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RESEARCH ARTICLE

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Study of solar irradiance and performance analysis of submerged monocrystalline and polycrystalline solar cells

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Abstract

Underwater photovoltaic (PV) systems supported with modern-day technology can lead to possible solutions for the lack of long-term power sources in marine electronics, navy corps, and many other remotely operated underwater power systems. Currently, most of these systems are powered by conventional batteries, which are bulky, costly, and require periodic maintenance and replacement. Harnessing the underwater Solar energy by using Solar PV cells is simple, reliable, and leads to tremendous advantageous as water itself provides cooling, cleaning, and avoid challenges due to land constraints. The present work encompasses an experimental study on Solar radiation in water and its changes with varying water conditions. Accordingly, the performance of monocrystalline and polycrystalline silicon solar cells with different submerged water conditions and water depths up to 20 cm has been studied. Most importantly, these studies have been carried out with different types of water conditions, consisting of salinity, bacteria, algae, and other water impurities. These investigation results manifest that the percentage decrease of maximum power output in monocrystalline and polycrystalline Solar cells is 65.85% and 62.55%, respectively, in the case of ocean water conditions, whereas in deionized (DI) water conditions, it is 63.06% and 60.72% up to 20 cm. Such results conclude that valuable amount of Solar energy is can be explored underwater. These experimental studies pave the way to explore further to utilize Solar PV cells efficiently in underwater conditions.

KEYWORDS

monocrystalline Solar cell, PDMS (polydimethylsiloxane), photovoltaic (PV) technology, polycrystalline Solar cell, underwater Solar radiation, water salinity

1 | INTRODUCTION

Solar photovoltaic (PV) cells are one of the most substantial technologies in renewable energy sources, which are simple and reliable to utilize in many different ways. The futuristic approach is to utilize them in submerged water conditions to power the underwater sensing systems and monitoring devices, which can be a considerable advantage in marine electronics applications. Several offshore/onshore equipment, like water inspection systems, underwater vehicles (UVs), and other sensors, have a vast requirement of sustainable power sources. Batteries or onshore sources power these types of equipment, but certainly, Solar PV has the tremendous potential to power this equipment powered with modern electronics. Around 40 years ago,[1] the PV cells and its performance under the ocean water environment were studied, and the underwater applications for the Solar cells posed a practical challenge, particularly in the applications mentioned above as the output power from the solar cells is relatively low. Moreover, in the submerged conditions, the Solar cells with electrical connections need to withstand hydrostatic pressure and also remain dry and free of biofouling, which leads to the limitations for utilization of the Solar cells underwater, which needs to be solved by harnessing the modern-day technology.

Although there are many challenges and constraints, Solar cells under the ocean water environment have been found to positive and also successful. However, their power output is reduced significantly with an increase in water depths. In addition to that, it is a huge advantage for the availability of the novel, environmentally safe, and also the source of electrical power for many sensors' platforms, oceanographic, defense, navigation, and marine electronics applications. The UVs and the unmanned aerial vehicles (UAVs), with many self-governing systems, are being utilized for surveillance and intelligence, and keeping situational alertness over the oceans is challenging. Large sensor networks are complicated to deploy and to sustain in large part due to limited energy sources available in underwater environments. Harvesting the wave energy has specific requirements, such as a generator placed either above or below the tideline. However, the extraction of the wave energy may be challenging at more than two meters depth from the surface due to the dissipation of the waves.[2,3] A computer program and mathematical models have been developed in Jamal and Muaddi[4] to analyze the Solar energy at various water depths by assuming two sets of data, namely, the Solar spectrum at sea level in the same spectral range and the extinction coefficient of water in the spectral range of 300 to 2500 nm. The Solar radiation behaves as a monoenergetic beam of radiation at depths more than 3 m in water because the extinction coefficient is significantly high, and initially, in the first centimeter, around 27% of the Solar energy was transmitted and absorbed and about 70% at 3 m of depth.[4]

Another study was carried out about the Solar spectrum underwater showing that the transmission of Solar energy underwater experiences the air-water interface and suffers some reduction in intensity, and the refractive index at short wavelengths of the Solar spectrum becomes higher. The total Solar intensity at sea level is reduced to around 70%, and the distribution of solar spectrum becomes limited in the region 300 to 3200 nm while more than 95% of Solar energy is confined to 300- to 2500-nm range.[5,6] When a Solar cell is placed under the water surface, it undergoes the air-water-cell effect leading to the variation in the Solar spectrum with depths. The decrease in Solar radiation with water depth is obtained by finding the area under the solar spectrum. The reduction in solar radiation with depth corresponds to the decrease in the solar cell current. The relative efficiency of solar cells underwater illustrates a peculiar behavior with an increase in water depth, which increases initially with a depth of the water and returns to its original value at 3.5-m depth; further, the decrease in relative efficiency is not too significant.[5] The study of placing the Solar cells underwater over 4 months and its measurements have been carried out without encountering any problem in the management of electrical parameters.[6]

Moreover, it is mentioned that the temperature of the submerged Solar panel is consistent and varies very little throughout the day, which is a huge advantage to avoid the nonuniform cell temperature and the mismatch based on the cell behavior that affects the efficiency of the Solar panels.[7,8] A specific study on the optical and thermal behavior of submerged Solar cells is also studied by experimental field tests and mathematical models in Tina et al.[9] It demonstrates that there is an increase in efficiency based on the cooling effects in submerged conditions. Recent studies by the Naval Research Laboratory from the United States show that using high-bandgap energy materials for Solar cells can harvest underwater solar energy very efficiently.[10,11] Moreover, the performance of conventional silicon Solar cells and a high-bandgap Solar cell, like GaInP, underwater reported that at a depth of maximum 9.1 m, the power output of the GaInP shows 0.7 mW/cm^2 which is sufficient enough to power the monitor the underwater sensors platforms using modern-day electronics. Further, the performance of conventional crystalline silicon Solar cells shows 28% drop in the operating voltage, whereas the GaInP Solar cell shows only 10% dropped and as we go deep into the water.[10]

