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SUSTAINABLE HYBRID SOLAR CELLS: DEVELOPMENT AND PERFORMANCE EVALUATION USING BIOCHAR FROM AGRICULTURAL WASTE

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ABSTRACT

This research paper developed and experimentally investigated a hybrid solar cell using agricultural waste products. The amount of energy generated by the developed samples was compared with that of the control samples. Ten (10) samples were tested, and a maximum power output of 18-32 W was achieved, with suitable efficiencies of 20.94, 20.88, and 20.88 obtained from samples 8, 9, and 10, respectively, compared to 20.78 in the control sample. The results also show a positive relationship between solar radiation intensity and efficiency. This means that all environmental parameters are strong determinants of performance. The results confirm that agricultural products such as rice husks and peanut shells can be used to improve the power output of solar cells and enhance sustainability. The research highlighted the promise of hybrid solar technologies as a potential alternative in renewable energy. Therefore, future research should focus on the materials optimisation of the product's composition from agricultural waste.

Keywords: agricultural waste, hybrid solar cells, power output, energy efficiency, performance analysis of biochar.

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1. INTRODUCTION

The race for cleaner energy has put solar power in the limelight. People want solutions that meet growing electricity demands without trashing the planet, and solar energy sits right at the centre of all this [1]. It's clean, practically limitless, and way better for the environment. Still, old-school solar panels-especially the ones made from crystalline silicon-aren't perfect. They cost a lot to manufacture, use up plenty of energy during production, and their performance drops when the weather isn't just right. That's why scientists started making hybrid solar cells [2]. By blending organic and inorganic materials, these newer panels absorb more sunlight and conduct electricity more smoothly. That means better results, plain and simple. But the story doesn't end there. Now, researchers care about more than just making panels that work harder. They consider where all these materials come from, how the panels affect the environment from start to finish, and whether they can fit into a system in which nothing goes to waste [3-4].

One clever approach? Using biochar, a material made from agricultural waste. Farmers throw away rice husks, groundnut shells, plantain peels, and palm kernel shells all the time, and that waste usually pollutes the air and contributes to greenhouse gas emissions [5]. By turning this waste into biochar through a process called pyrolysis, people reduce pollution and produce something useful for solar technology. It's a double win: a cleaner planet and a smarter way to build solar panels [6].

Biochar is special because it's rich in carbon, has a porous structure, and has a massive surface area packed with active sites. In the past, people mostly saw biochar as a handy tool for cleaning up pollution, boosting soil health, or storing carbon [7]. Lately, though, scientists have noticed its ability to boost performance in batteries and solar devices. It conducts electricity, handles heat like a champ, and helps electrons zip around. In hybrid solar cells, biochar can take centre stage or play a supporting role, helping electrons move faster, reducing energy waste, and steadying temperatures. New experiments continue to show that when you make biochar from farm leftovers, solar panels actually work better [8-9]. If the biochar happens to be loaded with silicon and oxygen, it's even better-it boosts energy conversion rates and keeps things stable when the cell heats up, sometimes performing almost as well as traditional silicon solar cells [10]. Since you can make biochar from cheap, local waste, there's a real chance to cut costs and make solar power more available, especially in areas where resources are tight. Banda *et al.* [11] conducted a study to improve the efficiency of PV panels by incorporating 1% graphene, 40% charcoal, and 1-tetradeconal phase change materials (PCMs). The comparative study's main conclusions indicated that, compared with other PV panels, the PV-NBPCM reduced the maximum surface temperature by about 18.86 K. Finally, the main benefit of employing PCMs in solar panels is to increase their longevity and electrical efficiency by controlling the heat generated during operation. Khalil *et al.* [12] reported that solar dryers have become increasingly popular across several industries for drying agricultural products. However, using open sun drying has its limitations. Photovoltaic/thermal (PVT) panels are quite successful in addressing these constraints using the latest technologies [13].

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Patil *et al.* [14] noted that using biochar in hybrid solar cells is still relatively new, and there's much we don't yet know. For starters, it's not clear how to fine-tune the biochar production process to work best, or exactly how it interacts with the other materials in the cell. Researchers also don't know how these cells hold up over time or on a bigger scale. There's a lot more work to do, especially in testing how these biochar-based cells perform when real-world conditions aren't perfect. Without that, it's hard to know just how reliable they'll really be. When it comes to making biochar, everything starts with the right feedstock and the way you run the pyrolysis. Pyrolysis, essentially heating material with limited oxygen, is the go-to method for producing high-quality biochar with specific structural and chemical properties [15]. Tweak the temperature, change the heating speed, or swap out the starting biomass, and you'll end up with biochar that looks and behaves differently. These changes affect things like how porous it is, how well it conducts electricity, and what kinds of chemical groups cover its surface, which all play a big role in how useful it'll be for solar cell tech [16]

