water Quality: At the beginning, water used for solar panels was examined to identify the changes in water quality. pH and TDS of water were measured for seven days. For better yields, maintaining the water quality is a must. For this reason, water quality (TDS and pH) has been continuously monitored. pH was measured to keep the acidity or alkalinity of water under control. The comfortable range for perch fish is 5.5 to 8.5. Before releasing fish, TDS and pH were measured of panel cleaned water several times on different days. Generally, TDS around 850-950 ppm, is suitable for perch fish. pH of the water was around 6.3 to 8.2, which can be considered ideal for perch fish.

Collection of Microalgae: Algae for the experiment, was collected from the shallow ditches of the Dhaka University area to use it as inoculum for algae culture. It was then put in a centrifuge machine in the lab. The centrifuge machine was set to 1800 rpm for 30 seconds on average. At the end of each cycle, microalgae present in the water sample was separated and piled up at the bottom of the tubes. The algae sediment was collected by removing the water.

Algae Culture Setup: The collected algae inoculum was kept in a reservoir to be used for algae culture. Wastewater collected from the solar panel cleaning is used as the water source. Air pump along with air pipe and air stone was used to prepare the setup to provide a continuous flow of air in the pot. A very small amount of NPK fertilizer was added on the very first day to assist the growth of algae. The setup was placed beside a window to ensure enough sunlight. To find out the gradual growth of algae, lux meter app was used. Firstly, measurement was taken beneath the light source. Then, measurement was taken beneath the algae tube. The light source, lux meter, and algae tube were kept aligned to minimize errors in reading. The difference in lux indicates the light absorption by algae and confirms the gradual bloom. The denser the algae solution, the more it will consume the light. The main parts of the developed system were photo-bioreactor, valves, dc pump, solar PV, etc. In this project, tubular tank photo-bioreactors were developed. Transparent acrylic materials were used for this purpose. A dc pump was used to pump fluid (air/ liquid) into the photo-bioreactor. No external electricity was required to run the pump as a solar panel was connected to the pump through a regulated dc power supply. Algae was poured into the photo-bioreactors from the 'Liquid In' point. The sunlight penetrated through the transparent acrylic body and triggered photosynthesis. At the 'Gas In' point, CO_2 enriched biogas was injected into the inlet of the pump. The outlet was connected to a pipeline such that it leads to the inside of the first photo-bioreactor. In the proposed system, five such photo-bioreactors were cascaded in parallel through pipes and valves. The last reactor had a 'Gas Out' point where CO_2 derived gas was collected. In this experiment, available biogas was used as sample carbon enriched gas. And to save time and complexity a dc pump was connected to the variable dc source. A variable dc source is used to simulate solar PV panels. The scrubbing cycle lasted on an average of 20 minutes. A gas analyzer was utilized for measuring the amount of carbon di oxide gas along with H_2S in the sample. Water can absorb CO_2. In consequence, we will scrub the sample gas with both pure water and algae to find out the difference.

RESULT AND DISCUSSION

Measurement of Cleaning Water Quantity

Table 1 shows the amount of water supplied and water recovered at each stage. To find out the maximum recoverable amount of water, an experiment was done at the beginning. With an average flow rate of 20 liters per minute, water was drawn from an external reservoir. Primarily water was supplied for solar panel cleaning and then water was recovered in the water collector. On an average of 16.44 and 15.6 liters of water was supplied to the RAS fish tank and the vegetation area.

Table 1: Amount of Water Recovered during Various Stages (in Liter)

Date	Water supplied	Solar panels	Water collectors	Fish tanks	Vegetation area
Day 01	20	20	16.5	16.1	16
Day 02	20	20	16.2	16.1	15.9
Day 03	20	20	14.8	14.3	14.3
Day 04	20	20	17.9	16.1	15.9
Day 05	20	20	18	17.4	17
Day 06	20	20	16.1	15.3	15.2
Day 07	20	20	15.6	15	14.8

Analysis of Fish and Vegetation Growth

The perch fish (*Anabas testudineus*), which is locally known as Koi fish, is chosen for the experiment to cultivate it in the fish tank. Water spinach and Napier grass were considered for the experiment.