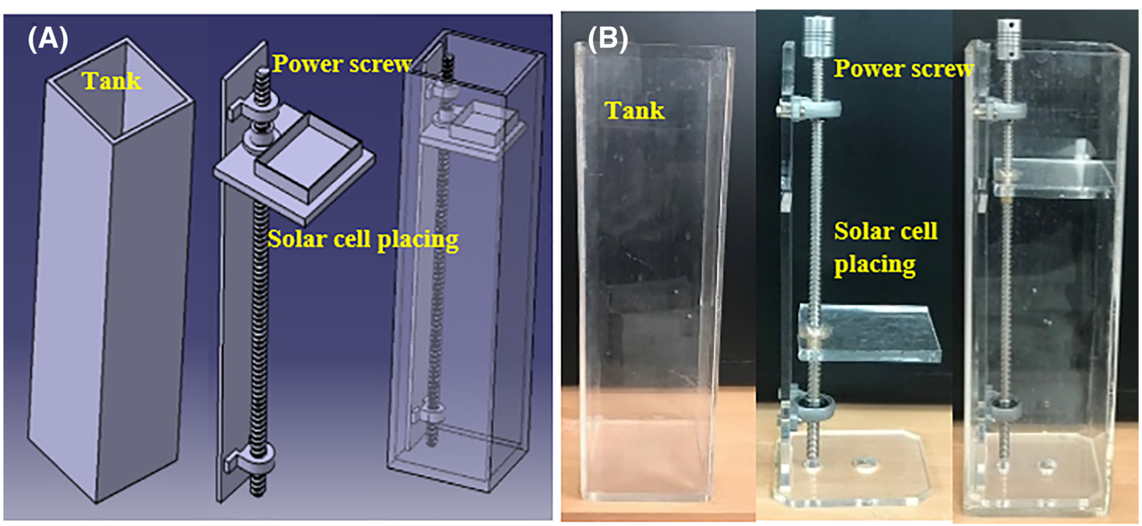

FIGURE 1 Design (A) and fabrication (B) of experimental system [Colour figure can be viewed at wileyonlinelibrary.com]

Subsequently, it shows that the organic PV cells with the multi-junction design of two absorber layers can efficiently match the filtered underwater Solar spectrum due to their capability to result well in lower light settings.[12]

Recent studies show that the monocrystalline Solar cell placing under a water layer provides cooling and the performance of solar cells under low-light conditions was also analyzed.[13] Moreover, a dye-sensitized Solar cell using different light sources has been studied in order to notice the performance of Solar cell with the change in the type of light source with different intensities and also using the water flow lens system in order to provide cooling.[14] The study to power automated jellyfish vehicles using Solar cells underwater showed better conversion efficiency underwater with water depth before reaching a peak at 0.2 m.[15] The utilization of Solar PV underwater has been studied to observe the temperature reduction and the cooling effect using a diverse water flow rate. It was noticed that at a flow rate of 30 mL/s, the surface temperature was reduced from 47.6% to 38%, which provided extreme power settings and efficacy at 4-cm depth. It demonstrated that more heat could be reduced while increasing the water depths.[13] In another study, various constraints of Solar cells underwater were intended demonstrating that cooling factor played an important role in boosting its efficiency.[16] At 1-cm depth, the maximum efficiency obtained is 4.76%, and it has been observed that the temperature of the Solar panel at the surface decreases, and further, relative efficiency was increased with water depth.[17] In addition to this, Solar cell's encapsulation was also more important to keep in underwater conditions to escape the electrical connectors like short circuiting and other physical parameters that