According to Senthil [17], efficient use of solar energy can increase the sustainability of the world's energy supply. The efficient maintenance of solar cells should be the main focus, even though the use of photovoltaic solar installations is growing worldwide. Because it reduces energy requirements, incorporating solar into photovoltaic units is crucial. Solar air/water heating systems in PV are used in drying, space roasting, solar purification, process heating, and boiling water because photovoltaic solar cooling improves electrical productivity and longevity. Solar photovoltaic panels are among the fastest-growing energy sources and have significantly reduced carbon emissions. Indeed, there is a chance that it will overtake all other renewable energy sources by the middle of the century [18]. According to Alamayreh and Alahmer [19], thermal energy storage in solar plate machinery can be enhanced by using a consistent heat source, even when solar radiation is weak or sporadic. Biochar made from agricultural waste can increase soil fertility and effectively adsorb pollutants from gas streams, anaerobic digestion, catalysis, and composting [20-22]. Lately, researchers have been pushing biochar into all sorts of energy-related roles, from supercapacitors and catalysts to cooling materials. These studies highlight the flexibility of biochar and suggest its promise for hybrid solar cells [23-24]. Still, there aren't many studies that actually pull together all the pieces-developing the material, building the devices, and testing how they work. There's plenty of room for deeper research that connects the whole process.

Even though solar cells have become a popular renewable energy source, they still have drawbacks, including high production costs, significant energy losses at high temperatures, and relatively low efficiency. These obstacles prevent solar energy from being widely used, despite its promise to drastically lower greenhouse gas emissions and dependency on fossil fuels [25]. Therefore, the current study intends to investigate the appropriateness of using agricultural waste materials to manufacture hybrid solar cells to lower their temperature, minimise energy waste, and increase their energy production efficiency at a lower cost.

2. METHODOLOGY

2.1 Compilation and Formulation of Plantain Peels

In Ikire, Nigeria, a community market booth provided the plantain peels. The peels were dried in an electric oven for eight hours at 50 °C. The materials were moved to a lab ball mill for grinding after drying. The inside of the ball mill was cleaned with a damp cloth and allowed to dry before the pieces were ground. The peel was milled for 5 hours at 330 rpm and 2000 revolutions. The more fragile powder was removed from the uncrushed peel parts using a sieve. Crushing and sieving were essential to expand their surface area and ensure thorough adhesion of the ingredients during mixing. Figure-1 presents the process of carrying out the method. For additional examination, the recovered powdered shells were kept in a zip-lock bag. The sieved plantain peels are shown in Figure-2.

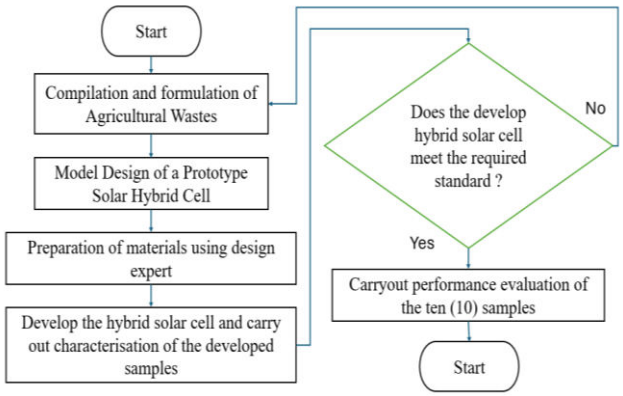


Figure-1. The flow chart for the development of the sustainable hybrid solar cell.



Figure-2. Granulated and filtered agricultural waste from plantain peel.

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2.1.2 Compilation and Formulation of Peanut Shells

For this study, an equal ratio of roasted and freshly harvested peanuts and groundnuts, in-shell, was sourced from a market in Ado Ekiti, Ekiti State, Nigeria. In the mechanical engineering lab at Afe Babalola University in Ado, Nigeria, the peanuts were manually shelled. The shells were separated and then cleaned with water to remove any adherent impurities. The cleaned shells were left to air-dry at ambient temperature until the moisture content was completely evaporated, then dried in an industrial oven at 10 for 8 hours. The same ball mill used to grind the plantain peel shells was also used to grind the full batch of dried shells, which were then sieved. For additional characterisation, the ground shells were kept in a zip-lock bag [16]. A sample of the sieved peanut shells is shown in Figure-3.



Figure-3. Granulated and filtered peanut shells.

2.1.3 Compilation and Formulation of Rice Hulls

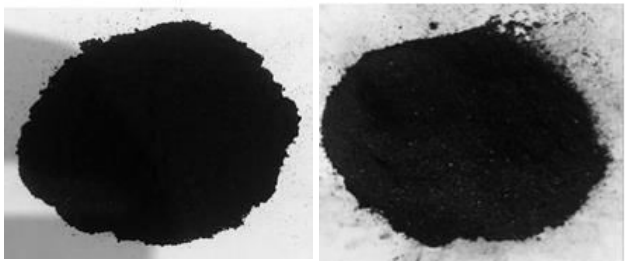
Rice hulls that had already been ground were bought from the Bodija market in Ibadan, Oyo State, Nigeria. To provide porosity in the filter construction, the rice hulls were sieved while still unprocessed. As a binder, the kaolin material was utilised. The ground-up rice hulls used in the experiment are shown in Figure-4.



