



DEVELOPMENT OF POLYMER AND TEXTILES THERMOELECTRIC BASED ON
PEDOT:PSS

BY

MEKHALA INSAWANG

A Dissertation Submitted in Partial Fulfillment of the Requirements for
The Doctor of Philosophy in Physics Program
at Sakon Nakhon Rajabhat University

February 2026

All Rights Reserved by Sakon Nakhon Rajabhat University

DEVELOPMENT OF POLYMER AND TEXTILES THERMOELECTRIC BASED ON
PEDOT:PSS

BY
MEKHALA INSAWANG

A Dissertation Submitted in Partial Fulfillment of the Requirements for
The Doctor of Philosophy in Physics Program
at Sakon Nakhon Rajabhat University

February 2026

All Rights Reserved by Sakon Nakhon Rajabhat University

ชื่อเรื่องวิทยานิพนธ์ (ภาษาไทย) การพัฒนาพอลิเมอร์และสิ่งทอเทอร์โมอิเล็กทริกโดยใช้ PEDOT:PSS

เป็นฐาน

(ภาษาอังกฤษ) Development of Polymer and Textiles Thermoelectric based on
PEDOT:PSS

วิทยานิพนธ์

ของ

เมขลา อินสว่าง

วิทยานิพนธ์นี้ได้รับทุนสนับสนุนการจัดทำวิทยานิพนธ์จากมูลนิธิ

การบริหารและพัฒนาการศึกษาสัมพันธ์ พ.ศ. ๒๕๕๘ มหาวิทยาลัยราชภัฏสกลนคร

เดือน กุมภาพันธ์ พ.ศ. ๒๕๖๙



DISSERTATION APPROVAL
SAKON NAKHON RAJABHAT UNIVERSITY
DEGREE OF PHILOSOPHY
PHYSICS PROGRAM

Dissertation Title: Development of Polymer and Textiles Thermoelectric based on PEDOT:PSS

Author: Mekhala Insawang

Dissertation Examination Committee

<u>A. Tubtimtae</u> (Assoc. Prof. Dr. Auttasit Tubtimtae)	Chairperson	<u>AT</u> (Assoc. Prof. Dr. Athorn Vora-ud)	Committee and Advisor
<u>Mati Horprathum</u> (Dr. Mati Horprathum)	Committee	<u>T. Seetawan</u> (Prof. Dr. Tosawat Seetawan)	Committee
<u>Wilawan</u> (Assoc. Prof. Dr. Wilawan Kumharn)	Committee	<u>H. Wattanasarn</u> (Assoc. Prof. Dr. Hassakorn Wattanasarn)	Committee

Approval by the Curriculum Committee

AT
(Assoc. Prof. Dr. Athorn Vora-ud)
Curriculum Chairperson
Sakon Nakhon Rajabhat University

Approval by Graduate School

Surasak
(Assist. Prof. Dr. Surasak Santhaveesuk)
The Director of Graduate School
Sakon Nakhon Rajabhat University

3 February 2026

Copyright of Sakon Nakhon Rajabhat University

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, Assoc. Prof. Dr.Athorn Vora-ud for continuous guidance, insightful feedback and unwavering support throughout the course of this research. Who has been invaluable in shaping both the direction and quality of this work from start until successful.

I would like to express high gratitude toward the thin film research laboratory and thermoelectric research laboratory under Center of Excellence on Alternative Energy (CEAE), Research and Development Institution, Sakon Nakhon Rajabhat University and program of Physics, faculty of science and technology, Thailand for all your kindness throughout my studies.

I am also would like to acknowledge my university and lab members particularly Dr.Somporn Thaowankaew and Dr.Surasak Ruamruk for their assistance in conducting experiments, preparing PEDOT:PSS-coated yarns and performing thermoelectric measurements. Their collaboration and technical support have been essential to the successful completion of this research.

This work was supported by The National Research Council of Thailand (NRCT) and Sakon Nakhon Rajabhat University financially supported through a Mid-Career Research Grant (N42A660826), the Program Management Unit for Human Resources & Institutional Development Research and Innovation (PMU-B) (B16F650001) and Foundation for Educational Administration and Development 2015 Sakon Nakhon Rajabhat University.

Finally, I wish to thank my family and friends for their patience, encouragement and motivation during the course of this dissertation. Their unwavering support has been a source of strength throughout this journey.

Mekhala Insawang

ชื่อเรื่อง	การพัฒนาพอลิเมอร์และสิ่งทอเทอร์โมอิเล็กทริกโดยใช้ PEDOT:PSS เป็นฐาน
ผู้วิจัย	เมขลา อินสว่าง
กรรมการที่ปรึกษา	รองศาสตราจารย์ ดร.อาทรณ์ วรอัด
ปริญญา	ปร.ด. (ฟิสิกส์)
สถาบัน	มหาวิทยาลัยราชภัฏสกลนคร
ปีที่พิมพ์	2569

บทคัดย่อ

งานวิจัยนี้ได้ศึกษาประสิทธิภาพเทอร์โมอิเล็กทริกของวัสดุ PEDOT:PSS ในรูปแบบแผ่นพอลิเมอร์เพื่อประยุกต์ใช้สำหรับเส้นด้ายสิ่งทอ โดยงานวิจัยนี้แบ่งงานเป็น 3 ส่วน ส่วนที่ 1 การศึกษาประสิทธิภาพเทอร์โมอิเล็กทริกของวัสดุ PEDOT:PSS ในรูปแบบแผ่นพอลิเมอร์โดยการเติมผง SnSe_2 ที่ 0.1, 0.2 และ 0.3 g ด้วยวิธีทางเคมี พบว่า การเติมผง SnSe_2 และการอบให้ความร้อน ได้เพิ่มประสิทธิภาพทางเทอร์โมอิเล็กทริกของแผ่นพอลิเมอร์ PEDOT:PSS อย่างมีนัยสำคัญ มีค่าสภาพต้านทานไฟฟ้าของแผ่นพอลิเมอร์ PEDOT:PSS ลดลง ในขณะที่เดียวกันมีการเพิ่มค่าสัมประสิทธิ์ซีเบค และแสดงสมบัติเทอร์โมอิเล็กทริกชนิดพี (P-type) ที่อุณหภูมิห้อง โดยปริมาณของผง SnSe_2 ที่เหมาะสมคือ 0.2 g มีค่าตัวแปรกำลังสูงสุดถึง $37.4 \mu\text{W m}^{-1} \text{K}^{-2}$ ที่อุณหภูมิการอบ 220°C แสดงให้เห็นถึงประสิทธิผลของการปรับโครงสร้างโมโครและการอบ

ส่วนที่ 2 การศึกษาประสิทธิภาพเทอร์โมอิเล็กทริกของเส้นด้ายสิ่งทอผ่านการย้อมด้วยสารละลาย PEDOT:PSS โดยถูกเตรียมและทดสอบการผลิตพลังงานไฟฟ้าจากความร้อน รวมถึงวัดค่าสัมประสิทธิ์ซีเบค ค่าสภาพต้านทานไฟฟ้า และค่าตัวแปรกำลัง ที่อุณหภูมิห้อง โดยเส้นด้ายในงานวิจัยนี้ได้แก่ 1) เส้นด้ายเรยอน (Rayon) 2) เส้นด้ายเรยอนที่ย้อมครามอ่อน (Indigo-Kram (Soft)) และ 3) เส้นด้ายเรยอนที่ย้อมครามแก่ (Indigo-Kram (Intensive)) พบว่าเส้นด้ายเรยอนที่ย้อมครามอ่อน (PEDOT:PSS-Coated Indigo-Kram (Soft)) แสดงสมรรถนะทางเทอร์โมอิเล็กทริกสูงที่สุด โดยมีค่าสัมประสิทธิ์ซีเบคเท่ากับ $21.75 \mu\text{V K}^{-1}$ ค่าสภาพต้านทานไฟฟ้าต่ำที่ $0.074 \text{ m}\Omega\cdot\text{m}$ และค่าตัวแปรกำลังสูงสุดถึง $6.39 \mu\text{W m}^{-1} \text{K}^{-2}$ สรุปได้ว่า คุณสมบัติ

ของพื้นผิวและผลของสีย้อมครามธรรมชาติมีผลต่อการเคลือบของพอลิเมอร์ PEDOT:PSS ให้เป็นไปอย่างสม่ำเสมอและเพิ่มประสิทธิภาพของการขนส่งประจุ

ส่วนที่ 3 ทำการทดสอบการผลิตพลังงานไฟฟ้าจากความร้อนของมอดูลต้นแบบเทอร์โมอิเล็กทริกอินทรีย์ (OTE) ที่ประกอบด้วยเส้นด้ายตัวนำ PEDOT:PSS-Coated Rayon, Indigo-Kram (Soft) และ Indigo-Kram (Intensive) พบว่า มอดูลด้ายย้อมคราม PEDOT:PSS-Coated Indigo-Kram (Intensive) ให้แรงดันไฟฟ้าสูงสุดมากถึง $\sim 18-19$ mV และกำลังไฟฟ้าสูงสุด ~ 0.9 nW ที่ $\Delta T \approx 18$ K ตามด้วยมอดูลด้ายย้อมคราม PEDOT:PSS-Coated Indigo-Kram (Soft) และ PEDOT:PSS-Coated Rayon ผลลัพธ์นี้บ่งชี้ว่า ปริมาณสีย้อมอินดิโกบลูและโครงสร้างพื้นผิวมีผลอย่างสำคัญต่อการรวมตัวของพอลิเมอร์ PEDOT:PSS ต่อคุณสมบัติการนำไฟฟ้า และประสิทธิภาพของการแปลงพลังงานทางเทอร์โมอิเล็กทริกโดยรวม โดยสรุปแล้ว งานวิจัยนี้แสดงให้เห็นถึงศักยภาพของวิศวกรรมวัสดุและสิ่งทอบนพื้นฐานของกลยุทธ์ในการเพิ่มประสิทธิภาพอุปกรณ์เทอร์โมอิเล็กทริกแบบยืดหยุ่นและสวมใส่ได้

คำสำคัญ: พอลิเมอร์เทอร์โมอิเล็กทริก, สิ่งทอเทอร์โมอิเล็กทริก, วัสดุ PEDOT:PSS

TITLE	Development of Polymer and Textiles Thermoelectric based on PEDOT:PSS
AUTHOR	Mekhala Insawang
ADVISORS	Assoc. Prof. Dr.Athorn Vora-ud
DEGREE	Ph.D. (Physics)
INSTITUTION	Sakon Nakhon Rajabhat University
YEAR	2026

ABSTRACT

This research investigated the thermoelectric performance of PEDOT:PSS materials in polymer sheet form for potential application in textile yarns. The study was divided into three parts. In the first part, the thermoelectric properties of PEDOT:PSS polymer sheet were examined by chemically incorporating SnSe₂ powder at contents of 0.1, 0.2, and 0.3 g. The results demonstrated that the incorporation of SnSe₂ powder and applying rapid thermal annealing (RTA) significantly enhanced the thermoelectric performance of the PEDOT:PSS polymer sheet. The electrical resistivity of a sheet decreased, while the Seebeck coefficient increased, indicating P-type thermoelectric behavior at room temperature. The optimal SnSe₂ content was found to be 0.2 g, which achieved a maximum power factor of 37.4 $\mu\text{W m}^{-1} \text{K}^{-2}$ at an annealing temperature of 220 °C. These results highlight the effectiveness of microstructural modification and RTA in improving the thermoelectric performance of PEDOT:PSS-based polymer sheets.

In the second part, the thermoelectric performance of textile yarns coated with PEDOT:PSS via a dyeing process was investigated. The yarns were prepared and evaluated for thermoelectric power generation (P_{max}), including measurements of the Seebeck coefficient, electrical resistivity, and power factor at room temperature. The textile yarns examined in this study included: (1) Rayon yarn, (2) Indigo-dyed rayon yarn with soft shade (Indigo-Kram (Soft)), and (3) Indigo-dyed rayon yarn with intensive shade (Indigo-Kram (Intensive)). It was

found that, the PEDOT:PSS-coated Indigo-Kram (Soft) exhibited the highest thermoelectric performance with a Seebeck coefficient of $21.75 \mu\text{V K}^{-1}$, a low electrical resistivity of $0.074 \text{ m}\Omega\cdot\text{m}$ and a maximum power factor of $6.39 \mu\text{W m}^{-1} \text{ K}^{-2}$. These findings indicate that surface characteristics and the presence of natural indigo dye significantly influence the uniform coating of PEDOT:PSS on textile yarns, thereby enhancing charge transport and thermoelectric performance.

In the third part, the power generation tests on OTE prototype modules comprising PEDOT:PSS-coated Rayon, Indigo-Kram (Soft), and Indigo-Kram (Intensive) modules revealed that the Indigo-Kram (Intensive) module exhibited the highest voltage ($\sim 18\text{--}19 \text{ mV}$) and power output ($\sim 0.9 \text{ nW}$ at $\Delta T \approx 18 \text{ K}$), followed by the Soft and Rayon modules. This result indicates that indigo dye content and surface morphology critically influence PEDOT:PSS integration, electrical conductivity, and overall thermoelectric conversion efficiency. In addition, this work demonstrates the potential of material engineering and textile based on strategies for optimizing flexible, wearable thermoelectric devices.

Keywords: Polymer Thermoelectric, Textiles Thermoelectric, PEDOT:PSS Materials

TABLE OF CONTENTS

CHAPTER	Page
1 INTRODUCTION	1
MOTIVATION	1
RESEARCH OBJECTIVES	4
SCOPE AND LIMITATION OF THE THESIS	4
ANTICIPATED OUTCOMES OF THE THESIS	5
2 THEORY AND LITERATURE REVIEWS	6
THERMOELECTRIC	6
Seebeck Effect	8
Peltier Effect	13
Thomson Effect	15
THERMOELECTRIC BASED ON PEDOT:PSS	17
Poly 3, 4 ethylenedioxythiophene Polystyrene sulfonate (PEDOT:PSS)....	17
Inorganic Polymer Thermoelectric Sheet	23
Organic Thermoelectric Textiles	42
RESEARCHES RELATED	50
3 METHODOLOGY	55
POLYMER THERMOELECTRIC PREPARATION	56
Materials	56
Preparation process	56

TABLE OF CONTENTS (Continue)

CHAPTER	Page
TEXTILES THERMOELECTRIC PREPARATION	58
Materials.....	58
Preparation process.....	59
CHARACTERIZATIONS AND MEASUREMENT	61
Crystalline characterizations.....	61
Morphology and Atomic composition	62
Thermoelectric properties measurement.....	63
TEXTILES THERMOELECTRIC NODULE FABRICATION.....	66
Materials.....	66
Fabrication process.....	66
POWER GENERATION TEST OF OTE-TEXTILES PROTOTYPE MODULE.....	68
4 RESULT AND DISCUSSION.....	70
POLYMER THERMOELECTRIC RESULTS.....	71
Physical properties and crystalline characterizations	71
Morphology and atomic composition characterizations.....	73
Thermoelectric properties measurement.....	76
TEXTILES THERMOELECTRIC RESULTS	84
Physical properties of the yarns.....	84
Electrical conductivity of PEDOT:PSS-Coated	87
Morphology and atomic composition characterizations.....	91
Thermoelectric properties measurement.....	104
TEXTILES THERMOELECTRIC MODULE RESULTS.....	112
Physical properties of the module.....	112

TABLE OF CONTENTS (Continue)

CHAPTER	Page
Power generation measurement results	116
5 CONCLUSIONS AND SUGGESTIONS	126
CONCLUSIONS	126
SUGGESTIONS	128
REFERENCES	130
APPENDICE	148
APPENDICE A DATA OF OUTCOMES	149
APPENDICE B INTERNATIONAL CONFERENCES WORKSHOPS AND PUBLICATIONS..	162
APPENDICE C A BRIEF HISTORY OF RESEARCHER	189

LIST OF TABLES

Table	Page
1 The various grades of commercial PEDOT: PSS (Alam, et al., 2024).....	19
2 The lattice Conventional of SnSe ₂ (Materials Explorer(a), 2025).	24
3 The lattice Conventional of SnSe (Materials Explorer(b), 2025).	26
4 The ZT and PF values of Inorganic Thermoelectric in various materials.	28
5 The PF values of PEDOT:PSS+Selenide compositions in various ways.	33
6 The thermoelectric properties of SnSe thin film in various synthesis methods.	39
7 The Organic Thermoelectric Textiles in various ways.	47
8 Comparison of thermoelectric performance of PEDOT:PSS/SnSe ₂ with previously reported PEDOT:PSS-based composites.	81
9 The comparative summary of the PEDOT:PSS-Coated yarns.	91
10 Summary of SEM Observations for All Yarns Before and After PEDOT:PSS Coating.	98
11 Comparison TE of PEDOT:PSS-Coated yarns with previously reported textile- based thermoelectric materials.	107

LIST OF FIGURES

Figure	Page
1 The condition of thermoelectric properties.....	7
2 The Seebeck Effect (Deen Dayal Upadhyaya College, 2024).	9
3 The diagram of Seebeck effect in open circuit with the different type of material (Deen Dayal Upadhyaya College, 2024).....	10
4 Variation of Thermo emf with temperature hot junction.(Physics Catalyst, 2024).	12
5 The Peltier thermoelectric couple. (a) Refrigeration mode. (b) Power generation (Tritt, 2002).	14
6 The valuable diagram of PEDOT:PSS thermoelectric applications.	18
7 PEDOT:PSS solution.	20
8 The structure of PEDOT:PSS at different stages. From initial synthesis (left) to gel particles (centre) to thin film structure (right) of PEDOT (blue) and PSS (grey) (Ossila enabling science, 2025).....	21
9 The chemical structure of PEDOT:PSS (Ossila enabling science, 2025).	22
10 SnSe ₂ crystal structure (Materials Explorer(a), 2025).	24
11 The SnSe crystal structure (Materials Explorer(b), 2025).....	25

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

LIST OF FIGURES (Continue)

Figure	Page
12 The PEDOT:PSS/SnSe nanosheet. (a) The XRD patterns of SnSe NSs, SWCNTs, pure PEDOT:PSS, and flexible SWCNT/SnSe NS/PEDOT:PSS composite film with 60 wt% SWCNTs. (b) XPS S2p spectra of pure PEDOT:PSS and flexible SWCNT/SnSe NS/PEDOT:PSS composite film with 60 wt% SWCNTs. (c) Prototype module of PEDOT:PSS/SnSe conductive sheet (Liu, Du, Meng, Dou, Jin, Xu, & Shen, 2020).	32
13 The prospective applications for leveraging the intrinsic flexibility of thermoelectric yarns (Wu & Hu, 2017).	36
14 The FE-SEM Analysis of SnSe thin film was as-deposited and annealed. (a) SnSe Asd. (b) 300 °C Anl. (c) 350 °C Anl. (d) 400 °C Anl. (e) 450 °C Anl (Insawang, et al., 2024).	41
15 Architecture and thermal performance of TE textiles (Kim, et al., 2020).	43
16 Don Koi Phakram village center, Sakon Nakhon province, Thailand. (a) Ban Don Koi Indigo Dyeing Learning Center. (b) Ban Don Koi Indigo Dyeing community textiles. (c) Some part of Indigo Dyeing process.	45
17 Schematic of PEDOT:PSS+SnSe ₂ based on sheet preparation by wet chemical technique.	57
18 Shown the process diagram of RTA technique of inorganic conductive sheet.	58
19 The sewing thread. (a) Intensive kram. (b) Soft Kram. (c) Rayon.	59

LIST OF FIGURES (Continue)

Figure	Page
20 The manufacturing of conductive dyeing yarns. (a) PEDOT:PSS solution (b) Ultrasonic solution (c) PEDOT:PSS is soaking with Kram and Rayon yarns (d) Dyeing part (e) Drying the yarns (f) The yarns were taken to form sewing thread dyeing conductive.	61
21 The X-ray diffraction, XRD6100 Shimadzu.	62
22 The Field Emission Scanning Electron Microscope-Energy Dispersive X-ray Spectroscopy (FESEM-EDS) (Ubon Ratchathani University, 2025).	63
23 The ZEM-3 series (ULVAC Technologies, 2024).	64
24 The prototype module diagram design.	67
25 The schematic illustration of the fabrication process for the PEDOT:PSS-Coated yarn thermoelectric module.	68
26 Schematic illustration of the power generation testing setup for the PEDOT:PSS-coated yarn thermoelectric module.	69
27 The XRD patterns of (a) SnSe ₂ powder and (b–e) PEDOT:PSS sheets mixed with SnSe ₂ powder of 0.0 g, 0.1 g, 0.2 g, and 0.3 g, before annealing.	72
28 The XRD patterns of (a) SnSe ₂ powder and (b–e) PEDOT:PSS sheets mixed with SnSe ₂ powder of 0.0 g, 0.1 g, 0.2 g, and 0.3 g, after annealing.	73
29 SEM images of surface morphology before & after annealing (1) Before annealing (2) After annealing and thickness (3) EDX spectra with (insets) atomic mapping and composition of PEDOT:PSS sheets mixed with SnSe ₂ powder of (a) 0.0 g, (b) 0.1 g, (c) 0.2 g and (d) 0.3 g.	75

LIST OF FIGURES (Continue)