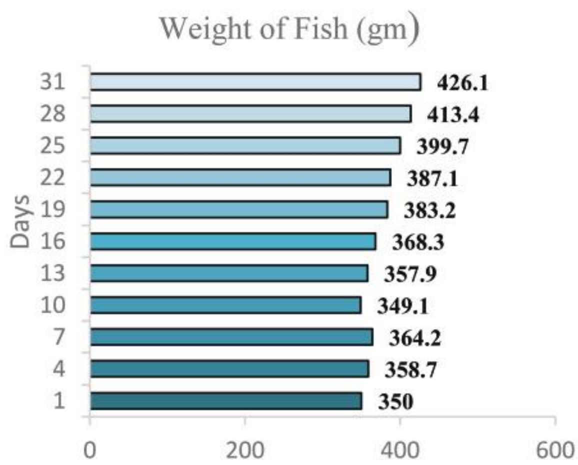

Figure 5: Growth of Fish in the Experimental Setup (in grams)

The Growth Rate of Perch Fish: In the study, Vietnam Koi was considered for the experiment. Weight data was measured after every three days. Thirteen (13) Vietnam koi fish were taken. Total of 13 koi fishes were kept separately in two tanks but finally, four of the shoals died. For this reason, the fish growth rate was observed unstable in Figure 5. After 30 days of the experiment, the average weight gain of Koi fish is around 207gm.

The Growth of Vegetation: As vegetation, Napier grass and water spinach were selected. Figure 6 shows that Napier grass and water spinach planted in the system had steady growth. The initial height of the crops was 13 cm and the final height was 170 cm. Total yields from Napier grass and water spinach were 5000 grams and 3000 grams respectively.

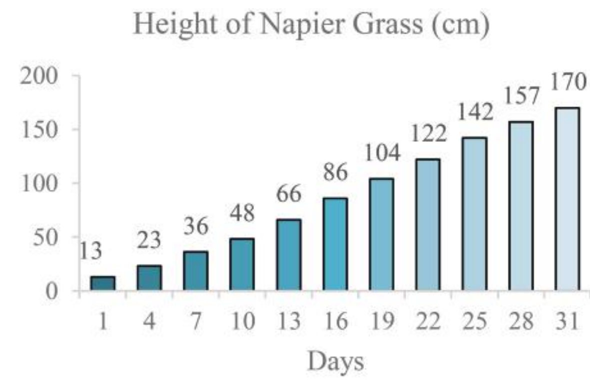

Figure 6: Growth of Napier Grass in the Experimental Setup (in Centimeter)

Change in Water Quality: From Figure 6, water quality did not change drastically in this time period. Water used for solar panel cleaning automatically replaced the water in every three days later on a regular basis. As a result, the pH and TDS level of water in the fish tank remain in tolerable range. pH records show that it has fluctuated within the range of 7.5 to 8.1 (Fig. 7) and TDS of the water was within 855 to 953 ppm.

