GRAPHENATED CARBON NANOTUBES-BASED COUNTER ELECTRODE FOR DYE-SENSITIZED SOLAR CELLS

By

YUSNITA BINTI YUSUF

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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This thesis is dedicated to my beloved parents; Siti Ausun Hj.Saibi and late father Mahmud Zamhari, mother in law Rohani Khalib, late father in law Zainudin Nagin for their endless love, financial support and encouragement. To my beloved husband, Dr. Afiq Azri Zainudin who always encouraged me until this work was completed, thank you for always being my rainbow after the storm. Without your guidance, I would never complete this work.

May Allah bless all of you with mercy and barakah, and reward you with a home in Jannah.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Ir. Suhaidi bin Shafie, Ph.D
Institute : Nanoscience and Nanotechnology

The counter electrode is one of the most critical components in the dye-sensitized solar cell (DSSC). It catalyzes the reduction of iodide/tri-iodide in the electrolyte, bringing the electrons from external loads connected to the cells. A conventional platinum counter electrode is extensively used; however, the concern with platinum-based is that expose to corrosion in an iodine-based electrolyte, which affects the long-term stability of the cell. Therefore, using the carbon-based material to replace the platinum-based in DSSC can address the mentioned problems. This work synthesized a graphenated-carbon nanotube (g-CNT) via the floating-catalyst chemical vapor deposition method. Then, the g-CNT paste was prepared and deposited for the counter electrode. The morphological results revealed that the g-CNT8 obtained 34.5 S/cm, forming a highly conductive network due to graphene foliates at the sidewalls of CNT. This excellent finding is due to the hybrid structure of the g-CNT8, which provides a high defect structure that creates efficient electron transfer in the materials resulting in higher conductivity. For the counter electrode DSSC, briefly, GCC500 film provided good electrical conductivity of 6.28 S/cm. In addition, the GCC500 counter electrode offered excellent catalytic activity for the iodide/triiodide reaction. That is a significant feature in employing counter electrodes to enhance DSSC performance. Furthermore, the DSSC-based GCC500 exhibited 5.68 % of photovoltaic conversion energy, much higher than platinum (3.79 %). Therefore, the GCC500 is an excellent candidate to replace the conventional platinum as a counter electrode in DSSC.

Keywords: g-CNT; carbon-based; counter electrode; DSSC

SDG: GOAL 7: Affordable and Clean Energy

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ELEKTROD BERLAWANAN DENGAN TIUB NANO KARBON BERGRAFENA UNTUK SEL SURIA TERPEKA PEWARNA

Oleh

YUSNITA BINTI YUSUF

Jun 2023

Pengerusi : Profesor Ir. Suhaidi bin Shafie, Ph.D
Institut : Nanosains dan Nanoteknologi (ION2)

Elektrod berlawanan adalah salah satu komponen paling kritikal dalam sel suria terpeka pewarna (DSSC). Ia memangkinkan pengurangan iodin/tri-iodida yang membawa elektron daripada beban luaran yang disambungkan kepada sel. Elektrod berlawanan platinum konvensional digunakan secara meluas, namun, kebimbangan terhadap bahan berasaskan platinum adalah terdedah kepada kakisan dalam elektrolit berasaskan iodin, yang menjejaskan kestabilan jangka panjang sel. Oleh itu, penggunaan bahan berasaskan karbon untuk menggantikan platinum dalam DSSC dapat menyelesaikan masalah tersebut. Kajian ini mensintesis tiub nano karbon-grafen (g-CNT) melalui kaedah pengendapan wap kimia pemangkin terapung. Kemudian, pes g-CNT disediakan untuk elektrod berlawanan. Hasil morfologi menunjukkan bahawa g-CNT8 mencapai 34.5 S/cm membentuk rangkaian yang sangat konduktif kerana pertumbuhan foliat grafen di dinding sisi CNT. Penemuan cemerlang ini adalah disebabkan oleh struktur hibrid g-CNT8 yang menyediakan struktur kecacatan yang tinggi untuk menghasilkan pemindahan elektron yang cekap dalam bahan, lantas meningkatkan kekonduksian yang lebih tinggi. Untuk elektrod berlawanan dalam DSSC, secara ringkas, filem GCC500 memberikan kekonduksian elektrik yang tinggi 6.28 S/cm. Selain itu, GCC500 menawarkan aktiviti pemangkin yang sangat baik untuk tindak balas iodida/triiodida. Ini adalah ciri penting untuk meningkatkan prestasi DSSC. Tambahan pula, GCC500 menunjukkan 5.68% kecekapan penukaran tenaga, jauh lebih tinggi daripada platinum (3.79%). Oleh itu, GCC500 merupakan calon terbaik untuk menggantikan platinum konvensional sebagai elektrod berlawanan dalam DSSC.

Kata Kunci: g-CNT; berasaskan karbon; elektrod berlawanan; DSSC

SDG: MATLAMAT 7: Tenaga Mampu Milik dan Bersih

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Suhaidi bin Shafie, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Nizar bin Hamidon, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Ismayadi bin Ismail, PhD
Senior research officer
Institute of Nanoscience and Nanotechnology
Universiti Putra Malaysia
(Member)

Fauzan bin Ahmad, PhD
Senior lecturer
Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia
(Member)

Lei Wei, PhD
Professor
School of Electronic Science and Engineering
Southeast Univerisity China
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:9 November 2023

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LIST OF ABBREVIATIONS

0D	Zero dimensional
1D	One dimensional
2D	Two dimensional
3D	Three dimensional
Ar	Argon
C	Carbon
CB	Conduction Band
CdTe	Cadmium telluride
CE	Counter electrode
CIGS	Copper indium gallium selenide
CNTs	Carbon Nanotubes
CV	Cyclic Voltammetry
DSSC	Dye-sensitized solar cells
EDX	Energy Dispersive X-ray Spectroscopy
FCCVD	Floating-Catalyst Chemical Vapor Deposition
FESEM	Field Emission Scanning Electron Microscopy
FF	Fill factor
FTO	Fluorine-doped Tin Oxide
GCC	Graphenated-carbon nanotubes counter electrode
G-CNT	Graphenated-carbon nanotubes
H2	Hydrogen
HOMO	Highest Occupied Molecular Orbital
HRTEM	High Resolution Transmission Electron Microscopy
IEA	International energy agency
LUMO	Lowest Unoccupied Molecular Orbital
NREL	National Renewable Energy Laboratory

Pt	Platinum
PtI_4	Platinum iodide
RGO	Reduced graphene oxide
Sccm	Standard cubic centimeters per minute
SnO_2	Tin (IV) Oxide
TCO	Transparent conductive oxide
Ti	Titanium
$TiCl_4$	Titanium Tetrachloride
TiO_2	Titanium dioxide
UV	Ultraviolet
UV-Vis	Ultra Violet Visible Spectroscopy
π	Pi bond
σ	Sigma bond

CHAPTER 1

INTRODUCTIONS

1.1 Background

Emerging economies drive the world's growing demand for energy and an increasing population, especially in developing countries [1]. That leads to global warming resulting from the large-scale emission of the greenhouse effect and air pollution, which can be caused countless illnesses [2]. Nonrenewable energy sources such as petroleum, natural gas, coal, and fossil fuels are used in daily activities [3]. Many strategies have been implemented to tackle the global issue, such as green, sustainable, and energy-efficient [4], [5].

Sustainable and renewable energy resources such as biomass, tidal energy, hydro energy, solar thermal, and solar cell are among the potential option for renewable energy and the most efficient [6]. The most potential among renewable energy is solar cell technology (photovoltaic). This technology has received worldwide attention and turned into a billion, especially in industry. The International Energy Agency (IEA) has predicted that 30% of solar energy is projected to supply the world's power in 2050 and is supposed to increase up to 60% of electricity in 2100 [7].

A solar photovoltaic (PV) system generates electrical power from the sunlight. Semiconducting layers are often referred to as silicon-based PV systems. It is composed of *p*-type and *n*-type components forming a *p*-*n* junction. The semiconducting material absorbs the incident photons when the system is exposed to sunlight, creating positive or negative charges. The *n*-type semiconductor tends to gather electrons, whereas the *p*-type semiconductor tends to collect holes. The electricity will readily flow into the cell if an external load is present. Becquerel discovered the PV effect in 1839 through his research on how light impacts electrolyte cells [8], [9]. Later, in 1954, Bell in the United States developed a PV solar cell that was deployed to supply electricity for space satellites [10].

