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Advancement in Photogalvanic Cell for Solar Energy Harvesting: A Review

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Abstract: ***The Photogalvanic effect is a promising mechanism for the conversion of solar energy into electrical energy, utilizing a variety of chemical systems to enhance efficiency and storage capacity. The operation of Photogalvanic cells is characterized by the absorption of solar energy by a photosensitizer, which generates energy-rich species in an electrolyte solution. This process creates a Photopotential between two electrodes, enabling the production of electricity without the need for complex semiconductor materials found in conventional solar cells. About 196 research articles on the development of Photogalvanic cell we have been reviewed here. With comparison of 87 system, the electric parameters of the cell containing single dye, mixed dye and natural dye with reductant and surfactant have presented in tabular form (Table-1). We have also focus on the challenges limitation, future aspect in field of photochemical conversion of solar energy and its storage. This review explores the recent advancements in Photogalvanic cells, devices that convert light energy into electrical energy via photochemical processes. It highlights innovations in materials, the mechanisms of charge generation and transfer, challenges in efficiency and stability, and the diverse applications of Photogalvanic cells, in sustainable energy production. The paper also discusses future trends and emerging technologies that could shape the development of Photogalvanic cells, positioning them as a promising technology in the renewable energy landscape.***

Keywords: photopotential, photocurrent, conversion efficiency, storage capacity, fill factor.

I. INTRODUCTION

Solar energy is a form of renewable energy. It is created when the sun undergoes nuclear fusion. In 1.5 days, the sun generates 1.7 x 10^{22} J of energy. This energy is equivalent to the total energy contained in the world's 3 trillion barrels of oil reserves. Humans use 4.6 x 10^{20} J of energy each year. The sun produced this amount of energy in one hour.[1] Solar energy is a low-cost, easily available, and environmentally friendly source of energy that has the potential to produce almost no emissions.[2]

People have been using sun energy since the 17th century BCE. Ancient civilizations (Rome and Greece) displayed the first documented use of sunlight by lighting torches with mirrors for religious purposes, and ancient buildings employed passive solar design, which entails harnessing sunlight to heat and light inside spaces. A.E. Becquerel discovered the outstanding and revolutionary Becquerel effect in 1839. The photoelectric effect was discovered in the 20th century by Einstein and other scientists. This encouraged research into materials whose chemical composition would enable them to be used to generate electrical energy from solar radiation.[3] Solar energy is directly converted into solar power via solar cells, which are based on the photovoltaic effect. Solar cells can be made with a single layer of light-absorbing material (single-junction) or in a variety of physical configurations (multi-junctions) to take advantage of varied absorption and charge separation methods.[4] Solar cells includes, silicon solar cells, thin-film solar cells, perovskite solar cells, quantum dot cells, organic solar cells, dye-sensitized solar cells, photogalvanic cells. Photogalvanic cells are electrochemical devices, that use dye-sensitized solutions to convert and store solar radiation through the “Photogalvanic Effect.” Rideal and Williams discovered it[5], while Rabinowitch conducted an extensive investigation and firstly used the word.[6], [7] Furthermore, several research groups, including Waber and Matijevic[8], Kamat and Lichtin[9], [10], Albery and Foulds[11], etc., have examined this effect on various systems of photogalvanic cells for solar power conversion and storage.

II. COMPONENTS OF PHOTOGALVANIC CELLS (PG CELLS)

The fundamental elements of PG cells are electrolytes, electrodes, assembly setup, and a light source.

A. Electrolytes

The electrolyte facilitates the movement of ions between the two electrodes in the photogalvanic cell. The electrolyte helps to stabilize the photogalvanic cell by maintaining the proper ionic conditions necessary for continuous operation. A well-chosen electrolyte can enhance the conversion of solar energy into electrical energy and improve the cell's longevity.

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Photogalvanic cells containing dye/photosensitizer, reductant, surfactant, and acid/alkali are important electrolytes component for storage and low-cost assembly setup.

1) *Photosensitizer:* Dyes/photosensitizers are essential to the operation of photogalvanic cells because they absorb solar light and start the processes that lead to electron transfer. So, photosensitizer should be photostable and good light-harvesting material. Photochemical reactions require a specific concentration of the dye. Light and dye molecules are both particles in nature and interact according to Stark-Einstein's law, a lower concentration of photosensitizer led to a decrease in photopotential and photocurrent because there were fewer photosensitizer molecules available for excitation and subsequent electron donation to the platinum electrode. Similarly, at larger concentrations, a large amount of the light is absorbed by dye molecules because photogalvanic cells are diffusion-controlled. Increased concentration may also result in faster recombination between injected electrons and dye. Hence, when photosensitizer concentration rises, photopotential and photocurrent are increased until they reach their highest values and further decrease.[3]

   Dyes are classified into synthetic and natural dyes. Natural dyes consist of complex blends of components sourced from natural materials like plants, animals, or minerals. Synthetic dyes are produced in a lab. Chemicals are produced to create synthetic dyes. Thionine dye was mostly used as a primary electrolyte until around the 1980s.[6], [7], [8], [10] Later on, a variety of dyes from various classes were tested in photogalvanic cells as photosensitizers like Malachite Green[12], Congo red[13], Rose Bengal[14], Quinoline Yellow[15], Alizarine Red S[16], etc. Dube[17] used a mixed dye system (Azur A, Azur B, and Azur C with mannitol and NTA) in photogalvanic cells to improve conversion efficiency and also discovered that the dyes increased the ability of solution to absorb solar energy, which led to a larger area of light absorption. Later, a variety of mixed dye systems of the photogalvanic cells have been explored, including Toluidine Blue + Brilliant Cresyl Blue[18], Brilliant Green + Celestine Blue[19], Naphthol Green B + Janus Green B[20], Xylene Cyanol FF + Patent Blue[21], Sudan Black- B + Azur-B[22], etc. Synthetic dyes exhibit high conversion efficiency and superior chemical stability, rendering them among the top sensitizers; however, they tend to be quite costly and hazardous. Also, using artificial dye sensitizers goes against the main goals of solar energy harvesting's sustainability and renewable nature.

