

**PERFORMANCE OF NATURAL DYE SENSITIZED  
SOLAR CELLS FOR LOW POWER APPLICATIONS**



**Commodore C.I.F. Attanayake**  
University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
www.lib.mrt.ac.lk

**Degree of Doctor of Philosophy**

**Department of Chemical & Process Engineering**

**University of Moratuwa**

**Sri Lanka**

**15 March 2015**

## **TERMS OF REFERENCE**

This Report is made to fulfill the practical and academic requirements of the Doctor of Philosophy Research Degree in Electrochemical Engineering pertaining to the 3rd generation Solar Photovoltaic Cell Technology of Dye – Sensitized Solar Cells (DSSC's) of Renewable Energy Systems.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

Copyright by :Commodore C.I.F.Attanayake and University of Moratuwa, Katubedda, Sri Lanka

## DECLARATION

This is a report of research work carried out at the Department of Chemical and Process Engineering and its Laboratories of the University of Moratuwa, Katubedda, and Laboratories of the Solid State Chemistry Division of the Institute of Fundamental Studies (IFS), Hantana, Sri Lanka between November 2008 and November 2014. Except where the references are made to other work, the contents of this research work are original. This work has not been submitted in part or in whole to any other University.

Commodore C.I.F. Attanayake  
Department of Chemical & Process Engineering,  
University of Moratuwa, Katubedda,  
Sri Lanka.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

Professor B. A.J.K. Premachandra  
Professor  
Department of Chemical &  
Process Engineering  
University of Moratuwa,  
Katubedda,  
Sri Lanka

Professor G.K.R.Senadheera  
Institute of Fundamental Studies  
Hantana, and Open University of  
Sri Lanka, Polgolla,  
Sri Lanka.

Professor A.A.P. De Alwis  
Professor  
Department of Chemical & Process Engineering,  
University of Moratuwa,  
Katubedda,  
Sri Lanka

## ACKNOWLEDGEMENTS

I wish to express my most sincere gratitude and appreciation to my principal project supervisor – Professor A.A.P. De Alwis, who provided me with the most valuable and wonderful opportunity to read for a PhD research degree under his guidance in the field of renewable energy pertaining to nanotechnology. It is difficult to express in words for the constant guidance, supervision, support, assistance, motivation, and encouragement given to explore new frontiers of knowledge for mankind boldly and with enthusiasm. He also helped me to come closer to finding ways to provide electricity from the Sun at low cost utilizing nature's abundant photosynthetic living plant resources, especially to people living in rural areas of Sri Lanka.

I am also most grateful to my other project supervisor, mentor, teacher and good friend – Professor B.A.J.K.Premachandra, who strongly argued and convinced certain Senior Academics at the University of Moratuwa who had doubts and misgivings about the practical implementation of a renewable energy project at its infancy, which has now become a world-class research project of 3<sup>rd</sup> generation solar photovoltaic technology. I am deeply indebted to him for the valuable guidance, advice, support and assistance provided to me throughout this research project.

Professor G.K.R. Senadheera my other project supervisor, mentor, guide and teacher with his vast experience and professional knowledge in this specialist field of research gathered at Institute of Fundamental Studies (IFS), Hantana, Sri Lanka, Universities in Japan, Denmark and Portugal, kept me on track with his guidance, supervision and support throughout the research project. I am also grateful to Professor C.B.Dissanayake, the Director of IFS for the provision of laboratory facilities and accommodation at the IFS throughout the project.

I am also indebted and immensely thankful to Professor Sohan Wijesekera, the Chairman of the Senate Research Grant Committee for providing me with a valuable research grant to realize this research project.

Professor Ananda Jayawardena, the former Dean of the Faculty of Engineering of the University of Moratuwa, who is the present Vice Chancellor of the University has also been tower of strength and a moral support to me. He has regularly provided me with guidance, support advice and encouragement when I carried out a Master of Engineering Degree in Electrical and Electronic Engineering Research Project for the Sri Lanka Navy on the “ Use of High Frequency Over - the - Horizon Radar Systems (OTH Radars) to detect and locate ships and surface targets at sea over relatively long distances” .