Solar cells can be classified into three generations: first, second, and third. The first-generation solar cells are wafer silicon-based, amorphous silicon, single-crystalline and poly-crystalline silicon, and hybrid silicon cells. Silicon photovoltaics commonly demonstrated 15% to 25% energy conversion efficiency, leading to the photovoltaic market. The advantages of this solar cell technology are good performance and high stability. However, they require an expensive production cost to build the module technology that demands high-purity silicon.

The second-generation solar cells are made from thin-film semiconductor-based) amorphous silicon, cadmium telluride (CdTe), copper indium gallium selenide (CIS or CIGS). They usually recorded 12% to 15% of energy efficiency. The thin film has offered a potential reduction of cost using the active materials between two pieces of glass and flexible cells. However, it still requires high temperatures, complicated module technology, and poor stability, and some materials like cadmium used in thin-film solar cells are toxic to humans.

Meanwhile, third-generation solar cells are often described as a new thin-film emerging technology, including organic photovoltaics, polymer photovoltaics, perovskite photovoltaics, dye-sensitized solar cell, and quantum dots solar cells. Yet, low energy efficiency than Si-based solar cells, third-generation solar cells have offered the cheapest photovoltaic technology, are friendly to the environment, and typically demonstrate an energy efficiency of 11% to 14.1 % [11]–[13]. Most recently, the Grätzel group has exhibited a high power conversion efficiency of 15.2 %, which is the new record in DSSC TiO_2-based and co-adsorbed sensitizers [14].

An effort is being made to develop third-generation solar cells, which it is hoped will soon replace existing solar technology and address its shortcomings. Generally speaking, this technology consists of non-semiconductor (polymer-based and biomimetic) cells, tandem/multi-junction cells, hot-carrier cells, dye-sensitized solar cells (DSSC), and up-conversion technologies. It has attracted attention because its benefit lies in easy fabrication, low-cost production, light, affordable source of renewable energy, outstanding performance under low light conditions, and several options for improving power conversion efficiency [13], [15]–[19].

The dye-sensitized solar cells (DSSC) were invented by Brian O'Regan and Micheal Grätzel in 1991 [20], [21]. The utmost components for common DSSC are wide band gap semiconductor, sensitizer to act as photoanode, catalyst, and redox couple. The photoanode, usually a dye particle coated with the nano porous metal oxide semiconductor film, was deposited on the transparent conductive oxide (TCO) glass as the photoanode, platinum (Pt) catalyst was deposited on TCO substrates as a counter electrode and redox mediator iodide/triiodide electrolyte.

The revolution of solar cells in industry and the prediction of solar cell growth around the world showed in Figure 1.1. The chart reports the highest confirmed conversion efficiencies for different solar cell technologies as written by the National Renewable Energy Laboratory (NREL), the USA to the date of September 2022.

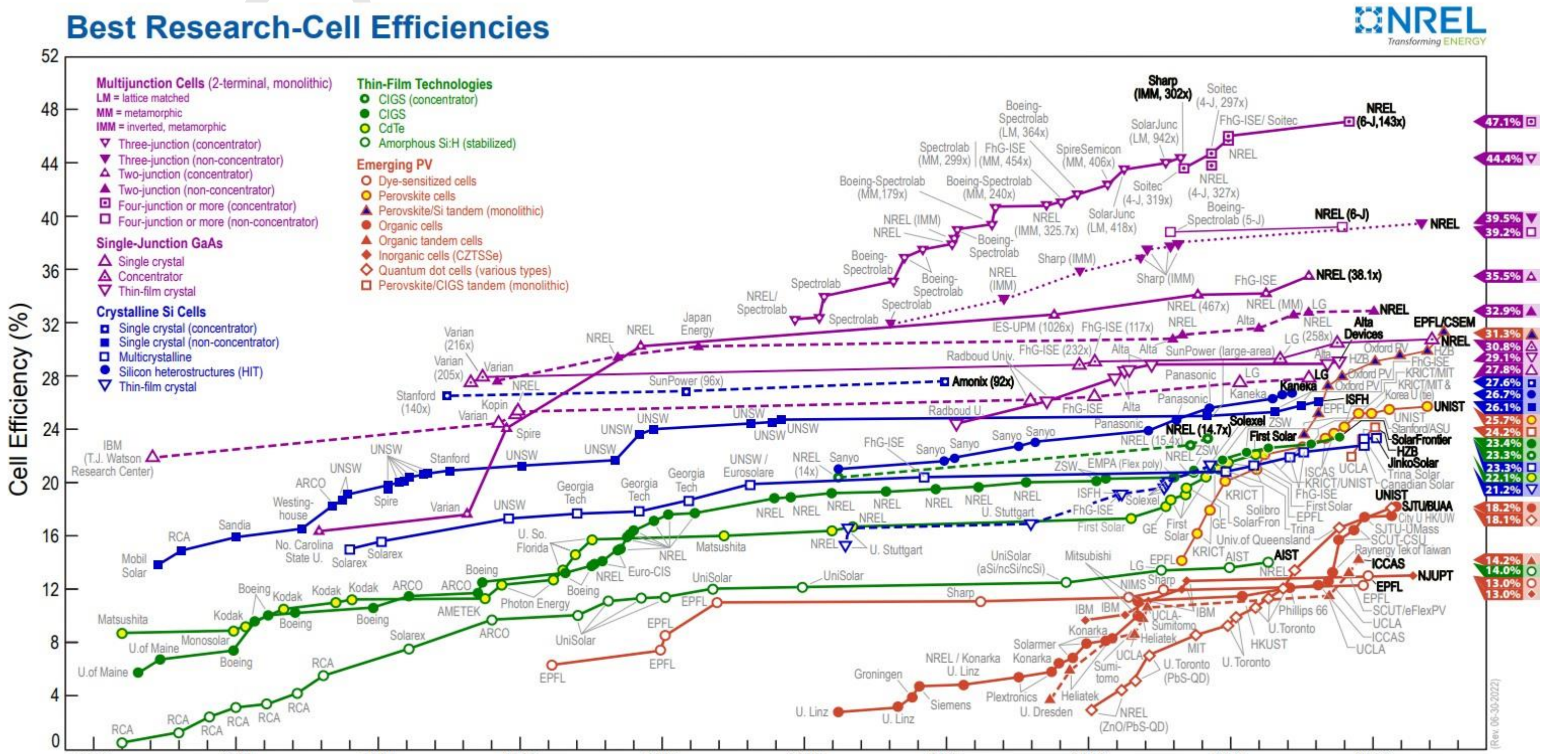

Figure 1.1: Chart of highest efficiencies obtained from solar cells of different photovoltaic technologies (Source: https://www.nrel.gov/pv/cell-efficiency.html)

1.2 Problem Statements

The counter electrode (CE) is one of the most critical components in the DSSC. It catalyzes the Iodide/Tri-iodide (I_3^-/I^-) redox reaction which bring the electrons from external loads connected to the cells and catalyze the I_3^-/I^- reaction in the electrolyte. Conventional platinum (Pt) CE is extensively used due to its outstanding conductivity and electrocatalytic ability [21]. However, Pt-based CE is a precious metal and obtains low resistance toward corrosion in an iodine-based electrolyte, which decomposes the Pt into platinum iodide (PtI_4) [22].

These led many researchers to explore other low-cost materials with low resistance and excellent electrocatalytic ability. For instance, carbonaceous [23], [24], alloys [25], [26], conducting polymers [27], [28], and composites [29]–[31] have been developed as Pt-free CE.

Recently, extensive studies have investigated carbon-based CE materials, such as carbon nanotubes (CNT) [23], carbon fibres [32], [33], carbon black [34], graphene, and graphite [35], [36]. Carbon-based materials are chemically stable in iodine-based electrolytes and do not degrade when exposed to iodine. It also provides active catalytic sites at their edges. Nevertheless, many carbon materials with good catalytic properties do not have the competence for electron transfer. Therefore, initiating the hybrid carbonaceous materials will improve the charge transfer of conducting electrons. CNT alone does not show good improvement in conductivity; hence hybrid can enhance electrical conductivity. Graphene tends to form stacking phenomena, leading to stronger interlayer π-π stacking and van der Walls interactions that prevent electron transport and iodide/triiodide ion transfer producing active defect region. It causes an increase in internal resistance and diffusion resistance of the redox reaction. Hybrid can prevent stacking, thereby improving the conductivity of the materials.