   Consequently, numerous, researchers have turned to natural dyes because of their wide range of possibilities, due to their completely biodegradability, inexpensive, non-toxic, and readily available, they can be utilized for the same application. Natural dyes are present in different parts of plants like leaves, flowers, fruits, and seeds which are obtained with easy methods. Many natural dyes derived from plant sources have been used as photosensitizers in photogalvanic cells for solar energy harvesting showed in Table - 1.

2) *Reductant:* In the first systematic photogalvanic cell, iron salt was used as an electron donor. However, the photocurrent and photopotential were low due to recombination and dissipation of free energy into heat. In 1958, W. Hendrich[23] used ascorbic acid as an irreversible reductant, which was easily soluble in dyes and faster for redox transfer, enhancing conversion efficiency. Albery et al.[24] proved that irreversible reducing agents are more beneficial than reversible ones in photogalvanic cells. Several irreversible reductants have been used as electrolytes like EDTA, triethylamine, triethanolamine[25], hydroquinone[26], ascorbic acid[27], [28], oxalic acid[29], fructose[30], etc, and mixed reductants mannitol-nitrilotriacetic acid[31], EDTA with oxalic acid, nitrilotriacetic acid, and dextrose, respectively[32], etc have been used to improve electrical output.

   Similar to the dye concentration, the reductant concentration also follows a similar trend. Lower reductant concentrations result in lower electrical output because fewer reductant molecules are available to donate electrons to photosensitizers, and higher reductant concentrations cause photopotential and photocurrent to fall because an excess of reductant molecules prevent dye molecules from reaching the electrode in the appropriate time.

3) *Surfactant:* Surfactants are chemical substances that are naturally amphiphilic. This implies that they include both water-soluble (hydrophilic) and water-insoluble (hydrophobic) groups. Surfactants are commonly used to inhibit the recombination reaction in photochemical processes. SLS was initially used by Zhi-Chu Bi[33] as a surfactant in a solution that contained thionine as a dye and Fe^{2+}/Fe^{3+} as a reductant. It is interesting to observe that SLS surfactant solution is used in photogalvanic cells to dissolve thionine in water. In India, first of all, Srivastava et al.[34] used polyvinyl methyl ether as a surfactant to improve photogalvanic cell conversion efficiency. Valenty[35] investigated the interactions of functionalized surfactants monolayer films and discovered that methylene blue adsorption to photogalvanic electrodes is connected to the orientation and absorption spectra of its surfactant analogues. SLS is widely used as a surfactant in the photogalvanic cells.[36], [37] Other surfactants, such as Triton-X 100[14], Brij-35[38], DSS[22], CPC[39], Tergitol-7[40], CTAB[41], Tween 80[42], Benzalkonium Chloride[29], etc, and mixed surfactants such as NaLS+CTAB and NaLS+Tween-80[43], NaLS+CPC+Tween-80[44], Brij-

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35+NaLS[45], etc are being utilized to enhance the electrical output of photogalvanic cells. The use of surfactants has been found to improve cell stability and electrical output because surfactant molecules interact with dye through charge transfer or coulombic interaction, depending on the nature of the dye and surfactants. The cell is more stable in a cationic micelle medium (if the dye is anionic) than in an aqueous medium.[46] However, the conversion efficiency of systems with different surfactants is often found to be in the order anionic>non-ionic>cationic (if the dye is cationic).[47] When a surfactant and dye have opposite charges, a strong dye-surfactant complex forms in which the dye molecule is covered by surfactant micelles in a regular shape that inhibits intermolecular twisting and increases fluorescence.[48] Studies have shown that when surfactant concentration increased both the photo-potential and photo-current increased until they reached a maximum and subsequently decreased.

4) *Alkali/acid:* The conductivity of the cell is affected by the medium of the solution. An appropriate pH can increase the electrical output because pH affects the back reaction. Initially, several acids such as oxalic acid[49], H_2SO_4[50], HCl[51], and CH_3COOH[52] were utilized to maintain the pH of electrolytes. Nowadays, alkali mediums such as NaOH[53], [54], [55], KOH[56] are used in the fabrication of the photogalvanic cells, because most of the photosensitizers/dyes are more soluble and stable in an alkali medium. It is commonly observed that, when the concentration of solution medium (pH) increases, the cell output of the regenerative photogalvanic cell also increases until it reaches a maximum and then decreases. The optimal pH is related to the pK_a value of the reductant. The desired pH is greater than the pK_a value (pH> pK_a). This could be explained by the reductant being available in its anionic form, which is a better donor form.[57]

B. Electrode

The photogalvanic cell technique uses two electrodes: the working electrode (acting as the anode), which is exposed to light, and the counter electrode (acting as the cathode), which is kept in the dark chamber. The working electrode facilitates electron exchange between the semi/leuco reduced sensitizer molecule and the external circuit, while the counter electrode completes the circuit and conducts current.

Initially, researchers used both coated and uncoated Pt electrodes as the working electrode, but the electrical output obtained from both was low due to the large size of the platinum electrode.[6] Later on, small-sized Pt electrodes were used to improve the performance of photogalvanic cells.[58], [59], [60], [61] A platinum electrode is considered inert because platinum has a high ability to facilitate electron exchange. However, it is costly and not easily accessible in the local market, making its procurement expensive and time-consuming. Nowadays, different types of electrodes such as Cu, Cu-Zn alloy (brass)[62], Al, Cu-Ni alloy, Al-Mg alloy[63], etc., are used as working electrodes in PGCs. A saturated calomel electrode is usually used as a counter electrode or reference electrode but in recent times various types of reference electrodes such as graphite counter electrodes[64] have been used.