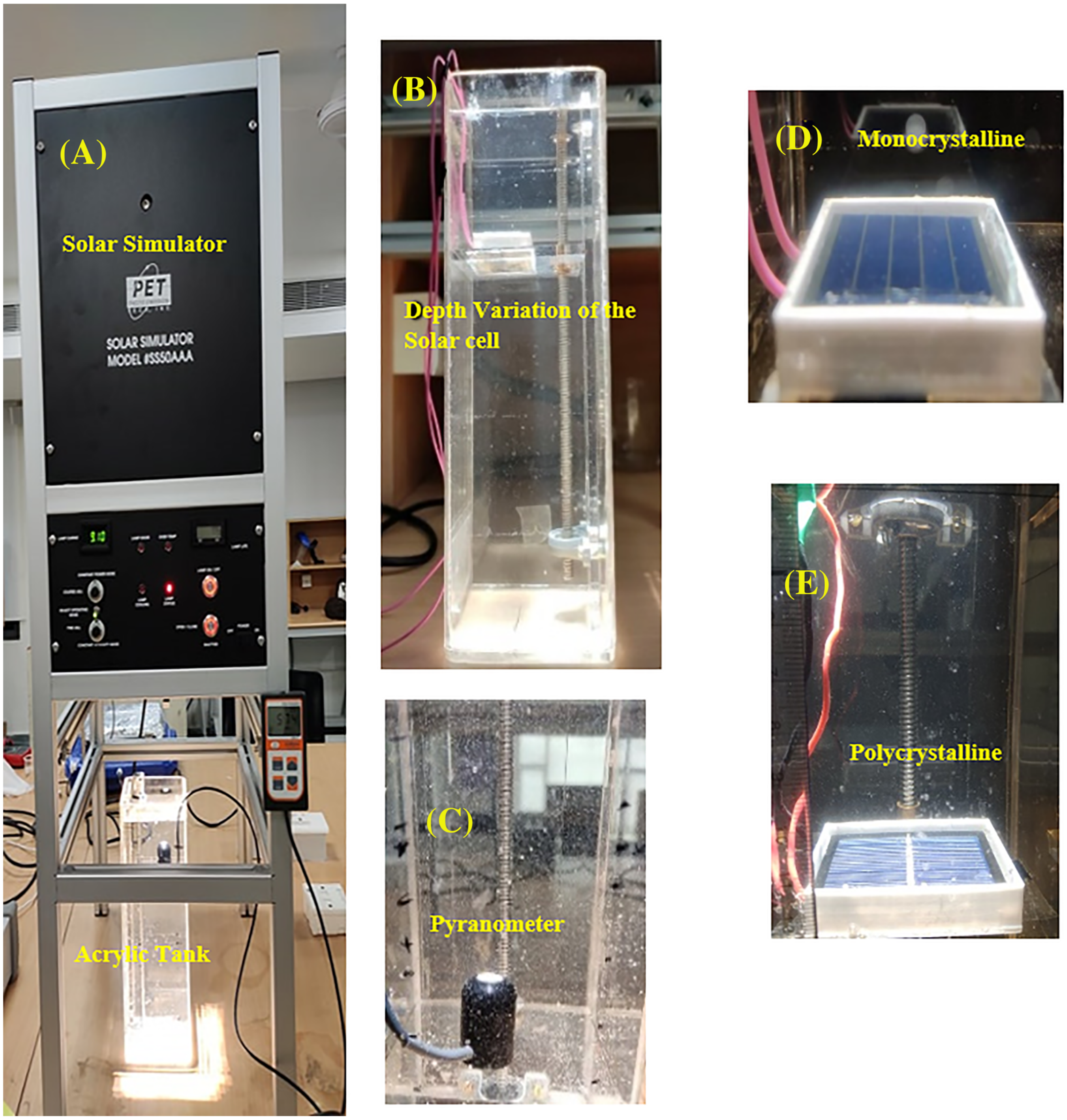

FIGURE 2 (A) Characterization under Solar simulator. (B) Change in water depth using power screw mechanism. (C) Pyranometer under ocean water. (D) Submerged monocrystalline Solar cell. (E) submerged poly crystalline Solar cell [Colour figure can be viewed at wileyonlinelibrary.com]

could harm the solar cell underwater. Many encapsulation methods such as the ethylene-vinyl acetate (EVA) films, polydimethylsiloxane (PDMS), silicone, and ionomer have been explored for the encapsulation ofSolar cells. In this work, we have encapsulated the Solar cell using PDMS due to its excellent transparency, in 240- to 1100-nm wavelengths range, and also hydrophobicity. Moreover, PDMS is hydrophobic, which will help in protecting the Solar cells underwater efficiently, and also, it is inert, nontoxic, and nonflammable.[18,19]

Our earlier studies have analyzed monocrystalline and amorphous silicon solar cells underwater with varying conditions. It was noticed that the amorphous silicon Solar cell exhibited a better performance compared with the monocrystalline silicon solar cell.[20] In this work, the same experimental setup is carried out to characterize the transmission of Solar energy underwater and its variations with changing water conditions up to 20 cm, and also, corresponding to that, the performance of submerged polycrystalline and monocrystalline silicon Solar cells was analyzed in a controlled indoor environment. The monocrystalline and polycrystalline silicon Solar cells were used because they are readily available in commercial aspects compared with amorphous silicon Solar cells. This investigation result shows a better understanding of the transmission of Solar radiation with different water conditions in the presence of salinity, bacteria, algae, and also other water impurities up to 20 cm of water depths and also the performance analysis of monocrystalline and polycrystalline silicon Solar cells in submerged conditions.

2 | EXPERIMENTAL

As shown in Figure 1, a platform has been designed, using a modeling software CATIA, and fabricated to create an underwater setting and conduct various experiments. The fabrication of the design was made using commercial plexiglass or acrylic, with a mechanism to vary the height up to 20 cm. It was selected due to its optical properties, which are similar to a glass and also relatively having good machinability. The tank dimensions were 10 * 10 * 30 cm (length * breadth * height). The working distance for the depth variation of Solar cells in the tank is up to 20 cm in height. Further, the encapsulation of Solar cells was made to protect them from underwater environments. The artificial ocean water also prepared with 3.5% salinity, and after that, the characterization has been carried out using a solar simulator.

2.1 | Encapsulation of Solar cells

The encapsulation of the Solar cells was carried out by placing the solar cell in a 3D printed rectangular enclosure and encapsulated using PDMS due to its many unique properties.[19] The mixture of PDMS was prepared using the Slygard 184 silicone elastomer mixing base (20 g) and silicone elastomer curing agent (2 g) in the ratio of 10:1.[21] Subsequently, it was properly mixed and kept in a vacuum desiccator for degassing to remove the air bubbles for 30 minutes. After removing the air bubbles, the PDMS mixture dispensed on the Solar cell, which was placed in the 3D printed rectangular enclosure. Further, the PDMS layer on the Solar cell was cured at room temperature for 48 hours to complete the encapsulation process.

2.2 | Characterization

In this study, the monocrystalline and polycrystalline silicon Solar cells were used for various characterization in underwater environments. Initially, the transfer of Solar radiation underwater was measured with different types of water, such as the deionized (DI) water, real ocean water, prepared ocean water or artificial ocean water, and lake water up to 20 cm, and accordingly, the performance of submerged monocrystalline and polycrystalline Solar cells were analyzed. A Solar simulator system of class AAA (Model: SS50AAA) with Standard Test Conditions (STC) (Solar radiation 1000 W/m^2, air mass AM 1.5G at 25°C) has been used for characterization. The calibration of a Solar simulator was done using a photodetector, and the transfer of solar radiation underwater was measured using a Submersible Pyranometer (PYR) Sensor with a digital display from Apogee Instruments Inc, USA. The monocrystalline Solar cell was purchased from IXYS, South Korea, with ratings of 5.01 V and 44.6 mA, and also, the polycrystalline Solar cell was purchased from Kitronik Ltd, China, with ratings of 3.0 V and

TABLE 1 Characterization of different types of water

Type of Water	Conductivity, mS/cm^2	TDS, ppm	pH
Deionized (DI) water	0.0337	16.7	7.07
Ocean water	45.8	32,900	8.22
Artificial ocean water	40.1	30,000	7.9
Lake water	0.806	399	6.8