The hybrid properties of the graphenated-carbon nanotube structure are hypothesized to provide a way to optimize the hybrid structure by creating a bridging for electrons to improve the conductivity. High defect of basal and edges plane enhancing electrons transfer by electron bridging lead to increasing conductivity. That allowed for superior electronic conductivity and catalytic activity than any of the two materials could achieve independently.

1.3 Objectives

This research aims to achieve high power conversion efficiency dye-sensitized solar cells by implementing graphenated-carbon nanotubes cotton as a counter electrode in dye-sensitized solar cells. The working objectives that have been considered in this research are:

i. To synthesize and characterize graphenated-carbon nanotubes via the floating-catalyst chemical vapor-deposition method and determine the structural and morphological properties.
ii. To investigate the graphenated-carbon nanotubes films on electrical and electrocatalytic properties.
iii. To implement and evaluate the graphenated-carbon nanotubes-based counter electrode in DSSC for high power conversion DSSC.

1.4 Scope and Limitations

This research aimed to examine the performance of carbon-based counter electrodes for DSSC. Since the study focuses only on implementing graphenated/CNT-based counter electrodes, the photoanode TiO_2-FTO coated and Pt-based counter electrodes serve as a benchmark for the conventional DSSC. The approached material, hybrid graphenated/CNT (g-CNT) was synthesized and characterized, which would later be used to fabricate a counter electrode. During the g-CNT synthesis, the carbon sources injection rate was fixed at 6 ml/hr and 8 ml/hr due to less formation of g-CNT under 6 ml/hr, whereas at more than 8 ml/hr there is no formation of graphene foliates. Therefore, the selection of injection rate in this work is limited to as stated and other than that injection rates are out of the research scope. As there are different types of electrolytes and dyes, this research focuses on Iodine-electrolyte and synthetic N719 dye. DSSC fabrication and characterization are based on conventional Pt-based counter electrodes and the proposed graphenated/CNT-based counter electrodes. The photoanode fabrication procedure is optimized and characterized, but all parameters related to the photoanode are still out of the research scope.

1.5 Thesis Contents

The layout of this thesis is: Chapter 1 reviews the background of the study. It also explains solar cell generation and DSSC and enlightens on the previous research that led to the problem statement of this study. Chapter 2 is a literature review of the previous research related to the background on the improvement of DSSC. Besides, the explanation of the operation principles and device structure of DSSC. Chapter 3 explains the research methodology. This chapter briefly describes the method, equipment, and materials used in this research. The synthesis of GCC, preparation of carbon paste for counter electrode, and DSSC fabrication experimental setup involved in the DSSC characterization were explained in detail. Chapter 4 discusses the experimental results from the characterization techniques and analyzes the outcome, including morphological, structural, electrochemical, electrical properties and DSSC performance. Lastly, Chapter 5 concludes the finding and highlights the contribution of this research and recommendations for future research to improve the DSSC performance.

REFERENCES

[1] K. Yao, C., Feng, K., Hubacek, "Driving forces of CO2 emissions in the G20 countries: an index decomposition analysis from 1971 to 2010," *Ecol. Inform.*, vol. 26, pp. 93–100, 2015.

[2] R. A. Kerr, "Scientists tell Policymakers We're All Warming the World.," *Sci. Total Environ.*, vol. 315, pp. 754–757, 2007.

[3] F. A. Meyerson, "Population, Development and Global Warming: Averting the Tragedy of the Climate Commons," *Popul. Environ.*, vol. 19, no. 5, pp. 443–463, 1998.

[4] X. Zhang, Z. Wu, Y. Feng, and P. Xu, "Turning Green into Gold: A Framework for Energy Performance Contracting (EPC) in China's Real Estate Industry," *J. Clean. Prod.*, vol. 109, pp. 166–173, 2015.

[5] M. Quader, M. A., Ahmed, S., Ghazilla, R. A. R., Ahmed, S., & Dahari, "A Comprehensive Review on Energy Efficient CO2 Breakthrough Technologies for Sustainable Green Iron and Steel Manufacturing," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 594–614, 2015.

[6] A. Bilgili, M., Ozbek, A., Sahin, B., Kahraman, "An Overview of Renewable Electric Power Capacity and Progress in New Technologies in the World," *Renew. Sustain. Energy Rev.*, vol. 49, pp. 323–334, 2015.

[7] I. E. Agency, "Net Zero by 2050: A Roadmap for the Global Energy Sector," Paris, 2021.

[8] T. M. Razykov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, and H. M. Upadhyaya, "Solar photovoltaic electricity: Current status and future prospects," *Sol. Energy*, vol. 85, no. 8, pp. 1580–1608, 2011.

[9] L. El Chaar, L. A. Lamont, and N. El Zein, "Review of photovoltaic technologies," *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2165–2175, 2011.

[10] G. R. Timilsina, L. Kurdgelashvili, and P. A. Narbel, "Solar energy: Markets, economics and policies," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 449–465, 2012.

[11] R. Eisenberg and D. G. Nocera, "Preface: Overview of the forum on solar and renewable energy," *Inorg. Chem.*, vol. 44, no. 20, pp. 6799–6801, 2005.

[12] M. A. Hasan and K. Sumathy, “Photovoltaic thermal module concepts and their performance analysis: A review,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 1845–1859, 2010.

[13] J. Gong, J. Liang, and K. Sumathy, “Review on dye-sensitized solar cells (DSSCs): Fundamental concepts and novel materials,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5848–5860, 2012.

[14] Y. Ren *et al.*, “Hydroxamic acid pre-adsorption raises the efficiency of cosensitized solar cells,” *Nature*, pp. 1–3, 2022.

[15] M. Sokolský and J. Cirák, “Dye-sensitized solar cells: materials and processes,” *Acta Electrotech. Inform.*, vol. 10, no. 3, pp. 78–81, 2010.

[16] A. Apostolopoulou, D. Karageorgopoulos, A. Rapsomanikis, and E. Stathatos, “Dye-Sensitized Solar Cells with Zinc Oxide Nanostructured Films Made with Amine Oligomers as Organic Templates and Gel Electrolytes,” *J. Clean Energy Technol.*, vol. 4, no. 5, pp. 311–315, 2015.

[17] M. A. Green, E. D. Dunlop, D. H. Levi, J. Hohl-Ebinger, M. Yoshita, and A. W. Y. Ho-Baillie, “Solar cell efficiency tables (version 54),” *Prog. Photovoltaics Res. Appl.*, vol. 27, no. 7, pp. 565–575, 2019.

[18] S. Ito *et al.*, “Fabrication of thin film dye sensitized solar cells with solar to electric power conversion efficiency over 10 %,” *Thin Solid Films*, vol. 516, pp. 4613–4619, 2008.

[19] N. H. Shamsudin *et al.*, “Power conversion efficiency (PCE) performance of back-illuminated DSSCs with different Pt catalyst contents at the optimized TiO2 thickness,” *Optics*, vol. 203, p. 163567, 2020.

[20] B. O’Regan and M. Gratzel, “A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films,” *Nature*, vol. 353, no. 6346, pp. 737–740, 1991.

[21] A. Andualem and S. Demiss, “Review on dye-sensitized solar cells (DSSCs),” *Edelweiss Appl. Sci. Technol.*, vol. 2, no. 1, pp. 145–150, 2018.

[22] E. Olsen, G. Hagen, and S. Eric Lindquist, “Dissolution of platinum in methoxy propionitrile containing LiI/I2,” *Sol. Energy Mater. Sol. Cells*, vol. 63, no. 3, pp. 267–273, 2000.

[23] N. Shahzad *et al.*, “Counter electrode materials based on carbon nanotubes for dye-sensitized solar cells,” *Renew. Sustain. Energy Rev.*, vol. 159, p. 112196, 2022.

[24] M. Zambrzycki, S. Łoś, and A. Fraczek-Szczypta, "Structure and electrical transport properties of carbon nanofibres/carbon nanotubes 3D hierarchical nanocomposites: Impact of the concentration of acetylacetonate catalyst," *Ceram. Int.*, vol. 47, no. 3, pp. 4020–4033, 2021.

[25] U. A. Kamarulzaman, M. Y. A. Rahman, M. S. Su'ait, and A. A. Umar, "Improvement of the performance of dye-sensitized solar cells employing NickelPalladium alloy-reduced graphene oxide counter electrode: Influence of palladium content," *Optik (Stuttg).*, vol. 276, no. October 2022, p. 170658, 2023.

[26] X. Zhang *et al.*, "Preparation of CoNi@CN composites based on metal-organic framework materials as high efficiency counter electrode materials for dye-sensitized solar cells," *Sol. Energy*, vol. 231, no. December 2021, pp. 767–774, 2022.