Figure	Page
30 The n and μ values of PEDOT:PSS+SnSe ₂ polymer sheets as measured by the Hall effect method at room temperature.....	77
31 The TE of polymer sheets (a) Electrical resistivity, (b) Seebeck coefficient, and (c) power factor of PEDOT:PSS, PEDOT:PSS+SnSe ₂ (0.1 g), PEDOT:PSS+SnSe ₂ (0.2 g), and PEDOT:PSS+SnSe ₂ (0.3 g).....	79
32 The sample of a yarns. (a) Rayon (b) Indigo-Kram (Soft) (c) Indigo-Kram (Intensive) (d) PEDOT:PSS-Coated Rayon (e) PEDOT:PSS-Coated Indigo-Kram (Soft) (f) PEDOT:PSS-Coated Indigo-Kram (Intensive)	86
33 The measured electrical resistance of rayon yarns after dip-coating with PEDOT:PSS as a function of yarn length (0–60 cm).....	88
34 The measured electrical resistance of Indigo-Kram (Soft) yarns after dip-coating with PEDOT:PSS as a function of yarn length (0–60 cm).....	89
35 The measured electrical resistance of Indigo-Kram (Intensive) yarns after dip-coating with PEDOT:PSS as a function of yarn length (0–60 cm).....	90
36 The SEM analysis of the yarns (before & after coating) (a) Rayon (b) Indigo-Kram (Soft) (c) Indigo-Kram (Intensive) (d) PEDOT:PSS-Coated Rayon (e) PEDOT:PSS-Coated Indigo-Kram (Soft) (f) PEDOT:PSS-Coated Indigo-Kram (Intensive).	94
37 The EDX spectra and atomic composition of the yarns before & after coating with PEDOT:PSS.	102
38 Thermoelectric measurement setup for PEDOT:PSS-Coated yarn.	105
39 The PEDOT:PSS-coated Rayon thermoelectric module consisting of five series connected yarn legs mounted on a wool substrate.....	112

LIST OF FIGURES (Continue)

Figure	Page
40 The PEDOT:PSS-coated Indigo-Kram (Soft) thermoelectric module consisting of five series connected yarn legs mounted on a wool substrate.	113
41 The PEDOT:PSS-coated Indigo-Kram (Intensive) thermoelectric module consisting of five series connected yarn legs mounted on a wool substrate.	114
42 The power output of the PEDOT:PSS-Coated Rayon module.....	117
43 The power output of the PEDOT:PSS-Coated Indigo-Kram (Soft) prototype module.	119
44 The power output of the PEDOT:PSS-Coated Indigo-Kram (Intensive) prototype module.	121

CHAPTER 1

INTRODUCTION

MOTIVATION

To realize thermoelectric textiles that can convert body heat to electricity with excellent mechanic and thermoelectric properties are needed. Poly 3, 4-ethylenedioxythiophene Poly (styrene sulfonate (PEDOT:PSS) as the p-type material is among the most promising Organic Thermoelectric (OTE) materials because conducting polymers offer new opportunities to design soft, conformable and light-weight (Kim, et al., 2020; Lund, Tian, Darabi, & Müller, 2020). The textile format from PEDOT:PSS is highly attractive for the design of truly wearable electronics that are set to transform health care, sports, and even fashion (Kim, et al., 2020). Here, Organic/Inorganic electrically conducting PEDOT:PSS+Indigo-dyed kram and PEDOT:PSS+SnSe₂ sheet are presented to component of electronic textiles (E-textiles). Indigo-dyed kram sewing thread (*Indigofera tinctoria*) as traditional unique fabric have getting attention, we can visit at Don Koi phakram village, Sakon Nakhon Thailand. The Indigo-dyed kram sewing thread was made from Rayon yarns are include with Intensive indigo-dyed kram and Soft indigo-dyed kram yarn, they were taken to compared the performance of organic thermoelectric e-textiles. Furthermore, the use of natural materials like Indigo-dyed kram yarns offer a number of advantages because they can be derived from renewable sources, are biocompatibility and being

traditional textile materials according to readily compatible with existing manufacturing routines (Müller & Inganas, 2012). As the same time, Inorganic thermoelectric materials selenide group such as Tin selenide (SnSe) and Tin diselenide (SnSe₂) single crystal phase was found out the high ZT value around 2.6 at 923 K that is the current data of the best valuable inorganic substances (Zhao, Lo, Zhang, Sun, Tan, Uher, & Kanatzidis, 2014).

Nowadays, there are many type of yarns or fabric such as Polyester, Cotton, Silk and Nonwoven fabrics to perform the thermoelectric textiles followed by several methods and formulations are made like coating treatment (Du, Cai Chen, Wang, Shen, Donelson, & Lin, 2015), dip coating (Wu & Hu (2016), dyeing & Roll-to-Roll (Lund, Tian, Darabi, & Müller, 2020) and wet-spinning & De-doping (Kim, et al., 2020). However, the yarn or fabrics mentioned above are not dyed with natural dyes. Consequently, many countries were encountered the problem of environmental pollution, one of the causes of which was synthetic chemicals, including dyes. Most textile dyes are heavy metal oxides. In addition, many heavy metals are carcinogens and wearing them makes you feel hot. Therefore, natural dyes are very popular and perform to thermoelectric textiles having better like air-permeability, wearability, flexibility and more suitable for wearable electronics (Wu & Hu, 2017; Phakram Sakon Nakhon, 2024). As key components in a thermoelectric system, the energy conversion efficiency of a thermoelectric textiles can be evaluated by the higher ZT value, we called the figure of merit as shown in Eq. (1)

$$ZT = \frac{S^2 T}{\rho \kappa} \quad (1)$$

Where S , ρ , κ and T are the Seebeck coefficient, electrical resistivity, thermal conductivity and absolutely temperature, respectively (Thaowonkaew, et al.,

2023). An additional, the high performance of thermoelectric textiles requires to high power factor (PF) with low thermal conductivity, the power factor was defined by Eq. (2) (Insawang, et al., 2024).

$$PF = \frac{S}{\rho} \quad (2)$$

In this direction, few works have been reported that improve organic-based TE material for practical use and then exhibiting the advantage of being customizable by doping with several inorganic TE materials. Among other inorganic TE materials, SnSe and SnSe₂ are semiconductor material (Yu, et al., 2016; Insawang, Vora-ud, Seetawan, Muntini, Phan, & Kumar, 2024) had exhibited an outstanding ZT value maximum to 3.1 along with its -axis at 783 K (Zhao, Lo, Zhang, Sun, Tan, Uher, & Kanatzidis, 2014) (Hoang, et al., 2022; Kushwaha, A.K., Kalita, H., Suman, S., Bhardwaj, A., & Ghosh, R, 2021). Even though, selenide group like heavy metal oxides corresponds to environmental pollution. Nonetheless, they have high thermoelectric properties that is challenge between organic and inorganic group to compare. Moreover, it is well known that single crystalline selenide group materials are unsuitable for industrial company applications due to their difficulty in fabrication and brittle nature (Singh, Anwar, Dubey, & Mishra, 2023; Zhao, Lo, Zhang, Sun, Tan, Uher, & Kanatzidis, 2014; Insawang, et al., 2024).

Lastly and most importantly, the yarns dyed with natural indigo (kram) will be more comfortable to wear. Then, for our idea is highlight of Indigo-dyed kram yarn because have a unique identity of Sakon Nakhon people and selenide group for the best ZT value to perform the organic and inorganic conductive yarns. By the way, technologies of the coating can be adaption to our work toward fabrication in new innovation of thermoelectric textiles. This will be great design to flexibility organic/inorganic thermoelectric generator by using natural fabric dyes as thermoelectric legs. Therefore, the outstanding and challenge is

effect and performance of Indigo-dyed kram to enhance the power factor or ZT value and selenide group to improve character thermoelectric conductive yarns. As least, this work which will bring new inspirations to the next generation for development of organic thermoelectric e-textiles from natural dyes.

RESEARCH OBJECTIVES

1. To the preparation and characteristics of the polymer thermoelectric from the PEDOT:PSS materials.
2. To the preparation and characteristics of the textile thermoelectric from the PEDOT:PSS materials onto the Indigo Kram.
3. To fabricate and test the power generator of the TE-textiles prototype module.

SCOPE AND LIMITATION OF THE THESIS

1. Poly 3, 4-ethylenedioxythiophene Poly (styrene sulfonate); PEDOT:PSS (PH1000 M122) was used for thermoelectric materials base.
2. SnSe_2 nano powder was used for doping PEDOT:PSS polymer.
3. Indigo (Kram) sewing thread from Don Koi phakram village was used for supporting thermoelectric textiles.
4. Thermoelectric properties based on polymer and textiles were measured by the ZEM-3 method.
5. Power generation of thermoelectric (OTE) textile prototype modules were tested by using Keithley 6485, PICOAMMETER and PICOTEST, M3500A 61/2 digit multimeter.

ANTICIPATED OUTCOMES OF THE THESIS

1. New organic/inorganic polymer thermoelectric of PEDOT:PSS+SnSe₂ materials.
2. New innovation of OTE-textiles prototype module from Indigo-Dyed Kram yarns (PEDOT:PSS+Indigo) natural dyed.
3. Two international journal publications.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

CHAPTER 2

THEORY AND LITERATURE REVIEWS

In chapter 2 we were review the theories and research involved in our work thermoelectric, the dissertation is Development of Polymer and Textiles Thermoelectric based on PEDOT:PSS. Additionally, the researcher has studied various concepts, theories, experiment and researches related. Then, the researcher has presented the following topics as follow:

1. Thermoelectric

- 1.1 Seebeck Effect

- 1.2 Peltier Effect

- 1.3 Thomson Effect

2. Thermoelectric based on PEDOT:PSS

- 2.1 Poly 3, 4 ethylenedioxythiophene Polystyrene sulfonate (PEDOT:PSS)

- 2.2 Inorganic Polymer Thermoelectric Sheet

- 2.3 Organic Thermoelectric Textiles

- Researches related

Thermoelectric

In a world that is becoming ever more concerned with climate change and an ever dwindling supply of fossil fuels, there needs to be a transition toward green and sustainable energy sources (Burton, Howells, Mehraban, McGettrick, Lavery, Carnie, 2023). The carbon peaking and carbon neutrality goals

have put forward higher, and more urgent requirements to improve the current energy efficiency and development more green energy technologies (Qin, et al., 2023). Additionally, harvesting this wasted energy could contribute to energy efficiency targets, helping to reduce the need for fossil fuels, causing a reduction in greenhouse gas emissions, and helping to tackle climate change (Burton, et al., 2018). Thermoelectric (TE) technology realizes the direct conversion between heat and electricity, playing an increasingly significant role in the current global energy development strategy (Qin, et al., 2023). It works on the principle of the Seebeck effect, Peltier effect, and Thomson effect as show in Figure 1, the properties of this material are organic and inorganic thermoelectric materials. The smart of these materials can convert a considerable amount of unwanted waste heat energy compared to the dimensionless Figure of Merit (ZT). The higher ZT value show more efficient of material is at harvesting heat energy and converting it into useable electrical energy (Burton, et al., 2018; Singh, Anwar, Dubey, & Mishra, 2023; Insawang, et al., 2024)

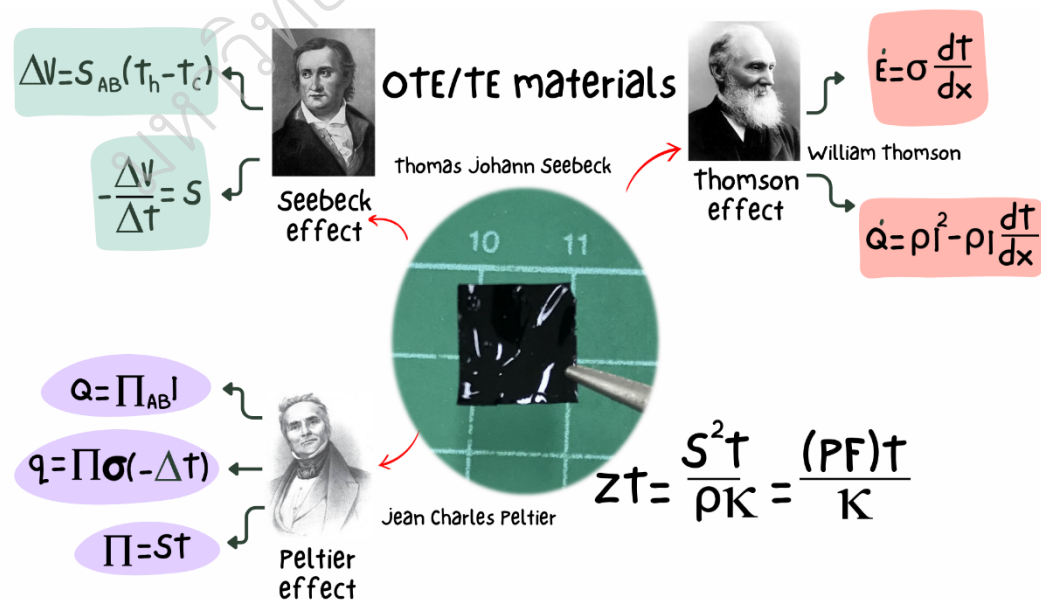


Figure 1 The condition of thermoelectric properties.

Thermoelectric effects and the existence of an intrinsic connection between charge and heat transport phenomena in materials have been well known since the discoveries of Thomas Seebeck in the early 19th century. When a material is subject to a temperature gradient, high energy carriers residing in hot regions tend to diffuse to the cold ones, producing a charge build-up and an electrostatic potential difference and make charge carrier diffuse from hot side to cold side. TE effects provide a very interesting way to convert waste heat into useful energy using solid state converter this possibility has been widely explored since the 1950s. As the same time, in practice TE devices have been relegated so far to a small group of niche scientific, medical, or military applications (Rossella, Pennelli, & Roddaro, 2018). However, this effect can be used to generate electricity, measure temperature or change the temperature of objects because the direction of heating and cooling is determined by the polarity of the applied voltage, then thermoelectric devices can be used as temperature controllers (Deen Dayal Upadhyaya College, 2024; Mameekul, 2024).

1.1 Seebeck Effect

In 1821 Thomas Seebeck, a German physicist discovered that when two dissimilar metal (Seebeck used copper (Cu) and bismuth (Bi)) wires are joined at two ends to form a loop, a voltage is developed in the circuit and then the two junctions are kept at different temperatures. The pair of metals forming the circuit is called a thermocouple. The Seebeck effect is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between two substances. When heat is applied to one of the two conductors or semiconductors, heated electrons flow toward the cooler one, If the pair is connected through an electrical circuit direct to DC current flows through that circuit. Then, the voltages

produced by Seebeck effect is small, usually only a few microvolts (millionths of a volt) per kelvin of temperature difference at the junction, if the temperature difference is large enough then Seebeck effect devices can produce a few millivolts (thousandths of a volt). Moreover, numerous such devices can be connected in series to increase the output voltage or in parallel to increase the maximum deliverable current and the large arrays of Seebeck effect devices can provide useful. Therefore, small scale electrical power under a large temperature difference is maintained across the junctions.

Additionally, the valence electrons in the warmer part of metal are solely responsible and the reason behind this is thermal energy because the kinetic energy of these electrons, these valence electrons migrate more rapidly towards the other (colder) end as compare to the colder part electrons migrate towards warmer part. Besides, in the hot side Fermi distribution is soft and the higher concentration of electrons above the Fermi energy but on cold side the Fermi distribution is sharp. Thus, we have fewer electrons above Fermi energy. Supplemental, the Seebeck effect electrons is transmittal where the energy is lower. Therefore, it will move from warmer end to the colder end which leads to the transporting energy and then equilibrating temperature eventually as shown in Figure 2 (Deen Dayal Upadhyaya College, 2024).

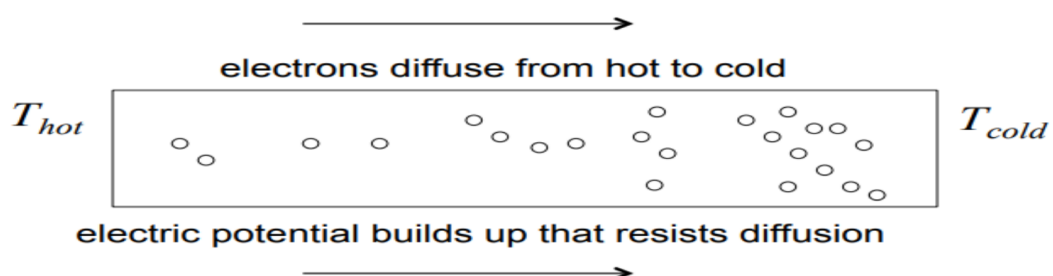


Figure 2 The Seebeck Effect (Deen Dayal Upadhyaya College, 2024).

In simple words we can come to conclusion that the electrons on a warmer end have a high average momentum as compared to the colder one. Then, they will take energy with them (more in no.) as compared to the other one. This movement results in the more negative charge at colder part than warmer part, which leads to the generation of electrical potential. As the same time, this connected through an electrical circuit this is results of the generation of DC. In any case, the voltage produced is few microvolt (10^{-6}) per Kelvin temperature difference and all of them are aware to the fact voltage increase in series and also has current increase in parallel. Then, for keeping this fact in mind, if we can connect many such devices to increase the voltage (in case of series connection) or to increase the maximum deliverable current (in parallel) to keeping care of only one thing that a large temperature difference is required for this purpose. Additionally, one thing must keep in mind that we have to maintain constant but different temperature. Therefore, the energy distribution at both the end will be different and leads to the successful mentioned process.

However, when open circuit the potential will be difference in the circuit that junctions are maintained at temperatures T_h and $T_c (< T_h)$ is given by Eq. 3.

$$\Delta V = S_{AB}(T_h - T_c) \quad (3)$$

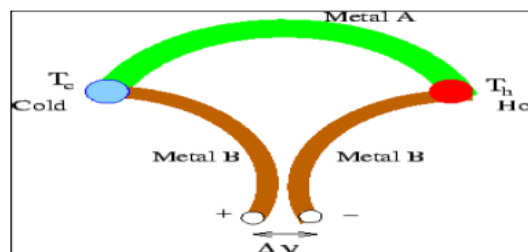


Figure 3 The diagram of Seebeck effect in open circuit with the different type of material (Deen Dayal Upadhyaya College, 2024).

Figure 3 shown the diagram of Seebeck effect in open circuit with the different type of material consider as metal A and B in giving desirable hot or higher temperature T_h and cold or lower temperature T_c . The potential difference $V(\Delta V)$ is generated across the circuit junctions held at different temperatures proportional to the temperature difference between junction $(T_h - T_c)$. This ratio is resulting coefficient of proportionality called Seebeck coefficient. This will be given by Eq. 4.

$$-\frac{\Delta V}{\Delta T} = S \quad (4)$$

Where S is Seebeck coefficient or thermo power, ΔV is voltage gradient, and ΔT is temperature difference. The Seebeck coefficient also a symbol of potential of cold side respected to the hot side of metal in open loop. The negative sign is representation of charge across the material mainly electron and the convention of current flow (Hofmann, Kroon, & Müller, 2019).

Where the coefficient of proportionality is known as the thermoelectric power or the Seebeck coefficient. Then, the term of thermoelectric power is a misnomer because can not measure any power and measured in V/K . By convention, the Seebeck coefficient sign is the sign of the potential of the cold end with respect to the hot end. Thus, S_{AB} is positive conventional current flows from A to B at the hot junction, Seebeck coefficient is not a constant but is dependent on temperature. The temperature dependence of a commercial thermocouple is usually expressed as a polynomial expansion in powers of temperature. For instance, the thermocouple with Pt as one of the metals and an alloy of Pt-Rh (90:10). Then, the open circuit voltage is given approximately by Eq. 5.

$$V = c + aT + \nu T^2 \quad (5)$$

So, the thermoelectric power is given by Eq. 6.

$$\frac{dV}{dT} = a + 2bT \quad (6)$$

In addition, the relationship between V and T is a parabola. The temperature $T_n = -a/2b$ at which the thermoelectric power maximum is called the neutral temperature. The temperatures $T_i = T_0$ and $T_i = T_0 - a/b$ at which a small change in the difference of the junction temperatures leads to a change in the sign of Thermo emf is called inversion temperature as shown in Figure 4.

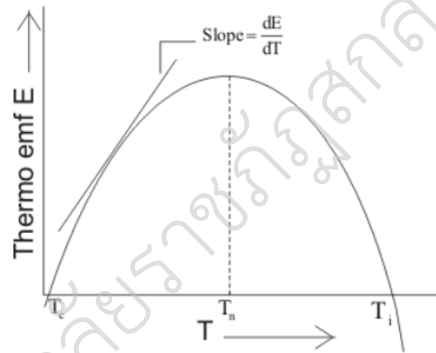


Figure 4 Variation of Thermo emf with temperature hot junction. (Physics Catalyst, 2024).

A complete understanding of Seebeck effect requires knowledge of behavior of electron in a metal which is rather complicated. The Seebeck coefficient depends on factors like work functions of the two metals, electron densities of the two components, scattering mechanism within each solid. Moreover, the Seebeck effect is a manifestation of the fact that two points in a conductor (or a semiconductor) are maintained at different temperatures, the charged carriers (electrons or holes) in the hotter region, being more energetic will diffuse towards region of lower temperature. The diffusion stops when the electric field generated because of movement of charges has established a strong

enough field to stop further movement of charges. Accordingly, a metal carriers being negatively charged electrons, the colder end would become negative so that Seebeck coefficient is negative. In part of a p-type semiconductor holes diffuse towards the lower temperature resulting in a positive Seebeck coefficient (Mameekul, 2024).

1.2 Peltier Effect

Tritt (2002) The Peltier effect is the basis for many modern TE refrigeration devices and the Seebeck effect is the basis for TE power generation devices (see Thermoelectric Devices Refrigeration and Power Generations with no Moving Parts). The versatility of TE materials is illustrated in Figure 5, which shows a diagram of a thermoelectric couple composed of an n-type (negative thermo-power and electron carriers) and a p-type (positive thermo-power and hole carriers) semiconductor material connected through metallic electrical contact pads. Both refrigeration and power generation may be accomplished using the same module as shown in Figure 5(a, b). Besides, a TE module or device is built up of an array of these couples, which are arranged electrically in series and thermally in parallel. Thermoelectric energy conversion utilizes the Peltier heat generated when an electric current is passed through a thermoelectric material to provide a temperature gradient with heat being absorbed on the cold side, transferred through (or pumped by) the thermoelectric materials and rejected at the sink, thus providing a refrigeration capability. The advantages of TE solid state energy conversion are compactness, quietness (no moving parts), and localized heating or cooling. Many of the potential applications and importance of these devices have already been discussed in the background and applications section.