Figure-4. The pulverised sample of the rice husks.

2.1.4 Compilation and Formulation of Biochar

Similar to charring, pyrolysis is a chemical process (heat decomposition) that removes all non-carbon atoms from the fuel. The pyrolysis process is usually carried out at temperatures between 600 and 1200 degrees in an inert environment containing nitrogen but no oxygen. To prepare biochar, this study used biomass (plantains, rice hulls, peanuts, and groundnut shells). The items were weighed and documented in grams prior to pyrolysis [26]. Each of the four medium-sized ceramic crucibles was filled with groundnut and peanut shell powders, respectively. After that, the ceramic vessels were taken into a muffle furnace. The carbonisation process was carried out in a non-circulating air atmosphere at 600 degrees Celsius for 3 hours, with a heating rate of 10 degrees per minute. As shown in Figure-5, the biochars produced were allowed to cool after pyrolysis. To remove ash and other impurities, the biochar particles were thoroughly washed with distilled water. The filtrates were then sieved, dried at 105 for a full day, and kept in airtight containers for further use.



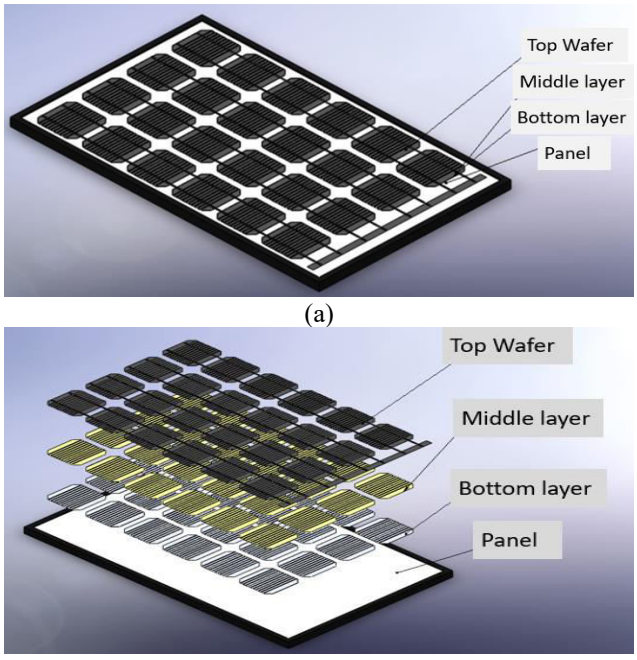
(a) (b)

Figure-5. (a) The develop Biochar and (b) the filter Biochar.

2.2 Model Design of a Prototype Solar Hybrid Cell

2.2.1 The Design of the Samples for Optimization Evaluation

The hybrid solar cell's design was optimised to maximise energy efficiency based on the literature review.



(a)

(b)

Figure-6. (a) The design of the Solar Cell Model; (b) the exploded view of the Solar Cell.

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As seen in Figure-6(a-b), AutoCAD and other pertinent technologies were used to complete the design. The optimised design will be used to create a hybrid solar cell prototype. Transparent conductive electrodes will be applied after organic and inorganic layers have been deposited onto an appropriate substrate as part of the production process. After that, the device will be characterised to assess its performance metrics, including temperature, power-output characteristics, external quantum efficiency, and stability across various environmental settings.

2.2.2 Preparation of Materials Using Design Expert

Design-Expert was used to prepare the materials using the formulated ratio at a proportioned percentage ratio for an optimal mixing ratio of the materials used: peanut shells ranging from 10 - 30 g, groundnut shells from 10-30g, the rice hulls, ranging from 25-50 g, and the Plantain Peel, 10-30 g, to form ten (10) samples for the analysis