[27] M. Fairul Sharin Abdul Razak, A. Badri, A. Shukor, M. Nazry Salleh, W. Izhan Nawawi, and N. Sabani, "The study of modification dye sensitized solar cell (DSSC) using biopolymer and conducting polymer as modifiers," *Mater. Today Proc.*, vol. 66, no. P10, pp. 4088–4095, 2022.

[28] Y. Kurokawa, T. Kato, and S. S. Pandey, "Controlling the electrocatalytic activities of conducting polymer thin films toward suitability as cost-effective counter electrodes of dye-sensitized solar cells," *Synth. Met.*, vol. 296, no. February, p. 117362, 2023.

[29] A. Asok and K. Haribabu, "Synthesis and performance of polythiophene-iridium oxide composite as counter electrode in dye sensitized solar cell," *Curr. Appl. Phys.*, vol. 49, no. July 2022, pp. 64–69, 2023.

[30] K. Wu, Z. Wang, F. F. Nie, B. Ruan, H. Zhao, and M. Wu, "Pyrolysis synthesis of CuWO4@C composite catalysts as Pt-free counter electrode for dye-sensitized solar cells," *J. Anal. Appl. Pyrolysis*, vol. 170, no. October 2022, p. 105873, 2023.

[31] C. Dawo, P. Krishnan Iyer, and H. Chaturvedi, "Carbon nanotubes/PANI composite as an efficient counter electrode material for dye sensitized solar cell," *Mater. Sci. Eng. B*, vol. 297, no. November 2022, p. 116722, 2023.

[32] M. Gao *et al.*, "Tungsten phosphide microsheets In-Situ grown on carbon fiber as counter electrode catalyst for efficient dye-sensitized solar cells," *Adv. Mater. Interfaces*, vol. 10, no. 4, pp. 1–11, 2023.

[33] S. Liu *et al.*, "Synthesis of carbon nanofibers supported NiMoO4 nanoparticles composites used for liquid thin film solar cells counter electrode," *Int. J. Hydrogen Energy*, 2023.

[34] V. Shanmuganathan, C. I-Ting, T. Hsisheng, and L. Yuh-Lang, "High-performance carbon black-based counter electrodes for copper (I)/(II)-mediated dye-sensitized solar cells," *ACS Sustain. Chem. Eng.*, vol. 11, no. 32, pp. 12166–12176, 2023.

[35] S. Mathew *et al.*, "Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers," *Nat. Chem.*, vol. 6, no. 3, pp. 242–247, 2014.

[36] D. Devadiga, M. Selvakumar, P. Shetty, and M. S. Santosh, "Dye-sensitized solar cell for indoor applications: A mini-review," *J. Electron. Mater.*, vol. 50, no. 6, pp. 3187–3206, 2021.

[37] S. Iijima, "Helical microtubules of graphitic carbon," *Nature*, vol. 354, pp. 56–58, 1991.

[38] R. H. Baughman, A. A. Zakhidov, and W. A. De Heer, "Carbon nanotubes-The route toward applications," *Science (80-.).*, vol. 297, no. 5582, pp. 787–792, 2002.

[39] A. Thess *et al.*, "Crystalline ropes of metallic carbon nanotubes," *Science (80-.).*, vol. 273, no. 5274, pp. 483–487, 1996.

[40] D. Zhang, X. Li, S. Chen, Z. Sun, X. J. Yin, and S. Huang, "Performance of dye-sensitized solar cells with various carbon nanotube counter electrodes," *Microchim. Acta*, vol. 174, no. 1, pp. 73–79, 2011.

[41] T. J. Sisto, L. N. Zakharov, B. M. White, and R. Jasti, "Towards pi-extended cycloparaphenylenes as seeds for CNT growth: investigating strain relieving ring-openings and rearrangements," *Chem. Sci.*, vol. 7, no. 6, pp. 3681–3688, 2016.

[42] I. Ismail, S. Mamat, N. L. Adnan, Z. Yunusa, and I. H. Hasan, "Novel 3-Dimensional cotton-like graphenated-carbon nanotubes synthesized via floating catalyst chemical vapour deposition method for potential gas-sensing applications," *Journals Nanomater.*, vol. 2019, pp. 1–10, 2019.

[43] X. Dong *et al.*, "One-step growth of graphene-carbon nanotube hybrid materials by chemical vapor deposition," *Carbon N. Y.*, vol. 49, no. 9, pp. 2944–2949, 2011.

[44] K. Yu, G. Lu, Z. Bo, S. Mao, and J. Chen, "Carbon nanotube with chemically bonded graphene leaves for electronic and optoelectronic applications," *J. Phys. Chem. Lett.*, vol. 2, no. 13, pp. 1556–1562, 2011.

[45] N. Van Chuc, C. T. Thanh, N. Van Tu, V. T. Phuong, P. V. Thang, and N. T. T. Tam, “A simple approach to the fabrication of graphene-carbon nanotube hybrid films on copper substrate by chemical vapor deposition,” *J. Mater. Sci. Technol.*, vol. 31, no. 5, pp. 479–483, 2015.

[46] C. B. Parker, A. S. Raut, B. Brown, B. R. Stoner, and J. T. Glass, “Three-dimensional arrays of graphenated carbon nanotubes,” *J. Mater. Res.*, vol. 27, no. 7, pp. 1046–1053, 2012.

[47] N. Wan *et al.*, “Synthesis of graphene-CNT hybrids via joule heating: Structural characterization and electrical transport,” *Carbon N. Y.*, vol. 53, pp. 260–268, 2013.

[48] J. S. Barnard, C. Paukner, and K. K. Koziol, “The role of carbon precursor on carbon nanotube chirality in floating catalyst chemical vapour deposition,” *Nanoscale*, vol. 8, no. 39, pp. 17262–17270, 2016.

[49] L. F. Sun *et al.*, “Growth of straight nanotubes with a cobalt-nickel catalyst by chemical vapor deposition,” *Appl. Phys. Lett.*, vol. 74, no. 5, pp. 644–646, 1999.

[50] B. Orbán and H. Tibor, “The promoter role of sulfur in carbon nanotube growth,” *Dalt. Trans.*, vol. 51, no. 24, pp. 9256–9264, 2022.

[51] S. Suzuki and M. Shinsuke, “The role of sulfur in promoted growth of carbon nanotubes in chemical vapor deposition proposed through the characterizations on catalytic nanoparticles,” *Appl. Surf. Sci.*, vol. 471, pp. 587–594, 2019.

[52] B. Orbán and T. Höltzl, “The promoter role of sulfur in carbon nanotube growth,” *Dalt. Trans.*, vol. 51, no. 24, pp. 9256–9264, 2022.

[53] M. D. Argyle and C. H. Bartholomew, “Heterogeneous catalyst deactivation and regeneration: a review,” *Catalysts*, vol. 5, no. 1, pp. 145–269, 2015.

[54] M. Aggarwal, A. Kapoor, and K. N. Tripathi, “Solar cell array parameters,” *Sol. Energy Mater. Sol. Cells*, vol. 45, no. 4, pp. 377–384, 1997.

[55] S. Wenger, “Strategies to optimizing dye-sensitized solar cells,” No. THESIS. EPFL, 2010.

[56] T. Xu *et al.*, “Transparent MoS2/PEDOT composite counter electrodes for bifacial dye-sensitized solar cells,” *ACS omega*, vol. 5, no. 15, pp. 8687–8696, 2020.

[57] M. R. Samantaray *et al.*, “Synergetic effects of hybrid carbon nanostructured counter electrodes for dye-sensitized solar cells : A review,” *Materials (Basel).*, vol. 13, no. 2779, 2020.

[58] J. Wu *et al.*, "Counter electrodes in dye-sensitized solar cells," *Chem. Soc. Rev.*, vol. 46, no. 19, pp. 5975–6023, 2017.

[59] P. Poudel and Q. Qiao, "Carbon nanostructure counter electrodes for low cost and stable dye-sensitized solar cells," *Nano Energy*, vol. 4, pp. 157–175, 2014.

[60] M. Kouhnavard, N. A. Ludin, G. Babak V, S. Kamarozzaman, and I. Shoichiro, "Carbonaceous materials and their advances as a counter electrode in dye-sensitized solar cells: Challenges and prospects," *ChemSusChem*, vol. 8, no. 9, pp. 1510–1533, 2015.

[61] A. Hagfeldt, "Brief Overview of Dye-Sensitized Solar Cells," *Ambio*, vol. 41, no. SUPPL.2, pp. 151–155, 2012.