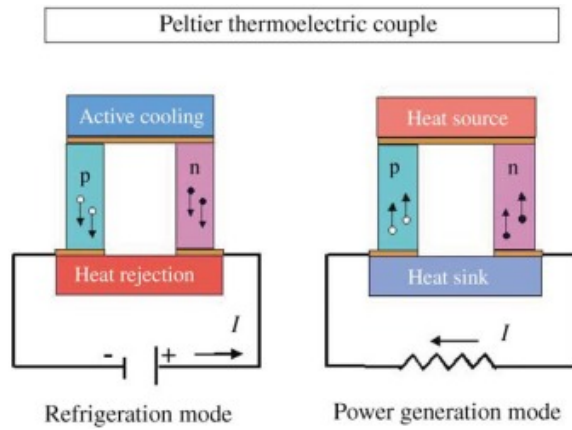


Figure 5 The Peltier thermoelectric couple. (a) Refrigeration mode. (b) Power generation (Tritt, 2002).

The amount of heat Q liberated to the surroundings in order that the junction may be kept at the same temperature is proportional to the current I passing through the junction was calculate by Eq. 7.

$$Q = \Pi_{AB} I \quad (7)$$

Where the constant Π_{AB} is thermal current density to electrical current density that called the Peltier coefficient. Peltier coefficient represent amount of heat current is carried per charge thorough material. The Peltier coefficient depends on the pair of materials A and B of the junction and also on the junction temperature that can search for charge was use Eq. 8 and 9 as follow:

$$q = \Pi j \quad (8)$$

$$q = \Pi \sigma (-\Delta T) \quad (9)$$

Furthermore, the heat is difficult to measured precisely than thermal difference, this phenomenon connected Seebeck coefficient since it is capable to measurement. Where the both of equation may related to Seebeck as Eq. 10 (Terasaki, 2011).

$$\Pi = ST \quad (10)$$

Therefore, the Peltier effect is used in heat pumps, which remove heat (although they can also add heat) using a controlled, reversible solid state device (meaning there are no mechanical parts). Solid State heat pumps using the Peltier effect will effectively transfer heat from one side of the device to the other (Phononic, 2025).

1.3 Thomson Effect

Thomson indicated that as the current passes into unequally heated conductors, the thermal energy is either consumed or formed in the metal structure. In other words, the Thomson effect is the generation of reversible heat when an electrical current is passed through a conductive material subjected to a temperature gradient. The Thomson effect describes the heat loss of a substance with a current through it and this transfer of heat is immediately observable. It is different from the effects of Peltier and Seebeck, for which only the net effect of two different materials can be measured (Jouhara, et al., 2021).

We can represent the effect of the thermal gradient responsible for the diffusive motion of the carriers by an effective field ($\vec{E}$). This effective field is proportional to the thermal gradient and can be written as Eq. 11.

$$E' = \sigma \frac{dT}{dx} \quad (11)$$

Where σ is Thomson coefficient for the material conductor, the Thomson electromotive force (*emf*) is ε_{th} given by Eq. 12.

$$\varepsilon_{th} = \int E' dx = \int_{T_1}^{T_2} \sigma dT \quad (12)$$

Where T_1 and T_2 are the temperatures at of two ended of the rod.

Thomson effect is a manifestation of the Thomson *emf* described above.

Clearly, one cannot demonstrate the existence of the *emf* by using it to drive a current in a close circuit. This is because one uses a single metal with a temperature gradient, the integral σdT around a close loop is zero. Furthermore, dis similar metals Peltier effect dominates over Thomson effect (Bilotti, Fenwick, Schroeder, Baxendale, Taroni-Junior, Degousée, & Liu, 2018).

When a current is passed through a homogeneous conductor with a temperature gradient, the rate of heat production per unit volume is given by Eq. 13.

$$Q' = \rho I^2 \frac{dt}{dx} \quad (13)$$

Where ρ is resistivity, the first term is the irreversible Joule heat. The second term is Thomson *emf*.

In metals such as copper and zinc, the hotter end is at a higher potential in such a situation of the current due to an external supply is in the same direction as the direction of decreasing potential. Besides, there is additional evolution of heat due to Thomson effect and the net heat produced is more than the Joule heat. If the direction of the current is reversed, heat energy is converted to electrical energy due to Thomson effect and the rate production of heat is reduced. This is known as positive Thomson effect.

Summary In this generation, thermoelectric field have recently attracted considerable interest owing to their unique ability of converting heat to electrical energy in an environmentally efficient manner. These are promising as alternative power generators for harvesting electrical energy compared to conventional batteries. Inorganic crystalline semiconductors have dominated the

thermoelectric material fields. Nevertheless, their application has been restricted by their intrinsic high toxicity, fragility, and high cost. In contrast, organic thermoelectric materials with low cost, low thermal conductivity, easy processing, and good flexibility are more suitable for fabricating thermoelectric devices (Zhang, Heo, Park, & Park, 2019).

Thermoelectric based on PEDOT:PSS

2.1 Poly 3, 4 ethylenedioxythiophene Polystyrene sulfonate (PEDOT:PSS)

PEDOT, especially in its doped form like PEDOT:PSS (poly (3,4-ethylenedioxythiophene) polystyrene sulfonate), is highly valuable for thermoelectric applications due to its exceptional properties, including high electrical conductivity, low thermal conductivity, flexibility, and ease of processing. As a soft material, PEDOT:PSS is an excellent choice for flexible and wearable thermoelectric devices (Figure 6). It can be fabricated into films, coatings, fibers, or composites, facilitating a wide range of applications. Recent advancements emphasize PEDOT:PSS's potential as a leading material among organic and polymeric compounds, particularly in wearable technology and sustainable energy applications. This review paper highlights recent developments and innovative strategies in PEDOT:PSS-based thermoelectric research (Mulla, 2025).

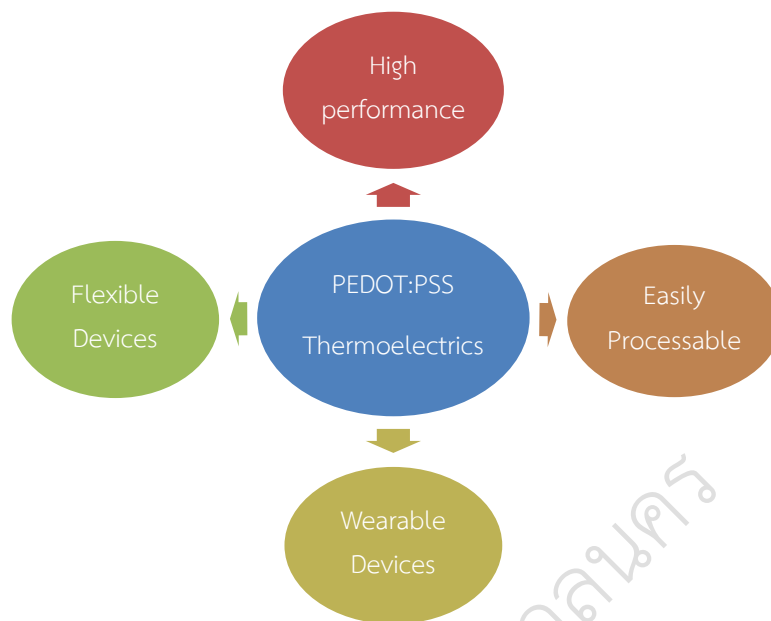


Figure 6 The valuable diagram of PEDOT:PSS thermoelectric applications.

PEDOT:PSS as a conducting polymer, conducting polymers represent a distinctive class of materials that possess the ability to conduct electricity as a result of their unique conjugated carbon chains, which are made up of alternating single and double bonds. Unlike conventional polymers that are typically insulators because they lack a delocalized π -electron system, conducting polymers possess conjugated carbon chains that enable them to conduct electricity. The emergence of polyacetylene in the 1970 s by a team of researchers comprising of Hideki Shirakawa, Alan Heeger, and Alan MacDiarmid, marked a significant breakthrough in the field of organic conducting polymers, and subsequently led to a significant surge in the study of conductivity in such materials. Consequently, a vast library of conducting polymers has been developed. Among these conducting polymers, PEDOT:PSS stands out for its high electrical conductivity (σ) and low thermal conductivity, making it a promising candidate for thermoelectric applications (Rout, 2021). Bayer Central Research Department was at the forefront of conducting polymer research in the 1980 s,

and they made a significant breakthrough by polymerizing 3,4-ethylenedioxythiophene (EDOT) with iron (III) chloride as an oxidative reagent, producing PEDOT. It was discovered to be stable in its doped state and exhibited conductivities of up to 200 S cm^{-1} . In the same year, they also examined the first electropolymerized PEDOT.

Although PEDOT features high σ and stability in air and water, it is black, insoluble, and infusible when chemically synthesized. Electrochemically synthesized PEDOT, on the other hand, could only be formed on conductive substrates. Therefore, finding a processable alternative is crucial. The Bayer team discovered a solution while working with Agfa chemists developing antistatic coatings for photographic films. They used the sodium salt of polystyrene sulfonate (PSSNa) as an antistatic coating, which had humidity-dependent conductivity. By stabilizing the solution with PSS as a counter anion, an aqueous solution of PEDOT was produced, and per sulfates oxidized EDOT to facilitate polymerization in water (Jonas & Morrison, 1997). Since then, PEDOT:PSS has proven beneficial to both commercial and academic applications. Various grades of commercial PEDOT:PSS as Shown in Table 1 (Alam, et al., 2024).

Table 1 The various grades of commercial PEDOT: PSS (Alam, et al., 2024).

Name	Ratio (PEDOT:PSS)	Solid content (wt%)	Particle size (nm)	$\sigma \text{ (S cm}^{-1}\text{)}$
Clevios P	1:2.5	1.2-1.4	80	0.2-1
Clevios PH 500	1:2.5	1.0-1.4	30	0.2-1
Clevios PH 510	1:25	1.5-1.9	30	0.2-1
Clevios PH 1000	1:2.5	1.0-1.3	30	0.2-1
Clevios PVP CH8000	1:20	2.5-3.0	25	10^{-5} - 10^{-6}
Clevios PVP AI 4083	1:6	1.3-1.7	40	10^{-3} - 10^{-4}

For practical high-performance application in thermoelectric polymer sheet and thermoelectric e-textiles. Consequently, the poly 3, 4-ethylenedioxythiophene-polystyrene sulfonate (PEDOT:PSS) PH1000 grades (Figure 7) polymer is a significant area of interest in the field of organic/inorganic thermoelectric with good electrical conductivity and extremely low thermal conductivity. PEDOT:PSS has been reported to have a ZT value of 0.42 at room temperature. PEDOT-PSS has been intensively investigated owing to its solution process ability and easy tenability of its redox state (i.e., bipolar or neutral) that facilitates the optimization of the S and ρ values (Insawang, Vora-ud, Seetawan, Muntini, Phan, & Kumar, 2024).



Figure 7 PEDOT:PSS solution.

Ossila enabling science (2025) This combination forms a p-type semiconductor which is highly valued for its ability to conduct electricity and its ease of processibility. The ratio of PEDOT to PSS can be adjusted to modify the material's conductivity and solubility. This versatility makes it a widely used hole transport material in charge transport applications. PEDOT is highly conductive with impressive mechanical flexibility, while PSS offers stability and allows

dispersion in water. Together, they create a material that is transparent in the visible spectrum and exceptionally conductive. This makes PEDOT:PSS an extremely attractive material for use in many optical and electronic devices.

Although the characteristics of PSS are well defined, PEDOT:PSS has a much more complex structure. The intimate association of two polymers in solution leads to some interesting dynamics in the suspension and in the subsequent thin film. One term for this intricate combination of PEDOT and PSS is a “chain structure entanglement” as shown in Figure 8.

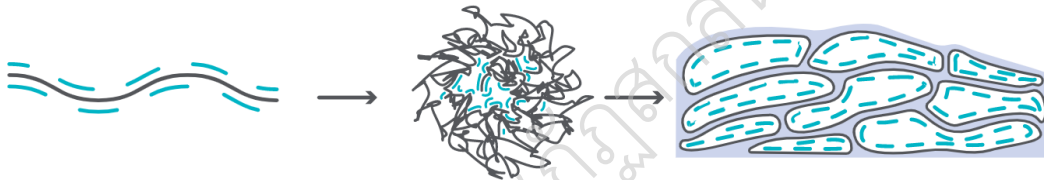


Figure 8 The structure of PEDOT:PSS at different stages. From initial sythesis (left) to gel particles (centre) to thin film structure (right) of PEDOT (blue) and PSS (grey) (Ossila enabling science, 2025).

Moreover, during synthesis, it seems that PEDOT synthesizes onto the PSS template. In the resulting suspension, small segments of PEDOT are in close contact with PSS bundles bound by Coulomb forces as shown in Figure 9. These entangled PEDOT:PSS bundles form a colloidal suspension of gel particles in water where:

- (1) Hydrophobic PEDOT populates the inner core
- (2) Hydrophilic PSS makes up the outer layer

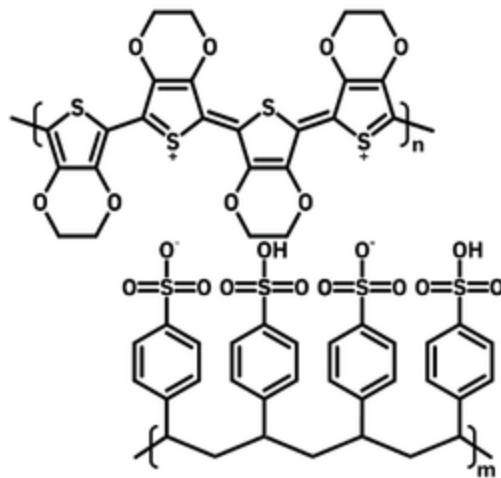


Figure 9 The chemical structure of PEDOT:PSS (Ossila enabling science, 2025).

When deposited into a thin film, the film morphology is driven by this chain structure entanglement. The PEDOT:PSS gel particles will form pancake like structures, with these bundles stacking on top of one another in the thin film. The morphological and electronic properties of a PEDOT:PSS film depend on the formation of these gel particles and their stacking. Therefore, film properties are dependent on many factors including:

- (1) PEDOT and PSS ratio and synthesis method
- (2) PEDOT:PSS deposition and processing methods
- (3) Any additives in the precursor solution
- (4) Any pre- and post-treatment of the deposited films

It is also widely used for industrial applications. For example, both aqueous and non-aqueous deep-blue PEDOT:PSS dispersions are now commercially available from Heraeus Clevios™ and Agfa Orgacon™.

Supplementary, PEDOT:PSS was used in many fielded application as follow

- (1) Perovskite Photovoltaics. PEDOT:PSS has been used as a hole extraction material in inverted PSC devices. This material facilitates the extraction

of charge carriers at the interface between the transparent conductive oxide and the active perovskite layer.

(2) Transparent Conductors. PEDOT:PSS is a potential replacement for expensive transparent metal oxides, such as ITO and FTO. Its effectiveness in both organic photovoltaic and perovskite photovoltaic devices has been demonstrated. In addition, in combination with metallic grid structures, it is possible to achieve sheet resistances comparable to metallic films.

(3) Organic Light Emitting Diodes. The use of PEDOT:PSS in organic light emitting diodes, as a well-established standard hole injection material, has been widespread for over a decade. Recent work still uses PEDOT:PSS due to its deep work function. This allows for efficient charge injection into white emitting polymers as well as host materials for thermally activated delayed fluorescence materials.

(4) Organic Photovoltaics. PEDOT:PSS has long been used in OPV fabrication, often used in combination with materials such as P3HT and PCDTBT. To this day, it remains a popular material choice for polymer solar cell research.

(5) PEDOT:PSS-Based Conductive Fabric. PEDOT:PSS has attracted interest in smart textile technology due to its relatively high electrical conductivity, water dispersibility, ease of manufacturing, environmental stability, and commercial availability. Several methods apply PEDOT:PSS to textiles. They include polymerization of the monomer, coating, dyeing, and printing methods (Alamer, et al., 2022).

2.2 Inorganic Polymer Thermoelectric Sheet

2.2.1 Selenide Group Materials Properties

(1) SnSe₂ Material Character, SnSe₂ is trigonal omega structured and crystallizes in the trigonal $\overline{P}3m1$ space group is Shown in Figure 10. The structure

is two-dimensional and consists of one SnSe_2 sheet oriented in the (0, 0, 1) direction. Sn^{4+} is bonded to six equivalent Se^{2-} atoms to form edge-sharing SnSe_6 octahedra. All Sn-Se bond lengths are 2.72 Å. Se^{2-} is bonded in a distorted T-shaped geometry to three equivalent Sn^{4+} atoms (Materials Explorer(a), 2025). The Lattice Conventional of SnSe_2 as Shown in Table 2.

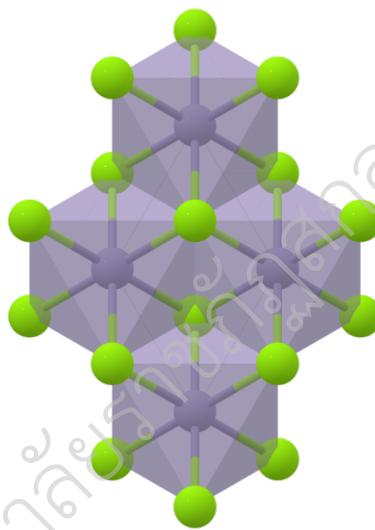


Figure 10 SnSe_2 crystal structure (Materials Explorer(a), 2025).

Table 2 The lattice Conventional of SnSe_2 (Materials Explorer(a), 2025).

Lattice (Conventional configuration)	
a	3.84 Å
b	3.84 Å
c	6.49 Å
α	90°
β	90°
λ	90°
Volume	82.91 Å

(2) SnSe Materials Character, SnSe is Hittorf-derived structured and crystallizes in the orthorhombic $Pnma$ space group as Shown in Figure 11. The structure is two-dimensional and consists of two SnSe sheets oriented in the (0, 0, 1) direction. Sn^{2+} is bonded in a distorted T-shaped geometry to three equivalent Se^{2-} atoms. All Sn-Se bond lengths are 2.77 Å. Se^{2-} is bonded in a trigonal non-coplanar geometry to three equivalent Sn^{2+} atoms (Materials Explorer(b), 2025). According to the Lattice Conventional of SnSe as Shown in Table 3.

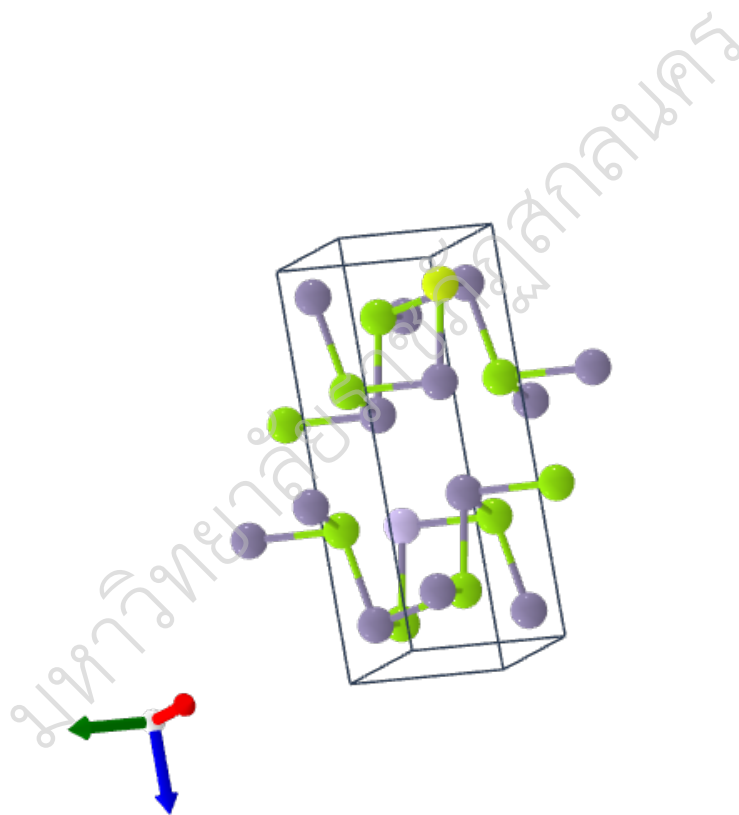


Figure 11 The SnSe crystal structure (Materials Explorer(b), 2025).

Table 3 The lattice Conventional of SnSe (Materials Explorer(b), 2025).

Lattice (Conventional configuration)	
a	4.13 Å
b	4.70 Å
c	11.66 Å
α	90°
β	90°
λ	90°
Volume	226.26 Å

In the main point of Selenide group character, Inorganic sheet, fiber and yarns based on thermoelectric exhibit more excellent thermoelectric performance and designable nanostructures compared with organic or inorganic/organic hybrid, which can be attributed to their suitable electronic structures and low lattice thermal conductivity. Thus, various types of low-dimensional thermoelectric materials such as nano or micro based on sheet and yarns have been applied in thermoelectric textiles or flexible thermoelectric generators (Xin, Basit, Li, Danto, Tjin, & Wei, 2021). Furthermore, in various inorganic thermoelectric materials of telluride, selenides and homologous such as PbTe, Bi₂Te₃, Bi_{0.5}Sb_{1.5}Te₃, Bi₂Te_{2.7}Se_{0.3}, Bi_xSb_{2-x}Te₃, Ge_{0.94}Bi_{0.06}Te, Sb-doped Ag₂Sb_xTe_{1-x}, SnSe, SnSe₂, Sn-doped SiGe, and Si nanowires have also been reported. Nevertheless, all of the above were presented in inorganic thermoelectric materials and exhibited significantly lower the *ZT* values than SnSe single crystal phase as shows in Table 4. Among them, SnSe has a promising state of inorganic thermoelectric materials for the generation and attracted rapidly growing research interest for its high inorganic thermoelectric performance

and the intrinsic layered structure that leads to strong anisotropy (Xie, He, & He, 2021; Insawang, et al., 2024).