Professor Ranjith Perera the Professor of Electrical Engineering, University of Moratuwa (present Dean of the Faculty of Engineering, General Sir John Kotalawala Defence University, Ratmalana, Sri Lanka) also provided me with regular advice, guidance and encouragement, and support and this enabled me to successfully complete the M Eng Degree, and to move to gain education at the highest possible academic level during the PhD programme.

I also wish to express my sincere gratitude for the education imparted to me during the current research project to Professor U.G.A. Puswewala, the Dean Faculty of Engineering, University of Moratuwa, Professor R.A. Atalage the former Director of Postgraduate Studies and present Deputy Vice Chancellor, and Professor Chinth Jayasinghe the present Director of Postgraduate Studies.

Professor S.A.S. Perera and Dr. P.G. Ratnasiri of the Department of Chemical of Process Engineering of the University of Moratuwa also provided me with several useful inputs, and stimulating discussions during my research project, and allied fields of renewable energy systems to provide a broader perspective. I am also deeply grateful to Dr. A.D.V.S. Amarasinghe, the former Head of the Department of Chemical and Process Engineering of the University, and the present Head of this Department Dr.P.G.Ratnasiri also enabled me to successfully complete this research project by providing me constant administrative support in accomplishing this task, and I am also deeply indebted for their assistance and support.

I also wish to place on record the latest cutting-edge technology research techniques and research laboratory facilities provided to me at the Piramal Glass PLC Ceylon, Horana, Sri Lanka by the Chief Chemist Mr. Thusith Peiris, who was instrumental in the preparation of Fluorine - doped Tin oxide (FTO) coated conducting glass slides according to world standards required for the manufacture of modern low-cost DSSC's.

I also wish to place on record the valuable support and assistance on practical aspects received during the entire research project from Mr. R.T. Massacorale Senior Staff Technical Officer of the Department of Chemical and Process Engineering, Mr. I.K. Athukorale, Technical Officer of Industrial Chemical Laboratory and its Laboratory Assistant, Mr. L.D.Fernando, Mrs. S.M.N.D. Martino, Technical Officer of Environmental Engineering Laboratory, Mr. C.L. Gunaratne, Technical Officer of Polymer Processing and Process Control Laboratories and Mr. S.Shantha of Unit Operations Laboratory.

I would also like to express my sincere gratitude to Mr. Prasad Lamahewa, Instructor, Division of Polymer, Textile and Chemical Engineering Technology, Institute of Technology, University of Moratuwa for the assistance and support to develop DSSC's to provide propulsion power to the Cataraman Boat.

Finally, I would like to express my gratitude and most sincere appreciation and thanks for the very useful academic and practical advice received from Dr. Priyantha Wijesooriya, Chairman and Director of several leading Renewable Energy and Solar Power Companies in Sri Lanka.

## ABSTRACT

The need for renewable energy sources in Sri Lanka is assessed and solar photovoltaics (PVs) is identified to be the most technically suitable and economically viable power source for the conversion of solar energy to electricity in future. Three generations of solar PVs comprising 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> generations are identified, and Dye – Sensitized Solar Cells (DSSCs) comprising the 3<sup>rd</sup> generation cutting – edge solar cell technology is identified being the low-cost easy to manufacture, durable, stable, long life time with reasonably high solar energy to power conversion efficiency (11% max with expensive , scarce, synthetic dyes like Ruthenium bipyridyl complex technology ), or of about 1% with cheap, low-cost, abundant, non-toxic, environmentally friendly natural dyes of photosynthetic green plants. Natural dyes were selected to carry out further research and development work for practical applications.

Research done on DSSC's since inception in Sri Lanka were scrutinized and assessed at the Institute of Fundamental Studies (IFS), Hantana, Sri Lanka, and other Institutions in Sri Lanka. It has been observed that most of the research at the IFS has been done using very expensive synthetic Ruthenium metallic dyes and have achieved a high conversion efficiency of 10% in May 2001.