[62] G. Boschloo and A. Hagfeldt, "Characteristics of the iodide/triiodide redox mediator in dye-sensitized solar cells," *Acc. Chem. Res.*, vol. 42, no. 11, pp. 1819–1826, 2009.

[63] Z. Nuran Arini, T. Kento, M. Daiki, and A. Fujiki, "The basic research on the dye-sensitized solar cells (DSSC)," *J. Clean Energy Technol.*, vol. 3, no. 5, pp. 382–387, 2015.

[64] U. Mehmood, S. U. Rahman, K. Harrabi, I. A. Hussein, and B. V. S. Reddy, "Recent advances in dye sensitized solar cells," *Adv. Mater. Sci. Eng.*, vol. 2014, p. 12, 2014.

[65] D. W. Han, J. H. Heo, D. J. Kwak, C. H. Han, and Y. M. Sung, "Texture, morphology and photovoltaic characteristics of nanoporous F: SnO2 films," *J. Electr. Eng. Technol.*, vol. 4, no. 1, pp. 93–97, 2009.

[66] Y. Fukai, Y. Kondo, S. Mori, and E. Suzuki, "Highly efficient dye-sensitized SnO2 solar cells having sufficient electron diffusion length," *Electrochem. commun.*, vol. 9, no. 7, pp. 1439–1443, 2007.

[67] C. Bauer, G. Boschloo, E. Mukhtar, and A. Hagfeldt, "Ultrafast studies of electron injection in Ru dye sensitized SnO2 nanocrystalline thin film," *Int. J. Photoenergy*, vol. 4, no. 1, pp. 17–20, 2002.

[68] L. Y. Lin and K. C. Ho, "Dye-sensitized solar cells," *Encyclopedia of Modern Optics*. Oliver Walter, pp. 270–281, 2018.

[69] N. G. Park, J. Van de Lagemaat, and A. A. Frank, "Comparison of dye-sensitized rutile-and anatase-based TiO2 solar cells," *J. Phys. Chem. B*, vol. 104, no. 38, pp. 8989–8994, 2000.

[70] S. Yuvapragasam, A., Muthukumarasamy, N., Agilan, D. Velauthapillai, T. S. Senthil, and S. Sundaram, "Natural dye sensitized TiO2 nanorods assembly of broccoli shape based solar cells," *J. Photochem. Photobiol. B Biol.*, vol. 148, pp. 223–231, 2015.

[71] J. Zhang, P. Zhou, J. Liu, and J. Yu, “New understanding of the difference of photocatalytic activity among anatase, rutile and brookite TiO2.,” *Phys. Chem. Chem. Phys.*, vol. 16, no. 38, pp. 20382–20386, 2014.

[72] M. Law, L. E. Greene, J. C. Johnson, R. Saykally, and P. Yang, “Nanowire dye-sensitized solar cells,” *Nat. Mater.*, vol. 4, no. 6, pp. 455–459, 2005.

[73] J. A. Mikroyannidis, D. V. Tsagkournos, S. S. Sharma, A. Kumar, Y. K. Vijay, and G. D. Sharma, “Efficient bulk heterojunction solar cells based on low band gap bisazo dyes containing anthracene and/or pyrrole units,” *Sol. Energy Mater. Sol. Cells*, vol. 94, no. 12, pp. 2318–2327, 2010.

[74] M. Grätzel, “Recent advances in sensitized mesoscopic solar cells,” *Acc. Chem. Res.*, vol. 42, no. 11, pp. 1788–1798, 2009.

[75] J. Wu *et al.*, “Electrolytes in dye-sensitized solar cells,” *Chem. Rev.*, vol. 115, no. 5, pp. 2136–2173, 2015.

[76] L. M. Gonçalves, V. de Zea Bermudez, H. A. Ribeiro, and A. M. Mendes, “Dye-sensitized solar cells: A safe bet for the future,” *Energy Environ. Sci.*, vol. 1, no. 6, pp. 655–667, 2008.

[77] N. Papageorgiou, W. F. Maier, and M. Grätzel, “An iodine/triiodide reduction electrocatalyst for aqueous and organic media,” *J. Electrochem. Soc.*, vol. 144, no. 3, p. 876, 1997.

[78] A. Hauch and G. Andreas, “Diffusion in the electrolyte and charge-transfer reaction at the platinum electrode in dye-sensitized solar cells,” *Electrochim. Acta*, vol. 46, no. 22, pp. 3457–3466, 2001.

[79] R. F. Service, “Is it time to shoot for the sun?,” *Science (80-.).*, vol. 309, no. 5734, pp. 548–551, 2005.

[80] J. E. Trancik, S. C. Barton, and H. James, “Transparent and catalytic carbon nanotube films,” *Nano Lett.*, vol. 8, no. 4, pp. 982–987, 2008.

[81] L. F. Reid and K. J. Dooley, “Expandable crack inhibitors and methods of using the same,” Patent 20120304577

[82] W. Hou, Y. Xiao, and G. Han, “An Interconnected Ternary MIn2S4 (M= Fe, Co, Ni) Thiospinel Nanosheet Array: A Type of Efficient Platinum-Free Counter Electrode for Dye-Sensitized Solar Cells,” *Angew. Chemie*, vol. 129, no. 31, pp.9274–9278, 2017.

[83] C. Longo and M.-A. De Paoli, “Dye-sensitized solar cells: a successful combination of materials,” *J. Braz. Chem. Soc.*, vol. 14, pp. 898–901, 2003.

[84] M. Wu and M. Tingli, "Low-cost pt-free counter electrode catalysts in dye-sensitized solar cells," in *Green Energy and Technology*, L. Zhiqun and W. Jun, Eds. London: Springer, 2014, pp. 77–87.

[85] Q. Tang, J. Duan, Y. Duan, B. He, and L. Yu, "Recent advances in alloy counter electrodes for dye-sensitized solar cells. A critical review," *Electrochim. Acta*, vol. 178, pp. 886–899, 2015.

[86] M. Wang *et al.*, "An organic redox electrolyte to rival triiodide/iodide in dye-sensitized solar cells," *Nat. Chem.*, vol. 2, no. 5, pp. 385–389, 2010.

[87] A. Yella *et al.*, "Molecular engineering of push–pull porphyrin dyes for highly efficient dye-sensitized solar cells: The role of benzene spacers," *Angew. Chemie*, vol. 126, no. 11, pp. 3017–3021, 2014.

[88] R. Bashyam and P. Zelenay, "A class of non-precious metal composite catalysts for fuel cells," *Nature*, vol. 443, no. 7107, pp. 63–66, 2006.

[89] T. N. Murakami and G. Michael, "Counter electrodes for DSC: application of functional materials as catalysts," *Inorganica Chim. Acta*, vol. 361, no. 3, pp. 572–580, 2008.

[90] S. Ahmad, E. Guillén, L. Kavan, M. Grätzel, and M. K. Nazeeruddin, "Metal free sensitizer and catalyst for dye sensitized solar cells," *Energy Environ. Sci.*, vol. 6, no. 12, pp. 3439–3466, 2013.

[91] S. Yun, P. D. Lund, and A. Hinsch, "Stability assessment of alternative platinum free counter electrodes for dye-sensitized solar cells," *Energy Environ. Sci.*, vol. 8, no. 12, pp. 3495–3514, 2015.

[92] W. Mingxing, L. Xiao, W. Yudi, and M. Tingli, "Counter electrode materials combined with redox couples in dye and quantum dot-sensitized solar cells," *J. Mater. Chem. A*, vol. 3, no. 39, pp. 19638–19656, 2015.

[93] S. Yun, J. N. Freitas, A. F. Nogueira, Y. Wang, S. Ahmad, and Z. S. Wang, "Dye-sensitized solar cells employing polymers," *Prog. Polym. Sci.*, vol. 59, pp. 1–40, 2016.

[94] K. E. Jasim, "Dye Sensitized Solar Cells - Working Principles, Challenges and Opportunities," *Sol. Cells - Dye. Devices*, vol. 8, p. 172Ā210, 2011.

[95] S. Zhang, X. Yang, Y. Numata, and L. Han, "Highly efficient dye-sensitized solar cells: progress and future challenges," *Energy Environ. Sci.*, vol. 6, pp. 1443–1464, 2013.

[96] S. Yun, *Counter electrode catalysts in dye-sensitized solar cells – An overview*, First Edit. Wiley-VCH Verlag GmbH & Co. KGaA., 2018.