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

Table 4 The ZT and PF values of Inorganic Thermoelectric in various materials.

Methods	Materials	ZT	Temp. (K)	PF ($Wm^{-1} K^{-2}$)	Ref.
Czochralski	PbTe single crystals	0.41	300	P-type 1.91×10^{-3} N-type 0.063×10^{-3}	(Seetawan, Vora-Ud, Ullah, Thang, Kumar, & Kim, 2022)
MSS + CP	Bi_2Te_3 (n)	0.91	350	-	(Hong, Chen, & Zou, J, 2018)
MSS + CP	$Bi_{0.5}Sb_{1.5}Te_3$ (p)	1.2	363	-	
SG + SPS	$Bi_2Te_{2.7}Se_{0.3}$ (n)	0.55	300	-	
RMAS	$Bi_xSb_{2-x}Te_3$ nanoplates	1.2	325	28.3×10^{-4}	(Hong, Chen, Yang, & Zou, 2016)
Precipitates	$Ge_{0.94}Bi_{0.06}Te$	1.9	723	35×10^{-6}	(Jin, Xiao, Wang, Huang, Qiu, & Zhao, 2019)
Vacuum & Melting	Sb-doped $Ag_2Sb_xTe_{1-x}$	1.4	410	1.07×10^{-3}	(Zhu, et al., 2020)
Arc melting	SnSe poly crystal	1.8	816	10×10^{-6}	(Gainza, et al., 2020)

\

Table 4 (Continued)

Methods	Materials	<i>ZT</i>	Temp. (K)	<i>PF</i> ($\text{Wm}^{-1} \text{K}^{-2}$)	Ref.
Solvothermal	SnSe poly crystal	0.47	703	4.4×10^{-6}	(Zhang, Ning, Qi, Chen, Tang, & Chen, 2019)
Solid State Reaction	SnSe poly crystal	0.5	834	4×10^{-6}	(Sassi, Candolfi, Vaney, Ohorodniichuk, Masschelein, Dauscher, & Lenoir, 2014)
Mechanical alloying	SnSe poly crystal	0.7	823	3.9×10^{-6}	(Cho, Siyar, Bae, Mun, Kim, Hong, & Park, 2020)
-	SnSe singlecrystal	2.6	923	-	(Zhao, Lo, Zhang, Sun, Tan, Uher, & Kanatzidis, 2014)
-	SnSe ₂ layer	1.1	950	0.49	(Das, Rosul, & Zebarjadi, 2023)
SPS	Sn-doped SiGe	1.26	573	13×10^{-4}	(Meng, et al., 2022)
-	Si-nanowires	0.71	700	-	(Yang, et al., 2021)

*MSS = Microwave solvothermal

*RMAS = Rapid Microwave-Assisted Solvothermal.

*CP = Cold pressing.

*SPS = Spark plasma sintering. *SG = Solution grown.

In here we focus on SnSe_2 and has a semiconductor material with a bulk bandgap of 1.0 eV and which shows a mobility of $28 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in thin-film. In addition, SnSe_2 has additionally demonstrated a potential for applications in the fields of optoelectronics, photovoltaics, infrared optoelectronic devices, holographic recording systems, and memory switching devices. Moreover, SnSe_2 material has been promoted for new 2-dimensional thermoelectric materials based on structure regulation and nano particles etc (Rehman, Ali, Ikram, Amami, & Mahmood, 2022; Salah, Abdullahi, Salah, Alshahrie, & Koumoto, 2024). It is well known that the single crystalline Selenide group materials giving high performance. Nevertheless, they unsuitable for industrial company applications due to their difficulty in fabrication and brittle nature (Singh, Anwar, Dubey, & Mishra, 2023) and they have some inherent limitations like poor processability, toxicity, rare availability, and high cost of manufacturing (Jangra, Maity, & Vishnoi, 2022).

2.2.2 Inorganic Thermoelectric based on Conductive Fiber & Sheet

Inorganic fiber based on thermoelectric exhibit more excellent thermoelectric performance and designable nanostructures (Xin, Basit, Li, Danto, Tjin, & Wei, 2021). For e-textiles to be practically useful they must retain their electronic properties despite day-to-day wear as well as machine laundry (Lund, Darabi, Hultmark, Ryan, Andersson, Ström, & Müller, 2018). As the same time, traditionally, thermoelectric materials are inorganic semiconductors which have been limited in their application by low efficiency and high cost. Since the 1990s, both theoretical and experimental studies have shown that low dimensional thermoelectric materials, such as super lattices and nanowires, can enhance the value of the thermoelectric figure of merit (ZT) which is an indicator of thermoelectric thermodynamic efficiency.

Nonetheless, when compared to inorganic materials, organic conducting polymers possess some unique features, such as low density, low cost, low thermal conductivity, easy synthesis and versatile processability and their use in preparing polymer inorganic thermoelectric nanocomposites (Figure 12) and then appears to have great potential for producing relatively low cost and high performances thermoelectric materials. Recently, for increasing number of studies have reported on polymeric and polymer inorganic thermoelectric nanocomposite materials in Selenide group and many methods for synthesis are Shown in Table 5 (Du, Shen, Cai, & Casey, 2012).

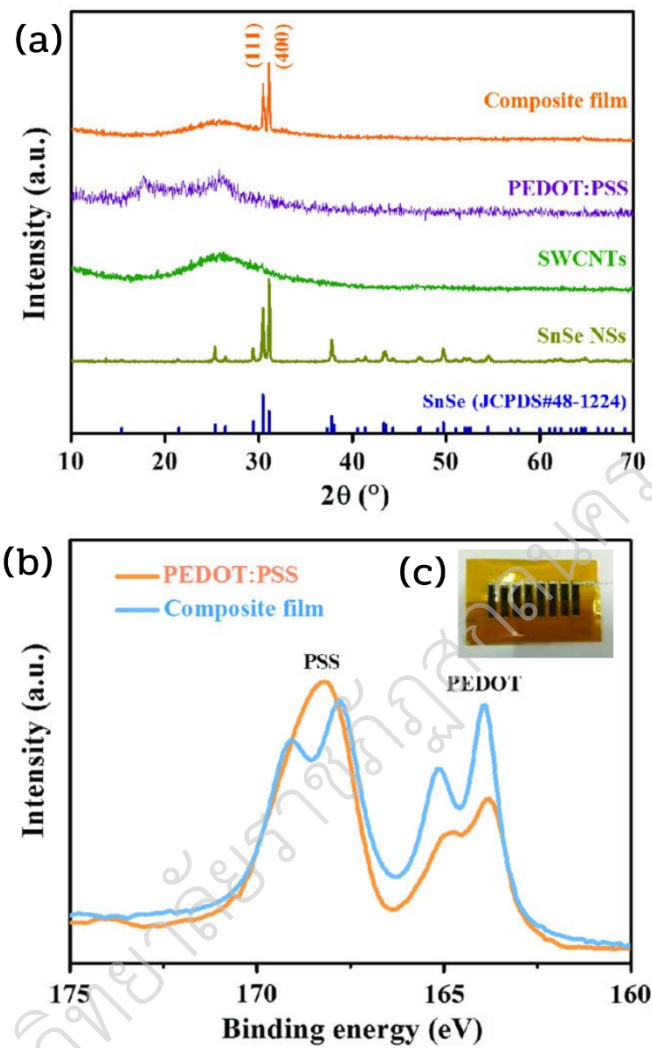


Figure 12 The PEDOT:PSS/SnSe nanosheet. (a) The XRD patterns of SnSe NSs, SWCNTs, pure PEDOT:PSS, and flexible SWCNT/SnSe NS/PEDOT:PSS composite film with 60 wt% SWCNTs. (b) XPS S2p spectra of pure PEDOT:PSS and flexible SWCNT/SnSe NS/PEDOT:PSS composite film with 60 wt% SWCNTs. (c) Prototype module of PEDOT:PSS/SnSe conductive sheet (Liu, Du, Meng, Dou, Jin, Xu, & Shen, 2020).

Table 5 The *PF* values of PEDOT:PSS+Selenide compositions in various ways.

Methods	Compositions	Temp. (K)	<i>PF</i> ($\mu\text{W m}^{-1} \text{K}^{-2}$)	Ref.
Vacuum filtration	PEDOT:PSS/SnSe	623	24.42	(Yan, et al., 2020)
Direct vacuum-filtration	PEDOT:PSS/MoSe ₂ nanosheets	300	48.6	(Li, et al., 2017)
Vacuum filtration	PEDOT:PSS/SnSe enhancing by MWCNTs	393	59.35	(Liu, et al., 2022)
Facile Vacuum filtration	PEDOT:PSS/SnSe nanosheet enhancing by SWCNT	380	109.9	(Liu, Du, Meng, Dou, Jin, Xu, & Shen, 2020)
Cold-pressing & Vacuum filtration	PEDOT:PSS/SnSe-MWCNTs	393	166.5	(Liu, et al., 2021)

*MWCNTs = Multiwall Carbon Nanotubes

*SWCNT = Single-Walled Carbon Nanotube.

As we knew fiber based on clothes have been developed and used by human beings for more than 10000 years ago because of their comfortability and conformability on human body. In the past decade, textile based on thermoelectric devices have attracted more and more attentions and become one emerging division of wearable, though it is still in its initial stage.

Thermoelectric e-textiles assembled from fibers, filaments and fabrics constitute the frontier of wearable thermoelectric generator that are of 3D comfortability, referring to flexible, stretchable, and twistable, to the dynamic curved surface on human body (Chen, Yang, Han, Ruan, Xu, Huang, & Zhang, 2023).

2.2.3 Inorganic Thermoelectric based on Conductive yarns

Achieving both formability and functionality in thermoelectric materials remains a significant challenge due to their inherent brittleness. Previous approaches, such as polymer infiltration often compromise thermoelectric efficiency and underscoring the need for flexible all inorganic alternatives (Jang, et al., 2024). In contrast, the conventional thermoelectric generators based on flexible yarns offer sophistication in wearable energy harvesting owing to their potential to be integrated into wearable textiles (Jiang, et al., 2023). Conductive yarns thermoelectric materials are composed of yarns coated with thermoelectric materials and it provides more design flexibility in thermoelectric generator as compared to thermoelectric generator made out of fabrics (Jangra, Maity, Vishnoi, 2022).

Thermoelectric generator in the form of the yarns is establishing their positions in the e-textiles market as the very promising materials for wearable applications. These thermoelectric yarns have excellent mechanical properties, heat & moisture permeability, and cost effective mass production. Based on the structure of the device developed, they are categorized into four different classes, viz. (i) One-dimensional (1D) thermoelectric generator in fiber yarn/filament/yarn forms, (ii) Two-dimensional (2D) thermoelectric generator that are fabric-based, (iii) Three-dimensional (3D) thermoelectric generator with assembled thermoelectric yarn/filament/fiber into textile cloths, and (iv) 3D thermoelectric generator with incorporated inorganic thermoelectric ingots. As flexible materials, these materials can cover body contour perfectly and utilize body temperature in most efficient way to convert to an electric signal. Then, 3D thermoelectric generators are more useful for this purpose due to their structural advantage (Wang & Zhang, 2019; Jangra, Maity, Vishnoi, 2022).

The thermoelectric yarns are flexibility enough to be suitable for weaving, knitting and embroidery to prepare 3D wearable garments. The knitted

structure is highly stretchable (500%), bulky, porous and giving better performance in terms of thermal insulation. There is woven structure such as plain, twill and satin that can be prepared from the thermoelectric yarns. Various decorative patterns can be made on the garment by the embroidery technique using needles and thermoelectric yarns. By these method, various p-type and n-type thermoelectric yarns can be electrically connected in series joining electrodes from the top and bottom of the fabric surface. By application of thermoelectric polymer PEDOT:PSS on fabric and connecting these coated strips with conducting materials like metal wires, etc.

A flexible thermoelectric generator is fabricated using a tree-dimensional fabric and thermoelectric materials coated yarns. Even though, it is a low-performance prototype but its efficiency can be further improved by improving transport properties or finding materials with high ZT value like inorganic thermoelectric material that can be used (Wu & Hu, 2017). It is also observed that P3HT coated cotton fabric has better performance than that of PEDOT:PSS coated cotton fabric (Wang & Zhang, 2019; Wu & Hu, 2017; Jangra, Maity, Vishnoi, 2022). Additionally, Bi_2Te_3 also was excellent choice for thermoelectric yarns in inorganic materials as Shown in Figure 13.

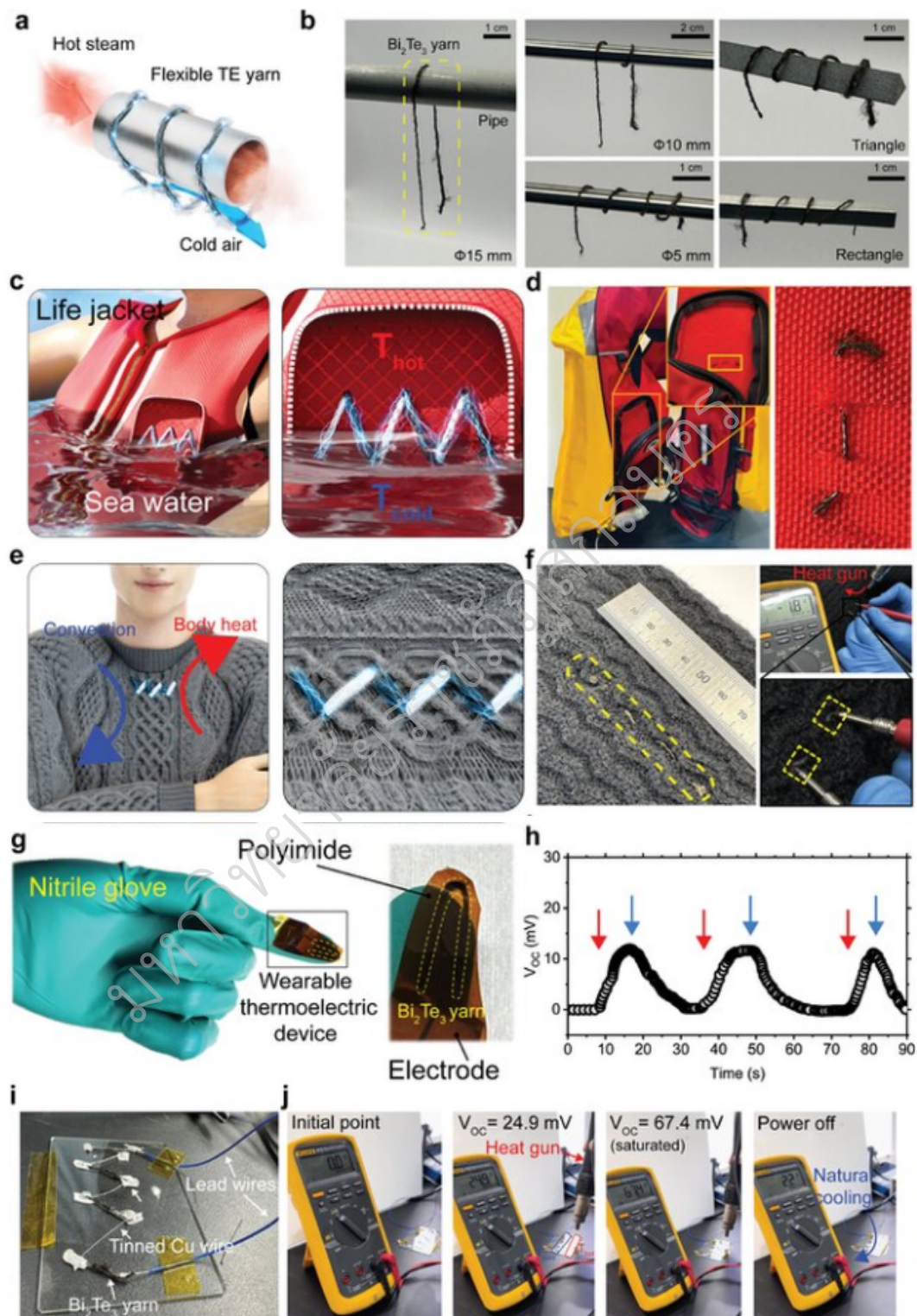


Figure 13 The prospective applications for leveraging the intrinsic flexibility of thermoelectric yarns (Wu & Hu, 2017).

From Figure above shown the prospective applications for leveraging the intrinsic flexibility of thermoelectric yarns. (a) Mentioned a schematic illustration depicting the energy harvesting scenario exploiting the temperature differential between the hot fluid inside a pipe and the colder external air. (b) Shown the photographic images showcasing Bi_2Te_3 yarn suspended and coiled around metallic pipes of various dimensions and shapes. (c) A schematic illustration depicting the energy harvesting scenario leveraging the temperature contrast between a warm human body and cold seawater. (d) Photographic images demonstrating Bi_2Te_3 yarn integrated into a life jacket through knitting. (e) A schematic illustration the energy harvesting scenario utilizing the temperature disparity between a warm human body and the surrounding cold air. (f) Photographic images exhibiting Bi_2Te_3 yarn incorporated into a sweater through knitting. (g) Digital photograph of the wearable thermoelectric device with the Bi_2Te_3 yarn. (h) Time-dependent open circuit voltage (V_{OC}) of the wearable thermoelectric generator in (g). Red and blue arrows indicate the points where the thermoelectric generator is attached to and detached from the hot surface, respectively. (i) Shown the photographic image of a 4-pair thermoelectric generator consisting of Bi_2Te_3 yarns and tinned copper wires. (j) Photographic images showing thermoelectric voltage generation upon heating with a heat gun.

Therefore, substantiating the effectiveness of thermoelectric yarns in waste heat harvesting, these advances not only challenge the traditional limitations posed by the brittleness of thermoelectric materials but also open new avenues for their application in wearable and structural electronics and then we can adaption selenide group to conductive yarns like telluride yarns (Jang, et al., 2024).

2.2.4 Inorganic Thermoelectric based on Thin Film

Integration of inorganic thin film thermoelectric into textiles has been primarily focused on creating small scale energy harvesting devices that can power other on body wearable devices by harvesting the body heat. A film is considered thin as long as its surface properties are different from its bulk behavior, extending from a few micrometers to the nanometer, inorganic thin film devices are usually prepared via deposition techniques that can be classified into either physical vapor deposition (PVD) or chemical vapor deposition (CVD). Compared to bulk alloyed materials used in state of the art devices such as p-type $\text{Bi}_x\text{Sb}_{2-x}\text{Te}_{3-y}\text{Se}_y$ ($x \approx 0.5$, $y \approx 0.12$) and n-type $\text{Bi}_2(\text{Se}_y\text{Te}_{1-y})$, thin film thermoelectric materials (thickness less than 10 nm) offer the advantage of being able to achieve higher ZT values using techniques such as quantum confinement effects to obtain an enhanced density of states near the Fermi energy creating super lattice (SL) structures with low κ_l values, and creating hetero structures (Chatterjee & Ghosh, 2021). The example of inorganic thin film such as SnSe single crystals along the b-axis was review (Shi, et al., 2018).

Furthermore, various materials have been explored for use as thin-film thermoelectric materials (Chatterjee & Ghosh, 2021). However, SnSe is excellent choice because high the ZT value performance. SnSe thin films are usually applied onto various flexible substrates. Accordingly, various methods are also were synthesis them, are Shown in Table 6 (Insawang, et al., 2024).

Table 6 The thermoelectric properties of SnSe thin film in various synthesis methods.

Synthesis method	Materials	ZT	Temp. (K)	PF (mW m ⁻¹ K ⁻²)	Ref.
RF magnetron sputtering	SnSe thin film	0.44	300	0.35	(Insawang, et al., 2024)
Thermal evaporation	SnSe thin film	0.055	501	0.11	(Burton, et al., 2018)
Magnetron sputtering	SnSe thin film	0.83	700	2.43	(Singh, Anwar, Dubey, & Mishra, 2023)
Sputtering	SnSe thin film	0.28	675	2.4	(Song, Zhang, & Iversen, 2019)
Chemical vapor transport	SnSe thin film	0.16	300	-	(Ho, Lin, Chao, Lee, Inagaki, & Hsueh, 2020)
Sonication-assisted liquid-phase exfoliation	SnSe thin film	-	600	1.55	(Duong, Chung, Phan, Nguyen, Nguyen, Le, & Pham, 2022)
Vacuum filtration	SnSe/PEDOT:PSS thin film	-	353	0.24	(Yan, Zhao, Liu, Zhang, Zheng, Cui, Zhang, & Xue, 2020)
Chemical vapor deposition	SnSe thin film	0.15	550	3.2	(Zhong, Zhang, Linseis, Qin, Chen, Zhao, & Zhu, 2020)
MPCVD	SnSe thin film	0.35	600	3.98	(Feng, Zhang, Lei, Nie, & Xiang, 2022)

Table 6 (Continued)

Synthesis method	Materials	ZT	Temp. (K)	PF (mW m ⁻¹ K ⁻²)	Ref.
Electrodeposited and delamination	SnSe thin film	0.4	675	5.8	(Burton, Boyle, Liu, McGettrick, Nandhakumar, Fenwick, & Carnie, 2020)
Reactive evaporation	SnSe thin film	1.2	42	7.2	(Urmila, Namitha, Rajani, Philip, & Pradeep, 2016)

*MPCVD = Microwave plasma chemical vapor deposition.

