UTS UNIVERSITY OF TECHNOLOGY SYDNEY

DEVELOPMENT OF NANOSTRUCTURED PHOTOTHERMAL MATERIALS FOR SOLAR DRIVEN WATER EVAPORATION TOWARDS CLEAN WATER PRODUCTION

by Idris Ibrahim

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Doctor of Philosophy

under the supervision of Dr. Leonard Tijing, Prof. Hokyong Shon and A/Prof. Andrew McDonagh

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *IDRIS IBRAHIM* declare that this thesis, is submitted in fulfilment of the requirements for the award of *Doctor of Philosophy*, in the *School of Civil and Environmental Engineering/ Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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DEDICATION

To my lovely parents and siblings, thank you for your support in all my life.

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LIST OF PUBLICATIONS, CONFERENCES AND AWARDS

Publications related to the thesis:

- **Idris Ibrahim**, Dong Han Seo, Alexander Angeloski, Andrew McDonagh, Ho Kyong Shon, Leonard Tijing*. 3D nanostructured CuS/Sn_2S_3 microflowers for highly efficient solar steam generation and water purification. Solar Energy Materials and Solar Cells 232 (**2021**): 111377.
- **Idris Ibrahim**, Dong Han Seo, MJ Park, Alexander Angeloski, Andrew McDonagh, Ho Kyong Shon, Avi Bendavid, Leonard Tijing*. A novel robust and scalable plasmonic membrane for a highly efficient solar steam generation under a harsh environment. Chemosphere (2022): 134394
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- **Idris Ibrahim**, Sayed Mukit Hossain, Dong Han Seo, Andrew McDonagh, Tim Foster, Ho Kyong Shon, Leonard Tijing*. Polydopamine nanostructures decorated a porous nickel foam toward efficient solar harvesting steam evaporator and anti-salt properties. Separation and Purification Technology. (2022): 121054
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CONFERENCES AND SEMINARS

Oral Presentations

- 14th International Conference on Challenges in Environmental Science & Engineering, CESE-2021 'Gold nanolayer membrane as solar harvester for efficient solar steam
- generation and seawater desalination' (6th and 7th November 2021, CESE conference series) (Online).
- 2020 VIRTUAL SCHOOL RESEARCH SHOWCASE 'Hierarchical CuS/Sn_2S_3 microflowers for highly efficient solar steam generation and water purification' (5th November 2020, University of Technology Sydney).
- 2021 VIRTUAL SCHOOL RESEARCH SHOWCASE 'Fabrication of a novel solar photothermal membrane for efficient solar seawater desalination' (22nd September 2021, University of Technology Sydney).

AWARDS

- Best Oral Presentation. 2021 VIRTUAL SCHOOL RESEARCH SHOWCASE (22nd September 2021, University of Technology Sydney).
- Best HIRO (Hazard and Incident Reporting Online) FEIT-UTS 2021.

LIST OF ABBREVIATIONS

Full name	Abbreviations
1H,1H,2H,2H-perfluorooctyltrichlorosilane	PFOTS
1H,1H,1H,2H-perfluorodecyltriethoxysilane	PFDTES
Absorption	A
AM 1.5	Air Mass Filter
Anodized alumina Oxide	AAO
Au nanocages	AuNCs
Air-laid paper	ALP
Au nanolayer membrane	Au-PTFE
Bandgap	E_g
Bound water	BW
Carbon nanotube	CNT
Chemical vapor deposition	CVD
Contact angles	CA
Copper sulfide	CuS
Cellulose sponge	CS
Cellulose membrane	CM
Carbon nanotube	CNT
Deionized water	DIW
Energy dispersive X-ray	EDX
Fourier transforms Infrared	FTIR
Free water	FW
Graphene	G

Heterostructure microflowers composed of vertically aligned CuS/Sn_2S_3 nanosheets	3D CSS-NS MF
Hydroxyl groups	-OH
Infrared	IR
Inductive Coupled Plasma-Mass Spectrometer	ICP-MS
Intermediate water	IW
Ion Chromatography	IC
Interfacial solar steam generation	ISSG
Iron sulfate	$FeSO_4.7H_2O$
Localized surface plasmon resonance	LSPR
Mixed cellulose ester	MCE
Magnetic sputtering	MS
Multi-stage flash	MSF
Multi-effect desalination	MED
Membrane distillation	MD
Molybdenum oxide	MoO
Nanoparticles	NPs
Nanocrystals	NCs
Nanowires	NWs
Near-infrared	NIR
Nickel foam	NF
Nitric acid	HNO_3
Photothermal materials	PTMs
Polytetrafluoroethylene	PTFE
Polydimethylsiloxane	PDMS