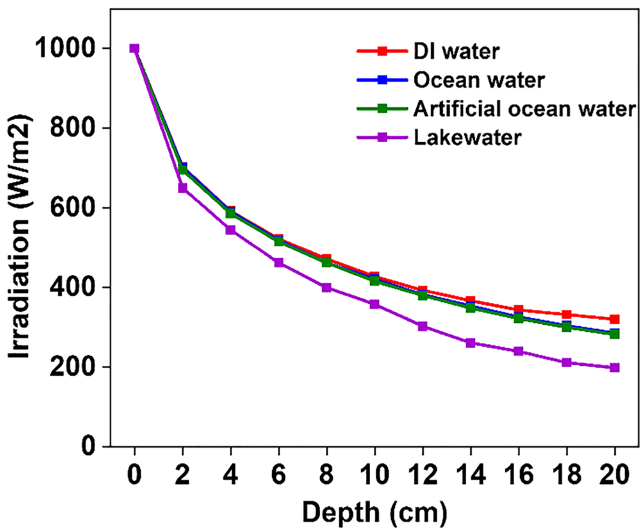

FIGURE 3 Comparison of Solar radiation at different water depths with varying water conditions. DI, deionized [Colour figure can be viewed at wileyonlinelibrary.com]

100 mA. The characteristics of both types of Solar cells, such as the Current -Voltage (IV) and Power-Voltage (PV) characteristics of monocrystalline and polycrystalline Solar cells, were attained using B2912A Precision Source/Measure Unit, 10 fA, 210 V, 3 A DC/10.5 Pulse from Keysight technologies. The entire experimental setup is shown in Figure 2. A Millipore DI water, ocean water (Visakhapatnam, India) with a salinity of 3.5%, artificial ocean water (prepared using the sea salt from Aqua forest), and lake water (Shamirpet Lake, Hyderabad, India) were utilized for various analysis. The water characterizations were performed using Adwa bench meter to analyze the conductivity and total dissolved salts (TDS) present in all these water types. The submerged Solar cells were encapsulated with PDMS to prevent the Solar cells and its terminal contacts to avoid the short circuit when placed inside the water.

2.3 | Artificial ocean water

The artificial ocean water or prepared ocean water was made using Aqua forest sea salt in DI water to preserve 3.5% salinity. The salinity values were measured using a handheld refractometer with automatic temperature compensation from Erma Inc, Japan. The performance of submerged Solar cells was analyzed at different water depths.

3 | RESULTS AND DISCUSSION

As shown in Table 1, this section discusses the characterization of different water types. The transfer of Solar radiation underwater with different water types and the performance of submerged monocrystalline and polycrystalline silicon Solar cells and their characteristics up to 20 cm have been accomplished. Table 1 shows the characterization of water types, such as the TDS conductivity and pH corresponding to the different kinds of water used in the experiments. In addition to that, the salinity 3.5% of real ocean water and the artificial ocean water was measured using the handheld refractometer. The real ocean water and artificial ocean water were found to be more in conductivity related to the DI water and lake water because of the TDS and the salinity 3.5% present in them.

Figure 3 shows the Solar irradiation and its changes with water depths as well as with water types. It exhibits that with the rise in water depth, the solar radiation underwater decreases because of the presence of water and the spectral changes that occur in underwater conditions. The solar radiation above the water surface is 1000 W/m^2 as per the STC, which is also considered as 0 cm for all the experiments. Further, the transfer of Solar radiation underwater also changes with the different types of water, as shown in the figure. The Solar radiation in the case of DI water is high when related to the other water types due to the salinity 3.5%, TDS, and

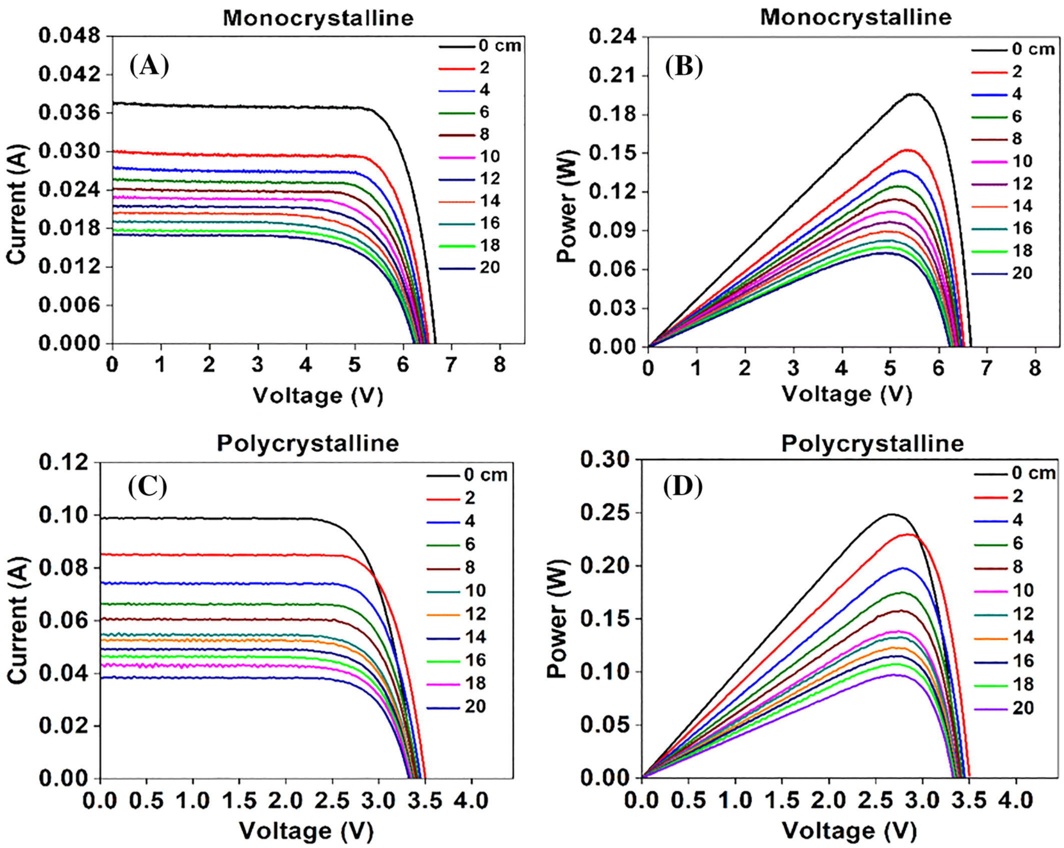

FIGURE 4 IV and photovoltaic (PV) characteristics for (A,B) monocrystalline and (C,D) polycrystalline silicon Solar cells under deionized (DI) water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