C. Light source

The electrical output of a cell is affected by the light source and its distance from the cell surface. Rabinowitch initially used a 1000 W lamp as the light source in the first thionine–iron photogalvanic cell.[6] Subsequently, various researchers used different light intensities, such as 900 W xenon lamp[65], 500 W xenon lamp[66], 450 W xenon lamp[67], 300 W[68], 250 W tungsten halogen lamp[69], 150 W xenon lamp[70], 100 W tungsten lamp[71], and 2 W Ar laser[72]. Nowadays, a 200 W tungsten lamp[19], [73], [74], [75] is used as the light source in PGCs. However, direct light is not useful because the radiation produces Infrared radiations that raise the temperature of the system. Therefore, filters are used for light filtration. Generally, water (flow) is used as a light filter[76], but in some systems, glass filters are also used[66]. Daul et al.[77] alternately illuminated the two electrodes and observed a very stable power output. Some scientists used other filters with water for light filtration, such as FeSO4 solution.[7], [8] However, water is mostly used as a filter in regular photogalvanic cell work nowadays. The distance between the light source and the cell surface is typically about 15 cm in recent work.[68]

As light intensity rises, more dye molecules are photoexcited and reduced by reductant due to the photogalvanic effect. This effect is correlated with the ratio of bleached and unbleached dye in the solution. Photocurrent and photopotential increase linearly and logarithmically with light intensity, respectively but the cell temperature also increases. In general, photogalvanic cells use 10.4mWcm^{-2} of light intensity[78], but at greater intensities (>150mWcm^{-2}), the photogalvanic effect approaches a limit.[79]

D. Experimental Setup and Mechanism

The two electrodes used in the photogalvanic cell technique are the working electrode (often platinum, Pt) which is exposed to light, and the counter electrode (commonly a saturated calomel electrode, SCE) which is in the dark.

A solution of photosensitizer (photon-absorbing species), reductant (electron-donating species), and surfactant (efficiency enhancer agent) in an alkaline medium are used to fill the space between the electrodes. The net volume of electrolyte remains 25 ml. The working electrode in photogalvanic cells facilitates electron exchange between the semi/leuco-reduced sensitizer molecule and the external circuit. The circuit is completed with the help of the counter electrode, which also conducts current flow.[62] They are shown in the experimental setup (Fig -1).

E. Mechanisms

Illuminated Chamber- On illumination, a photon is absorbed by the dye, which gets excited. The excited form of the dye removes an electron from the reductant and converts into a semi or leuco form of the dye.

$$D \xrightarrow{h\upsilon} D^*$$

$$D^* + R \longrightarrow D^- \text{ (semi or leuco)} + R^+$$

At the platinum electrode, the semi/leuco form of the dye passes the electron to the platinum electrode, resulting in the formation of the original form of the dye.

$$D^- \longrightarrow D + e^-$$

Dark Chamber- The dye absorbs an electron from the SCE and transforms into the semi/leuco form. The leuco/semi form of the dye and the oxidized form of the reductant combine to produce the original dye and reductant molecules, repeating the process. The result is an electron stream that transforms light into electricity.

$$D + e^- \longrightarrow D^- \text{ (semi or leuco)}$$

$$D^- + R^+ \longrightarrow D + R$$

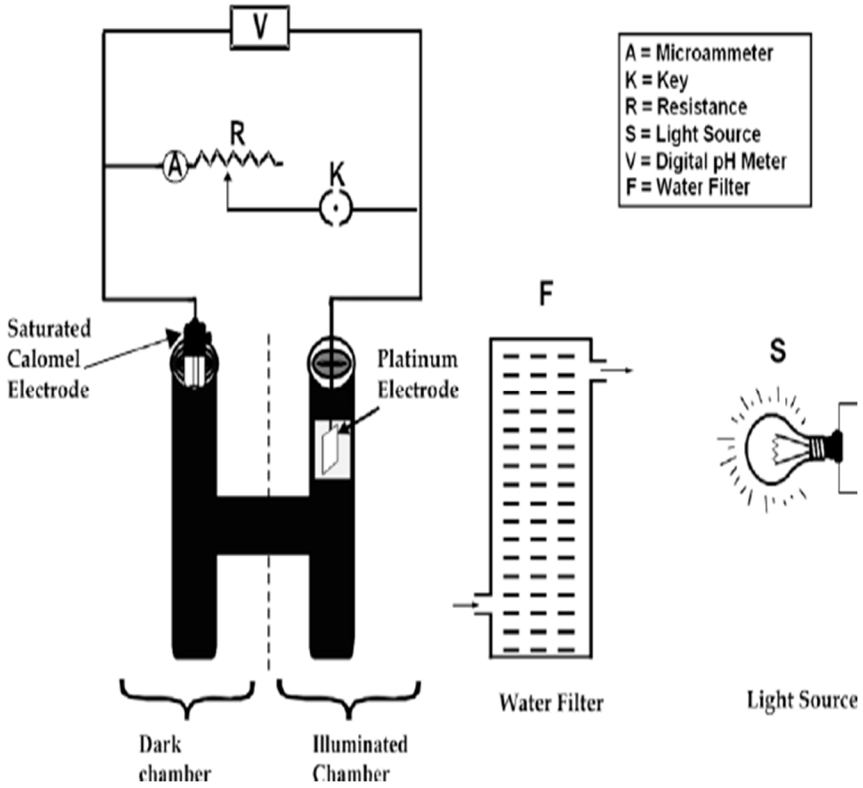

Fig- 1: Experimental setup of a Photogalvanic cell (Source- Ref.-2

Table 1: Different types of Dye-Surfactant-Reductant Systems were used in Photogalvanic cells.