[97] F. Hao, P. Dong, Q. Luo, J. Li, J. Lou, and H. Lin, "Recent advances in alternative cathode materials for iodine-free dye-sensitized solar cells," *Energy Environ. Sci.*, vol. 6, no. 7, pp. 2003–2019, 2013.

[98] S. Yun, A. Hagfeldt, and T. Ma, "Pt-free counter electrode for dye-sensitized solar cells with high efficiency," *Adv. Mater.*, vol. 26, no. 36, pp. 6210–6237, 2014.

[99] L. H. Chang, C. K. Hsieh, M. C. Hsiao, J. C. Chiang, P. I. Liu, and K. K. Ho, "A graphene-multi-walled carbon nanotube hybrid supported on fluorinated tin oxide as a counter electrode of dye-sensitized solar cells," *J. Power Sources*, vol. 222, pp. 518–525, 2013.

[100] P. Li, J. Wu, J. Lin, M. Huang, Y. Huang, and Q. Li, "High-performance and low platinum loading Pt/Carbon black counter electrode for dye-sensitized solar cells," *Sol. Energy*, vol. 83, no. 6, pp. 845–849, 2009.

[101] C. S. Wu, T. W. Chang, H. Teng, and Y. L. Lee, "High performance carbon black counter electrodes for dye-sensitized solar cells," *Energy*, vol. 115, pp. 513–518, 2016.

[102] S. I. Cha, B. K. Koo, S. H. Seo, and D. Y. Lee, "Pt-free transparent counter electrodes for dye-sensitized solar cells prepared from carbon nanotube micro-balls," *J. Mater. Chem.*, vol. 20, no. 4, pp. 659–662, 2010.

[103] M. Hatala *et al.*, "Screen-printed conductive carbon layers for dye-sensitized solar cells and electrochemical detection of dopamine," *Chem. Pap.*, vol. 75, no. 8, p. 123594, 2021.

[104] A. L. Gorkina *et al.*, "Transparent and conductive hybrid graphene/carbon nanotube films," *Carbon N. Y.*, vol. 100, pp. 501–507, 2016.

[105] J. Zhao, J. Ma, X. Nan, and B. Tang, "Effect of nanotube morphologies on multi-walled carbon nanotubes based counter electrode for dye-sensitized solar cell," *J. Nanosci. Nanotechnol.*, vol. 17, no. 1, pp. 788–795, 2017.

[106] E. Sim, V. D. Dao, and H. S. Choi, "Pt-free counter electrode based on FeNi alloy/reduced graphene oxide in liquid junction photovoltaic devices," *J. Alloys Compd.*, vol. 742, pp. 334–341, 2018.

[107] S. Ahmad, J. H. Yum, H. J. Butt, M. K. Nazeeruddin, and M. Grätzel, "Efficient platinum-free counter electrodes for dye-sensitized solar cell applications," *ChemPhysChem*, vol. 11, no. 13, pp. 2814–2819, 2010.

[108] Q. Tai *et al.*, "In situ prepared transparent polyaniline electrode and its application in bifacial dye-sensitized solar cells," *ACS Nano*, vol. 5, no. 5, pp. 3795–3799, 2011.

[109] C. Xu, Y. Jiang, J. Yang, W. Wu, X. Qian, and L. Hou, “Co-Fe-MoSx hollow nanoboxes as high-performance counter electrode catalysts for Pt-free dye-sensitized solar cells,” *Chem. Eng. J.*, vol. 343, no. February, pp. 86–94, 2018.

[110] S. S. Nemala, P. Kartikay, R. K. Agrawal, P. Bhargava, S. Mallick, and S. Bohm, “Few layers graphene based conductive composite inks for Pt free stainless steel counter electrodes for DSSC,” *Sol. Energy*, vol. 169, pp. 67–74, 2018.

[111] X. Mei, B. Fan, K. Sun, and J. Ouyang, “High-performance dye-sensitized solar cells with nanomaterials as counter electrode,” *Nanoscale Photonic Cell Technol. Photovoltaics II*, vol. 7411, p. 74110A, 2009.

[112] K. Kakiage, Y. Aoyama, T. Yano, K. Oya, J. I. Fujisawa, and M. Hanaya, “Highly-efficient dye-sensitized solar cells with collaborative sensitization by silyl-anchor and carboxy-anchor dyes,” *Chem. Commun.*, vol. 51, no. 88, pp. 15894–15897, 2015.

[113] I.-C. Chen *et al.*, “High performance dye-sensitized solar cells based on platinum nanoroses counter electrode,” *Surf. Coatings Technol.*, vol. 320, no. 25, pp. 409–413, 2017.

[114] D. L. Domtau, J. Simiyu, E. O. Ayieta, L. O. Nyakiti, B. Muthoka, and J. M. Mwabora, “Effects of TiO2 film thickness and electrolyte concentration on photovoltaic performance of dye-sensitized solar cell,” *Surf. Rev. Lett.*, vol. 24, no. 05, p. 1750065, 2017.

[115] S. Buda, S. Shafie, S. Abdul Rashid, H. Jaafar, and A. Khalifa, “Response surface modeling of photogenerated charge collection of silver-based plasmonic dye-sensitized solar cell using central composite design experiments,” *Results Phys.*, vol. 7, pp. 493–497, 2017.

[116] N. F. M. Sharif, M. Z. A. A. Kadir, S. Shafie, S. A. Rashid, W. Z. Wan Hasan, and S. Shaban, “Charge transport and electron recombination suppression in dye-sensitized solar cells using graphene quantum dots,” *Results Phys.*, vol. 13, p. 102171, 2019.

[117] M. Q. Lokman *et al.*, “Enhancing photocurrent performance based on photoanode thickness and surface plasmon resonance using Ag-TiO2 nanocomposites in dye-sensitized solar cells,” *Materials (Basel).*, vol. 12, no. 2111, 2019.

[118] N. Y. Muhammad, M. N. Mohtar, M. M. Ramli, S. Shafie, S. Shaban, and Y. Yusuf, “Enhancement of Dye Sensitized Solar Cell by Adsorption of Graphene Quantum Dots,” *Int. J. Mater. Mech. Manuf.*, vol. 8, no. 3, pp. 126–130, 2020.

[119] P. Roy, A. K. Vats, L. Tang, and S. S. Pandey, “Implication of color of sensitizing dyes on transparency and efficiency of transparent dye-sensitized solar cells,” *Sol. Energy*, vol. 225, no. April, pp. 950–960, 2021.

[120] S. A. A. Shah, Z. Guo, M. H. Sayyad, and S. Abdulkarim, “Layer-by-Layer Titanium (IV) Chloride Treatment of TiO2 Films to Improve Solar Energy Harvesting in Dye-Sensitized Solar Cells,” *J. Electron. Mater.*, vol. 50, no. 2, pp. 613–619, 2021.

[121] A. Khalifa *et al.*, “Comprehensive performance analysis of dye-sensitized solar cells using single layer TiO2 photoanode deposited using screen printing technique,” *Optik (Stuttg).*, vol. 223, no. September, p. 165595, 2020.

[122] A. S. A. Ahmed, W. Xiang, X. Hu, C. Qi, I. S. Amiinu, and X. Zhao, “Si3N4/MoS2-PEDOT: PSS composite counter electrode for bifacial dye-sensitized solar cells,” *Sol. Energy*, vol. 173, no. June, pp. 1135–1143, 2018.

[123] J. Ma, S. Qingfeng, Z. Fengbao, and W. Mingxing, “Improvement on the catalytic activity of the flexible PEDOT counter electrode in dye-sensitized solar cells,” *Mater. Res. Bull.*, vol. 100, no. July 2017, pp. 213–219, 2018.

[124] C. Wang, X. Li, Y. Wu, and S. Tan, “An efficient and thermally stable dye-sensitized solar cell based on a lamellar nanostructured thiolate/disulfide liquid crystal electrolyte and carbon/PEDOT composite nanoparticle electrode,” *RSC Adv.*, vol. 9, no. 61, pp. 35924–35930, 2019

[125] Y. Di *et al.*, “Electrocatalytic films of PEDOT incorporating transition metal phosphides as efficient counter electrodes for dye sensitized solar cells,” *Sol. Energy*, vol. 189, no. May, pp. 8–14, 2019.

[126] A. C. K. Reddy, M. Gurulakshmi, K. Susmitha, M. Raghavender, N. Thota, and Y. P. V. Subbaiah, “A novel PEDOT:PSS/SWCNH bilayer thin film counter electrode for efficient dye-sensitized solar cells,” *J. Mater. Sci. Mater. Electron.*, vol. 31, no. 6, pp. 4752–4760, 2020.