DSSCs sensitized with 145 natural dyes of plants growing in Sri Lanka were electrically and electronically tested and the ethanolic dye extracts of natural Mangoostein fruit rind (deep purple colour) exhibited the best conversion efficiency (of about 1%.) . It was also observed that other natural dyes such as Ekkiriya wood, Egg plant fruit peel, Karawalla kabilla fruit, Banana flower inflorescence, Beetroot tuber, Turmeric root and Fire fern leaf (not endemic to Sri Lanka) yield relatively good conversion efficiencies.

Natural dye-based DSSCs even though possess conversion efficiencies usually below 1%, may be improved by finding different additives. Such DSSCs are cost effective , easy to manufacture, environmentally friendly and stable . They are potential solar energy to electricity conversion devices for low power applications if further research is done to boost their conversion efficiencies to about 2% - 3%, and to increase their long term stability. The reasons why DSSC's have not been developed for commercial use in Sri Lanka have been identified, assessed and remedial measures proposed.

Research and development work were also initiated to develop practical DSSCs sensitized with low-cost abundant and environmentally friendly natural dyes of plants for low power applications such as battery charging of mobile telephones, iPod's, portable radio communications equipment, LED operated multi – coloured garden - night lights of hotels etc., construction of Building Integrated Photovoltaic (BIPV) systems to provide diffused lighting with multicoloured LED operated lighting systems, provision of propulsion power to small boats etc, in order to assist solve the impending energy crisis when all known sources of fossil fuel will be exhausted in a few decades.

# CONTENTS

	Page No.
Terms of Reference	i
Declaration of the Candidate & Supervisors	ii
Acknowledgement	iii
Abstract	v
Contents	vi
Bibliography	xi
List of Figures	xii
List of Tables	xvii
List of Photographs	xviii
List of Acronyms (Abbreviations)	xix
List of Publications	xx

## Chapter 1 - Introduction

1.1 The problem of energy sufficiency	1
1.2 Attempts made to solve the problem	1
1.3 Literature Survey + Need for Renewable Energy	1
1.4 Background information	2
1.5 Objective of this work	3
1.6 Thesis structure	3

## Chapter 2- Literature Review

2.1 Energy Crisis	5
2.2 Solar Energy Conversion to Electricity	5
2.2.1 Solar Radiation	5
2.2.2 Technologies available – Classical Systems	8
2.2.2.1 PV Crystalline Solar Cells	8
2.2.3 Emerging Technologies of Solar PV's	8
(a) Thin Film Solar Cells	8
(i) Cadmium telluride solar cells	9
(ii) Copper indium Gallium selenide solar cells	9
(iii) Gallium arsenide multi junction solar cells	9
(iv) Organic Polymer Solar Cells	9
(v) Dye-Sensitized Solar Cells	10

(a)	Dye-Sensitized Solar Cell Structure	9
(b)	General Operating Principles	10
(c)	Principles of Operation of DyeSensitized Solar Cells	10
(d)	Degradation	12
(e)	Advantages and drawbacks	12
(f)	Efficiency	13
(g)	Characterization	13
2.2.4	Materials for Dye-Sensitized Solar Cells and their operational principle	14
(a)	The working electrode	15
(b)	TiO <sub>2</sub> blocking layer made by spray Pyrolysis	16
(c)	The light absorbing material	16
(d)	Electrolyte / hole transporting material	17
(e)	Solar cell additives	17
(f)	Counter electrode	17
(g)	Solar cell preparation and assembly	17
2.2.5	Physical Factors which affect the characteristics of DSSC's	17
(a)	The ideal photodiode	18
(b)	Influence of diode ideality factor on IV characteristics	19
(c)	Influence of temperature	19
(d)	Influence of electrolyte conductivity	20
(e)	Influence of substrate conductivity, cell width and cell contacts	20
(f)	Influence of the counter electrode	21
(g)	Influence of Iodine concentration	22
(h)	Influence of transport conditions	23
(i)	TiO <sub>2</sub> layer thickness	24
(j)	Optical Engineering	24
(k)	Additional physical factors influencing IV Characteristics	24
(l)	Obstacles for increasing conversion efficiency of DSSC's	24
2.2.6	Natural Dyes for DSSC's	25
(a)	Natural Dyes	25
(b)	Plant pigmentation	26
(c)	Chlorophylls	27
(d)	Carotenoids	27
(e)	Flavonoids	28
(f)	Betalains	29
(g)	Anthocyanins	29
2.2.7	Effects of individual Components of a DSSC on its Overall Performance	30
(a)	Substrates	30
(b)	Nanoparticle electrodes	30