All of above thin film deposition, magnetron sputtering can deposit a better adherent and alter the structure by suitably adjusting the deposition parameters of a coating (Chen, Jan, Lin, & Hsueh, 2021; Insawang, et al., 2024). In addition, rapid thermal annealing on the physical properties of SnSe thin film shows smoothness increases at elevated temperatures, superior thermoelectric performance, and promising versatile material as Shown in Figure 14 (Insawang, et al., 2024). It provides a high degree of freedom to control the structure evolution over various substrates (Singh, Anwar, Dubey, & Mishra, 2023).

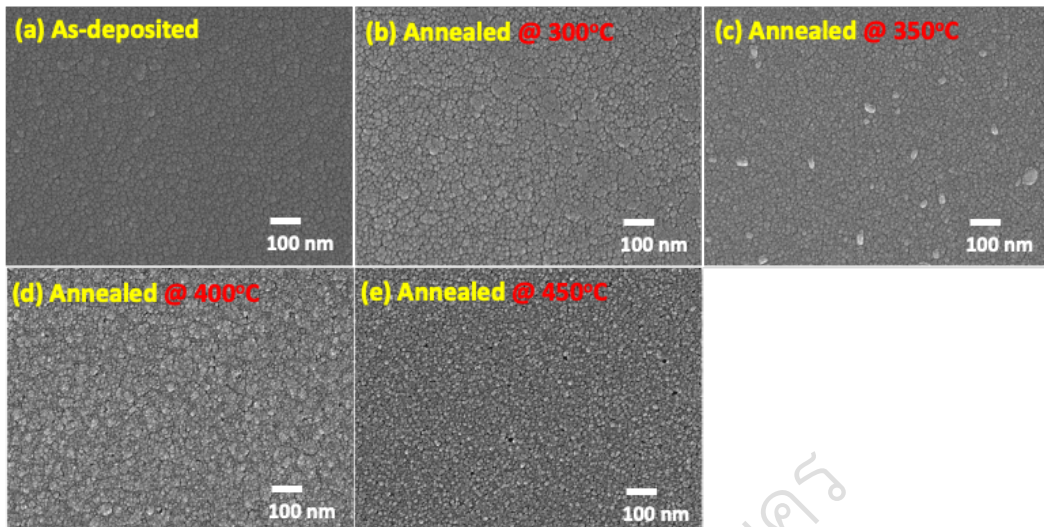


Figure 14 The FE-SEM Analysis of SnSe thin film was as-deposited and annealed.

(a) SnSe Asd. (b) 300 °C Anl. (c) 350 °C Anl. (d) 400 °C Anl. (e) 450 °C Anl
(Insawang, et al., 2024).

For integration into textiles, such inorganic materials are usually deposited onto flexible, organic substrates to allow flexibility and wearability. Nevertheless, in many of the cases of film based flexible thermoelectric it is apparent that these are not comfortable and wearable in the way conventional textile fabrics are. While film based thermoelectric can be integrated into wearable devices, it is important to understand that there is a distinction between “wearable” and “textile-based”. Since most conventional wearable textiles are composed of woven and knitted products, it is important to explore the application of flexible thermoelectric when integrated into textile fibers, yarns and fabrics. These applications have been reviewed in the past who categorized textile-based thermoelectric devices based on their structure fiber, yarns or fabrics (Chatterjee & Ghosh, 2021).

2.3 Organic Thermoelectric Textiles

Thermoelectric textiles assembling modules into fabric to harvest energy from body heat could one day power multitudinous wearable electronics (Sun, Zhou, Zheng, Wang, Jiang, & Snyder, 2020) as shown in Figure 15 that shown the thermoelectric e-textiles harvesting (a, b) Configuration modes of TE loops, (b) shows the conventional modes. (c, d) Schematic illustrations of TE textiles configured by mode a and b. (e, f) Illustrations of TE modules corresponding to the 3D TE devices c and conventional ones d. (g, h) Photographs of architecture with 15 units displayed in illustrations c ($L=32\text{ mm}$, $\phi=3\text{ mm}$). g shows the front view, and h shows the back view. (i, j) Photographs of architecture with 15 units displayed in illustrations d ($L=32\text{ mm}$, $\phi=3\text{ mm}$). (i) shows the front view, and (j) shows the back view (Sun, Zhou, Zheng, Wang, Jiang, & Snyder, 2020). Noticeable, thermoelectric e-textiles would allow to regulate the wearer's body temperature as they transport heat away from the skin to the typically colder surroundings. The basic building blocks that are needed for the bottom-up design of a thermoelectric textile are conducting fibers, sheet or yarns (Kim, et al., 2020). A critical component is electrically conducting fibers, sheet or yarns that can be incorporated through weaving, sewing, knitting, or embroidery (Eberle & Kilgus, 2008).

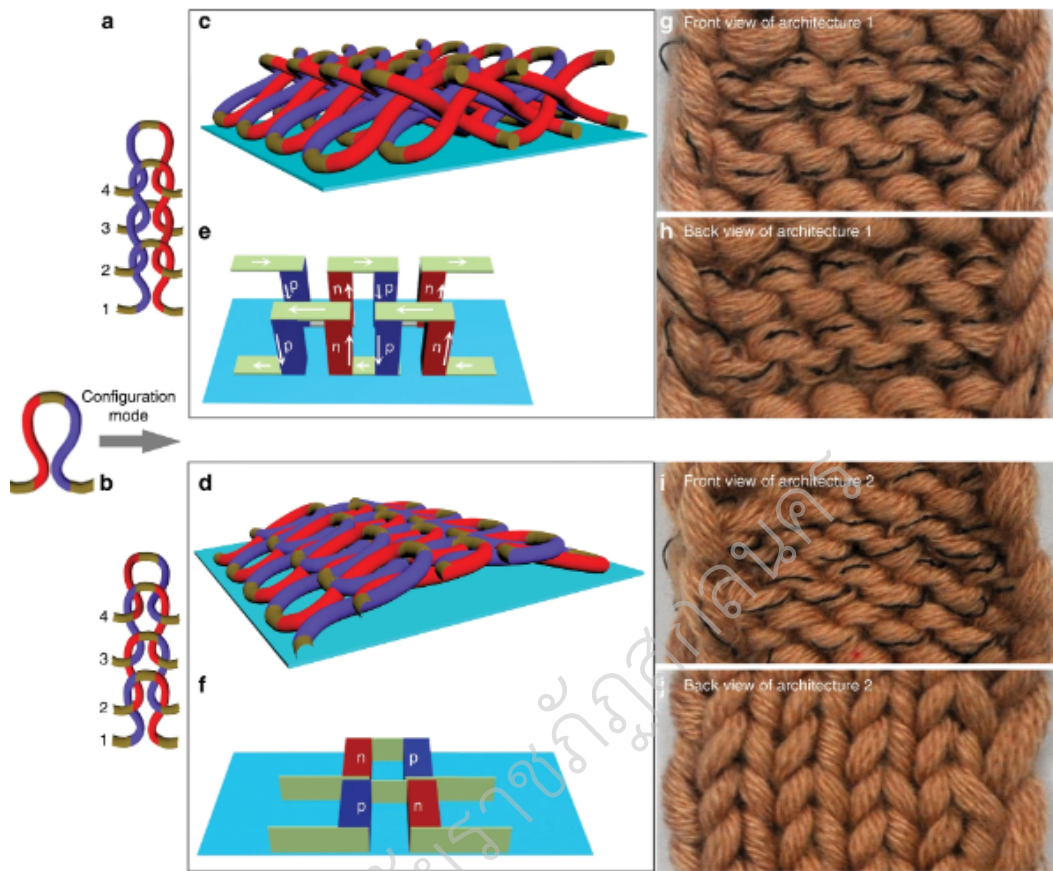


Figure 15 Architecture and thermal performance of TE textiles (Kim, et al., 2020).

From figure above the woven TE textiles based on thermoelectric yarns have been described using insulating yarns to separate hot and cold side or provide a locating point for the p/n junction in the heat flow direction (Sun, Zhou, Zheng, Wang, Jiang, & Snyder, 2020). According to fabric finishing and coating are mature technologies in textile industry that can be easily used for large scale production. Thus, it is a cost-effective and practical way to added effective thermoelectric materials on fabrics for both organic and inorganic materials (Wu & Hu, 2017).

Organic thermoelectric (OTE) materials are recently finding increasing interest owing to their advantages of being low-cost, non-toxic, and promising flexible applicability in various fields. Conjugated polymers and related processing

techniques have been developed for organic electronic devices ranging from lightweight photovoltaics to flexible displays. These breakthroughs have recently been used to create organic thermoelectric materials, which have potential for wearable heating and cooling devices, and near room temperature energy generation (Russ, Glaudell, Urban, Chabiny, & Segalman, 2016). Additionally, wearable electronic devices have emerged as a pivotal technology in healthcare and artificial intelligence robots. Among the materials that are employed in wearable electronic devices, organic thermoelectric materials possess great application potential due to their advantages such as flexibility, easy processing ability, no working noise, being self-powered, applicable in a wide range of scenarios, etc. However, compared with classic conductive materials and inorganic thermoelectric materials, the research on organic thermoelectric materials is still insufficient. In order to improve our understanding of the potential of organic thermoelectric materials in fabrics. Organic thermoelectric textiles are a class of electronic devices that come into direct contact with skin or clothing, and are often used to collect human vital signs or expand the capabilities of people with physical disabilities (Xiao, Zhou, Zhang, Liu, Han, & Che, 2024).

2.3.1 Indigo-Dyed Kram yarns

Phakram Sakon Nakhon (2024) Indigo-dyed kram yarns sewing thread from Don Koi phakram village, Sakon Nakhon as shown in Figure 16, Thailand. Phakram Sakon Nakhon this is another kind of wisdom inherited from ancestors, which will have knowledge and abilities. The wisdom of Indigo-dyed kram was succession since grandmothers, grandparents, and grandmothers have been hand woven for their own use, which is unique to the Sakon Nakhon people (Phakram Sakon Nakhon, 2023).

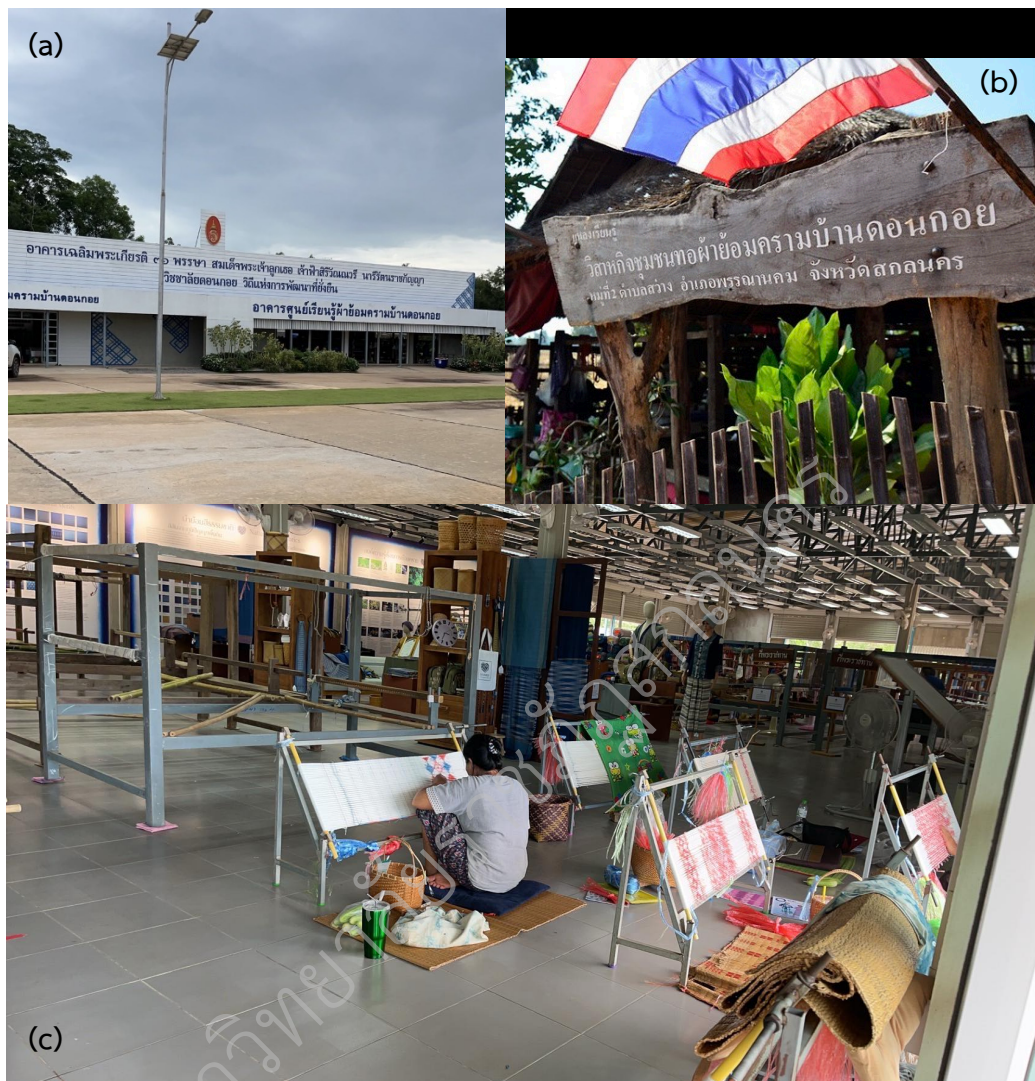


Figure 16 Don Koi Phakram village center, Sakon Nakhon province, Thailand. (a) Ban Don Koi Indigo Dyeing Learning Center. (b) Ban Don Koi Indigo Dyeing community textiles. (c) Some part of Indigo Dyeing process.

Sakon Nakhon Indigo dyed-kram fabric is made from a very ancient natural dye known to humans for over 6000 years. People living in tropical regions of the world used to make indigo from different types of trees in the area. Nevertheless, High quality indigo produced in Asia like Indigo from India is more popular with the British than indigo from Germany and France. As the same time, the use of indigo decreased to 4% of the world's total in 1914. Later,

around 1992, China encountered environmental pollution problems, one of which was caused by synthetic chemicals including dyes because most fabric dyes are heavy metal oxides. Many heavy metals are carcinogens and wearing them will make you feel very hot as mentioned previously. Then, the natural dyes were popular. In the same way, ancient wisdom it has been passed down since ancient times, almost disappeared and developed into the main profession for our children today. Besides, Indigo Dyed-Kram yarns had properties as detail below.

(1) The fabric is lightweight and comfortable because the craftsmanship is made naturally.

(2) 100% cotton soft fiber that we choose well and rayon synthetic fiber to make durability of yarns.

(3) Absorption.

(4) No allergy for soft skin.

In present, there are many researcher work in organic thermoelectric textiles flied to develop toward smart fabric or self-powered electronic devices. Especially, in daily use of portable devices and monitoring personal health. The textile-based on thermoelectric textiles devices exhibit the excellent, which fulfill demands of long-term wearing for the human body (Chen, Yang, Han, Ruan, Xu, Huang, & Zhang, 2023). The Organic thermoelectric textiles are shown in Table 7.

Table 7 The Organic Thermoelectric Textiles in various ways.

Methods	Type of Fabric	Formulations	S ($\mu\text{V K}^{-1}$)	Temp. (K)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	Ref.
Coating treatment	Polyester	PEDOT:PSS/DMSO	16	390	0.045	Du, Cai Chen, Wang, Shen, Donelson, & Lin (2015)
Dip coating	Cotton yarn & Polyester yarn	WPU/PEDOT:PSS/ MWCNT/DMSO	10	300	~1.41	Wu & Hu (2016)
Drop casting & Printed	Embedded in textiles	Tellurium-PEDOT:PSS	114.97	-	284	Bea, Kang, Jang, & Cho (2016)
Dip coating	Polyester	PEDOT:PSS/Colloidal graphite/DMSO	22	398	~0.025	Du, Xu, Wang, & Lin (2017)
Impregnated & Drop deposition	Cotton yarn	PEDOT:PSS	10.3	40	3.2×10^{-3}	Pope & Lekakou (2019)
Dyeing & Roll-to-Roll	Silk sewing thread	PEDOT:PSS/EG/DMSO	P-type ~14.3 (PEDOT:PSS coat threads) N-type ~0.3 (Silver-plated threads)	65	1.2	Lund, Tian, Darabi, & Müller (2020)

Table 2 (Continued)

Methods	Type of Fabric	Formulations	S ($\mu\text{V K}^{-1}$)	Temp. (K)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	Ref.
Wet-spinning & De-doping	PEDOT: PSS fiber was embroidered to thermoelectric fabric module	PEDOT:PSS wet-spinning into aqueous sulfuric acid	~15-30	-	30	Kim, et al., (2020)
Low-Temp. interfacial polymerization & Coating	Nonwoven fabrics	PEDOT: Tos	16.15	303	-	Zhang, et al., (2020)
Coating	Cotton yarn	PEDOT: PSS/DMSO/ILs	28	-	24.7	Li, et al., (2021)
Robust coating	Polyester yarn	PEDOT/CNT/ Bi_2Te_3	47.1	300	12.3	Ding, Wu, Gao, wang, Chen, & Li (2023)
Rapid and cost-effective wet-spinning	PEDOT: PSS fiber sewing on fabric	PEDOT: PSS/DMSO/ H_2SO_4	18	300	80.8	Wu, et al., (2024)

*WPU = Waterborne Polyurethane

*MWCNT = Multi-Walled Carbon Nanotubes

*IL = Ionic Liquid

To conclude, organic thermoelectric materials have been considered to be promising candidates for large area and low-cost wearable devices owing to their tailorable molecular structure, intrinsic flexibility, and prominent solution processability. More importantly, organic thermoelectric materials offer direct energy conversion from the human body, solid-state cooling at low electric consumption, and diversified functions (Zhao, Liu, Zhang, Di, & Zhu, 2021). Organic thermoelectric materials not only authorize energy harvesting from waste heat and solar heat but also can enable to embroidery textiles in a reversible character.

Researches related

Du, Cai Chen, Wang, Shen, Donelson, & Lin (2015) Fabrication Thermoelectric Fabrics: Toward Power Generating Clothing. Herein, they demonstrate that a flexible, air-permeable, thermoelectric (TE) power generator was prepared by applying a TE polymer (Poly (3, 4-ethylenedioxythiophene): Poly (4-styrenesulfonate) PEDOT: PSS) coated with commercial fabric polyester and subsequently by linking the coated strips with a conductive connection (e.g. using fine metal wires). As a results, the PEDOT:PSS coated fabric shows very stable TE properties from 300 K to 390 K and exhibit electrical conductivities ranged from 0.5-3 S/cm , Seebeck coefficient of 15.3-16.3 $\mu W/K$ at 300 K. The highest power factor around 0.045 $\mu W m^{-1} K^{-2}$ was achieved at 390 K and the fabric device can generate a TE voltage output (V) of 4.3 mV at a temperature difference (ΔT) of 75.2 K. In addition, the potential for using fabric TE devices to harvest body temperature energy has been discussed. Hence, the fabric-based TE devices may be useful for the development of new power generating clothing and self-powered wearable electronics.

Ryan, Mengistie, Gabrielsson, Lund, & Müller (2017) Fabrication Machine-Washable PEDOT: PSS Dyed Silk Yarns for Electronic Textiles. They were used degummed silk and cotton yarn for sample fabric and PEDOT:PSS as conjugated materials an acid dye. The PEDOT:PSS dispersion (pH 2) was mixed with 0.2 vol % Zonyl and 5 vol % EG or 5 vol % DMSO as indicated, vortexed, and allowed to settle for several hours. Then, silk or cotton yarns were submerged twice, and ultra sonication for 1 h and dried at 130 °C for 30 min. Then, PEDOT:PSS dyed silk yarns were sewn onto cotton fabrics and make in-plane textile thermoelectric device with 26 p-type legs. In conclusion, the

PEDOT:PSS silk and cotton yarn were treatment with EG and DMSO shows the electrical conductivity and Seebeck Coefficient as follow. The PEDOT:PSS silk yarn had electrical conductivity approximately 15 ± 6 and $14 \pm 4 \text{ S cm}^{-1}$, Seebeck Coefficient $\sim 14 \pm 1$ and $15 \pm 1 \text{ } \mu\text{W/K}^{-1}$. Subsequently, the PEDOT:PSS cotton yarn; 12 ± 3 and $15 \pm 6 \text{ S cm}^{-1}$ and equal $14 \pm 1 \text{ } \mu\text{W/K}^{-1}$ between EG and DMSO treatment. Then, this work confirmed and successful for fabrication PEDOT:PSS dyed silk and cotton yarns for electronic textiles.

Lund, Darabi, Hultmark, Ryan, Andersson, Ström, & Müller (2018) Design a capacitive touch sensor and manufacturing Roll-to-Roll Dyed Conducting Silk Yarns mixed with PEDOT:PSS for a versatile material e-textile devices. It was found that, the silk sewing thread into a wash and wear resistant functional thread with a conductivity of about 70 S cm^{-1} . Subsequently, the silk sewing thread was converted into e-textiles by both hand weaving and machine embroidery, the yarns are resistant to abrasion and wear, and can be machine washed at least 15 times with retained electronic properties. After the first washing cycle the average resistance dropped to a quarter of its original value. Additionally, the electrical conductivity of PEDOT: PSS can be increased from 0.02 to 0.03 S cm^{-1} by post-treatment with high boiling solvents 5 wt% ethylene glycol (EG) or dimethyl sulfoxide (DMSO). At least, their produced a woven band that can serve as a versatile “sensor-on-a-roll” e-textile component for use as a touch sensitive textile keyboard.