[127] U. Ghafoor, A. Bin Aqeel, U. Khaleeq, T. Zahid, M. Noman, and M. S. Ahmad, “Effect of Molybdenum Disulfide on the Performance of Polyaniline Based Counter Electrode for Dye-Sensitized Solar Cell Applications,” *Energies*, vol. 14, no. 13, p. 3786, 2021.

[128] M. A. K. L. Dissanayake, J. M. K. W. Kumari, G. K. R. Senadeera, and H. Anwar, “Low cost, platinum free counter electrode with reduced graphene oxide and polyaniline embedded SnO2 for efficient dye sensitized solar cells,” *Sol. Energy*, vol. 230, no. October, pp. 151–165, 2021.

[129] M. F. Ramli, W. H. Lim, I. Ishak, M. S. Su'ait, S. N. Gan, and S. W. Phang, "Adhesion improvement of polyaniline counter electrode in dye-sensitized solar cell using bio-based alkyd," *Appl. Phys. A Mater. Sci. Process.*, vol. 127, no. 5, pp. 1–9, 2021.

[130] Y. Kurokawa, A. K. Vats, T. Kato, S. Shafie, and S. S. Pandey, "Charge transfer and catalytic properties of various PEDOTs as Pt-free counter electrodes for dye-sensitized solar cells," *Jpn. J. Appl. Phys.*, vol. 61, no. SB, p. SB1010, 2022.

[131] A. Yildiz *et al.*, "Efficient Iron Phosphide Catalyst as a Counter Electrode in Dye-Sensitized Solar Cells," *ACS Appl. Energy Mater.*, vol. 4, no. 10, pp. 10618–10626, 2021.

[132] X. Cao, R. Ding, Y. Zhang, Y. Cui, and K. Hong, "A heterojunction film of NiS2 and MnS as an efficient counter electrode for dye-sensitized solar cells," *Mater. Today Commun.*, vol. 26, no. October 2020, p. 102160, 2021.

[133] P. V. Rajeev *et al.*, "Thermal decomposition derived nano molybdenum nitride for robust counter electrode in dye-sensitized solar cells," *Mater. Today Commun.*, vol. 26, no. August 2020, p. 102070, 2021.

[134] A. Zhao *et al.*, "Nickel foam supported Pt as highly flexible counter electrode of dye-sensitized solar cells," *Sol. Energy*, vol. 224, no. March, pp. 82–87, 2021.

[135] S. A. Ansari, S. Goumri-Said, H. M. Yadav, M. Belarbi, A. Aljaafari, and M. B. Kanoun, "Directly grown of NiCo2S4 nanoparticles on a conducting substrate towards the high-performance counter electrode in dye-sensitized solar cell: A combined theoretical and experimental study," *Sol. Energy Mater. Sol. Cells*, vol. 225, no. March, p. 111064, 2021.

[136] Z. Li *et al.*, "In-situ growth NiMoS3 nanoparticles onto electrospinning synthesis carbon nanofibers as a low cost platinum-free counter electrode for dye-sensitized solar cells," *J. Alloys Compd.*, vol. 850, p. 156807, 2021.

[137] C. Imla Mary, M. Senthilkumar, G. Manobalaji, and S. Moorthy Babu, "Solution processed Cu2ZnSnSe4 nanoink for inexpensive Pt-free counter electrode in dye-sensitized solar cells," *Solid State Sci.*, vol. 116, no. April, p. 106612, 2021.

[138] X. Gao *et al.*, "Sodium Molybdate-Assisted Synthesis of a Cobalt Phosphide Hybrid Counter Electrode for Highly Efficient Dye-Sensitized Solar Cells," *ACS Appl. Energy Mater.*, vol. 4, no. 4, pp. 3851–3860, 2021.

[139] S. Gnanasekar, Q. Van Le, and A. Nirmala Grace, “Template-free synthesis of Vanadium Nitride Nanopetals (VNNP) as a high performance counter electrode for dye sensitized solar cells,” *Sol. Energy*, vol. 213, no. December 2020, pp. 145–153, 2021.

[140] L. Li *et al.*, “NiCo2O4/carbon nanofibers composite as an efficient counter electrode for dye-sensitized solar cells,” *Mater. Res. Bull.*, vol. 145, no. August 2021, p. 111528, 2022.

[141] J. Ma, W. Shen, and F. Yu, “Graphene-enhanced three-dimensional structures of MoS2 nanosheets as a counter electrode for Pt-free efficient dye-sensitized solar cells,” *J. Power Sources*, vol. 351, pp. 58–66, 2017.

[142] Y.-C. Shih, H.-L. Lin, and K.-F. Lin, “Electropolymerized polyaniline/graphene nanoplatelet/multi-walled carbon nanotube composites as counter electrodes for high performance dye-sensitized solar cells,” *J. Electroanal. Chem.*, vol. 794, pp. 112–119, 2017.

[143] L. Chen, W. Chen, and E. Wang, “Graphene with cobalt oxide and tungsten carbide as a low-cost counter electrode catalyst applied in Pt-free dye-sensitized solar cells,” *J. Power Sources*, vol. 380, pp. 18–25, 2018.

[144] S. Wang *et al.*, “Monodispersed nickel phosphide nanocrystals in situ grown on reduced graphene oxide with controllable size and composition as a counter electrode for dye-sensitized solar cells,” *ACS Sustain. Chem. Eng.*, vol. 8, no. 15, pp. 5920–5926, 2020.

[145] Y. Zhang *et al.*, “Highly efficient bio-based porous carbon hybridized with tungsten carbide as counter electrode for dye-sensitized solar cell,” *Ceram. Int.*, vol. 46, no. 10, pp. 15812–15821, 2020.

[146] D. W. Zhang, X. D. Li, S. Chen, F. Tao, and Z. Sun, “Fabrication of double-walled carbon nanotube counter electrodes for dye-sensitized solar sells,” *J. Solid State Electrochem*, vol. 14, pp. 1541–1546, 2010.

[147] R. D. Costa, F. Lodermeyer, R. Casillas, and D. M. Guldi, “Recent advances in multifunctional nanocarbons used in dye-sensitized solar cells,” *Energy Environ. Sci.*, vol. 7, no. 4, pp. 1281–1296, 2014.

[148] Roy-Mayhew, J. D., and I. A. Aksay, “Graphene materials and their use in dye-sensitized solar cells,” *Chem. Rev.*, vol. 114, no. 12, pp. 6323–6348, 2014.

[149] A. K. Geim and K. S. Novoselov, “The rise of graphene,” *Nat. Mater.*, vol. 6, no. 3, pp. 183–191, 2007.

[150] L. J. Brennan, M. T. Byrne, M. Bari, and Y. K. Gun'ko, "Carbon nanomaterials for dye-sensitized solar cell applications: A bright future," *Adv. Energy Mater.*, vol. 1, no. 4, pp. 472–485, 2011.

[151] L. Changgu, X. Wei, J. W. Kysar, and J. Hone, "Measurement of the elastic properties and intrinsic strength of monolayer graphene," *Science (80-.).*, vol. 321, no. 5887, pp. 385–388, 2008.

[152] A. R. Ranjbartoreh, B. Wang, X. Shen, and G. Wang, "Advanced mechanical properties of graphene paper," *J. Appl. Phys.*, vol. 109, no. 1, p. 014306, 2011.

[153] F. Yu, Y. Shi, W. Yao, S. Han, and J. Ma, "A new breakthrough for graphene/carbon nanotubes as counter electrodes of dye-sensitized solar cells with up to a 10.69% power conversion efficiency," *J. Power Sources*, vol. 412, no. September 2018, pp. 366–373, 2019.

[154] E. Ramasamy, W. Lee Jae, D. Lee Yoon, and J. Sung Song, "Spray coated multi-wall carbon nanotube counter electrode for tri-iodide (I3-) reduction in dye-sensitized solar cells," *Electrochem. commun.*, vol. 10, pp. 1087–1089, 2008.

[155] G. R. Li and X. P. Gao, "Low-cost counter-electrode materials for dye-sensitized and perovskite solar cells," *Adv. Mater.*, vol. 32, no. 3, pp. 1–20, 2020.

[156] S. Kim, O. Dovjuu, S. Choi, H. Jeong, and J. Park, "Photovoltaic characteristics of multiwalled carbon nanotube counter-electrode materials for dye-sensitized solar cells produced by chemical treatment and addition of dispersant," *Coatings*, vol. 9, no. 4, p. 250, 2019.