(c )	Sensitizer dyes	30
(d)	Electrolytes	31
(e )	Solvents	32
(f )	Additives	33
(g)	Counter – Electrode Catalysts	33
(h)	Platinum	33
(i)	Carbon / Graphite	34
(j)	Electrical contacts	34
(k)	Sealing	34
2.3	Research done in Sri Lanka on DSSC's since 1994	35
2.3.1	All Research done in Sri Lanka on DSSC's since 1994	35
2.3.2	International Recognition of research done in DSSC's in Sri Lanka.	36
2.4	History of Research done on DSSC's	37
2.4.1	Development of Conventional Solar PV's / DSSC's	37
2.4.2	Introduction	37
2.4.3	DSSC Technology Trends and Market Forecast 2010 – 2015	39
2.4.4	Market Analysis and Investment Opportunities in Start-up Companies Active in the field of Solar PV's	40
2.4.5	Solar Photovoltaic Developments in U.S.A as a role model	41
2.5	GAP / SWOT Analysis of DSSC's in Sri Lanka	42
2.5.1	Market Analysis	43
2.5.2	GAP Analysis of Solar PV's / DSSC's based on Nanotechnology	45
2.5.3	How Nanotechnology could convert light to electricity	45
2.5.4	International developments	45
2.5.5	Nanotechnology R & D in the Energy Sector in Sri Lanka	46
2.5.6	Organic Photovoltaic Technology / DSSC's	46
2.5.7	Organic Technology	47
2.6	Main Research Organizations and Established Companies in the World carrying out R & D on Dye –Sensitized Solar Cells.	49
2.7	Reasons why DSSC's have not been developed for commercial use in Sri Lanka.	49
 <b>Chapter 3 - Materials and Methods</b>		
3.1	Methodology of Research done on DSSC's	55
3.2	Characerization of Dyes	56
3.3	Preparation of nanocrystalline TiO <sub>2</sub> films	56
3.4	Fabrication and characterization of solar cells	56

3.4.1 Purification and characterization of extracts from Mangoostein fruit pericarp to enhance conversion efficiency	57
3.5 Preparation methods of FTO glasses of DSSC's	59
3.6 Enhancement of Conversion Efficiency of DSSC's by altering the pH	60
3.7 Enhancement of PV parameters of DSSC's including Conversion Efficiency by Co- Sensitization	60
3.8 Electrochemical Impedance Spectroscopy of DSSCs	60
3.8.1 Cyclic Voltametry, Bode, Nyquist, Mott-Shottkey Plots of DSSCs	
3.8.2 Enhancement of PV parameters of DSSCs including Conversion Efficiency by examining Impedance Charactoristics	64
3.8.3 Investigating Catalytic Activity of Exfoliated Graphene Oxide coating using CV's	66
3.9 Construction of an Electrically Operated Natural Dye Extraction Unit	
3.10 Needed Achievements	67
<b>Chapter 4 - Results and Discussion</b>	
4.1 Characterization of Natural Dyes	74
4.1.1 Photoelectrochemical, Electrochemical, Structural and Electronic Impedance Spectroscopic Characterization	89
4.1.1.1 Photoelectrochemical Characterization of Natural Dyes	89
4.1.1.2 Electrochemical Characterization of Natural Dyes	89
4.1.2.1 Absorption Spectra of Natural Dyes	93
4.1.2.2 Effect of pH on Absorption Spectra and IV Characteristics of DSSCs	93
4.1.2 Purification of Dyes	98
4.1.2.3 Effect of Co- Sensitization on Absorption Spectra and IV Characteristics of DSSC's	114
4.1.2.4 Analysis of Characteristics of all types of Natural Dyes	119
4.1.3 Structural Characteristics of Best Natural Dyes of Plants identified	127