total suspended solids like bacteria, algae, and also other water impurities present in the real ocean water, artificial ocean water, and lake water. The transmission of solar radiation in the case of real ocean water and artificial ocean water conditions is 286 and 282 W/m^2, respectively, at 20-cm depth, which is slightly less compared with DI water as it shows 320 W/m^2. This is a massive advantage that the salinity shows very little significance in the transfer of Solar energy underwater. Moreover, in the case of lake water, the transmission of Solar radiation is very less because of the bacteria, algae, and other water impurities, but interestingly, useful amount of Solar radiation is available even in lake water environments with the presence of such high-water impurities. This study displayed a better realization of the transfer of Solar radiation underwater and its changes with different kinds of water because of the effect of water quality, which plays a substantial role in the transfer of solar energy underwater.

3.1 | DI water environment

Initially, the Solar underwater radiation was measured using the submersible pyranometer sensor, as shown in Figure 3, and it has been analyzed up to 20 cm of depth. The corresponding IV and PV characteristics of Solar cells were also obtained with the source/measure unit. The IV and PV characteristics of both submerged Solar cells with water depths are shown in Figure 4 up to 20 cm, which depicts a linear response with depth due to the water being steady and with any turbulence. The decrease in IV and PV characteristics with the depth of the water was primarily due to the reduction in Solar radiation and also the decrease in short circuit current in both submerged Solar cells. Usually, the short circuit condition of the solar cells hugely depends upon the incoming Solar radiation falling on them. Furthermore, it evidently shows that with an increase in water depths, various parameters of the solar cell such as the short circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum current (I_{max}), and maximum voltage (V_{max}) also decline; accordingly, the maximum power output (P_{max}) of the submerged monocrystalline and polycrystalline Solar cells also decreases. These electrical parameters might affect the efficiency and also performance of the Solar cells, which is largely due to the reduction in Solar radiation underwater. Moreover, maximum power output P_{max} also declines with the depth of the water, which is mainly due to the changes in the Solar radiation underwater in case of both monocrystalline and polycrystalline solar cells up to 20 cm.

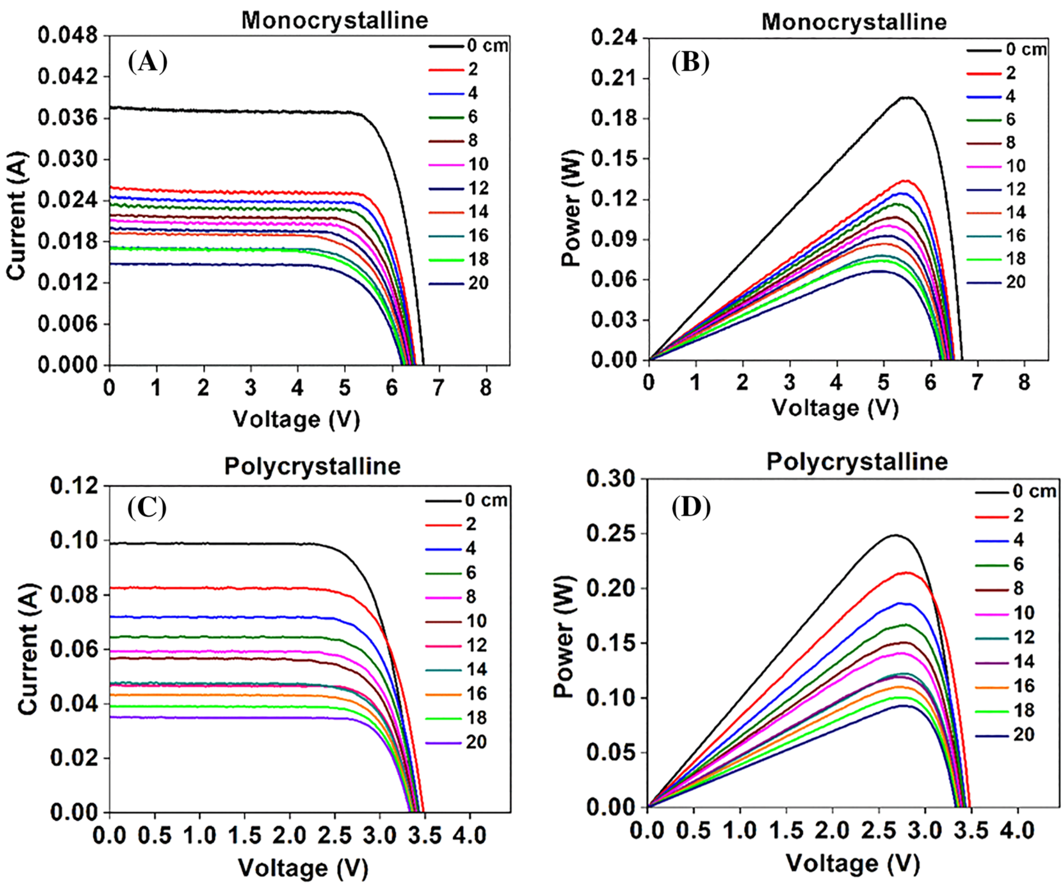

FIGURE 5 IV and photovoltaic (PV) characteristics for (A,B) monocrystalline and (C,D) polycrystalline silicon Solar cells under ocean water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Real ocean water and artificial ocean water environments

Similar experimental sets were carried out by using the real ocean water and artificial ocean water (3.5% salinity and other impurities). The conductivity of natural or real ocean water and artificial ocean water is more, as shown in Table 1, which indicates the number of dissolved salts present in them directly. The quantity of TDS in real ocean water is 32 900 ppm (parts per million) and in artificial ocean water 30 000 ppm, which is very high compared with DI water. Figures 5 and 6 show the IV and PV characteristics of submerged monocrystalline and polycrystalline Solar cells with the depth of the water in real ocean water and artificial ocean water settings. Hereby, a bahaviour similar to the one with DI water I has been observed, but the declination of Solar radiation is more in the case of real ocean water and artificial ocean water. The maximum power output P_{max} also reduces compared with DI water due to the salinity and other impurities in ocean water like alga and sand and debris.