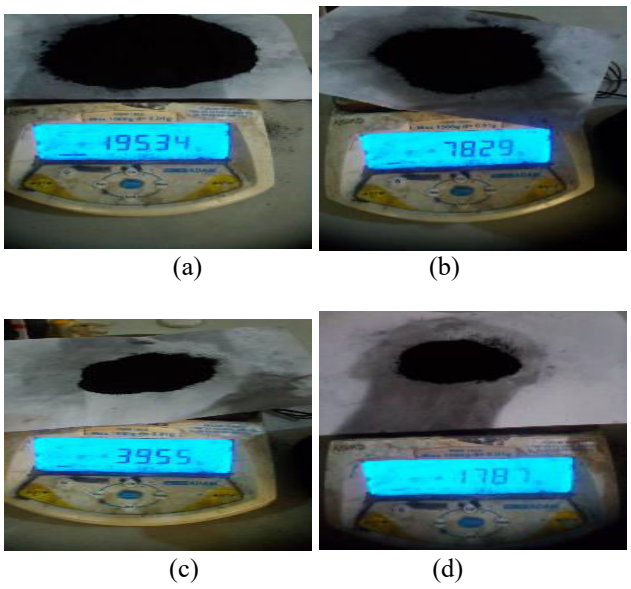
2.3 Development of a Hybrid Solar Cell

The biochar particles from the chosen agricultural wastes, totalling 2 kg across the samples (peanut shell, rice hull, plantain peel, and groundnut shell), were combined with adhesive materials at various mixing ratios. After utilising a design expert to determine the ideal mixing ratio, ten (10) solar cell examples were created with varying aggregate ratios of the materials. Scalability and manufacturability will also be considered in the design. A precise selection of resources and sample 8, with the same mixing ratio dimension, yielded the most suitable power for the solar cell to accomplish the goals and objectives of this study and to design a hybrid solar cell system.

Figure-7 displays samples of copper probes utilised in the cell manufacturing process; Figure-8 shows samples of the generated hybrid solar cells; and Figure-9 (a-d) illustrates the evaluation of biochar at their corresponding ratios.



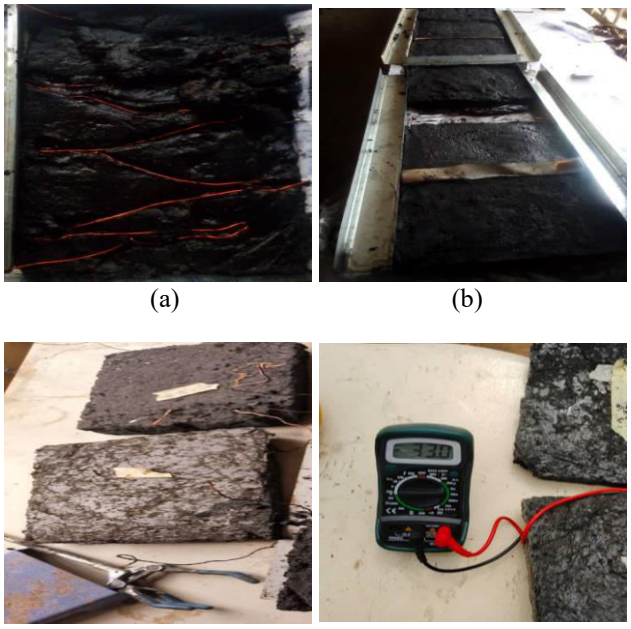
Figure-7. Copper rods for production.



(a) (b)

(c) (d)

Figure-8. (a-d) Weighing of the biochar at their respective percentage ratios.



(a) (b)

(c) (d)

Figure-9. (a-d): The different stages of production and evaluation of the solar cell samples.

2.4 Performance Analysis

2.4.1 Power Output Measurement:

A Solar power meter was selected for measuring the power output of solar cells. The solar cells were installed in an area with ample sunlight and connected to the solar power meter via appropriate cables and connectors [27]. The solar cells were placed so that they receive direct sunlight uniformly across their surfaces, with no shadows or obstructions blocking the light falling on them. The solar power meter was turned on and set to

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the appropriate power measurement mode in watts [28]. The solar power meter was pointed towards the solar cells, and measurements were taken and recorded in Table-1 (samples 1-5) and Table-2 (samples 6-11). It was ensured that the sensor area of the solar power meter covered the entire surface area of the solar cell.

2.4.2 Determination of Solar Cells' Efficiency

Solar irradiance was measured over 5 days in February, between 5th and 9th February 2025, from 10:00hr to 16:00hr.

Efficiency of solar cell: Once the maximum power point is identified or determined, the efficiency of the solar cell can be calculated as given in Eq. (1). According to Dubey *et al.* (2009)

$$\text{Solar Cell Efficiency } (\eta) = \frac{P_{max}}{A \times G} \times 100\% \quad (1)$$

where: P_{max} = Maximum Power of the Solar Cell (W); A = Area (m^2), G = Irradiance $\left(W/m^2\right)$.

Table-1. Samples 1-5 of the developed solar cell.

	Sample- 1	Sample- 2	Sample-3	Sample-4	Sample-5
Time (Hr)	Power (W)	Power (W)	Power (W)	Power (W)	Power (W)
10:00	10	12	15	13	16
11:00	11	16	17	15	18
12:00	14	14	14	14	20
13:00	18	18	18	25	21
14:00	12	20	22	27	24
15:00	13	16	21	21	22
16:00	14	15	14	17	15

Table-2. Sample 6-11 of the developed cell for performance evaluation.