Ahn et al. (2019) Researcher team was fabricated fabric heater based on Ag nanowire/carbon nanotube composites by printing and spray coating methods for increasing demand smart fabrics. In this study, their preparation of pattern heaters on commercial fabrics. It was found that, the combining structural stability of carbon nanotubes with the high electrical conductivity of Ag

nanowires to fabricate a stretchable fabric heater and excellent mechanical of stretchability $\approx 50\%$, electrical sheet resistance $\approx 20 \Omega \text{ sq}^{-1}$. Additionally, the fabricated wearable heater reaches typical operating temperatures of 35°C – 55°C at a low driving voltage $\sim 3\text{--}5 \text{ V}$ with a proper surface power density of $26.6\text{--}72.2 \text{ mW cm}^{-2}$ (heater area: $3 \text{ cm} \times 3 \text{ cm}$) and maintains a stable heating temperature for more than 30 h. Lastly, this heater shows a stable performance even when folded or rolled, thus being well suited for the practical wearable applications.

Lund, Tian, Darabi, & Müller (2020) Fabrication the polymer-based on textile thermoelectric generator for wearable energy harvesting. The advantage of textile thermoelectric are conformable and light-weight. Furthermore, thermoelectric textile generators also can be unobtrusively integrated into garments or upholstery. This work, the researcher team was using the widely available conducting polymer: polyelectrolyte complex Poly (3, 4-ethylenedioxythiophene): Poly (styrene sulfonate) (PEDOT:PSS) as the p-type material, their prepared an electrically conducting sewing thread by embroidered into thick wool fabrics to form out-of-plane thermoelectric textile generators. As a consequence, the performance of e-textile devices can be accurately predicted and optimized using modeling developed for conventional thermoelectric systems, provided that the electrical and thermal contact resistances also are included in the model. Moreover, thermoelectric textile device can generate for a polymer-based devices, unprecedented power of $1.2 \mu\text{W}$ at a temperature gradient ΔT of 65 K, and over $0.2 \mu\text{W}$ at a more modest ΔT of 30 K. Respectively.

Li et al. (2022) The Researcher was study and review about fabric-based flexible thermoelectric generators: Design methods and prospects. The Textile-based on thermoelectric materials are more suitable for use on the human body more than film or block types of devices, because an accordingly

avored for wearable smart devices. The design of textile thermoelectric materials was preparation from fibers, textiles, fabric-based films and some novel methods, like using three-dimensional modules to become two-dimensional fabrics by a weaving method, which not to rely something as a base for TE modules. They were selected Poly (3, 4-ethylenedioxythiophene) (PEDOT) complex with Poly (styrene sulfonate) (PEDOT:PSS) to form polymer thermoelectric textiles. Then, the gaining opportunities to make comfortable and effective fabric TEGs using a wider variety of materials.

Zheng et al. (2022) Fabrication durable, stretchable and washable inorganic-based woven thermoelectric textiles for power generation and solid-state cooling. Wearable inorganic semiconductor (ISC) based thermoelectric (TE) devices, especially fiber-based thermoelectric textiles (TETs), show promise in electrical power generation and solid-state cooling compared with bulk ISC-based TE generators (TEGs). Here, they report a strategy to produce ISC-based segmented hierarchically ternary coaxial TE strings at large scale for semi-automatically manufacturing a highly mechanically stable, stretchable, breathable and washable woven TET by a textile machine. For the conclusion, the TET demonstrates good stretchability (100% elongation), flexibility (bending radius of 2 mm), washability (>20 washing cycles) and output power density of 0.58 W m^{-2} at a temperature difference of 25 K (predicted power density of 6.06 W m^{-2} at $\Delta T = 80 \text{ K}$) Additionally, the assistance of finite element analysis and the significance of the fabric structure on the excellent mechanical TE performance of the TET has been clarified and reaches an output voltage of $\sim 0.28 \text{ V}$ at an ambient temperature of $\sim 8^\circ \text{C}$. For practical applications, it can continuously power on-body electronics for monitoring the environment or human body vital signals including activities by wearing it on the arm with a self-built temperature

gradient of ~ 16 K. In the end, the TET can stably generate solid-state cooling of 3.1 K in quiescent air ($T_{\text{ambient}} \sim 26$ °C, relative humidity $\sim 60\%$). Then, this work offering paves a new way for designing durable, stretchable and washable ISC-based TETs toward real on-body applications.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

CHAPTER 3

METHODOLOGY

Chapter 3 of the dissertation is divided into fifth parts, and we have presented all the process experiments in this section. First, polymer TE preparation materials were included entire trial of process. Second, TE-textiles preparation had included manufacturing of OTE-textiles. Third, characterization and measurement. Fourth, the TE-textiles module had designed and fabricated. Last order, OTE-textiles module need to test the power generator with step-by-step. Hence, the details of the experiment part are shows as follows:

1. Polymer thermoelectric preparation
 - 1.1 Materials
 - 1.2 Preparation process
2. Textiles thermoelectric preparation
 - 2.1 Materials
 - 2.2 Preparation process
3. Characterization and Measurement
 - 3.1 Crystalline characterizations
 - 3.2 Morphology and atomic composition
 - 3.3 Thermoelectric properties measurement
4. Textiles thermoelectric module fabrication
 - 4.1 Materials
 - 4.2 Fabrication process
- 5 Power generation testing of OTE-textiles prototype module

Polymer thermoelectric preparation

1.1 Materials

(1) PEDOT:PSS (Heraeus Clevios PH1000 M122 100 mL) 1.0-1.3 wt. % in water, 30 nm particle size distribution, 1:2.5 mass ratio from Germany.

(2) SnSe₂ powder nanoparticles (99.9%, APS<100 nm) 10 Gram Pack was purchased from Nano Research Elements, India.

1.2 Preparation process

1.2.1 Organic/Inorganic conductive sheet

(1) Step 1 Wet chemical technique

The PEDOT:PSS solution was used at 3 mL each to be mixed with several SnSe₂ powder (99.9%, APS < 100 nm) with 0.0 g, 0.1 g, 0.2 g, and 0.3 g. Secondly, the mixing solution was each converted into micro-sheets onto beaker via a hot plate at 40°C and stirred for 1 h. Then, the PEDOT:PSS+SnSe₂ polymer sheets onto beaker have stripped to obtain the sheet sample of PEDOT:PSS, PEDOT:PSS+SnSe₂ (0.1 g), PEDOT:PSS+SnSe₂ (0.2 g), and PEDOT:PSS+SnSe₂ (0.3 g), respectively. The sheet sample preparation process diagram is shown in Figure 17.

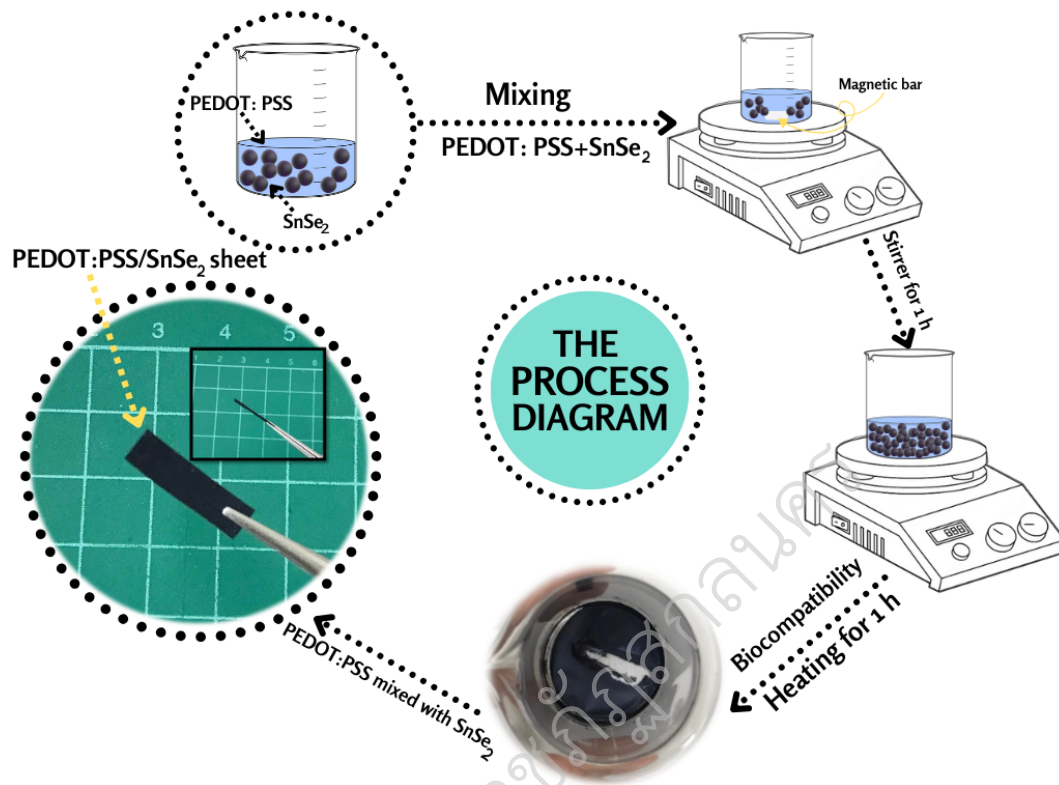


Figure 17 Schematic of PEDOT:PSS+SnSe₂ based on sheet preparation by wet chemical technique.

(2) Step 2 Rapid thermal annealing (RTA) technique

The PEDOT:PSS+SnSe₂ Organic/Inorganic sheet and all of sample was taken to annealed by an RTA process (Mila5000; Advanced Riko) under a vacuum state 2×10^{-2} torr. The temperature was fixed at 220 °C with a heating step of 5 °C/s for all the samples to obtain the treatment, the process diagram for RTA was shown in Figure 18, following (a) Turn on step. (b) Load in sample. b1 PEDOT:PSS+SnSe₂ sheet 10x10 mm size. b2 PEDOT:PSS+SnSe₂ sheet 3x15 mm size. b3 Turn off a chamber. (c) Digital pressure box. (d) Chiller. (e) Program working. (f) Load out of sample. f1 Room temp. for load out sample. f2 Shown the sample was placed onto thermocouples. (g) PEDOT:PSS+SnSe₂ sheet after

RAT process. g1 3x15 mm size. g2 10x10 mm size. g3 Maintain in box (Vora-ud, et al., 2020). Respectively.

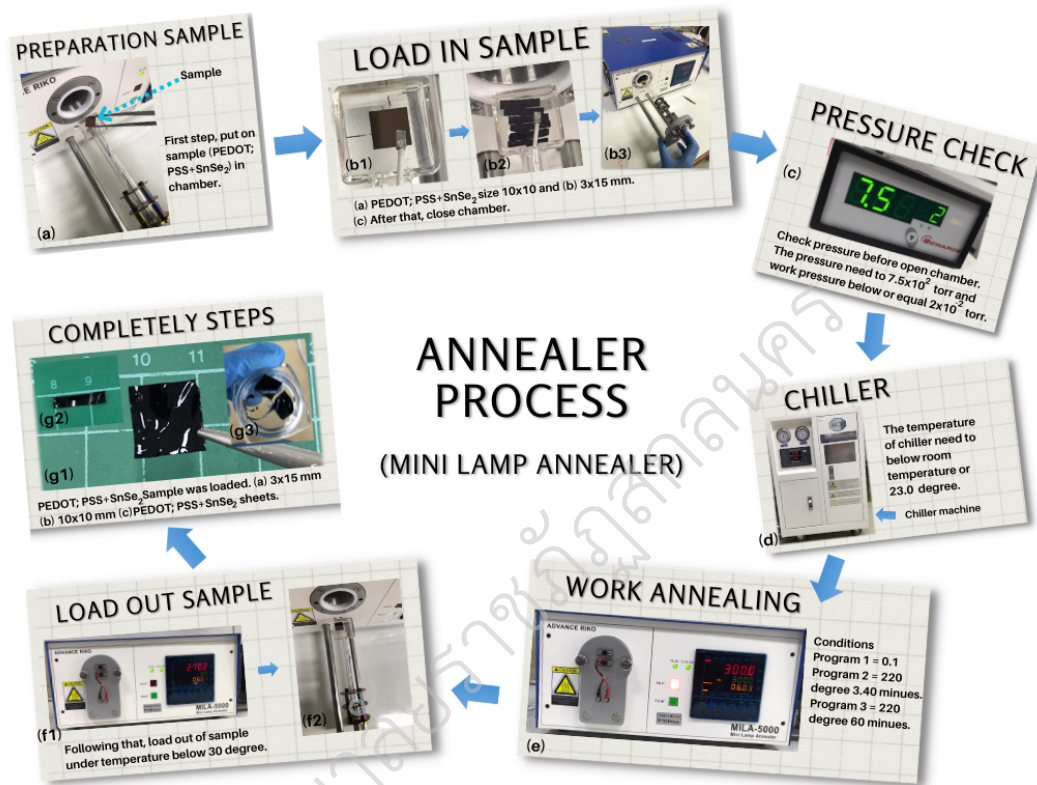


Figure 18 Shown the process diagram of RTA technique of inorganic conductive sheet.

Textiles Thermoelectric preparation

2.1 Materials

2.1.1 Substance Involved

Approximately 100 m of Kram and Rayon sewing thread from Don Koi phakram village, Sakon Nakhon Thailand.

2.1.2 Chemicals

(1) PEDOT:PSS (Heraeus Clevios PH1000 M122 100 mL) 1.0-1.3 wt. % in water, 30 nm particle size distribution, 1:2.5 mass ratio from Germany.

(2) Acetone (Dimethyl Ketone) Grade AR 2.5 Liter from New Zealand.

(3) Methanol 2.5 Liter from Germany.

(4) Deionized Water (DI-Water) from Thailand.

2.2 Preparation process

2.2.1 Organic/Inorganic conductive yarns

Approximately 100 m Kram and Rayon sewing thread was purchased from Don Koi phakram village, Sakon Nakhon Thailand as shown in Figure 19.



Figure 19 The sewing thread. (a) Intensive kram. (b) Soft Kram. (c) Rayon.

Kram sewing thread Intensive and Soft (Figure 16(a, b)) was made from Rayon, Rayon is a fabric made of semi-synthetic fiber this make it a soft and comfortable fabric, Rayon sewing thread shown in Figure 19(c) (Rayon, 2024). According to the Kram sewing thread was taken of each and passed through

dyeing bath prepared with an aqueous 3 mL PEDOT:PSS dispersion PH1000 M122 Heraeus Clevios, 1.0-1.3 wt. % in water. A low pH ionizes of amino groups and their combination with the negatively charged PSS can contribute to strong electrostatic interactions.

Subsequently, the solution was ultra sonication for 1 hour 20 min at room temperature in Chemical Preparation Laboratory (Sakon Nakhon Rajabhat University ; SNRU, Thailand). Next, Kram and Rayon sewing thread were unfold to the yarn and taken placed in a vial (Soak) in solution for 1 hour 20 min. After that, the yarn samples were ultra sonication for 2 hour and dried by using a hotplate for heat so that the water can remove at 50 °C for 2.5-4.7 hour. In the other hand, we were dried the yarns by sunlight under environment wind like indigenous knowledge because by this technique are able to continuous drying any length of yarn. After the yarns were dried, according to put them into solution again and soak around 30 min. Finally, the yarns were ultrasonic again for 30 min and dried at 130 °C for 20 min to form the PEDOT:PSS sewing thread dye conductive. Adaption dyeing method from Du, Cai, Chen, Wang, Shen, Donelson, & Lin (2015); Lund, Tian, Darabi, & Müller (2020). The process diagram is shown in Figure 20.

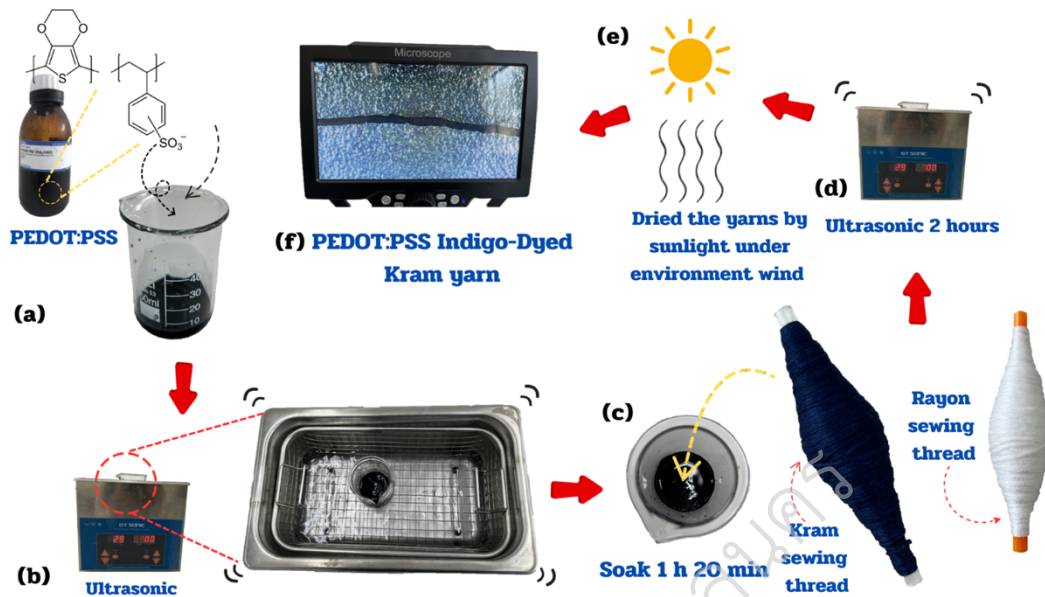


Figure 20 The manufacturing of conductive dyeing yarns. (a) PEDOT:PSS solution (b) Ultrasonic solution (c) PEDOT:PSS is soaking with Kram and Rayon yarns (d) Dyeing part (e) Drying the yarns (f) The yarns were taken to form sewing thread dyeing conductive.

Characterizations and Measurement

3.1 Crystalline characterizations

3.1.1 XRD analysis

X-ray diffraction (XRD) patterns of all of sample were analysis by using an X-ray diffractometer with a $CuK\alpha$ radiation. The X-ray diffraction is based on constructive interference of monochromatic X-rays and a crystalline sample. These X-rays are generated by a cathode ray tube, filtered to produce monochromatic radiation, collimated to concentrate, and directed toward the sample. The interaction of the incident rays with the sample produces constructive interference (and a diffracted ray) when conditions satisfy Bragg's Law as following by Eq. 14.

$$n\lambda = 2d\sin\theta \quad (14)$$

This law relates the wavelength of electromagnetic radiation to the diffraction angle and the lattice spacing in a crystalline sample (Nanotechnology in STEM, 2024). This work was used X-ray diffraction (XRD6100 Shimadzu, Japan, shown in Figure 21) with **CuK α** radiation in a 2θ range of 10-70 degree, with scan steps of 0.02°/1 s in Center of Excellence on Alternative Energy (CEAE) laboratory SNRU. The data was received and comparing with JCPDS or ICDD databases.



Figure 21 The X-ray diffraction, XRD6100 Shimadzu.

3.2 Morphology and Atomic composition

3.2.1 FE-SEM/EDX analysis

The morphology, thickness, and atomic composition of all sample were evaluated by the field-emission scanning electron microscopy and energy-

dispersive x-ray spectroscopy FE-SEM/EDX, SU8030, Hitachi (Figure 22) in Ubon Ratchathani University.



Figure 22 The Field Emission Scanning Electron Microscope-Energy Dispersive X-ray Spectroscopy (FESEM-EDS) (Ubon Ratchathani University, 2025).

3.3 Thermoelectric properties measurement

3.3.1 Electrical Conductivity

The electrical conductivity of each yarn and sheet was placed on a glass slide and investigate by multi-meter to make sure the first confirmation. Only yarn sample was applied to from 5 segments each of 8 mm length and the resistance of each length of yarn also was measured using a Keithley 2400 source meter unit (SMU) in Thin Film Research Laboratory (TFRL) SNRU. The electrical conductivity was calculated taking onto account the sample diameter as observed with an optical microscope (Lund, Tian, Darabi, & Müller, 2020).

3.3.2 Seebeck Coefficient and Electrical Resistivity

The seebeck coefficient and electrical resistivity were measured by the ZEM-3 series (Ulvac-Riko) in Thermoelectric Research Laboratory (TRL) SNRU as shown in Figure 23.



Figure 23 The ZEM-3 series (ULVAC Technologies, 2024).

First, the Seebeck coefficient was measured on at least 4 specimens of each yarn with a temperature and its low impedance board (gain=1000). The yarn sample ~5 mm long specimen was attached to the holder with silver paint. Subsequently, the sample is heated and kept at a specified temperature, the sample heated by a heater in the bottom block. As the same time, the sample was measuring and to from the achieve temperature gradient (ΔT) so that the seebeck coefficient need to measuring the upper (T_1) and the lower (T_2) temperature with a thermocouple. Thermocouples are activated by pressing the sides of the sample, following by measuring the electromotive force dE between the same wires on one side of the thermocouple. Accordingly, the electrical resistivity was measured by using a four-terminal DC method, which can currently be applied to both sides of the fabric thread sample. As a condition of measurement, the voltage drop dV between the same wires of the thermocouple must be determined (Chao-moo, 2019).

3.3.3 Power Factor calculation

The **PF** value which is the relationship between the actual electrical active power and apparent power in alternative current (AC) system. Active Power is electrical power supplied to electrical equipment and it is energy that can actually be used. However, apparent power is the total number of electricity power actually used and is the electrical power used to create a magnetic field or reactive power. This is a type of indirect power. Therefore, the power factor is equal to the relationship between active power and apparent power, it has been defined by $\cos\theta$. In the condition, the $\cos\theta$ value is not more than 1 (Siam Generator, 2024). Then, the power factor value can calculation by equation was mentioned previously. Accordingly, the **PF** value corresponding with the total thermal conductivity (κ), which was described by Eq. 15.

$$\kappa = \kappa_e + \kappa_L \quad (15)$$

Where κ_e and κ_L are electrical thermal and lattice thermal conductivity. Consequent, the κ_e as dependent on temperature. Hence, the electrical thermal conductivity was evaluated from the Wiedemann–Franz law based on electrical properties to estimate the **ZT** values. All of samples can calculate by Eq. 16.

$$\kappa_e = \sigma LT \quad (16)$$

Where L is proportionality constant defined as a Lorenz number is equal $2.44 \times 10^{-8} \text{ V}^2 \text{ K}^{-2}$ and σ is electrical conductivity as defined $1/\rho$. (Insawang, et al., 2024).