S.No.	Dye	λ_{max} (nm)	Surfactant	Reductant	V_{oc} (mV)	i_{sc} (μA)	P_{pp} (μW)	CE (%)	FF	$t_{1/2}$ (min.)	Ref.
Synthetic Dyes											
(a) Single Dye:											
1	Acid Fuchsin	544	Benzethonium Chloride	EDTA	1100	110	46.56	0.447	0.38	55	[78]
2	Acid Yellow 36/ Metanil Yellow	436	NaLS	Formic acid	1110	6000	822	20.41	0.206	105	[80]
			NaLS	Ascorbic acid	1020	335	104.72	1.006	0.388	110	[81]
			–	EDTA	685	230	71.50	2.75	0.45	160	[82]
3	Acridine Orange	430	NaLS	DTPA	1051	205	85.95	0.83	0.56	95	[83]
4	Alizarin Cyanine Green	642	Sodium stearate	EDTA	1033	477	164.1	1.798	0.264	180	[84]
			Cocamide DEA	EDTA	1038	480	138	1.231	0.308	189	[85]
5	Alizarin Red S	493	NaLS	Ascorbic acid	1075	672	197.29	1.897	0.273	140	[27]
			CPC	Oxalic acid	1189	420	147.42	2.16	0.299	16	[16]
			Brij 35	Galactose	432	12	–	0.019	0.395	24	[86]
6	Allura Red	504	DDAC Pt electrode	D-Galactose	721	2400	443.8	11.61	0.25	28	[87]
			DDAC Cu electrode	D-Galactose	713	4030	552.3	8.54	0.19	–	[62]
			DDAC Brass electrode	D-Galactose	739	5320	546.4	6.12	0.13	–	[62]
			NaLS	Ascorbic acid	920	760	144.54	1.38	0.206	110	[88]
7	Amido Black 10B	610	Tween 60	Ascorbic acid	1043	420	168.75	1.622	0.38	130	[48]
8	Aniline Blue	310	NaLS	Ascorbic acid	1485	750	240.24	2.31	0.244	130	[89]
9	Azur A	633	–	EDTA + Dextrose	1018	55	10.87	0.104	0.194	115	[32]
			–	EDTA + NTA	1097	292	124.30	0.983	0.319	230	[32]
			–	EDTA + Oxalic acid	1056	210	35.83	0.909	0.426	86	[32]
			NaLS	Ascorbic acid	1035	160	56.80	0.546	0.34	110	[90]
			NaLS	EDTA	1074	255	207.57	1.20	0.45	26	[91]
			NaLS	Glucose	893	147	–	0.478	0.38	128	[92]
			TTAB	Glucose	987	142	–	0.327	0.24	71	[92]
			Brij 35	Glucose	927	143	–	0.401	0.32	93	[92]
			–	Glucose	749	140	–	0.353	0.26	54	[92]
			NaLS	Glycerol	855	250	213.75	1.182	0.476	63	[93]
10	Azur B	647	CTAB	EDTA	1035	395	104.50	1.004	0.255	140	[94]
			NaLS	Ascorbic acid	1301	185	100.32	0.964	0.41	135	[95]
			NaLS	EDTA	814	255	207.57	1.20	0.45	26	[96]
			Tergitol 7	EDTA	1034	45	14.75	0.14	0.316	40	[40]
			–	EDTA	760	30	–	0.06	0.182	11	[40]
			NaLS	NTA	811	140	42.16	0.405	0.37	105	[97]
			Tween 80	NTA	729	95	22.65	0.217	0.32	74	[97]
			CPC	NTA	718	65	14.42	0.138	0.30	31	[97]
			–	NTA	996	70	17.52	0.168	0.25	12	[97]
11	Azur C	620	NaLS	Ascorbic acid	1085	145	47.50	0.456	0.30	95	[98]
			–	NTA	347	70	19.84	0.19	0.23	38	[99]
			Triton X 100	Glycerol	–	130	48.93	0.470	0.435	38	[100]
12	Biebrich Scarlet	536	Tween 60	Ascorbic acid	1072	210	93.15	0.896	0.41	75	[101]
13	Bismarck Brown	457	Brij 35	DTPA	970	115	54	0.519	0.48	117	[102]
			–	Ascorbic acid	1110	155	93.50	0.899	0.54	40	[103]
			–	EDTA	980	135	63.9	0.614	0.48	34	[103]
			–	Glucose	870	120	42.16	0.405	0.40	31	[103]
			–	Oxalic acid	1072	620	195.65	0.470	0.557	65	[104]
14	Brilliant Black PN	570	Ammonium Lauryl Sulphate	EDTA	–	1125	317.10	3.049	0.25	130	[105]
15	Brilliant Blue FCF	628	NaLS	Ascorbic acid	1025	445	120.56	1.159	0.264	130	[106]
16	Brilliant Cresyl Blue	622	–	Fructose	1115	590	183.30	1.958	0.291	228	[30]
			NaLS	Fructose	1061	2300	661	8.26	0.27	163	[107]
			NaLS	Mannose	1088	310	106.92	1.028	0.317	165	[108]
			–	Mannose	1034	240	–	0.711	–	85	[108]
			NaLS	Ascorbic acid	1124	220	62.40	1.236	0.252	120	[28]
			NaLS	D-Xylose	1085	440	115	1.105	0.240	140	[109]
			NaLS	Ethylene Glycol	1085	460	153.14	1.472	0.306	60	[18]
17	Brilliant Green	625	Ammonium Lauryl Ether Sulphate	Ascorbic acid	–	720	262.40	2.52	0.29	180	[110]
18	Brilliant Yellow	432	NaLS	Ascorbic acid	1120	585	224.25	2.156	0.342	140	[111]
19	Bromocresol Green	423	Tween 80	EDTA	760	748	100.13	0.96	0.150	100	[112]
			NaLS	Formaldehyde	1130	8000	–	9.02	–	70	[113]
			NaLS	Ascorbic acid	1045	350	83.52	0.803	0.228	140	[106]
20	Bromocresol Purple	212	Tween 60	Ascorbic acid	1031	65	34.16	0.328	0.50	150	[101]
21	Carmine	563	Tween 60	Ascorbic acid	1040	190	85.12	0.818	0.43	170	[101]
22	Carmoisine A	516	Cocamidopropyl Betaine	Lactic acid	731	2500	345	25.4	0.21	–	[114]
23	Celestine Blue	642	NaLS	EDTA	–	127		0.779	0.32	31	[36]
24	Chlorophenol Red	576	NaLS	Isopropyl alcohol	1273	735	233.011	2.240	0.275	165	[115]
25	Congo Red	498	NaLS	Formaldehyde	1074	3200	782	11.02	0.22	120	[13]
			CPC	D-Xylose	–	470	119.6	1.15	0.323	130	[116]
			–	EDTA	800	180	32.46	1.09	–	120	[117]
26	Coomassie Brilliant Blue	465	–	EDTA	920	380	97	1.86	0.27	190	[118]
			NaLS	Isopropyl Alcohol	734	140	118	0.879	0.306	114	[75]
27	Crystal Violet	590	DSS	Ascorbic acid	–	195	71.68	0.69	0.400	85	[54]
28	Eosin	525	–	Fructose	1071	240	87.52	0.841	0.34	55	[119]
			–	Arabinose	1066	240	73.08	0.702	0.28	85	[119]
			–	D-Xylose	1020	250	70.85	0.681	0.27	90	[119]