	Sample-6	Sample-7	Sample-8	Sample-9	Sample-10	Sample-11
Time (Hr)	Power (W)	Power (W)	Power (W)	Power (W)	Power (W)	Power (W)
10:00	15	12	14	15	14	15
11:00	16	14	16	17	18	16
12:00	21	20	18	18	19	19
13:00	28	18	25	32	32	33
14:00	27	21	29	27	26	30
15:00	18	13	15	20	25	25
16:00	12	10	12	10	12	18

4. RESULT AND DISCUSSIONS

4.1 Characterisation Results and Analysis of the Materials

4.1.1 Power output variance

The results obtained from the power output tests on the various samples, including the control sample, provide valuable insights into the performance of the hybrid solar cells. As shown in Figures 10 and 11, there is a trend in power output across the various samples, indicating that changes in the materials significantly affect their performance [29]. The analysis indicates a progressive increase in power output for samples 1, 2, 3, 4, and 5, with peak outputs of 18 W, 20 W, 22 W, 27 W, and 25 W, respectively. The trend suggests that changes in material content and processing techniques were incremental and improved the energy conversion properties of the samples [30]. It is interesting to note that sample 4 had the highest output in this group, suggesting that its formulation or structure was capable of optimising light absorption and charge transport.

However, in another assessment, samples 6, 7, 8, 9, and 10 showed a different trend, yielding power outputs of 28 W, 21 W, 29 W, 32 W, and 32 W, respectively. These findings indicate stronger performance, especially on samples 9 and 10, which have 32 W, 1 W less than the control sample (sample 11) with 33 W. The fact that these hybrid samples are so close to the control suggests they can serve as alternatives in solar technology. Interestingly, the intensity of solar radiation and ambient air temperature

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were greater in samples 8, 9, and 10 than in the control sample.

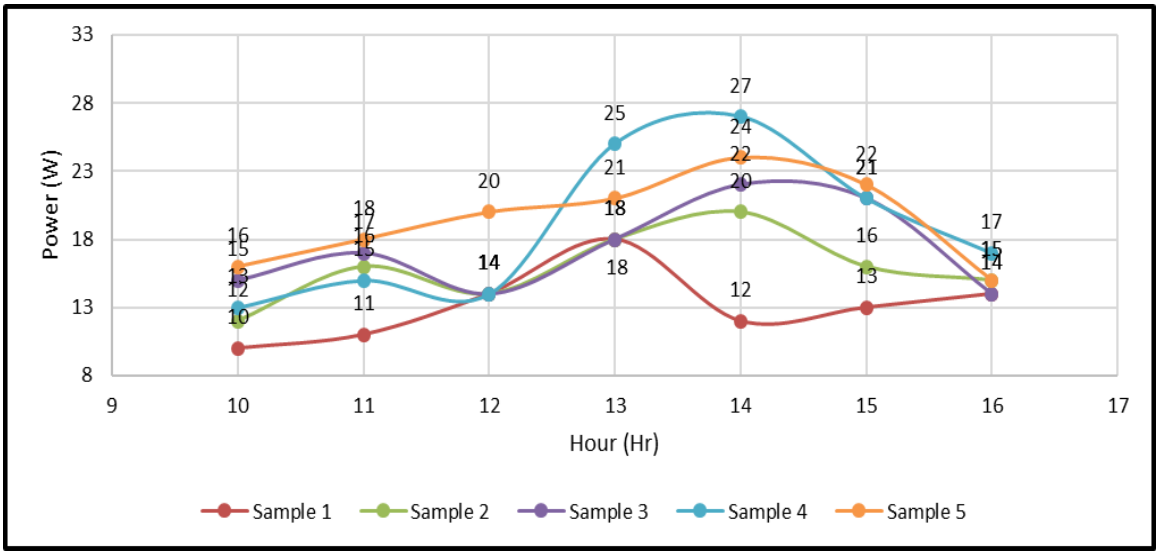


Figure-10. Graph of power measurement for samples 1-5.