Textiles Thermoelectric module fabrication

4.1 Materials

4.1.1 Substance Involved

- (1) Wool fabric (Wadmal, ~1 mm thick, 3.2 g/dm² from Harry Hedgren AB) to from the thermocouple legs.
- (2) 0.01 mm copper hookup wire precision maintenance flying lead (Fingerprint flying line dedicated) 200 m from China.

(3) Needle size 7-10

(4) Polyimide tape

4.1.2 Chemicals

Silver conductive paint with brush applicator cap 1 Troy oz. 31.1 g from USA.

4.2 Fabrication process

In this part, we were designed the PEDOT:PSS+Indigo-Dyed Kram prototype modules as shown in Figure 24. The conductive yarns were threaded onto a sewing needle and embroidery, then take to carried out by hand 1 layer of wool fabric ~1 mm thick. After embroidery, silver-conductive paint for textile was coatings to from the electrical connections between respective legs as p-type based on thermoelectric modules. We have presented this alternative approach for design. Likewise, we have designed a simple thermoelectric OTE-textiles module consisting with five P-type legs, which are approximately long 2 cm of the PEDOT:PSS+Indigo-Dyed Kram (4 and 5 yarns per leg for demonstrate) and 0.01 mm copper hookup wire as counterpart. The yarns and wires were again embroidered onto a piece of wool fabric and connected with silver paste, applied using a rubber stamp. As the same time, if the module isn't work, we

should test it again the resistance for make sure it connected, it still not working we will fabrication it again as a diagram. So, our module was connected and then we were covered with polyimide tape to prevent the structure and protect from heat source. Besides, the backside of they were getting sewing rayon yarns through the fabric. Which confirms the durability of the yarns despite rather robust handle. The process diagram shown in Figure 25.

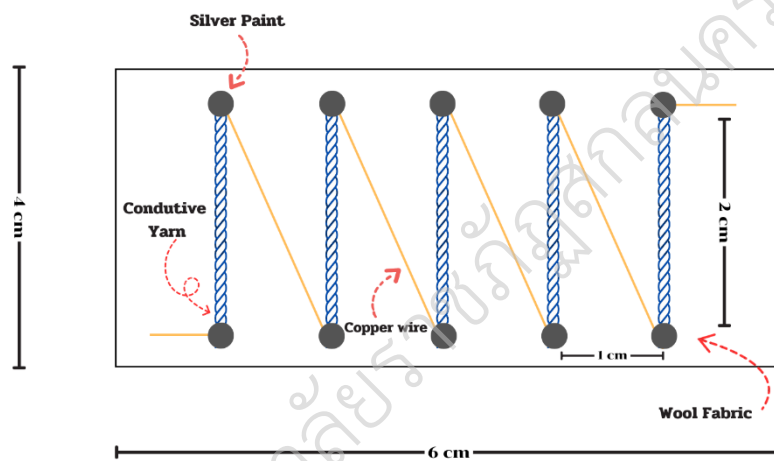


Figure 24 The prototype module diagram design.

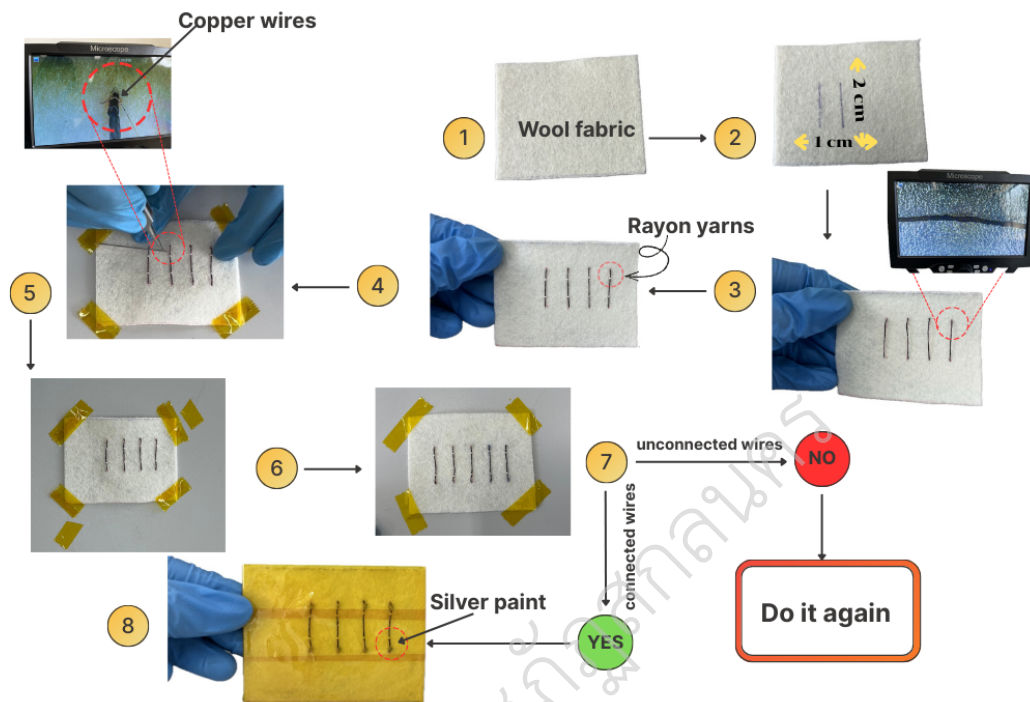


Figure 25 The schematic illustration of the fabrication process for the PEDOT:PSS-Coated yarn thermoelectric module.

Power generator test of OTE-textiles prototype module

To characterize OTE-textiles prototype module tested, an in-plane temperature gradient was applied by placing on box, the textile module was place under R resistor ceramic. Then, the generated voltage was measured with a Keithley 6485 picoammeter source/measure unit and temperatures were recorded by using thermocouple thermometer S22-T8 data logger with two surface mounted K-type temperature probes for monitoring the surface temperatures with internal temperature reference. DC power supply model GPS-3030D and M3500A 6 1/2 digit multimeter was combine in program tested as

shown in Figure 26. Eventually, the highly conducting silver paint was added to all electrical contact points for textile module.

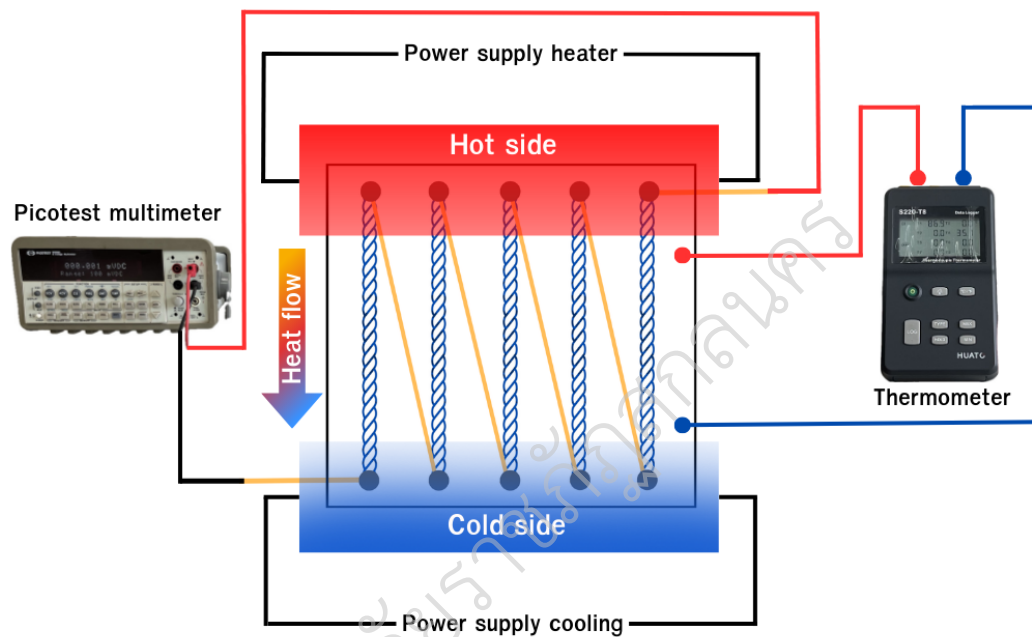


Figure 26 Schematic illustration of the power generation testing setup for the PEDOT:PSS-coated yarn thermoelectric module.

CHAPTER 4

RESULT AND DISCUSSION

The Chapter 4 we have presented the results and discussion of Development of Polymer and Textiles Thermoelectric based on PEDOT:PSS are including with 3 section like. First, Polymer thermoelectric results. Second, Textiles Thermoelectric results and Third, Textiles Thermoelectric module results, all of information had reported as below.

1. Polymer thermoelectric results
 - 1.1 Physical properties and crystalline characterizations
 - 1.2 Morphology and atomic composition characterizations
 - 1.3 Thermoelectric properties measurement
2. Textiles Thermoelectric results
 - 2.1 Physical properties of the yarns
 - 2.2 Electrical conductivity of PEDOT:PSS-Coated
 - 2.3 Morphology and atomic composition characterizations
 - 2.4 Thermoelectric properties measurement
- 3 Textiles Thermoelectric module results
 - 3.1 Physical properties of the module
 - 3.2 Power generation measurement results

Polymer thermoelectric results

1.1 Physical properties and crystalline characterizations

Organic/Inorganic nanocomposite sheets of poly (3,4-ethylenedioxythiophene) Poly (styrenesul-fonate) (PEDOT:PSS)+SnSe₂ powder were synthesized by wet chemical method followed by rapid thermal annealing (RTA) at 220 °C for 1 h. The ratio of PEDOT:PSS to SnSe₂ was varied by increasing incorporation of SnSe₂ powder as 0.0 g, 0.1 g, 0.2 g, and 0.3 g in the same volume of polymer solution (3 mL). It was found that, the as-prepared PEDOT:PSS+SnSe₂ nanocomposite sheets were amorphous and that the roughness of the sheets increased with increasing amounts of SnSe₂ powder.

The XRD patterns of the SnSe₂ powder and PEDOT:PSS+SnSe₂ polymer sheet samples are shown in Figure. 27. Figure 27(a) shows the XRD pattern of SnSe₂ powder which confirmed the single-crystal structure in hexagonal as aligned along the (001) plane (JCPDS#023-0602).³³, Figure 27(b–e) shows the XRD patterns of PEDOT:PSS+SnSe₂ within the SnSe₂ with added (b) 0.0 g, (c) 0.1 g, (d) 0.2 g, and (e) 0.3 g, which all indicate the amorphous phase of the polymers.

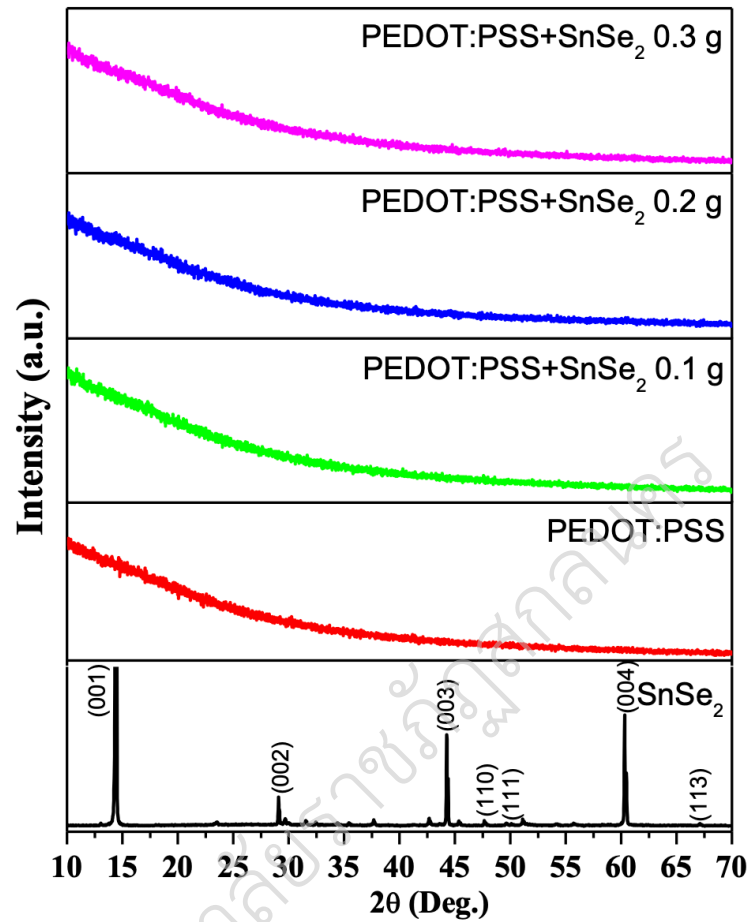


Figure 27 The XRD patterns of (a) SnSe_2 powder and (b–e) PEDOT:PSS sheets mixed with SnSe_2 powder of 0.0 g, 0.1 g, 0.2 g, and 0.3 g, before annealing.

In addition, we were taken the sheet sample to annealed as shown in Figure 28 that shows the XRD pattern of the PEDOT:PSS+ SnSe_2 annealed polymer sheet samples for (b) 0.0 g, (c) 0.1 g, (d) 0.2 g, and (e) 0.3 g. Accordingly, the effect of RTA can be seen in the composite phase of SnSe_2 with the major diffraction peaks of SnSe_2 (JCPDS#023-0602) appearing at $2\theta = 14.42^\circ$, 29.11° , 44.22° , and 60.24° corresponding to the (001), (002), (003), and (004) planes, respectively.

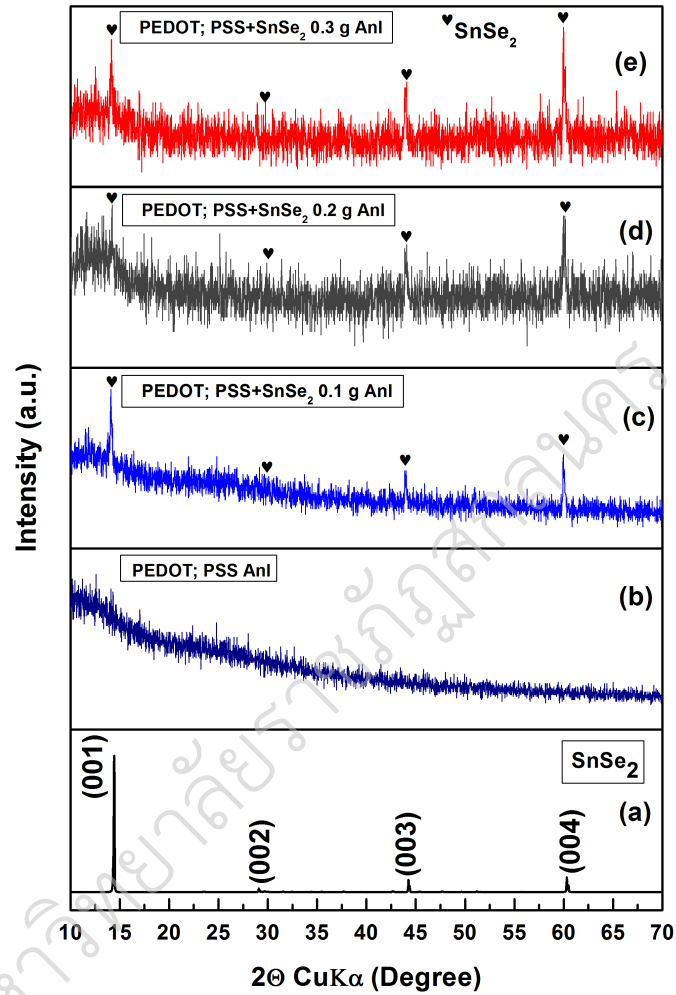


Figure 28 The XRD patterns of (a) SnSe_2 powder and (b–e) PEDOT:PSS sheets mixed with SnSe_2 powder of 0.0 g, 0.1 g, 0.2 g, and 0.3 g, after annealing.

1.2 Morphology and atomic composition characterizations

The morphology and chemical composition of the PEDOT:PSS+ SnSe_2 polymer sheets are shown in Figure 29. Figure 29(1) shows SEM images of the amorphous surface morphology before annealing for PEDOT:PSS within the SnSe_2 with added (a) 0.0 g, (b) 0.1 g, (c) 0.2 g, and (d) 0.3 g. As a result, the surface

morphology of the PEDOT:PSS polymer sheets were more homogenized and had very smooth roughness, and then the rough surface of the PEDOT:PSS+SnSe₂ polymer sheets were increased with the concentration of added SnSe₂. Figure 29(2) shows the SEM images of the composite surface morphology after annealing and cross-sections to obtain sheet thickness (insets) for PEDOT:PSS within the SnSe₂ with added (a) 0.0 g, (b) 0.1 g, (c) 0.2 g, and (d) 0.3 g. Therefore, the results show the surface morphology of the SnSe₂ as mixed onto the PEDOT:PSS polymer sheet. These results agree with the XRD results of the composite phase of SnSe₂ as affected by the RTA process.

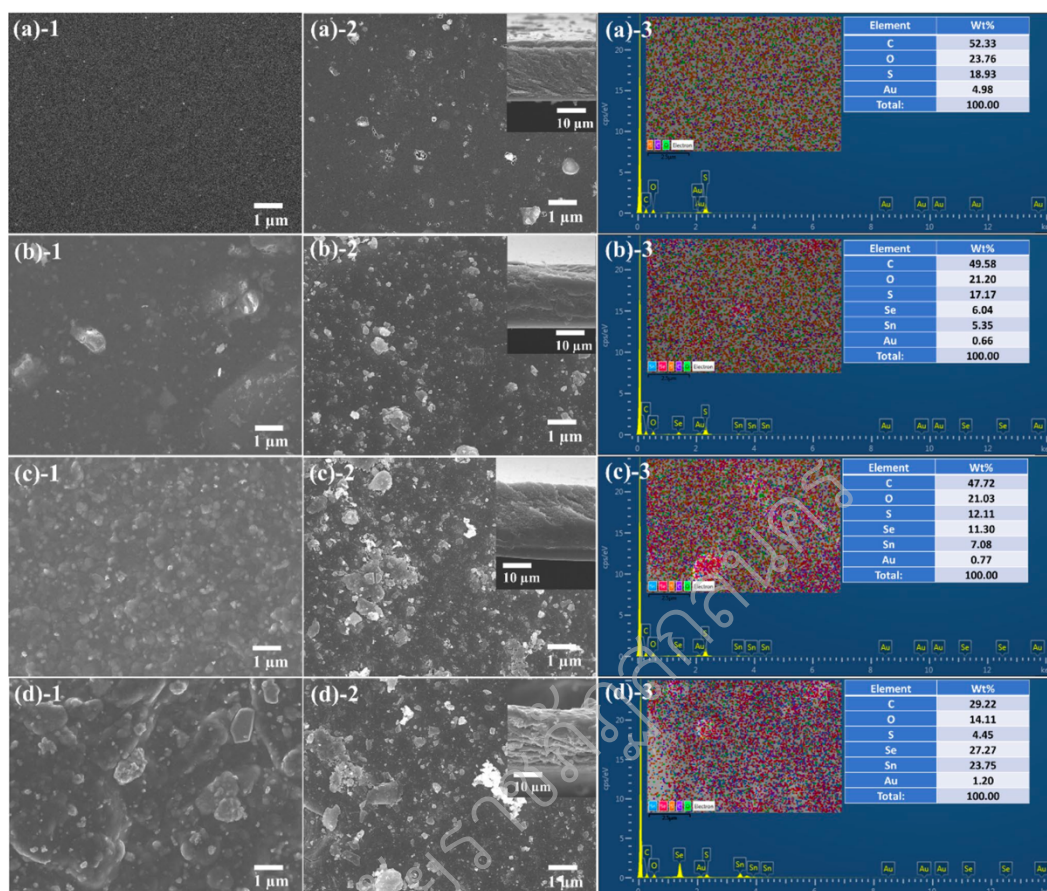


Figure 29 SEM images of surface morphology before & after annealing (1) Before annealing (2) After annealing and thickness (3) EDX spectra with (insets) atomic mapping and composition of PEDOT:PSS sheets mixed with SnSe₂ powder of (a) 0.0 g, (b) 0.1 g, (c) 0.2 g and (d) 0.3 g.

While all the sheet thicknesses are the same at around 30 μm, Figure 29(3) shows EDX spectra and element mapping of the atomic composition in PEDOT:PSS+SnSe₂ within the SnSe₂ with added (a) 0.0 g, (b) 0.1 g, (c) 0.2 g, and (d) 0.3 g. The results indicate that the atomic composition in PEDOT:PSS+SnSe₂ polymer sheets is composed of C, O, and S elements for PEDOT:PSS essential and C, O, S, Sn, and Se elements for PEDOT:PSS+SnSe₂. Then, the Au atomic composition was obtained from noble metal coating to especially helpful samples conducted during the SEM processing. Moreover, the atomic

composition of Sn and Se has been increased with the increase in the concentration of SnSe₂ to confirm the composition of the PEDOT:PSS+SnSe₂ polymer sheets.