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			–	Mannose	1057	170	67.20	0.646	0.37	75	[119]
29	Erythrosine	505	Benzethonium Chloride	EDTA	–	250	86.13	0.828	0.33	95	[120]
30	FCF Fast Green	625	NaLS	Fructose	1048	2250	649.6	8.12	0.22	59	[107]
			–	Fructose	1066	380	138.60	1.33	0.34	70	[121]
31	Indigo Carmine	608	DSS	EDTA	920	410	97.52	0.937	0.253	120	[122]
			NaLS	Formic acid	1080	3800	985.6	28.43	0.240	115	[55]
			–	Ascorbic acid	–	160	47.60	0.45	0.27	40	[123]
32	Janus Green B	654	NaLS	Ascorbic acid	806	775	122.55	1.17	0.196	130	[124]
33	Lissamine Fast Yellow		NaLS	Ascorbic acid	1100	375	108.15	1.039	0.268	160	[125]
34	Lissamine Green B	630	NaLS	Ascorbic acid	1100	375	106.68	1.025	0.259	170	[126]
35	Malachite Green	614	NaLS	EDTA	–	76	18.256	0.22	0.22	30	[127]
			NaLS	Arabinose	836	36	6.138	0.059	0.203	32	[12]
			–	Arabinose	845	33	11.900	0.112	0.426	36	[128]
			NaLS	Ascorbic acid	1124	586	225.26	2.252	0.34	141	[129]
36	Methyl Green	677	NaLS	DTPA	–	310	252.65	1.05	0.43	55	[130]
37	Methyl Orange	464	NaLS	D-Xylose	1085	480	168.95	1.624	0.321	160	[131]
			Brij 35	DTPA	735	95	28.16	0.270	0.400	94	[102]
38	Methylene Blue	665	–	Oxalic acid	–	70	12.6	0.121	0.28	35	[132]
			NaLS	D- Xylose	1001	90	32.72	0.31	0.363	55	[133]
			NaLS	Mannose	1041	80	37.63	0.361	0.451	48	[134]
			–	Mannose	918	73	30.24	0.290	0.451	40	[134]
			NaLS	Mannitol	–	–	32	0.264	0.32	45	[57]
			Triton X 100	EDTA	1082	420	113.80	1.087	0.248	160	[135]
			NaLS	EDTA	654	190	–	0.698	0.37	200	[136]
			–	Ascorbic acid	1121	165	148	0.83	0.46	165	[137]
			NaLS + Tween 80	D- Xylose	870	210	55.25	0.531	0.302	100	[43]
			NaLS + CTAB	D- Xylose	825	190	44.99	0.432	0.287	90	[43]
			Brij 35 + NaLS	D- Xylose	921	245	60.23	0.676	0.452	126	[38]
39	Naphthol Green B	714	NaLS	Fructose	1040	1850	422.4	10.6	0.21	260	[107]
			NaLS	Ascorbic acid	1050	365	107	1.028	0.279	160	[138]
40	Nile Blue	635	–	Arabinose	816	330	91.28	0.609	0.256	120	[139]
			NaLS	DTPA	812	165	75	0.72	0.559	25	[140]
41	Orange G	196	NaLS	EDTA	1249	350	158.9	1.52	0.47	80	[141]
			–	EDTA	1175	265	156.40	1.503	0.50	140	[142]
42	Phloxine B	550	–	D-Xylose	910	260	126.16	1.21	0.533	120	[143]
			CTAB	EDTA	1135	300	66.72	0.64	0.226	100	[144]
			–	EDTA	1155	250	135.3	1.300	0.46	120	[145]
43	Ponceau S	205	–	Mannitol	1080	240	–	0.456	0.45	36	[146]
			–	EDTA	1047	390	84	1.61	0.20	240	[147]
44	Quinoline Yellow	412	DTAB	Cellobiose	900	8000	989	15.08	0.14	100	[15]
			DOSS	Cellobiose	865	4500	695	13.78	0.18	100	[148]
45	Rhodamine B	546	–	Fructose	1044	960	240.58	6.93	0.24	216	[149]
			NaLS	Fructose	1017	2400	620.1	7.75	0.23	142	[107]
			NaLS	DTPA	–	185	77.28	0.74	0.495	85	[150]
			–	Ascorbic acid	1137	120	59.64	0.51	0.38	45	[137]
46	Rhodamine 6G	530	DSS	Oxalic acid	1080	200	176	0.86	0.41	131	[47]
			CTAB	Oxalic acid	620	90	37.26	0.24	0.45	68	[47]
			Triton X 100	Oxalic acid	897	165	110.88	0.55	0.38	96	[47]
			–	Oxalic acid	530	60	12.60	0.22	0.39	25	[47]
			NaLS	EDTA	1162	450	131.60	1.265	0.251	170	[151]
47	Rose Bengal	551	NaLS	D-Xylose	1095	460	158.72	1.52	0.315	145	[152]
			CTAB	Oxalic acid	550	75.1	7.005	0.067	0.169	175	[2]
			–	Mannitol	1080	160	62.8	0.744	0.44	60	[153]
			Triton X 100	Oxalic acid	289	29.1	2.96	0.023	0.293	45	[14]
			–	Oxalic acid	1239	175	64	0.981	0.51	90	[153]
48	Safranine	520	Sodium Octanoate	Mannitol	–	330	285.1	1.534	0.44	35	[154]
			DSS	Mannitol	–	150	130.50	0.760	0.50	40	[74]
			NaLS	Mannitol	1000	75	63.30	0.222	0.31	102	[155]
			NaLS	D-Xylose	1057	207	70.74	0.680	0.323	98	[156]
			Brij 35	DTPA	1048	155	66.96	0.643	0.41	122	[102]
			–	EDTA	1055	50	27.22	0.261	0.58	19	[157]
			–	Glucose	580	35	3.70	0.035	0.18	85	[157]
			–	NTA	655	35	8.75	0.084	0.37	8	[157]
			NaLS	Arabinose	1025	117	40.04	0.385	0.333	91	[158]
			–	Arabinose	989	87	29.63	0.312	0.280	77	[158]
			NaLS	Fructose	998	128.6	21.86	0.21	0.17	16	[159]
			–	Fructose	981	57.20	13.55	0.13	0.24	35	[159]
			–	Ascorbic acid	1061	150	120.60	0.65	0.42	115	[137]
49	Safranine O	518	NaLS	EDTA	1052	1700	364.70	8.93	0.20	40	[160]
			DSS	EDTA	1059	65	26.34	0.253	0.38	80	[53]
			–	EDTA	981	100	–	0.330	0.03	11	[53]
			Tween 80	EDTA	995	300	101.60	0.976	0.34	60	[161]
			CTAB	EDTA	973	185	15.28	0.146	0.084	20	[162]
			CPC	EDTA	913	80	15.28	1.469	0.21	25	[39]
50	Sudan I	476	NaLS	Fructose	1014	1350	367.8	11.49	0.26	30	[163]
51	Sunset Yellow FCF	480	DSS	EDTA	864	390	–	1.218	0.290	140	[164]
			CTAB	Ascorbic acid	777	5600	733.6	19.77	0.168	6	[56]
			Cetrimonium Bromide	Ascorbic acid	806	5400	552.0	11.19	–	–	[165]