It was shown that the Solar cells have a vast potential to harvest energy even in submerged ocean water conditions where salinity does not have significant effect on the performance of the Solar cells. Moreover, it exhibits that there is a useful amount of power to monitor the low-powered underwater systems in marine and navy crops applications with modern power electronic converters.

3.3 | Lake water environment

Similarly, Figure 7 shows the IV and PV characteristics that are attained in lake water conditions, which are identical to DI water, ocean water, and artificial ocean water environments. The analysis using the lake water conditions has been performed to analyze the effect on underwater Solar on the water quality and its changes in the scattering effect. Further, it is a fact that the water turbidity increases in the case of lake water, because of bacteria, algae, and other impurities, resulting in decreasing the transparency of the water. Moreover, the decrease in the amount of solar radiation is very high in the case of lake water compared with DI water, ocean water, and the artificial ocean water because of the transparency and the other suspended solids present in the lake water.

The IV and PV characteristics in lake water conditions decreased more in comparison with other types of water conditions.

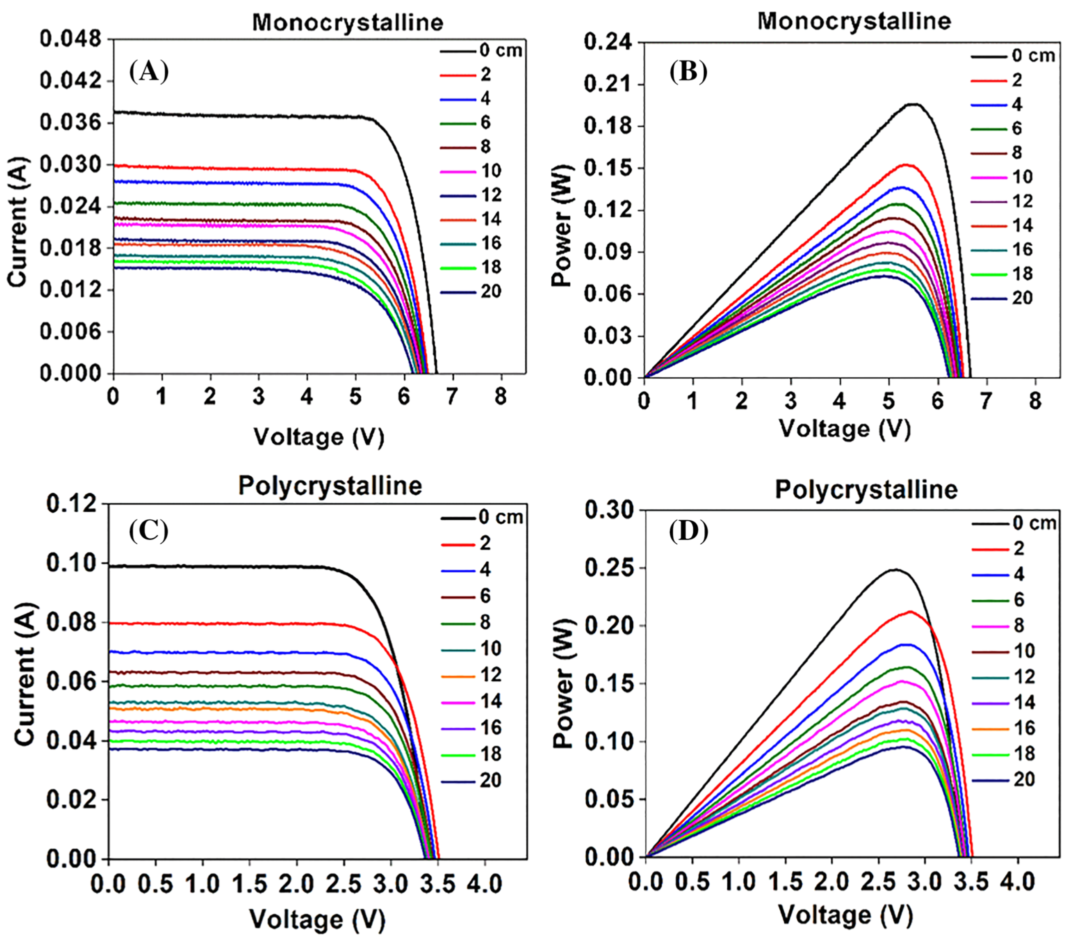

FIGURE 6 IV and photovoltaic (PV) characteristics for (A,B) monocrystalline and (C,D) polycrystalline silicon solar cells under artificial ocean water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