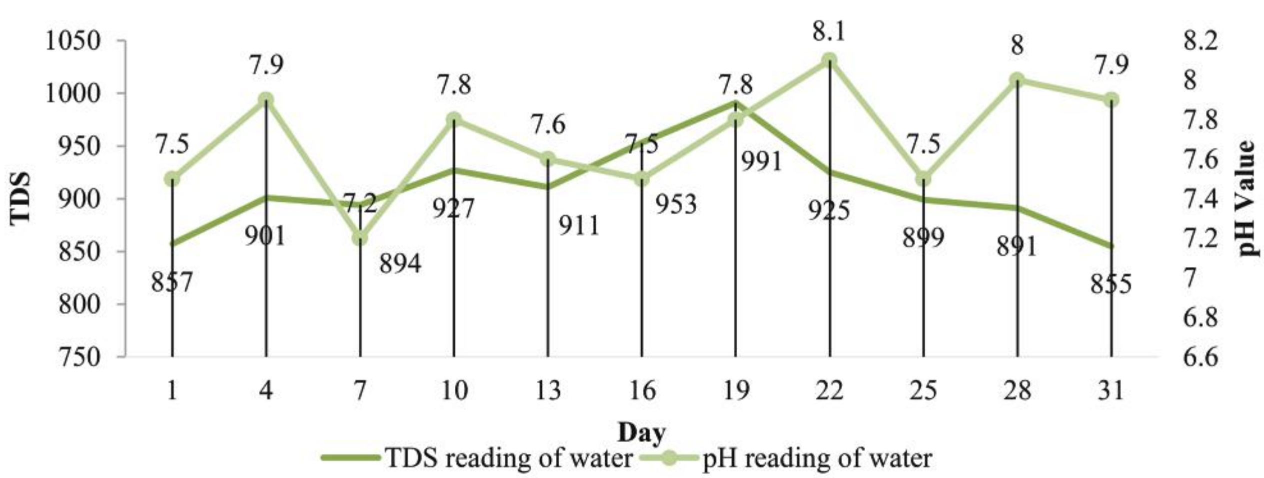

Figure 7: Change in pH and TDS (in ppm) in Wash Water after Solar Panel Cleaning

Carbon Capturing and

Desulphurization Device

Water Quality: Figure 8 represents the changes in the amount of Total Dissolved solids (TDS) before and after the cleaning of solar panels. Before cleaning, supply water TDS readings were 189, 154, 244, 307, 187, 130, and 243 ppm respectively. But after cleaning, TDS of wash water was recorded as 812, 924, 902, 876, 821, 833, and 826 ppm respectively. Variation in TDS indicates that the amount of dust deposition is dependent on the period of time taken for cleaning. Figure 9 shows the amount of variation in the pH of the rinse water. The result shows that pH of the wash water had a little change before and after the cleaning. Value for pH was highest recorded at 8 whereas it remained near 8 in almost all cases. An average difference in pH was 0.42 before and after the washing of solar panels. According to some literatures, 8.2 to 8.7 is the optimum pH for algae culture and high TDS can help algae bloom.