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52	Tartrazine	199	Lauryl Glucoside	D-Fructose	1523	544	435.32	0.799	0.538	129	[166]
			DSS	EDTA	879	220	–	0.616	0.280	100	[164]
53	Titan Yellow	402	–	EDTA	823	2800	511.10	17.57	–	–	[167]
54	Thionine	596	–	EDTA	–	–	72	0.280	0.36	49	[168]
			CTAB	EDTA	700	150	53.5	0.514	0.50	50	[41]
55	Thymol Blue	593	NaLS	Mannose	955	100	24.60	0.236	0.257	37	[169]
			–	Mannose	929	70	20.20	0.194	0.217	27	[169]
			–	Ascorbic acid	–	150	82.06	0.803	0.49	54	[170]
56	Toluidine Blue	630	NaLS	EDTA	1065	70	27.36	0.263	0.367	124	[37]
			NaLS	Arabinose	966	60	15.06	0.144	0.259	123	[12]
			–	Arabinose	885	55	15.375	0.145	0.315	90	[128]
			CTAB	Glucose	–	35	6.26	0.057	0.41	6	[171]
			NaLS	D- Xylose	1110	430	148.96	1.432	0.312	130	[172]
			CPC	EDTA	1005	35	11.04	0.106	0.313	38	[173]
			Tween 80	EDTA	710	50	14.40	0.138	0.405	60	[42]
			–	Maleic hydrazide	–	10	–	0.000	0.20	7	[174]
			Tergitol 7	Glucose	315	70	–	0.106	0.33	21	[175]
			NaLS	Ethylene glycol	1084	320	115.92	1.114	0.334	55	[18]
			NaLS + CPC + Tween 80	EDTA	897	234	54.13	0.547	0.281	109	[44]
57	Tropaeolin O	492	Benzalkonium Chloride	Oxalic acid	676	2000	340	10.54	0.25	410	[29]
			–	EDTA	860	340	150.68	1.44	0.51	80	[176]
58	Trypan Blue	607	–	Arabinose	–	350	83.52	0.80	0.23	140	[177]
59	Victoria Blue R	587	NaLS	Ascorbic acid	1045	360	110.39	1.061	0.293	140	[81]
60	Xylidine Ponceau	506	Tween 60	Ascorbic acid	1091	197	68.77	0.661	0.33	110	[178]
(b)	**Mixed Dyes:**										
61	Xylene Cyanol FF + Patent Blue		–	EDTA	868	230	199.64	0.64	0.24	115	[21]
62	Methylene Blue + Toluidine Blue		–	EDTA	–	110	81.62	0.539	0.49	34	[179]
63	Thionine + Azur B		–	EDTA	975	76	56.62	0.18	0.25	59	[180]
64	Methylene Blue + Azur B		–	EDTA	962	70	51.24	0.116	0.18	46	[181]
65	Methylene Blue + Thionine		–	EDTA	1000	90	67.68	0.43	0.49	30	[182]
66	Erythrosine B + Tartrazine		NaLS	EDTA	1040	270	72.42	0.31	0.31	80	[183]
67	Toluidine Blue + Thionine		–	EDTA	–	105	72.9	0.16	–	42	[184]
68	Brilliant Green + Celestine Blue		–	EDTA	894	93	59.1	0.31	0.39	65	[19]
69	New Methylene Blue+Safranine O		–	EDTA	1235	125	81.4	0.444	0.41	95	[185]
70	New Methylene Blue + Fast Green		–	EDTA	998	120	88.56	0.564	0.48	90	[185]
71	Brilliant Green + Fast Green		–	EDTA	930	112	77.28	0.418	0.41	72	[185]
72	New Methylene Blue + Celestine Blue		–	EDTA	795	88	51.04	0.301	0.44	45	[185]
73	Naphthol Green B + Janus Green B		–	EDTA	1248	210	213.78	1.002	0.40	180	[20]
74	Sudan I + Rhodamine B		NaLS	Fructose	1060	2200	550	6.87	0.235	105	[107]
75	Sudan I + Rhodamine B + Fast Green FCF		NaLS	Fructose	960	2150	528	6.60	0.255	45	[107]
76	Sudan I + Rhodamine B + Fast Green FCF+ Naphthol Green B		NaLS	Fructose	1014	2300	561	7.01	0.240	87	[107]
77	Naphthol Green B + Fast Green FCF + Brilliant Cresyl Blue		NaLS	Fructose	1090	2300	596.2	7.45	0.237	67	[107]
78	Brilliant Cresyl Blue + Toluidine Blue		NaLS	Ethylene Glycol	1090	630	195.36	1.878	0.284	70	[18]
79	Sudan Black B + Azur B		DSS	EDTA	965	340	84.83	0.815	0.258	110	[22]
(c)	**Natural Dyes:**										
80	Spinach Extract		NaLS	Fructose	1050	1750	384	9.22	0.20	44	[186]
81	Marigold Flower		Tween 80	Xylose	1080	674	199	1.892	0.273	121	[187]
			Brij 35	Xylose	1076	673	198	2.239	0.273	126	[188]
82	Rose Extract		–	NTA	998	176	82.18	0.79	0.46	42	[189]
			–	Mannitol	1078	170	87.20	0.83	0.47	55	[189]
			NaLS	Ascorbic acid	–	140	110.60	0.676	–	49	[190]
83	Curcumin		Tween 80	Arabinose	1044	836	105.45	1.01	0.120	120	[191]
			NaLS	Ascorbic acid	886	750	131.30	1.26	0.227	110	[192]
			Brij 35	Fructose	1070	784	120.50	1.15	0.143	100	[193]
84	Azadirachta Indica leaves Extract		Benzalkonium Chloride	Oxalic acid	1005	2200	602.4	20.25	0.27	–	[63]
85	Beetroot Extract		NaLS	Formic acid	1115	3200	674.4	15.31	–	155	[194]
86	Magnolia Champaca Flower Extract		CTAB	EDTA	1319	130	140.4	1.42	0.20	40	[195]
87	Pomegranate juice		NaLS	Fructose	700	984	268	10.30	0.38	220	[196]