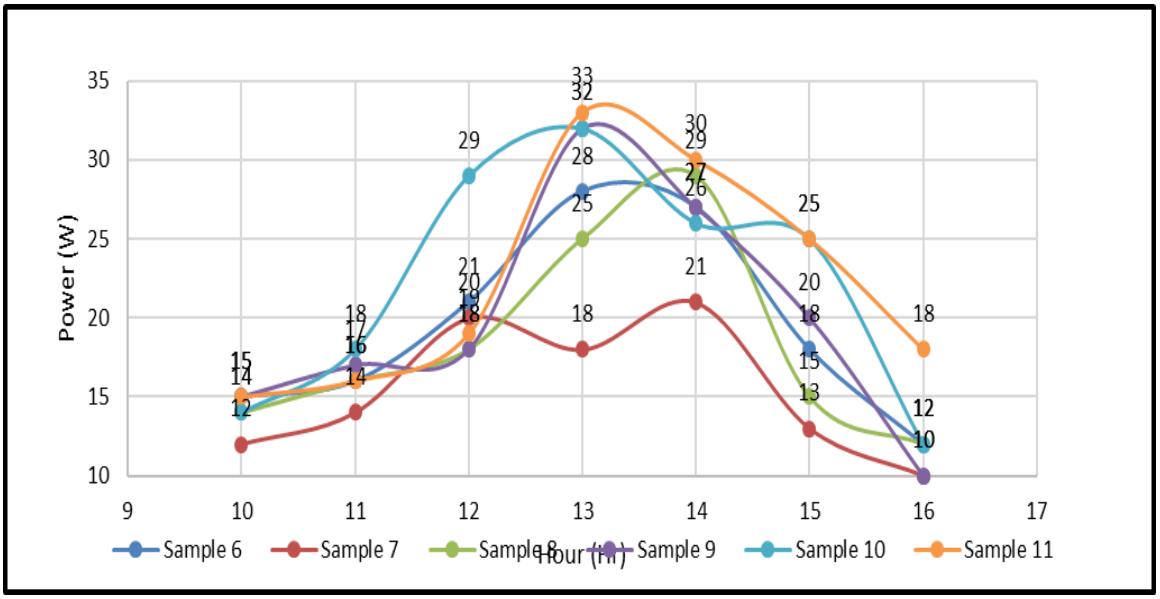


Figure-11. Graph of power measurement for samples 6-11.

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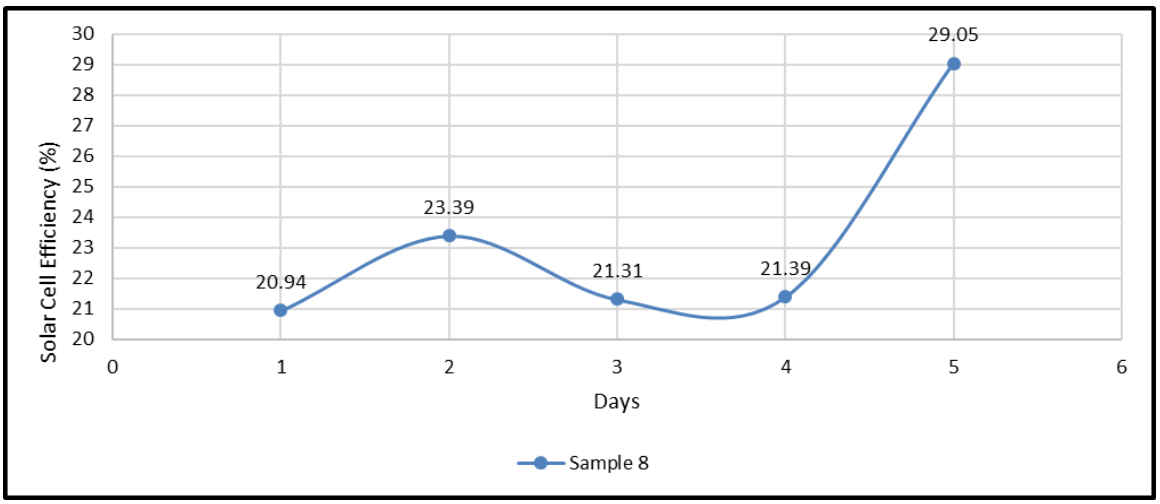


Figure-12. Analysis of solar cell effectiveness for sample 8 over the days.

These environmental conditions must have been important in the increase in power output of these samples [31]. Higher solar radiance is directly proportional to greater energy absorption by solar cells, thereby resulting in higher conversion of sunlight to electrical energy [32]. Additionally, an increase in ambient temperature can affect the electrical properties of solar cells, potentially reducing resistance and enabling more power to be produced. Solar cell performance has been widely reported as a function of environmental conditions, including temperature and irradiance. Ugochukwu *et al.* [33] assert that increased solar irradiance not only amplifies the power yield of solar cells but also improves their operational stability. The relationship is a key factor in analysing the performance of the hybrid solar cells developed in the current study, especially under different environmental conditions.

4.1.2 Analysis of the solar cell proficiency

The response of power output across different solar cell samples highlights the high sensitivity of solar cell efficiency to material composition and environmental conditions [34]. The highest power draw for samples 1 to 10 is between 18 W and 32 W, with sample 11 (control) recording the highest at 33 W. Samples 8, 9, and 10 showed significant values of 29 W and 32 W, which were close to the performance of the control sample reported in Figures 12-15. As shown in Figure 16, the efficiency of solar cells was highest on day 5 and for sample 8, at 29.05, compared to the control sample of 26.61. These results are consistent with the existing literature on the matter, which indicates that the performance of solar cells largely depends on material characteristics and external factors [35]. Indicatively, Chen *et al.* [36] affirm that the materials used, e.g., silicon and organic compounds, have a great influence on the conversion efficiency of solar cells. The solar cells developed in this paper, which utilise agricultural waste materials, indicate that new material combinations can yield competitive performance parameters. The intensity (irradiance) of solar radiation was found to be seven hours per day across five days in February, thus providing essential context for the power outputs [37]. The calculated efficiencies of samples 8 (20.94%), 9 (20.88%), and 10 (20.88%) exceed that of the control sample (20.78%). This trend indicates that the optimal light absorption and faster charge conduction in these hybrid materials, in particular formulations, lead to higher energy conversion efficiency [38-39]. Green *et al.* [40] hold that solar cells become more efficient as irradiance increases. They found that solar cells under ideal conditions can achieve efficiencies of more than 20 per cent, as in this experiment. The data for samples 8, 9, and 10 show that agricultural waste materials can help achieve high efficiencies and provide a sustainable way to do so, indicating a sustainable direction for developing solar energy technologies [41-42].