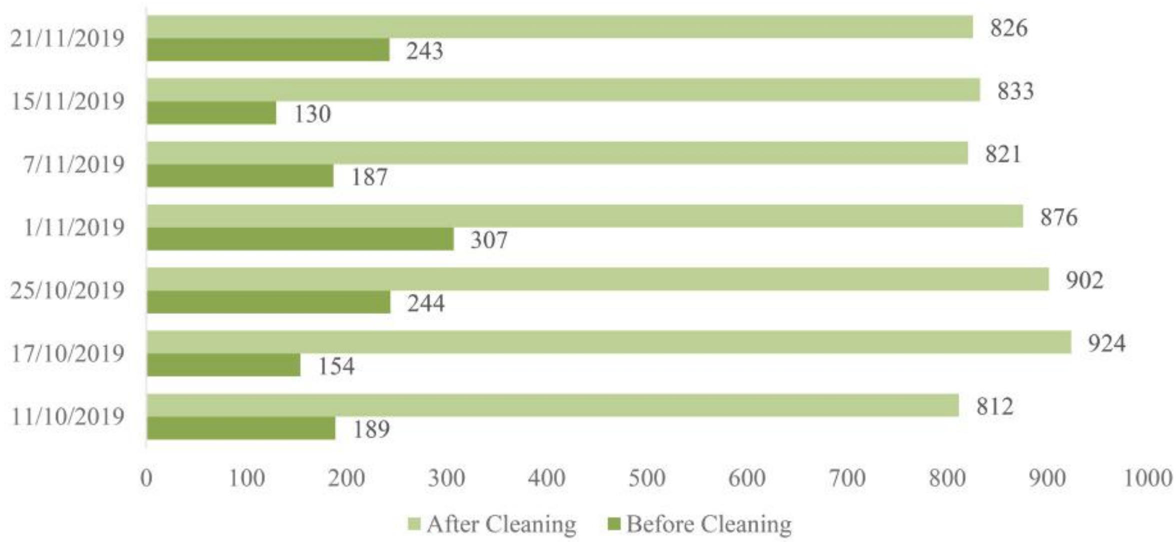

Figure 8: Change in TDS (in ppm) in Wash Water

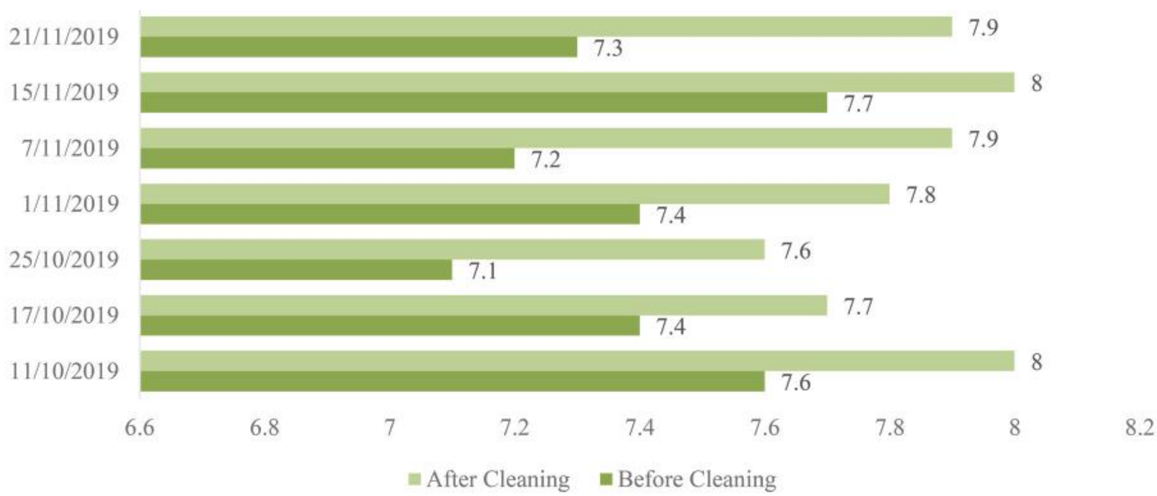

Figure 9: Change in pH in Wash Water

The setup was placed beside the window to ensure enough sunlight. To find out the gradual growth of algae, lux meter app was used. Firstly, measurement was taken beneath the light source. Then, measurement was taken beneath the algae tube. The light source, lux meter, and algae tube were kept aligned to minimize errors in reading. The difference in lux indicates the light absorption by algae and confirms the gradual bloom. Lux is the unit of illumination per unit area. The denser the algae solution, the more it will consume the light. There are other sophisticated methods for measuring algae growth. But it seems easier and cost-effective way of measuring. Figure 10 shows a gradual increase in lux difference since from the beginning of the experiment. In the beginning, the number of algae present in a container. But on day 18, lux difference has increased up to 581 and the algae solution was ready for using it in the photo-bioreactor. Figure 11 shows the effect of water scrubbing on biogas. Water scrubbing has the potential to reduce the amount of carbon dioxide.

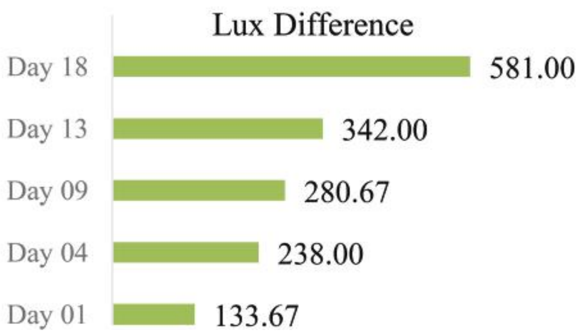

Figure 10: Gradual Increase in Lux Difference due to Algae Bloom

On an average 5% reduction of carbon dioxide was achieved from the experiments. The highest 6% reduction of carbon dioxide was possible from water scrubbing and the lowest reduction of carbon dioxide was 4.20%. Figure 12 shows the effect of algae scrubbing on biogas. It has been found that algae scrubbing has better results in respect to water scrubbing. On an average, 12.45% of carbon dioxide was reduced from biogas by algae scrubbing. The highest 14.3% of carbon di oxide was possible to reduce by algae scrubbing during the experiment and the lowest reduction rate of carbon di oxide by algae was 10.6%.