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III. CELL PARAMETERS

Dark potential (V_{Dark}): Initially, the whole system is placed in dark till it attains a stable potential. This stable potential is known as dark potential. It is represented by V_{Dark} and measured in V or mV.

Maximum potential (V_{max}): After obtaining the dark potential, a rise in potential is seen when the platinum electrode is illuminated. The highest observed potential is known as maximum potential and represented by V_{max}.

Open circuit voltage (V_{oc}): The highest voltage that a solar cell can generate at zero current in the open circuit voltage. It is represented by V_{oc} and measured in V or mV.

Photopotential (ΔV): The photopotential is calculated by the following mathematical expression

$$\Delta V = V_{oc} - V_{Dark}$$

Short circuit current (i_{sc}): The maximum current flowing through a solar cell when the voltage across it is zero (i.e. when the cell is short-circuited), is known as the short-circuit current. It is represented by i_{sc} and measured in A or mA.

Maximum current (i_{max}): The photocurrent increased sharply in the first few minutes of illumination and it reaches a maximum value. This value is called maximum photocurrent. It is represented by i_{max}.

Equilibrium current (i_{eq}): After obtaining the maximum photocurrent, the current decreased slowly during the illumination and finally achieved a constant value. This photocurrent in its equilibrium condition is known as equilibrium photocurrent. It is represented by i_{eq}.

Maximum power point (P_{pp}): The point at which the cell generates maximum electrical power. It is represented by P_{pp} and calculated by the following mathematical expression

$$P_{pp} = V_{pp} \times i_{pp}$$

Voltage at power point (V_{pp}): It is maximum potential at power point and represented by V_{pp}.

Current at power point (i_{pp}): It is maximum current at power point and represented by i_{pp}.

Fill Factor (FF): The fill factor is the most important parameter for evaluating the performance of solar cells. It is the ratio of maximum power to the product of short circuit current and open circuit voltage.

$$FF = \frac{P_{pp}}{V_{oc} \times i_{sc}} = \frac{V_{pp} \times i_{pp}}{V_{oc} \times i_{sc}}$$

Conversion efficiency (CE): It is also the most important parameter of each cell, which represents the capability of a cell. It is the ratio of the electrical power output to input (incident energy from sunlight).

$$CE\ (\%) = \frac{V_{pp} \times i_{pp} \times FF}{P \times A} \times 100\%$$

Storage capacity ($t_{1/2}$): To determine the storage capacity of a photogalvanic cell, add an external load (current at power point) when illumination ends and the potential approaches a constant value. The storage capacity is determined in terms of $t_{1/2}$, which is the time it takes for the output (power) to reduce by half at its power point in the dark. It can also be expressed as a percentage of charging time (charging time = t_{Vmax} - t_{Villum}).

IV. CHALLENGES AND LIMITATIONS

One of the main challenges is improving efficiency, particularly addressing recombination losses that reduce overall energy conversion rates. Photogalvanic cells generally exhibit lower solar energy conversion efficiencies compared to traditional photovoltaic cells. This limits their widespread adoption for grid-scale power generation. The amount of energy a photogalvanic cell can store is directly related to the volume of the electrolyte solution. This limits their energy storage density compared to batteries. Maintaining the long-term stability and performance of photogalvanic cells can be challenging due to factors like electrolyte degradation and electrode corrosion. The cost of advanced materials and fabrication processes remains a barrier to the commercial scalability of PGCs.