[157] J. H. Kim *et al.*, "Pt-free, cost-effective and efficient counter electrode with carbon nanotube yarn for solid-state fiber dye-sensitized solar cells," *Dye. Pigment.*, vol. 185, no. PA, p. 108855, 2021.

[158] C. Livache, B. Martinez, N. Goubet, and J. Ramade, "Road Map for Nanocrystal Based Infrared Photodetectors," vol. 6, no. November, pp. 1–11, 2018.

[159] A. Capasso *et al.*, "CVD-graphene/graphene flakes dual-films as advanced DSSC counter electrodes," *2D Mater.*, vol. 6, no. 3, p. 035007, 2019.

[160] P. A. Mithari, A. C. Mendhe, B. R. Sankapal, and S. R. Patrikar, "Process optimization of dip-coated MWCNTs thin-films: Counter electrode in dye sensitized solar cells," *J. Indian Chem. Soc.*, vol. 98, no. 11, p. 100195, 2021

[161] N. Yang, J. Zhai, D. Wang, Y. Chen, and L. Jiang, “Two-dimensional graphene bridges enhanced photoinduced charge transport in dye-sensitized solar cells,” *ACS Nano*, vol. 4, no. 2, pp. 887–894, 2010.

[162] A. Martínez-Muíño, M. Rana, J. J. Vilatela, and R. D. Costa, “Origin of the electrocatalytic activity in carbon nanotube fiber counter-electrodes for solar-energy conversion,” *Nanoscale Adv.*, vol. 2, no. 10, pp. 4400–4409, 2020.

[163] A. Monreal-Bernal, J. J. Vilatela, and R. D. Costa, “CNT fibres as dual counter-electrode/current-collector in highly efficient and stable dye-sensitized solar cells,” *Carbon N. Y.*, vol. 141, pp. 488–496, 2019.

[164] B. Siwach, D. Mohan, and M. Barala, “Fabrication and characterization of MWCNTs and Pt/MWCNTs counter electrodes for dye sensitized solar cells.,” in *AIP Conference Proceedings*, 2019, vol. 2142, no. 1, p. 050003.

[165] E. Igman, O. Bayram, A. Mavi, U. C. Hasar, and O. Simsek, “Photovoltaic performance of non-covalent functionalized single-layer graphene in dye-sensitized solar cells (DSSCs),” *J. Mater. Sci.*, vol. 56, no. 6, pp. 4184–4196, 2021.

[166] Ratul Kumar Biswas, S. S. Nemala, and S. Mallick, “Platinum and Transparent Conducting Oxide Free Graphene-CNT Composite Based Counter-Electrodes for Dye-Sensitized Solar Cells,” *Surf. Eng. Appl. Electrochem.*, vol. 55, no. 4, pp. 472–480, 2019.

[167] R. A. Wahyuono *et al.*, “Self-Assembled Graphene/MWCNT Bilayers as Platinum-Free Counter Electrode in Dye-Sensitized Solar Cells,” *ChemPhysChem*, vol. 20, no. 24, pp. 3336–3345, 2019.

[168] J. Ma, W. Shen, C. Li, and F. Yu, “Light reharvesting and enhanced efficiency of dye-sensitized solar cells based 3D-CNT/graphene counter electrodes,” *J. Mater. Chem. A*, vol. 3, no. 23, pp. 12307–12313, 2015.

[169] L. Qiu, Q. Wu, Z. Yang, X. Sun, and Y. Zhang, “Freestanding aligned carbon nanotube array grown on a large-area single-layered graphene sheet for efficient dye-sensitized solar cell,” *Mater. Views*, vol. 11, no. 9–10, pp. 1150–1155, 2015.

[170] N. L. Adnan, I. Ismail, and M. Hashim, “Effect of Ferrocene Concentration on the Carbon Nanotube Cotton Synthesized Via Floating Catalyst CVD Method,” *Aust. J. Basic Appl. Sci.*, vol. 9, no. 12, pp. 109–113, 2015.

[171] I. Ismail, J. Md Yusof, M. A. Mat Nong, and N. L. Adnan, *Synthesis of Carbon Nanotube-Cotton Superfiber Materials*. Elsevier Inc., 2018.

[172] N. I. Ibrahim, I. Ismail, S. Md Mamat, and N. L. Adnan, "Effect of Carbon Source Injection Rate on CNT Film via Floating Catalyst CVD Method," *Solid State Phenom.*, vol. 290, pp. 113–121, 2019.

[173] Y. Yusuf *et al.*, "A Comparative Study of Graphenated-Carbon Nanotubes Cotton and Carbon Nanotubes as Catalyst for Counter Electrode in Dye-sensitized Solar Cells," *Malaysian J. Microsc.*, vol. 17, no. 2, pp. 162–174, 2021.

[174] K. Hung and H. Wang, "A freeze-dried graphene counter electrode enhances the performance of dye-sensitized solar cells," *Thin Solid Films*, vol. 550, pp. 515–520, 2014.

[175] S. Ito *et al.*, "Control of dark current in photoelectrochemical (TiO2/I-/I3-) and dye-sensitized solar cells," *Chem. Commun.*, no. 34, pp. 4351–4353, 2005.

[176] M. S. Dresselhaus, A. Jorio, M. Hofmann, G. Dresselhaus, and R. Saito, "Perspectives on carbon nanotubes and graphene Raman spectroscopy," *Nano Lett.*, vol. 10, no. 3, pp. 751–758, 2010.

[177] Z. H. Ni, H. M. Fan, Y. P. Feng, Z. X. Shen, B. J. Yang, and Y. H. Wu., "Raman spectroscopic investigation of carbon nanowalls," *J. Chem. Phys.*, vol. 124, no. 20, p. 204703, 2006.

[178] H. B. Abdullah, R. Irmawati, I. Ismail, M. A. Zaidi, and A. A. A. Abdullah, "Synthesis and morphological study of graphenated carbon nanotube aerogel from grapeseed oil," *J. Nanoparticle Res.*, vol. 23, no. 11, 2021.

[179] K. A. Wepasnick, B. A. Smith, J. L. Bitter, and D. Howard Fairbrother, "Chemical and structural characterization of carbon nanotube surfaces," *Anal. Bioanal. Chem.*, vol. 396, no. 3, pp. 1003–1014, 2010.

[180] P. G. Collins, A. Zettl, H. Bando, A. Thess, and R. E. Smalley, "Nanotube nanodevice," *Science (80-.).*, vol. 278, no. 5335, pp. 100–103, 1997.

[181] D. Zhao, T. Peng, L. Lu, P. Cai, P. Jiang, and Z. Bian, "Effect of annealing temperature on the photoelectrochemical properties of dye-sensitized solar cells made with mesoporous TiO2 nanoparticles," *J. Phys. Chem. C*, vol. 112, no. 22, pp. 8486–8494, 2008.

[182] S. Shaban, S. Shafie, Y. Sulaiman, F. Ahmad, M. Q. Lokman, and N. F. M. Sharif, "Flexible photoanode on titanium foil for back-illuminated dye sensitized solar cells," *IEEE Int. Conf. Semicond. Electron. Proceedings, ICSE*, vol. 2018-Augus, pp. 197–200, 2018.

[183] S. Shaban *et al.*, “Efficiency performance effect of TiO2 thickness deposited on FTO coated glass photoanode,” *2019 4th IEEE Int. Circuits Syst. Symp. ICSyS 2019*, pp. 7–10, 2019.

[184] K. M. Reddy, S. V Manorama, and A. R. Reddy, “Bandgap studies on anatase titanium dioxide nanoparticles,” *Mater. Chem. Phys.*, vol. 78, no. 1, pp. 239–245, 2002.

[185] A. K. Ali, N. A. Bakr, and S. M. Jassim, “Fabrication of Dye Sensitized Solar Cell and Efficiency Enhancement by Using N719 and Z907 Dyes Mixture,” *J. Photonic Mater. Technol.*, vol. 2, no. 3, pp. 20–24, 2016.

[186] E. Ramasamy and J. Lee, “Ferrocene-derivatized ordered mesoporous carbon as high performance counter electrodes for dye-sensitized solar cells,” *Carbon N. Y.*, vol. 48, no. 13, pp. 3715–3720, 2010.

[187] X. Zhang *et al.*, “ZnSe nanoribbon/Si nanowire p-n heterojunction arrays and their photovoltaic application with graphene transparent electrodes,” *J. Mater. Chem.*, vol. 22, no. 43, pp. 22873–22880, 2012.