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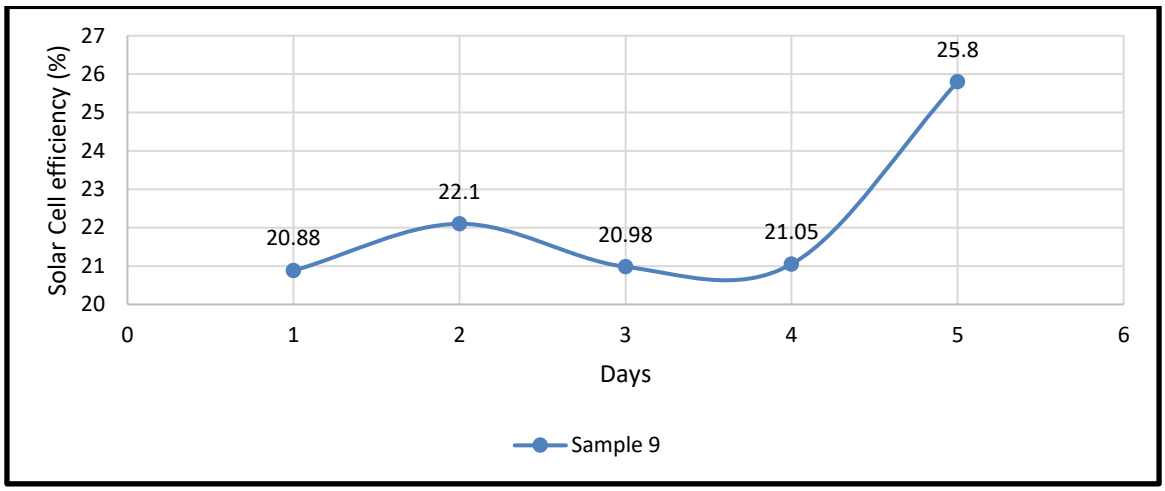


Figure-13. Analysis of solar cell effectiveness for sample 9 against days.

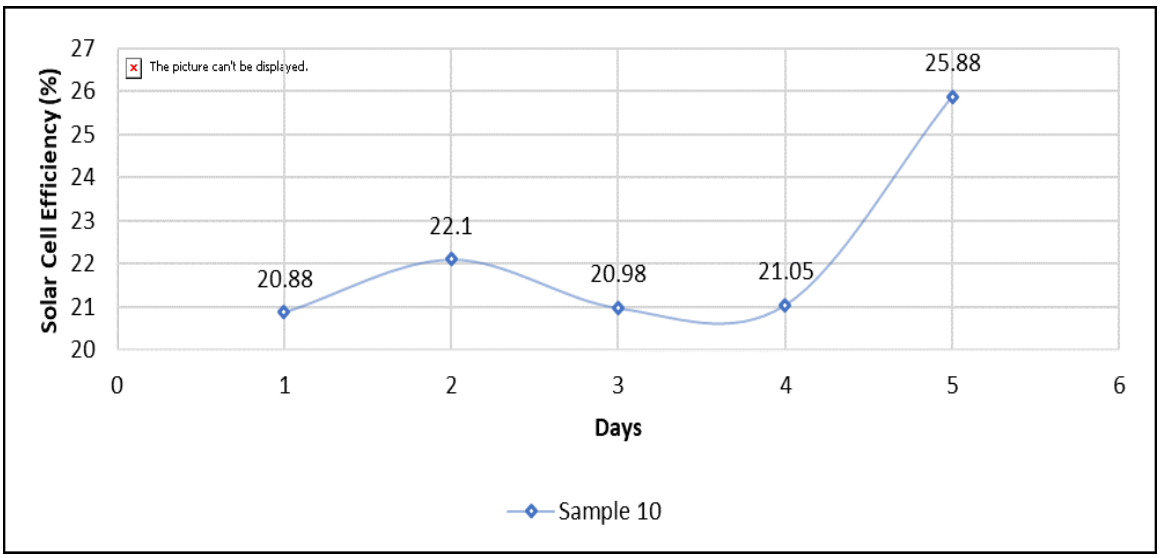


Figure-14. Analysis of solar cell effectiveness for sample 10 against days.