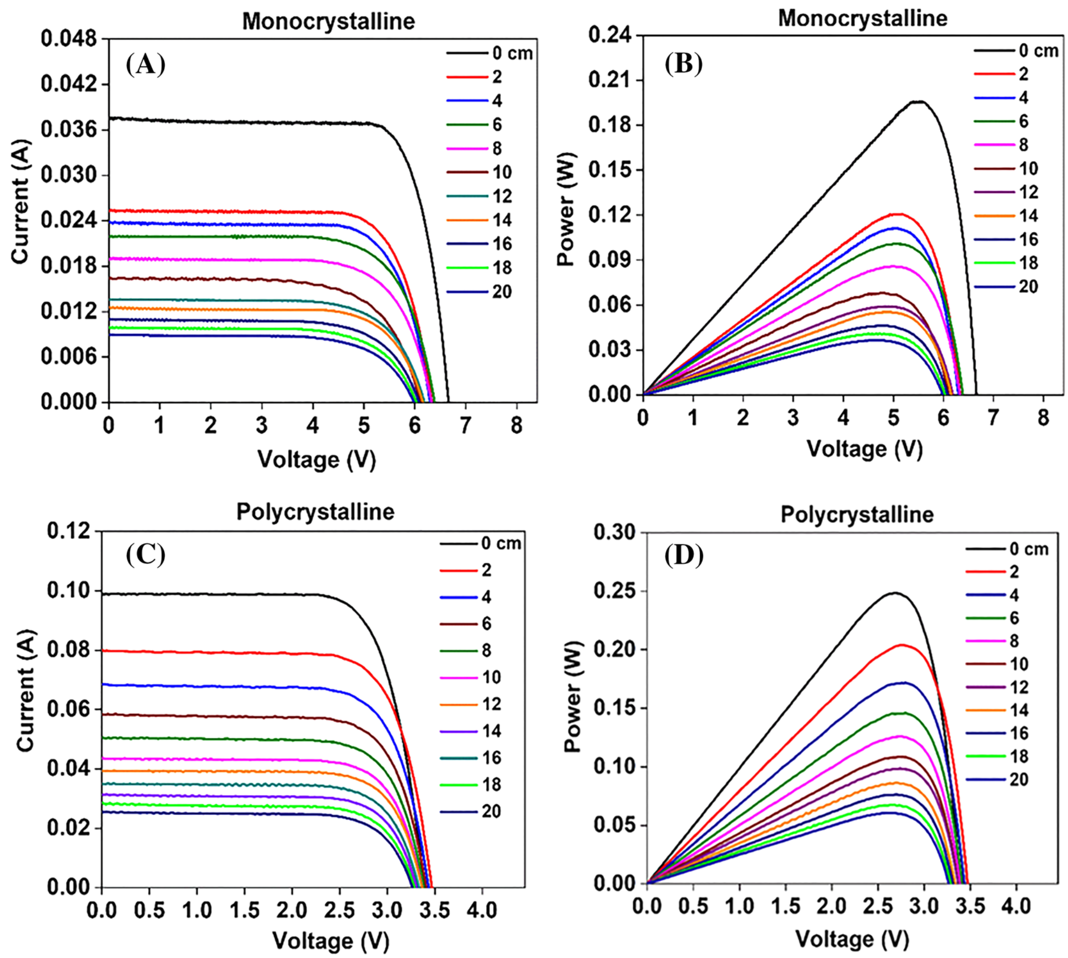

FIGURE 7 IV and photovoltaic (PV) characteristics for (A,B) monocrystalline and (C,D) polycrystalline silicon Solar cells under lake water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

Subsequently, the maximum power output P_{max} is studied, which is also decreased more in lake water conditions. Further, this investigation manifests that the diminishing power in monocrystalline and polycrystalline Solar cells with an increase in water depth was because of the spectral changes underwater, which lead to the decrease in solar radiation with respect to the depth of the water. Although the amount of power output is very less, in general, the lake water provides more cooling compared with other types of water due to the presence of suspended solids. The investigation of submerged monocrystalline and polycrystalline solar cells in lake water conditions

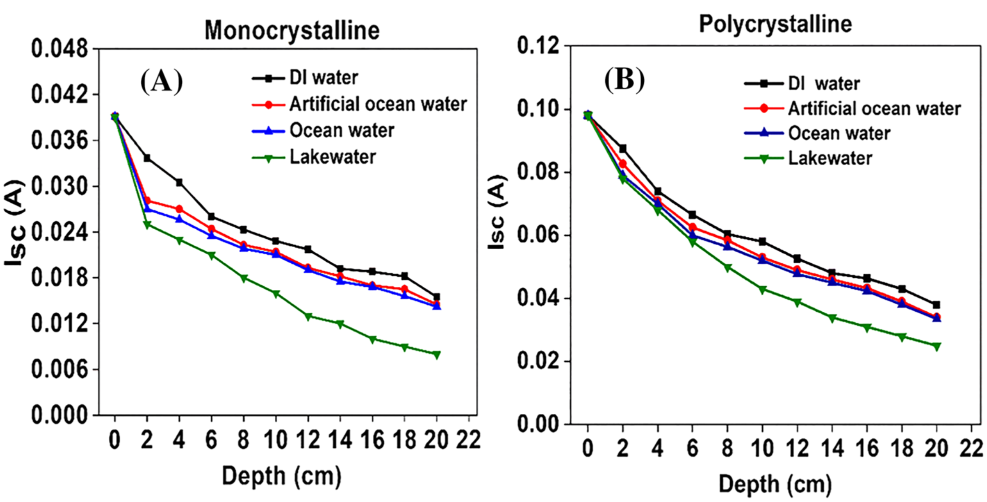

FIGURE 8 Comparison of short circuit current I_{sc} for (A) monocrystalline and (B) polycrystalline silicon Solar cells at varying water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

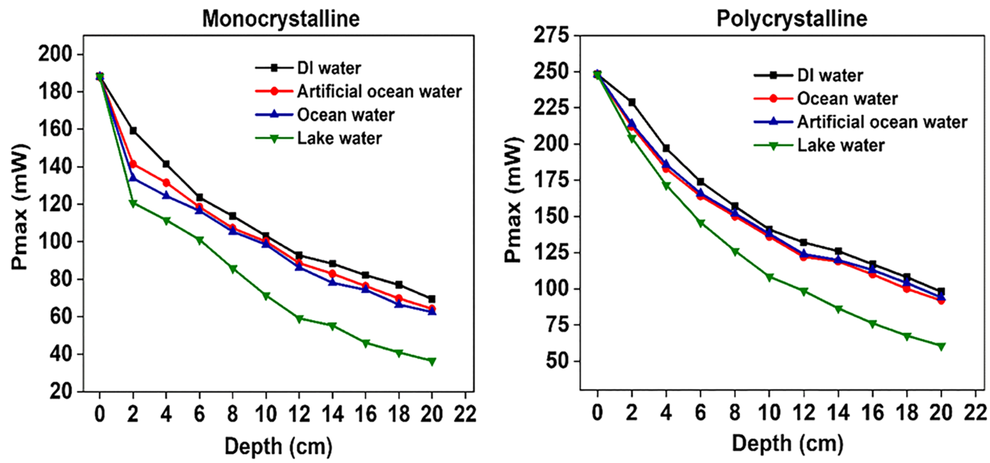

FIGURE 9 Comparison of maximum power output P_{max} for (A) monocrystalline and (B) polycrystalline silicon Solar cells at varying water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

shows a minimal amount of power, but it displayed that the solar PV technology has the tremendous potential as it performs better even in the presence of bacteria, algae, etc, which shows the solar cells ability to harness the energy under lake water conditions as well.