4.2	Why the performance of natural dye-based DSSC's low?	135
4.3	Research Priorities for DSSC Performance improvement	136
4.3.1	Research priorities	136
4.3.2	Reduction of material deprecation that leads to poor device longevity	136
4.3.3	Affordable encapsulation methods to protect against environmental degradation	137
4.3.4	Alternatives to dyes as sensitizers	137
4.3.5	Development of solid electrolytes to avoid leakage problems	138
4.3.6	Important Assessments	138
4.4	New Developments	140
4.4.1	Preparation of FTO glasses for DSSC's of Catamaran Boat	140
4.4.2	Introduction	140
4.4.3	Construction of FTO glasses for DSSC's	141
4.4.4	Improvement of conductivity of FTO glasses with Exfoliated Graphene nanoplate solution in Hydrazine	150
4.4.5	Investigating Catalytic Activity of ExGO coating using CV	156
4.4.6	Electrochemical Impedance spectroscopy of DSSC's	156
4.4.7	Analysis of performance of DSSC's with CV, Bode, Nyquist & MS plots	157
4.4.8	Investigating Catalytic activity of ExGO coating using CV	158
4.4.9	New Developments – Continued	
	Model Catamaran Boat of 4 feet length operating on DSSC's	189
4.4.10	Scale up of above Catamaran Boat to 18 feet length	
4.4.11	Construction of DSSC powered small Battery Charging Unit for ipods and Mobile Radio Telephones.	192
4.4.12	Construction of DSSC powered LED Garden Lights	193
4.4.13	Construction of a prototype Building Integrated Photovoltaic (BIPV) System using LED lights for high-rise Buildings to demonstrate the concept of its operation.	193
4.4.14	Preparation of Building Integrated Photovoltaics (BIPV)FTO glasses for DSSC's	194
4.4.15	Preparation of FTO coated DSSC's sensitized with Mangoostein fruit rind extract for provision of propulsion power for Catamaran Boat	195
4.4.16	Development of Fabric – Intergrated DSSC's	197
<b>Chapter 5</b>	<b>- Conclusions</b>	<b>199</b>
<b>Chapter 6</b>	<b>- Recommendations and Future Work</b>	<b>200 - 204</b>

# Bibliography

## Appendices

- Appendix A** : All Research Papers on DSSC's Published by the IFS, Hantana, Sri Lanka
- Appendix B** : Research Papers on DSSC's published by Institutions / Universities in Sri Lanka other than the IFS
- Appendix C** : Construction of DSSC's
- Appendix D** : Natural Dyes from Plants grown in Sri Lanka
- Appendix E** : Best Research - Cell Efficiencies Table at IFS, Kandy (since inception to –date)
- Appendix F** : Best Research – Cell Efficiencies at IFS and University of Moratuwa, Sri Lanka
- Appendix G** : Best Research – Cell Efficiencies (from NREL – Colorado , U.S.A)..
- Appendix H** : Band Gaps of various Solar Cell Materials and Conversion Efficiencies
- Appendix I** : PV Power Costs as a Function of Cell Efficiency and Module Cost
- Appendix J** : Efficiency vs. Cost for I,II,and III Generations of Solar Cells
- Appendix K** : List of major Solar PV Cell Manufacturing Companies
- Appendix L** : Main Research Organisations and Established Companies in the world carrying out R&D on DSSC'
- Appendix M** : Basin Trials of Organic / DSSC Powered Catamaran Boat