V. FUTURE PROSPECTS

Research continues to improve the efficiency, storage capacity, and stability of Photogalvanic cells. Exploring new and more efficient photosensitizers with broader absorption spectra and longer excited state lifetimes is crucial Developing stable electrolytes with higher ionic conductivity and improved charge transport properties can enhance cell performance. Incorporating Nanomaterials like quantum dots or metal nanoparticles can enhance light absorption and charge separation processes. Focus on exploring novel reductant which are eco-friendly and cost-effective and that can efficiently regenerate the oxidized dye molecules in the Photogalvanic cell, improving overall cell performance and longevity.

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Advances in materials science, particularly in the development of high-performance electrodes, electrolytes and Nanomaterials, have could further improve the efficiency and stability of Photogalvanic cells and Photogalvanic cells could play a significant role in sustainable energy distribution.

VI. CONCLUSION

Photogalvanic cells represent an exciting frontier in solar energy technology, merging conversion and storage capabilities in a single device. As the global energy landscape evolves, Photogalvanic cells are positioned as a promising technology that not only contributes to renewable energy generation but also supports the development of eco-friendly materials and systems. This review paper structure provides a comprehensive overview of Photogalvanic cells, covering materials, mechanisms, performance strategies, and future potential in the context of sustainable energy conversion. It would be suitable for researchers, students, and industry professionals interested in the latest developments and applications of this technology. Photogalvanic cells represent a promising avenue in the pursuit of sustainable energy technologies, with their unique mechanisms of energy conversion and storage. Continued advancements in this field may not only enhance their efficiency but also play a critical role in reducing reliance on fossil fuels and addressing global energy challenges. Research into their efficiency, materials, and long-term viability is ongoing, highlighting the need for further innovation in this field to optimize performance and scalability. As research continues to address their challenges and improve efficiency, these cells may play a crucial role in future sustainable energy systems, contributing to the global transition toward clean energy sources.

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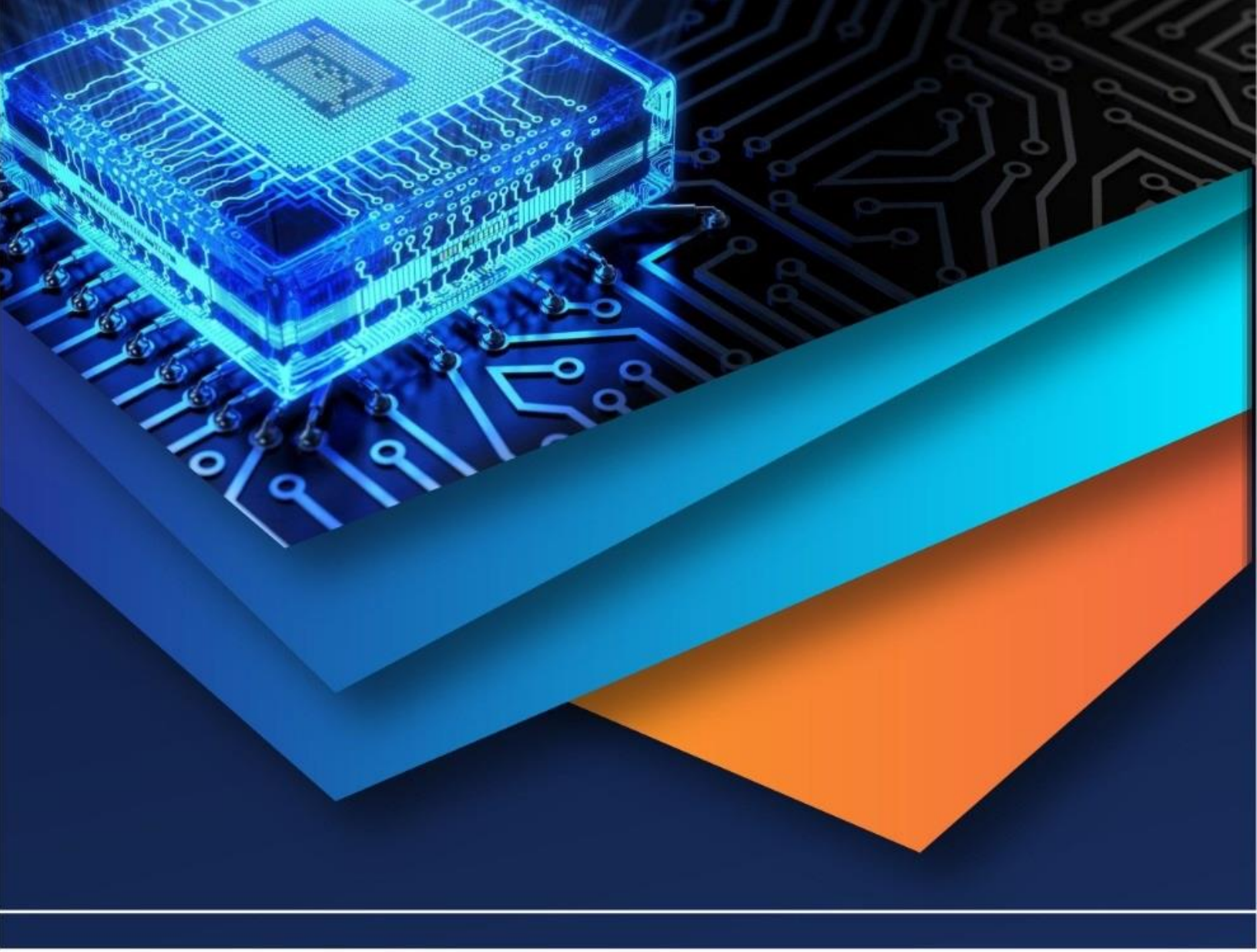

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