3.4 | Comparison of submerged monocrystalline and polycrystalline solar cells with varied water conditions

Figures 8 and 9 summarize the comparison of short circuit current I_{sc} and maximum power output P_{max} under four different water conditions up to 20 cm of water depth. In general, the transparency of water decreases as dissolved salts increase, which increases salinity and also suspended solids in water. The amount of Solar radiation underwater decreases with an increase in water depth, which in turn also influences more on short circuit current $I_{sc,}$ as shown in Figure 8. Usually, I_{sc} is directly proportional to the light-generated current I_L or the amount of Solar radiation falling on the solar cell. Under the lake water environment, the I_{sc} and P_{max} of both monocrystalline and polycrystalline silicon Solar cells decreased more as the water depth increases due to the total suspended solids, other water impurities like algae and bacteria, which reflect the transparency of the water very less compared with other water conditions. The real ocean water and artificial ocean water show excellent transparency, although there is a salinity present in the water. The salinity contains in real ocean water, and artificial ocean water shows less significance compared with lake water, although the power output of the solar cell decreases with an increase in water depth.

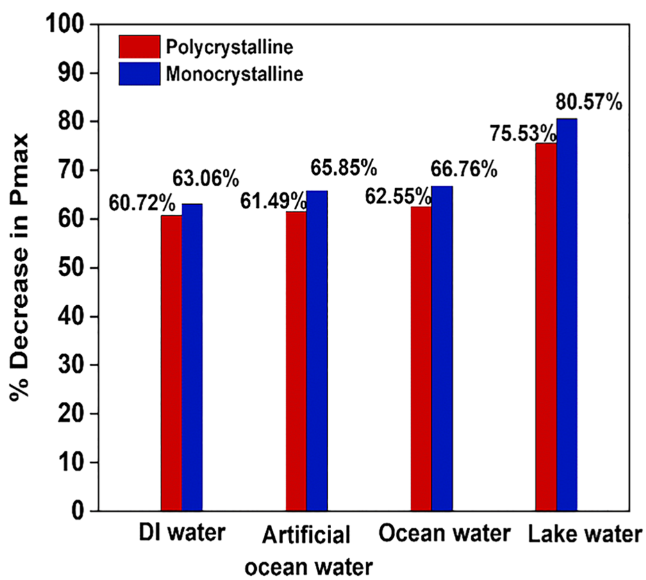

FIGURE 10 Decrease in maximum power output (P_{max}) for monocrystalline and polycrystalline silicon Solar cells at varying water conditions [Colour figure can be viewed at wileyonlinelibrary.com]

All the experiments have been carried out at least three times, and the average was reproduced. Figure 9 shows average P_{max} values vis-a-vis to the depth of the water under four different water environments. Initially, at the surface of the Solar cell, the solar radiation is maintained at 1000 W/m^2, which is calibrated by a photodetector, and it was measured by using the pyranometer. It has been observed that the P_{max} of both the silicon Solar cells is affected by the decrease in Solar radiation underwater, as shown in Figure 3.

This experimental study and analysis gave a better understanding of the decrease in the amount of Solar radiation underwater with the change in water types and its effects on the performance of the monocrystalline and polycrystalline silicon solar cell underwater up to 20-cm depth. Figure 10 shows the level of decrease in the P_{max} underwater in both types of silicon Solar cells. The amount of decrease in P_{max} in both types of silicon Solar cells underwater is almost similar because both are made up of crystalline silicon, but polycrystalline silicon Solar cells show slightly better in underwater conditions compared with the monocrystalline silicon Solar cell.

4 | CONCLUSION

The transfer of Solar radiation underwater decreases while increasing the water depth, and it manifests that salinity 3.5% has very little significance in the transfer of solar energy underwater, but it has a significant impact in the case of lake water conditions. The IV and PV characteristics of both monocrystalline and polycrystalline silicon solar cells decreases proportionally with the depth of the water in all the water environments harnessed in this work. Moreover, the maximum power output P_{max} of monocrystalline and polycrystalline silicon Solar cells also declines with the growth in the water depth up to 20 cm. In the case of lake water, IV and PV characteristics of monocrystalline and polycrystalline Solar cells show a further decrease due to the Solar radiation underwater, and also, the P_{max} of Solar cells decreases more compared with other water conditions. More interestingly, the solar PV cells have the potential to generate power at shallow depths even in lake water environment where the transparency is very less due to total suspended solids like bacteria, algae, and other impurities. In addition to that, the salinity 3.5% shows less significance on the power output of both monocrystalline and polycrystalline Solar cells underwater, which is a tremendous advantage specifically for the defense, navy, and marine crop applications where there is a massive requirement of long-endurance power sources. As it shows, the percentage decrease of P_{max} in monocrystalline and polycrystalline Solar cells is 65.85% and 62.55%, respectively, in the case of ocean water conditions, whereas in DI water conditions, it is 63.06% and 60.72%. Although there are few challenges and limitations, the results obtained show that there is an enormous possibility to harness for underwater solar PV technology for monitoring sensors or devices and various other defense and industrial applications with contemporary power electronics. Nevertheless, the results obtained from this work encourage us for further exploration of solar cells underwater and its performance in outdoor conditions and also with considering all other parameters underwater such as turbulence, temperature, and high-bandgap energy materials.

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