## LIST OF FIGURES

- Figure 2.1 The Path length of the solar radiation through the Earth's atmosphere
- Figure 2.2 The two most commonly used standard spectra AM 1.5 direct and AM 1.5 global
- Figure 2.3 (a) Principles of operation of a DSSC and (b) Schematic Diagram of component structure
- Figure 2.4 IV Curve of a typical DSSC
- Figure 2.5 Equivalent Circuit of a photodiode
- Figure 2.6 IV Curve for a typical commercial DSSC
- Figure 2.7 Overview of a microenvironment for DSSC technology
- Figure 3.1 Current – Voltage Characteristics of a typical DSSC
- Figure 3.2 Full Flow Chart for purification of Mangoostein extracts
- Figure 3.3 Nyquist plot of a DSSC
- Figure 3.4 Nyquist plot of a DSSC
- Figure 3.5 Representation of (a) Potential vs. Time plot and (b) Current vs. Potential plot of CV set up
- Figure 3.6 Representation of Voltage and Current plots
- Figure 4.1 Current – Voltage characteristics of 9 natural dyes tested at the IFS
- Figure 4.2 UV-vis Absorbance spectra of dye solutions extracted from various fruits and vegetables
- Figure 4.3 Current – Voltage characteristics of best 12 out of 50 natural dyes tested
- Figure 4.4 UV –vis Absorbance Spectra of DSSCs

Figure 4.5 UV-vis Absorbance Spectra of DSSCs

Figure 4.6 UV-vis Absorbance Spectra of DSSCs

Figure 4.7 Current Density vs. OpenCircuit Voltage characteristiuics of DSSCs.

Figure 4.8 Effect of pH on Absorbance Spectra of Mangoostein dye

Figure 4.9 Effect of pH on Absorbance Spectra of Turmeric dye

Figure 4.10 Characteristics of Mangoostein A1

Figure4.11 Characteristics of Mangoostein A

Figure 4.12 Characteristics of Mangoostein B

Figure 4.13 Characteristicsof Mangoostein C

Figure 4.14 Characteristics of Mangoostein D

Figure 4.15 Characteristics of Mangoostein E

Figure 4. 16 Characteristics of Mangoostein F

Figure 4.17 Characteristics of Mangoostein G

Figure 4.18 Characteritics of Mangoostein H

Figure 4.19 Characteritics of Mangoostein I

Figure 4.20 Characteritics of Mangoostein J

Figure 4.21 Characteritics of Mangoostein K

Figure 4.22 Characteriticsof Mangoostein L



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

- Figure 4.23 Absorbance Spectra of Purified Mangosteine extract
- Figure 4.24 Comparison of IV characteristics of Co-Sensitized DSSC's and DSSC's sensitized with Mangosteine, Turmeric and their Mixture
- Figure 4.25 UV-vis Absorption spectra of DSSC's sensitized with Mangosteine, Turmeric and their Mixture
- Figure 4.26 Chemical structure of Mangosteine fruit rind dye
- Figure 4.27 Chemical structure of Turmeric dye
- Figure 4.28 Chemical structure of Fire fern leaf dye
- Figure 4.29 Two classes of Tanins
- Figure 4.30 Common Glcoalkoid aglycones in Egg Plant fruit Peel
- Figure 4.31 Tannic acid and atype of Taninin present in Karawala kabilla fruit
- Figure 4.32 Chemical characteristics of Betanin in Beetroot tuber
- Figure 4.33 Croton aldehyde from Croton leaf
- Figure4.34 Chemical structure of major components in Venivel
- Figure 4.35 Effect of Transmittance on FTO glasses for DSSC's
- Figure 4.36 Effect of Transmittance on FTO galasses for DSSC's
- Figure 4.37. Effect of Ttransmittance on imported FTO glasses for DSSC's
- Figure 4.38 Effect of Exfoliated Graphene oxide on FTO glasses at various concentrations
- Figure 4.39 Effect of Surface Resistance on Exfoliated Graphene oxide Nanoplate concentration on FTOs

Figure 4.40 IV Characteristics of DSSC's sensitized with Mangostein dye with Exfoliated Graphene oxide nanoplate counterelectrode

Figure 4.41. Nyquist plot on Exfoliated Graphene oxide counter electrode of test DSSc

Figure 4.42. Cyclic Voltammetrogram of Exfoliated Graphene oxide counter electrode of a test DSSC