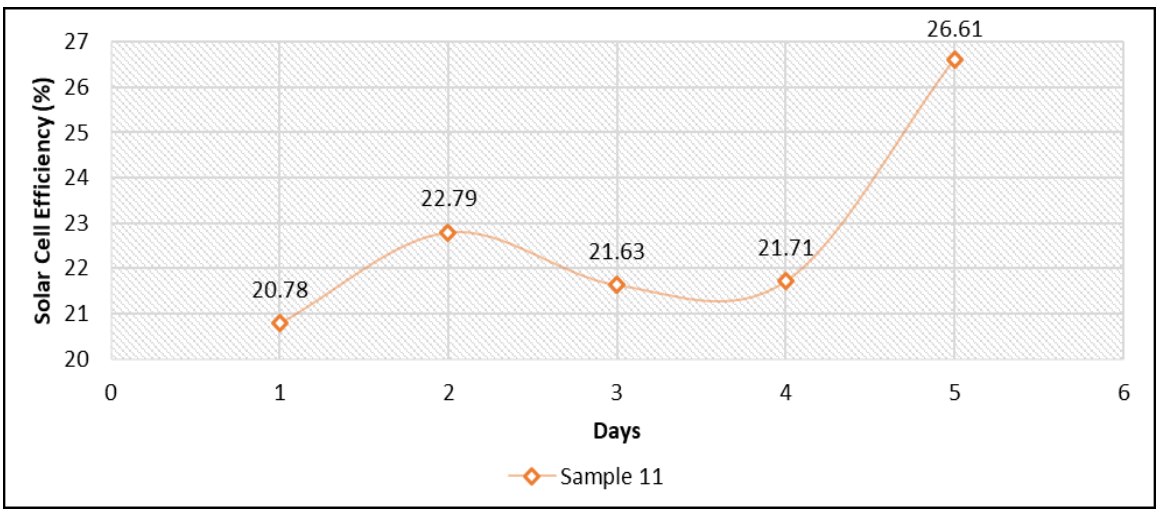


Figure-15. Analysis of solar cell productivity for sample 11 against days.

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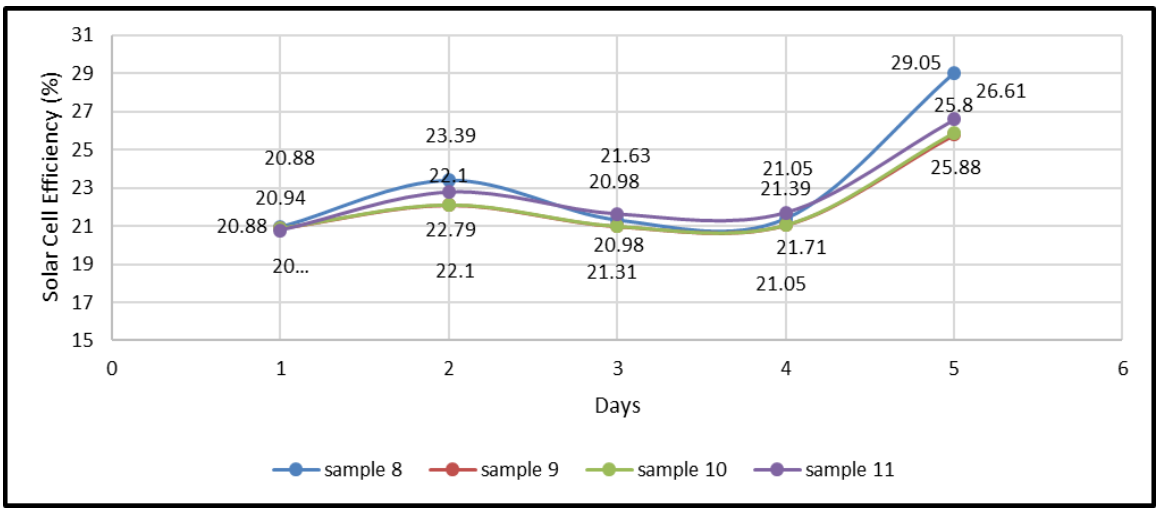


Figure-16. Analysis of solar cell effectiveness for samples 8-11 against days.

5. CONCLUSIONS

This paper demonstrated the potential of hybrid solar cells made from agricultural waste, particularly their competitive power outputs and efficiencies. The results of the experiment showed that the power outputs of the samples ranged from 18 W to 32 W, with samples 8, 9, and 10 having efficiencies of more than 20 per cent, which were very similar to the control sample's performance. The positive relationship between solar radiation intensity and efficiency further indicates the relevance of environmental factors in solar cell optimisation.

The use of materials such as rice hulls and peanut shells, among other agricultural waste products, not only increases the energy conversion capacity of solar cells but also contributes to sustainability by repurposing waste. The results of this research are important for the current investigation of solar technology, as the need for renewable energy sources increases. The study indicates that new combinations of materials can be used to create more effective and eco-friendly solar energy sources.

To improve the performance and stability of such hybrid materials, future studies should aim to maximise their performance and investigate other types of agricultural wastes. All in all, the present research confirms that hybrid solar cells are a feasible option for green energy and opens the possibility of novel technological developments in solar cells that can support environmental and cost-effective objectives.

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