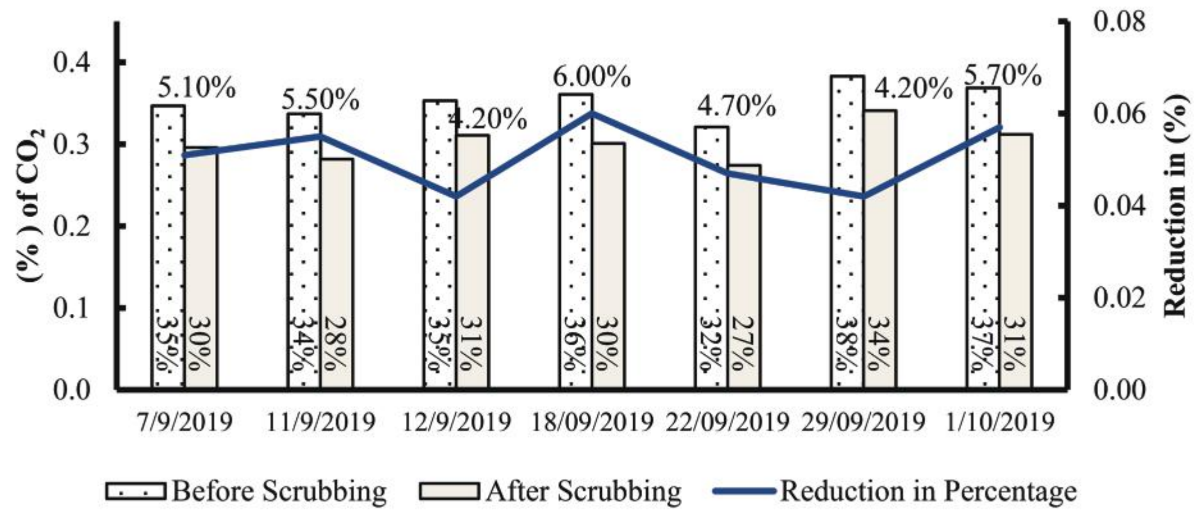

Figure 11: Reduction of Carbon Dioxide by Water Scrubbing

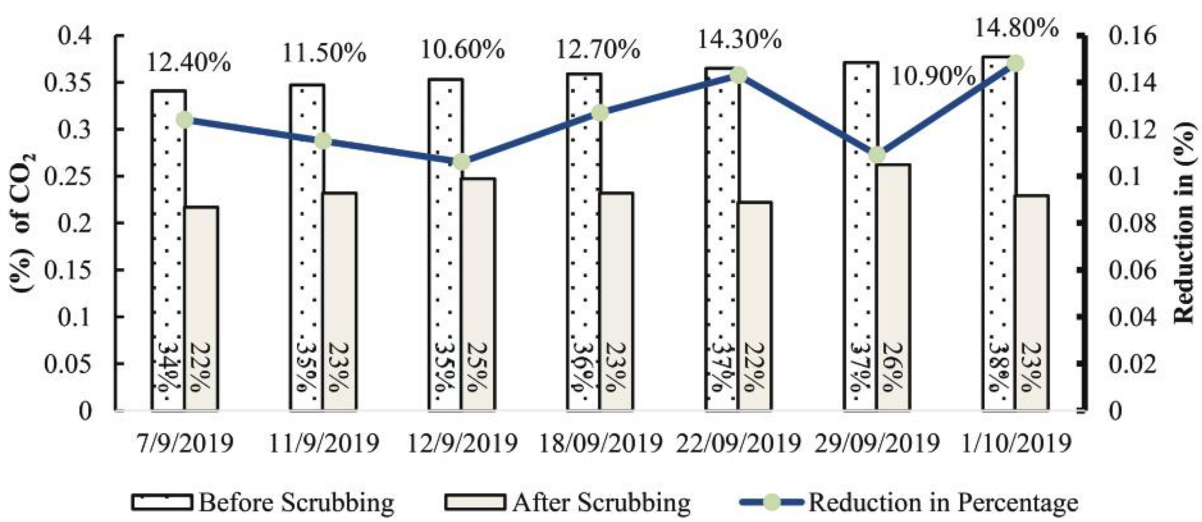

Figure 12: Reduction of Carbon Dioxide by Algae Scrubbing

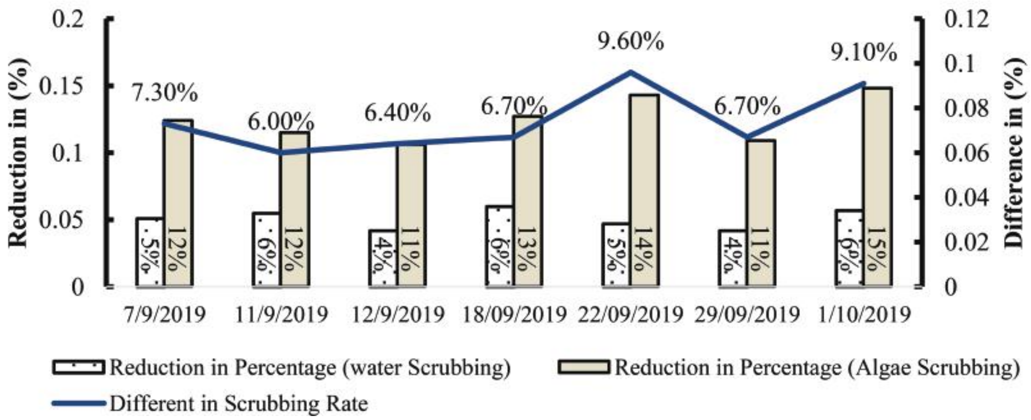

Figure 13: Comparison between Water Scrubbing and Algae Scrubbing

Figure 13 shows the comparison of the effectiveness of water and algae scrubbing in the reduction of carbon di oxide from biogas. In each case, algae scrubbing is showing a better outcome than water scrubbing. The difference between the carbon di oxide reduction percentages by water and algae shows that whereas the water scrubbing was only 5% (average) efficient, algae scrubbing can attain near about 15% efficiency. Experiment on the Separation of H_2S concluded in Table 2 shows that scrubbing of biogas has significantly reduced the amount of H_2S gas. The highest amount of H_2S reduction percentage was 78% and lowest was 59%. On average, the reduction of H_2S in the biogas was more than 60%.

Table 2: Data for Desulphurization Rate (Amount of Hydrogen Sulphide (in PPM))

Date	Before Scrubbing	After Scrubbing	Difference (%)
7/9/2019	22	9	59.09
11/9/2019	43	16	62.79
12/9/2019	31	11	64.52
18/09/2019	30	11	63.33
22/09/2019	38	8	78.95
29/09/2019	47	17	63.83
1/10/2019	32	17	46.87

CONCLUSIONS

This study used a new approach to assess prioritized environmental challenges and opportunities for solar technologies in the context of the tremendous growth envisioned in solar PV adoption. Utility scale solar power production facility requires a vast quantity of land. Although Bangladesh government encourages adoption of solar technology, the regulatory framework does not support its installation of such technology everywhere to limit biodiversity and agricultural land losses. This study suggests for adoption of the agrivoltaic system, which accommodates both agricultural and electricity production. This study has revealed that wastewater generated from