Figure 4.43. Cyclic Voltammetry curve for DSSC sensitized with Mangostein dye

Figure 4.44 . Bode phase plot for DSSC sensitized with Mangtoostein dye

Figure 4.45. Nyquist curve for DSSC sensitized with Mangostein dye

Figure 4.46 . Mott Shottkey plot for DSSC sensitized with Mangostein dye

Figure 4.47. EIS Monitor Impedance plot for DSSC sensitized with Mangostein dye

Figure 4.48 Cyclic Voltammetry curve for DSSC sensitized with Fire fern leaf dye

Figure 4.49. Cyclic Voltammetry curve for DSSC sensitized with Fire fern leaf dye

Figure 4.50 Bode phase plot for DSSC sensitized with Fire fern leaf dye

Figure 4.51 Nyquist curve for DSSC sensitized with Fire fern leaf dye

Figure 4.52 Mott Shottkey plot for DSSc sensitized with Fire fern leaf dye

Figure 4.53 EIS Monitor Impedance plot for DSSC sensitized with Fire fern leaf dye

Figure 4.54 Cyclic Voltammetry curve for DSSC sensitized with Turmeric dye

Figure 4.55 Cyclic voltametry curve for DSSC sensitized with Turmeric dye

Figure 4.56 Nyquist curve for DSSC sensitized with Turmeric dye





Figure 4.57 Bode plot for DSSC sensitized with Turmeric dye

Figure 4.58 EIS Monitor for DSSC sensitized with Turmeric dye

Figure 4.59 Mott Scottkey plot for DSSC sensitized with Turmeric dye

Figure 4.60 Cyclic voltammetry curve for DSSC sensitized with Banana flower dye

Figure 4.61 Cyclic Voltametry curve for DSSC sensitized with Banana flower dye

Figure 4.62 Bode phase plot for DSSC sensitized with Turmeric dye

Figure 4.63 Bode phase plot for DSSC sensitized with Turmeric dye

Figure 4.64 Bode phase ploty for DSSC sensitized wth Banana flower dye

Figure 4.65 Nyquist curve for DSSC sensitized with Banana flower dye

Figure 4.66 Mott Schottkey plot for DSSC sensitized with Banana flower dye

Figure 4.67 EIS Monitor for DSSC sensitized with Banana flower dye



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

Figure 4.68 Power Regulator and Protection circuit for DSSC Battery charger

Figure 4.69 Typical BIPV System

## LIST OF TABLES

- Table 2.1 Classification of Photovoltaic Solar Cells
- Table 2.2 Temperature increment effects in solar cells
- Table 2.3 Pigments in plants
- Table 3.1 List of plants and trees grown in Sri Lanka which contain natural dyes suitable for use in DSSC's
- Table 4.1 Characteristics of Solar Cells with different dye extracts - Initial Summary of Results
- Table 4.2 Summary of Photo electrochemical parameters of DSSC's using natural dyes
- Table 4.3 Current – Voltage characteristics of DSSC's using Natural Dyes measured with Keithley 2000 Electronic Multimeter.
- Table 4.4 Table of Results – IV Characteristics of 144 Natural Dyes
- Table 4.5 Extracted Table of Results - IV Characteristics of best 62 Natural Dyes
- Table 4.6 Characteristics of DSSC's fabricated using Mangoostein dye with different pH values
- Table 4.7 Characteristics of DSSC's using Turmeric dye with different pH values
- Table 4.8 Summary of Purified Mangoostein dyes
- Table 4.9 Photovoltaic parameters of Co-Sensitized DSSC's, Mangoostein , turmeric and their mixture
- Table 4.10 Preparation of FTO glasses
- Table 4.11 Results of improvements to Exfoliated Graphene oxide Nanoplate solution coated on FTO glasses



## LIST OF PHOTOGRAPHS

- Photograph 4.1 Photograph of 4 feet long Solar powered Model Catamaran Sail Boat
- Photograph 4.2 Photograph of 18 feet long Solar powered Catamaran Boat
- Photographs 4.3 Photographs of Basin Trials carried out on 18 feet long Solar powered Catamaran Boat
- Photographs 4.4 Photographs of Photovoltaic / DSSC Devices designed and developed at the University of Moratuwa , Katubedda, Sri Lanka



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## LIST OF ACRONYMS (ABBREVIATIONS)