Poly(p-phenylene benzobisoxazole) nanofibre	PBONF
Poly (vinyl alcohol)	PVA
Polyethylene	PE
Polydopamine	PDA
Polytetrafluoroethylene	PTFE
Potassium Hydroxide	KOH
Reverse osmosis	RO
Reflectance	R
Solar steam generation	SSG
Sulfuric acid	H_2SO_4
Ultraviolet	UV
Visible	vis
Quaternary sulphide, selenide p-type $Cu_2ZnSnSe_4$	CZTSe
Semiconductive hydrogel composed of MnO_2 nanowires/chitosan hydrogel	SPM-CH
Stainless steel	SS
Scanning electron microscopy	SEM
Solar water evaporation	SWE
Sodium chloride	NaCl
Transition metal oxides	TMOs
Tungsten oxide	WO_3
Titanium dioxide	TiO_2
Titanium sesquioxide	Ti_2O_3
Thermal gravimetric analysis	TGA
Tannic acid	TA

Transmittance	T
World Health Organization	WHO
X-ray photoelectron spectroscopy	XPS
X-ray diffraction	XRD

LIST OF SYMBOLS

Symbol	Meaning	Unit
ΔH_{vap}	The specific heat capacity of water	J g^{-1} K^{-1}
ΔT	The temperature variation during water	^{o}C
A	The area of the solar absorber	m^2
A	Absorption	%
C_{opt}	The optical concentration	W m^{-2}
C_p	The specific heat capacity	K)
E_g	The energy difference between the valence band and the conduction band	eV
m	The weight change during water evaporation	Kg m^{-2}
q_{in}	The solar irradiation energy density from the solar simulator	kW m^{-2}
R	Reflectance	%
T	Transmittance	%
t	The irradiation time	h
v_i	The mass loss of water under sunlight	Kg m^{-2}
v_0	The mass loss of water under dark	Kg m^{-2}

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ABSTRACT

The lack of access to fresh water is one of the most significant issues the world is facing today. Only a small percentage of the global water source is freshwater, while most (97.5%) exist as saline water. To help address fresh water scarcity, solar steam generation (SSG) has attracted tremendous attention as being scalable, low-cost, and affordable technology. In recent years, increasing interest in SSG for water purification has been mainly due to advancements in photothermal materials (PTMs). This doctoral study focuses on the rational design development of nanostructures PTMs with unique structural properties for high-performance SSG toward seawater desalination applications.

We initially used a single-step solvothermal method to synthesize heterostructure microflowers composed of vertically aligned CuS/Sn_2S_3 nanosheets (3D CSS-NS MF). The structural features are beneficial for effective heat localization through trapping and re-absorbing the heat along with the fast vapor escaping. This resulted in efficient solar-thermal conversion and water evaporation performances. Besides, a stable evaporation was attained using seawater over 10 continuous cycles with a negligible decrease.

Apart from 3D CSS-NS MF, we fabricated a nanoscale gold nanolayer on a polytetrafluoroethylene (PTFE) membrane. Our fabricated membrane displayed a robust mechanical strength and chemical stability arising from the adhesiveness of the thin film Au on the PTFE membrane. More remarkably, good reusability was observed in seawater and high salinity brine, even under severe chemical conditions.

Despite the outstanding anti-salt performances of Au-PTFE membrane, there is still a drawback with the low evaporation performance. For that reason, a scalable *in situ* oxidative polymerization approach was developed to fabricate polydopamine nanowires uniformly growing on 3D porous nickel foam. Notably, by taking advantage of the PDA containing

abundant hydrophilic hydroxyl groups, exceptional durability and stability were obtained using seawater and high brine salinity.

Lastly, we reported a facile method for preparation of hydrogel composed of polyvinylalcohol matrix and ferric-tannate. The prepared hydrogel possesses a rough surface, and diffusion-confined nanochannels. These features are beneficial for solar-thermal conversion, facilitate rapid vapor escape, and anti-salt properties. A stable performance was achieved for 3 consecutive days at seawater and high brine salinity. Moreover, the little salt formed on hydrogel surface during day gradually dissolve and back to the bulk saline water at night condition through the rich nanochannels. In summary, our innovated PTMs in this doctoral study provide insight into development of PTMs which might be promising for large scale solar evaporators towards seawater desalination applications.