solar panel cleaning can be applied for multiple applications. Fish production possibility was examined in this study. The initial weight of the fish was 350 gm, which increased up to 426 gm at the end of the experiment. This study has also found that wastewater can be utilized for crop production. Yields from the Napier grass and water spinach were in total 8000 gm during the experiment. Napier grass and water spinach grow very quickly. Thus, it is possible to get more yields. This study has also explored the potential use of algae culture in wastewater. Algae were used for developing a natural carbon capture device for sequestrating carbon from the biogas for experiments. Similar experiment was used to reduce the amount of H_2S from biogas. Water and algae scrubbing were tested. Algae scrubbing was found more effective than water scrubbing. Whereas water scrubbing could only reduce carbon dioxide concentration by 5% but algae scrubbing reduced more than 14% of carbon dioxide. In addition, a similar study has shown efficiency in reduction of H_2S from biogas was 60%. However, the limitations of this study are the lack of R&D efforts and the constraints of time in conducting deep investigations. This study was based on a prototype, but further study is required on this in a utility scale solar power plant to enrich the findings in terms of locations, implementation, land use, and water conservation.

RECOMMENDATION

The agrivoltaic system incorporates renewable resources, sustainability in land use and biodiversity protection allowing for symbiotic coexistence in energy and food production. Therefore, a pilot project on the agrivoltaic system and conducting a full-scale experiment in a commercial site is necessary. A techno economic and parametric analysis would help in assessing the scalability of the system and benefits of combined production of energy and food from an agrivoltaic system.

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