<b>Abbreviation</b>	<b>Description</b>
AM	Air Mass Density
PV	Photovoltaic
DSSC's	Dye –Sensitized Solar Cells
CB	Conduction Band
VB	Valance Band
WE	Working Electrode
FTO	Fluorine doped Tin oxide
CE	Counter Electrode
Pt	Platinum
IL	Ionic liquid
AN	Acetonitrile
I – V	Current – Voltage
Jsc	Short Circuit Current Density
Voc	Open Circuit Voltage
Io	Light intensity
ff	Fill Factor
$\eta$	Overall light to –electricity conversion efficiency
$P_{in}$	Intensity of incident light
$P_{max}$	Maximum Power
HOMO	Highest occupied Molecular Orbital
LUMO	Lowest Unoccupied Molecular Orbital
HTM	Hole Transporting Material
LHE	Light Harvesting Efficiency
IPCE	Incident Photon to Current Converse
OPV	Organic Photovoltaic
N	Electron concentration
P	Hole concentration
$R_s$	Series Resistance
$R_t$	Electron Transport resistance
P	Power Density
K	Kinetic Constant
$K_B$	Boltzmann Constant
L	Length
$L_D$	Electron Diffusion Length
T	Temperature
W	Watt
eV	Electron Volts



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
www.lib.mru.ac.lk

## LIST OF PUBLICATIONS

- I. Design and development of Dye-Sensitized Organic Semiconductor Based Photoelectric System utilizing Nanotechnology for Low Cost and Efficient Conversion of Solar Energy to Electricity. 15<sup>th</sup> Engineering Research Unit Symposium 6 November 2009, Faculty of Engineering, University of Moratuwa, Sri Lanka . C.I.F. Attanayake, B.A.J.K. Premachandra, A.A.P.De Alwis, and G.K.R.Senadheera.
- II. Solar Powered Naval Patrol Boat Operating on Dye Sensitized Solar Cells (DSSC's)utilizing Fruit and Spice Extracts. National Energy Symposium of Sri Lanka, Sustainable Energy Authority , 13 & 14 August 2011, Ministry of Power & Energy . C.I.F. Attanayake, B.A.J.K. Premachandra and A.A.P. De Alwis.
- III. Study of Novel Dyes to Support DSSC Research. First National Nanotechnology Conference, 24 – 25 August 2012, National Science Foundation, Sri Lanka .C.I.F. Attanayake, B.A.J.K.Premachandra, A.A.P De Alwis and G.K.R.Senadheera.
- IV. Dye Sensitized Solar Cells : Using over 100 Natural Dyes as Sensitizers. American Institute of Chemical Engineers (AIChE), Annual Meeting 3 – 8 November 2013,Global Challenges for Engineering a Sustainable Future , Hilton San Francisco Union Square, California, U.S.A. This invited research paper was accepted for oral presentation at the AIChE Annual Meeting , and published in the November 2013 Proceedings of the Annual Meeting .
- V. Study of Novel Dyes for use in DSSC s . International Journal of Solar Energy Materials & Solar Cells submitted on 24 March 2014, being followed up and awaiting publication . C.I.F. Attanayake, B.A.J.K., Premachandra, A.A.P. de Alwis and G.K.R.Senadheera.
- VI. Review of Dye Sensitized Solar Cell Research in Sri Lanka. 01 November 2011. Department of Chemical and Process Engineering, University of Moratuwa, Katubedda, Sri Lanka. C.I.F. Attanayake, B.A.J.K., Premachandra, A.A.P. de Alwis and G.K.R.Senadheera.
- VII. Comparison of Characteristics and Properties of Rutin and Mangostein Dye Sensitized Solar Cells. Submitted to the Chinese Chemical Society , Beijing, Peoples Republic of China , e-mail : [wlhxxb@pku.edu.cn](mailto:wlhxxb@pku.edu.cn) on 15 January 2016 for publication in the Solar Energy Materials and Solar Cells Journal and accepted for peer review process prior to publication . C.I.F.Attanayake, B.A.K.J. Premachandra, A.A.P.De Alwis and G.K.R.Senadheera.