1.3 Thermoelectric properties measurement

PEDOT:PSS+SnSe₂ polymer sheet in Figure 30 shows the n and μ values measured by the Hall effect method at room temperature of the PEDOT:PSS+SnSe₂ polymer sheets, indicating that the samples before annealing had very low mobility (0.014–0.15 cm² V⁻¹ s⁻¹). Then, after the annealing of the samples, the μ has reached a maximum of 1.84 cm² V⁻¹ s⁻¹ (PEDOT:PSS+SnSe₂ (0.2 g)). Therefore, the reaching of μ after annealing depends on the transport mechanism of carrier hopping behaviors, (Huang, Deng, Liu, Zhang & Chen, 2021) while the n values of the samples before and after annealing have displayed slight differences of around one order of magnitude (10²⁰ cm³ (before) to 10¹⁹ cm³ (after)) within the significance. Moreover, the n and μ values could be affected to the electrical resistivity and Seebeck coefficient of the TE materials in theoretical calculations, as defined by Eq. 17 and 18 (Truong, et al., 2022).

$$\rho = \frac{1}{qn\mu} \quad (17)$$

$$S = \frac{8\pi^2 k_B^2}{3eh^2} m_d^* T \left(\frac{\pi}{3n} \right)^{2/3} \quad (18)$$

Where q , h , k_B , m_d^* and e are carrier charges, the Planck constant, the Boltzmann constant, the density of states, effective mass of carrier, and elementary charge, respectively.

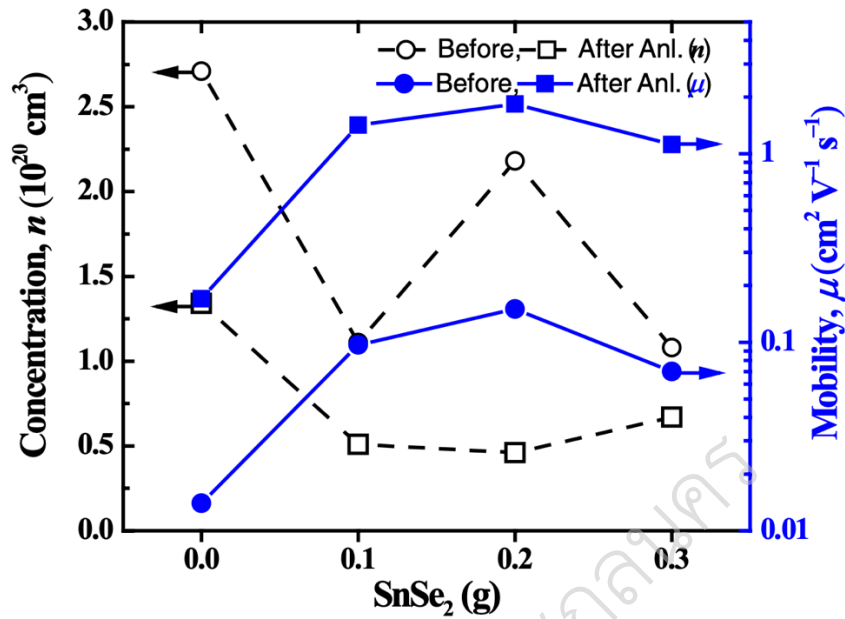


Figure 30 The n and μ values of PEDOT:PSS+SnSe₂ polymer sheets as measured by the Hall effect method at room temperature.

Figure 31 shows the TE properties composed of (a), ρ (b) S , and (c) the PF of PEDOT:PSS+SnSe₂ polymer sheets at room temperature. The values of the samples before annealing were slightly decreased with a SnSe₂ concentration of 0.1 g and 0.2 g and then increased after SnSe₂ powder concentration of 0.3 g. After the sample was annealed, the ρ values were slightly decreased and then trended stable with the SnSe₂ concentrations. The role of the RTA process induced the microstructure of SnSe₂ to decrease the ρ value by one order of magnitude (PEDOT:PSS+SnSe₂ (0.2 g); 1.91 m Ω m (before) and 0.74 m Ω m (after) due to the mobility enhancement within the carrier hopping behavior. While the S values for all samples indicated p-type thermoelectricity, the S values of samples before annealing were slightly increased with a SnSe₂ concentrations of 0.1 g and 0.2 g and then increased after a SnSe₂ concentration of 0.3 g. After the sample was annealed, the S values suddenly increased with a SnSe₂ concentrations of 0.1 g and 0.2 g and then they increased after a SnSe₂ concentration of 0.3 g. These results indicate that the increase in carrier mobility

and the decrease in carrier concentration after annealing have been induced to enhance the Seebeck coefficient. As the same ρ values, the role of the RTA process has increased the S values by around one order of magnitude compared to before annealing (PEDOT:PSS+SnSe₂ (0.2 g); 29 $\mu\text{V K}^{-1}$ (before) and 164 $\mu\text{V K}^{-1}$ (after)). From the low ρ and high S values of PEDOT:PSS+SnSe₂ (0.2 g), the PF yielded a maximum of 37.4 $\mu\text{W m}^{-1} \text{K}^{-2}$ after annealed at 220 °C. However, the dynamic range of annealing temperature of PEDOT:PSS polymer sheet suitable is 200-300 °C and then if we annealed more than this range your sample sheet will be brittle.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

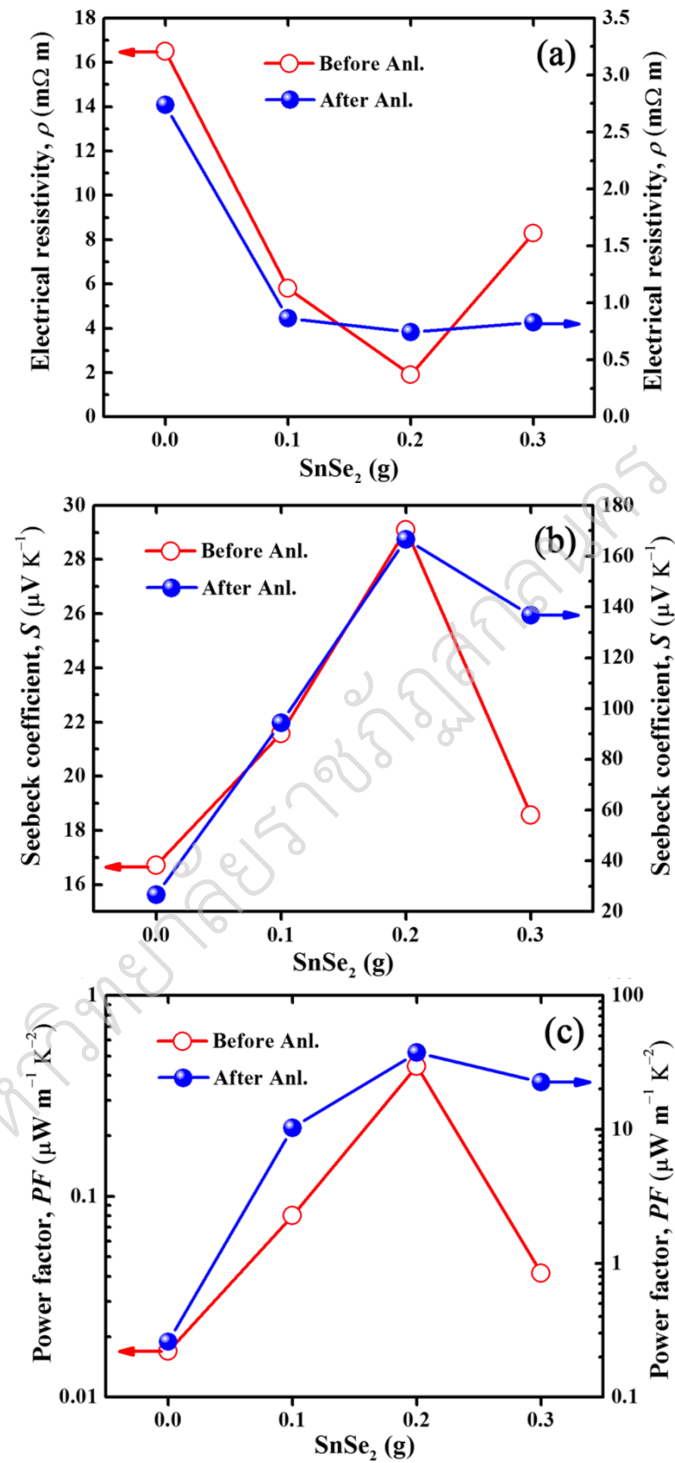


Figure 31 The TE of polymer sheets (a) Electrical resistivity, (b) Seebeck coefficient, and (c) power factor of PEDOT:PSS, PEDOT:PSS+SnSe₂ (0.1 g), PEDOT:PSS+SnSe₂ (0.2 g), and PEDOT:PSS+SnSe₂ (0.3 g).

In comparison, as listed in Table 8 shown the TE properties of the PEDOT:PSS+SnSe₂ polymer sheets are comparable to the literature on doped PEDOT:PSS polymer sheets. The enhanced TE power factor is affected by changes in the crystallography and morphology within the increased crystallinity of SnSe₂ due to rapid thermal annealing.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

Table 8 Comparison of thermoelectric performance of PEDOT:PSS/SnSe₂ with previously reported PEDOT:PSS-based composites.

Methods	Compositions	Temp (K)	<i>PF</i> ($\mu\text{W m}^{-1} \text{K}^{-2}$)	References
Vacuum filtration	PEDOT:PSS/SnSe thin film	353	24.42	Liu, Du, Meng, Dou, Jin, Xu & Shen, (2020)
Vacuum filtration	PEDOT:PSS/SnSe nanosheet enhancing by SWCNT	380	109.9	Liu, et al. (2020)
Vacuum filtration	PEDOT:PSS/SnSe enhancing by MWCNTs	393	59.35	Liu, et al. (2022)
Cold-pressing & Vacuum filtration	PEDOT:PSS/SnSe MWCNTs	393	166.5	Liu, et al. (2020)
Direct vacuum filtration	PEDOT:PSS/MoSe ₂ nanosheets	300	48.6	Li, et al. (2017)
Spin coating	PEDOT:PSS/Cu ₂ Se thin film	450	20.1	Butt, Farooq, Basit, Ali & Akram, (2023)
Wet chemical	PEDOT:PSS/SnSe ₂ polymer sheet	300	37.4	This work

* MWCNTs = multiwall carbon nanotubes.

*SWCNT = single-walled carbon nanotube.

Table 8 shown the thermoelectric performance achieved in this study clearly demonstrates the effectiveness of SnSe₂ as an inorganic component in PEDOT:PSS-based polymer thermoelectric systems. The PEDOT:PSS/SnSe₂ polymer sheet prepared via a wet chemical method exhibits a power factor of 37.4 $\mu\text{W m}^{-1} \text{K}^{-2}$ at 300 K, which is fully consistent with and in several cases superior to previously reported PEDOT:PSS–chalcogenide composites operating under comparable or more demanding conditions. When we were compared with PEDOT:PSS/SnSe thin films fabricated by vacuum filtration, which typically show power factors around 24 $\mu\text{W m}^{-1} \text{K}^{-2}$ at elevated temperatures, the present work achieves a higher power factor at room temperature. This result highlights the advantages of the wet chemical approach in promoting effective dispersion of SnSe₂ within the polymer matrix and enhancing interfacial interactions that facilitate charge transport. The improved performance at lower temperature confirms that the thermoelectric enhancement in this system is intrinsic rather than thermally driven.

Accordingly, in previous studies have reported significantly higher power factors for PEDOT:PSS/SnSe composites through the introduction of additional conductive networks, particularly carbon nanotubes. While such hybrid systems can exceed 100 $\mu\text{W m}^{-1} \text{K}^{-2}$, their performance depends on complex multicomponent architectures and processing steps. Importantly, the present work demonstrates that a competitive thermoelectric response can be achieved without carbon nanotube reinforcement, underscoring the inherent contribution of SnSe₂ nanosheets to optimizing the electrical conductivity and Seebeck coefficient trade off. This distinction is critical as it emphasizes material design rather than reliance on external conductive additives. The power factor obtained in this study is also comparable to or exceeds values reported for other

PEDOT:PSS-based chalcogenide systems, including PEDOT:PSS/MoSe₂ and PEDOT:PSS/Cu₂Se composites. The agreement across these studies confirms that layered metal chalcogenides consistently enhance thermoelectric performance through improved carrier transport and interfacial energy filtering effects. The consistency of the present results with established literature trends further validates the reliability and reproducibility of the proposed material system. Apparently, achieving this level of thermoelectric performance at ambient temperature, combined with a simple and scalable fabrication route, significantly enhances the practical relevance of the present work. Following, any reported polymer thermoelectric systems require elevated operating temperatures or additional conductive fillers to reach similar power factor values. In contrast, the PEDOT:PSS/SnSe₂ polymer sheet developed here offers a favorable balance between performance, processing simplicity and material flexibility, making it particularly suitable for low grade waste heat recovery and flexible thermoelectric applications.

Therefore, the results presented in this study establish PEDOT:PSS/SnSe₂ polymer sheets as a robust and competitive class of polymer thermoelectric materials. The clear agreement with prior studies, coupled with room temperature operation and straightforward fabrication that confirm this work makes a meaningful contribution to the development of efficient and scalable polymer-based thermoelectric systems. Further performance enhancement through compositional optimization and interfacial engineering represents a logical next step rather than a fundamental limitation of the material system.

Textiles Thermoelectric results

2.1 Physical properties of the yarns

The physical properties of the yarns were mentioned, we have 6 samples of the yarns (Figure 32) consisting of (a) Rayon (b) Indigo-Kram (Soft) (c) Indigo-Kram (Intensive) (d) PEDOT:PSS-Coated Rayon (e) PEDOT:PSS-Coated Indigo-Kram (soft) and (f) PEDOT:PSS-Coated Indigo-Kram (intensive). In discussion, we were observation of the rayon yarn (Figure 32(a)) revealed a staple-spun structure with moderate twist and visible surface hairiness. The rayon yarn exhibited irregular diameter along its length, suggesting moderate mass unevenness. The presence of protruding fibers indicates a relatively low fiber-to-fiber cohesion, which may influence fabric pilling and handle properties. Accordingly, the Indigo-Kram (Soft) in Figure 32(b) was examination of the indigo-dyed sample revealed that the yarn exhibits a smooth and uniform fiber surface characteristic of regenerated cellulose (rayon). The individual filaments appear long, straight, and free of surface scales or crimp, confirming the structural appearance typical of viscose rayon. The distribution of indigo dye is predominantly surface oriented. The outer layer of the yarn shows a continuous blue deposition, whereas the inner regions remain noticeably lighter. This indicates that dye penetration into the fiber core was limited. The results are consistent with the expected behavior of indigo, which adheres mainly to the fiber surface rather than diffusing deeply into the interior. The yarn's moderate-to-high twist further restricts dye penetration by reducing accessibility to the internal filaments. Twist direction and form are clearly visible, with the yarn presenting a consistent S-twist pattern. The structural compactness created by this twist likely contributes to the observed uneven dye saturation between the surface and core. Dye evenness across the yarn surface is generally acceptable, although slight variations in shade intensity are present. These lighter areas may result from differential wetting of the fibers, rapid oxidation of indigo between dipping cycles, or tight filament packing within the yarn. No evidence of fiber degradation or structural damage was observed,

indicating that the dyeing process did not negatively affect the rayon fiber morphology. Overall, the results confirm that the sample demonstrates:

- (1) typical rayon fiber morphology,
- (2) surface-dominant indigo deposition,
- (3) limited internal dye penetration due to twist constraints, and
- (4) generally uniform coloration with minor surface variability.

Figure 32(c) shown the Indigo-Kram (Intensive), the analysis of the indigo-dyed rayon yarns revealed that both samples exhibited surface-dominant dye deposition, consistent with the known behavior of indigo as a pigment forming vat dye. The yarn sample dyed with a lower indigo concentration showed a medium blue coloration with thinner surface coating, allowing the underlying rayon filaments to remain clearly visible. In contrast, the sample treated with a higher indigo concentration demonstrated a much darker blue–black appearance, accompanied by a thicker and more continuous indigo layer that obscured most fiber details. Neither sample showed significant dye penetration into the yarn core, likely due to the compact filament arrangement and moderate-to-high twist of the rayon yarn, which reduce internal accessibility. However, the high concentration sample exhibited slightly deeper color development in the upper layers of the yarn bundle. Therefore, the increased concentration of indigo enhanced surface saturation and color uniformity but did not fundamentally alter the surface-dependent nature of indigo attachment to rayon fibers.

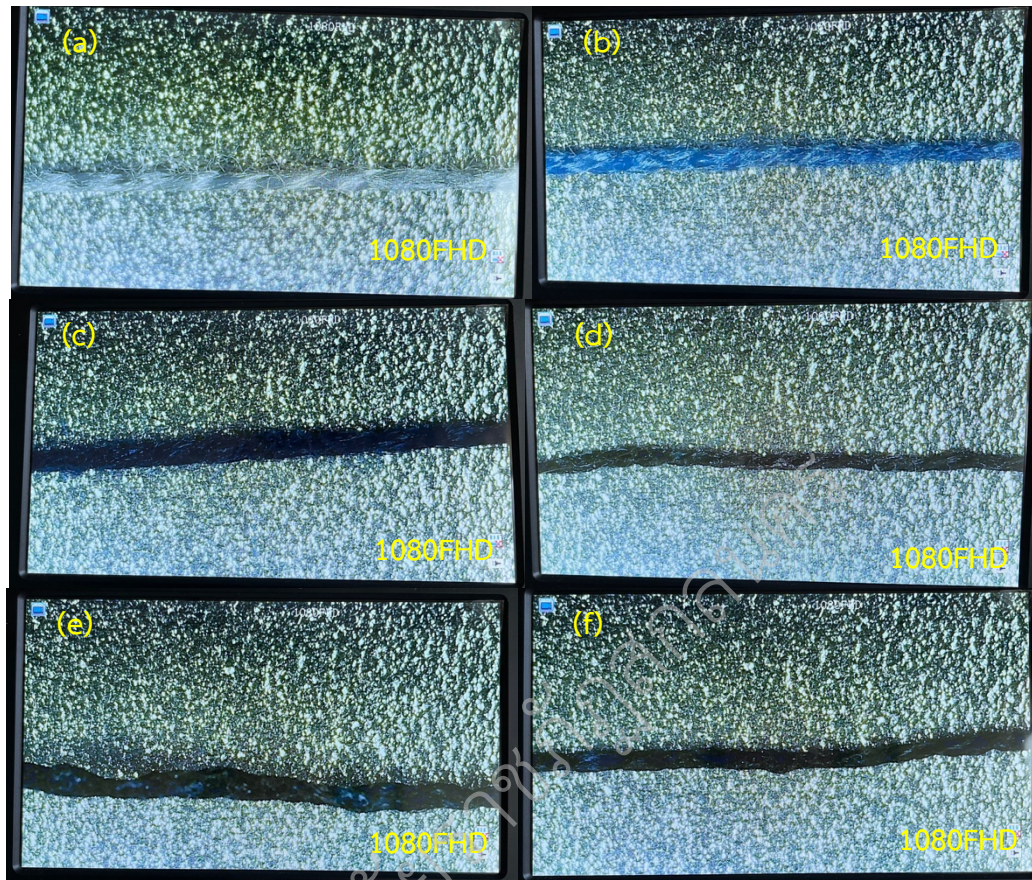


Figure 32 The sample of a yarns. (a) Rayon (b) Indigo-Kram (Soft) (c) Indigo-Kram (Intensive) (d) PEDOT:PSS-Coated Rayon (e) PEDOT:PSS-Coated Indigo-Kram (Soft) (f) PEDOT:PSS-Coated Indigo-Kram (Intensive)

Figure 32(d) (e) (f) shows the yarns were dip coating with conductive polymer PEDOT:PSS. It was found that, the dip-coating process successfully deposited a uniform layer of PEDOT:PSS onto the Rayon, Indigo-Kram (Soft) and Indigo-Kram (Intensive) samples. Visual and microscopic examination confirmed that the technique resulted in consistent surface coverage across the entire yarn length. During immersion, the aqueous PEDOT:PSS dispersion demonstrated good wetting behavior on the substrates, allowing the polymer to penetrate the outer filament spaces before forming a continuous film upon drying. After withdrawal from the solution, the yarns exhibited minimal dripping and no evidence of

coating separation, indicating that the withdrawal speed and solution viscosity were well-matched. The drying stage produced a stable and adherent coating layer as confirmed by the absence of cracking, peeling or delamination in the final samples. The polymer film was evenly distributed around the yarn circumference suggesting that the dip-coating parameters including immersion time withdrawal speed and drying conditions were appropriate for achieving full coverage. Generally, the results show that the dip-coating method is highly suitable for applying PEDOT:PSS to the yarns offering controlled film formation, strong adhesion and consistent morphology across all treated samples. The technique provided reliable coating quality that supports subsequent electrical and mechanical characterization.

As a consequence, the dip-coating method using PEDOT:PSS successfully transforms rayon yarn (undyed or indigo-dyed) into a uniformly coated, polymer-sheathed conductive yarn while maintaining structural integrity and providing a smooth, consolidated surface. The physical changes induced by coating including increased diameter, reduced surface roughness, tighter filament bundling and slightly reduced flexibility are qualitatively consistent across all yarn types, although the initial dye loading (indigo concentration) influences the degree of stiffness and appearance after coating. The results confirm that PEDOT:PSS dip-coating is a viable method to produce polymer coated yarns with consistent morphology and good coating adhesion, regardless of prior natural dye treatment. These observations support further functional testing (e.g., electrical conductivity, durability) and application development with the coated yarns.

2.2 Electrical conductivity of PEDOT:PSS-Coated

The electrical conductivity of PEDOT:PSS-Coated Rayon (Figure 33) shown the measured electrical resistance of rayon yarns after dip-coating with

PEDOT:PSS as a function of yarn length (0–60 cm). As a consequence, the PEDOT:PSS-coated Rayon yarns demonstrated stable and functional electrical conductivity with measured resistance values ranging between 2–7 k Ω across yarn lengths up to 60 cm. The data showed no linear correlation between yarn length and resistance, indicating that conductivity was primarily governed by coating uniformity rather than fiber length. Although the resistance values were scattered, this variability is attributed to natural surface roughness localized coating thickness differences and typical dip-coating dynamics. Importantly, resistance remained consistent over time with no observable degradation or drift across days confirming good coating stability.

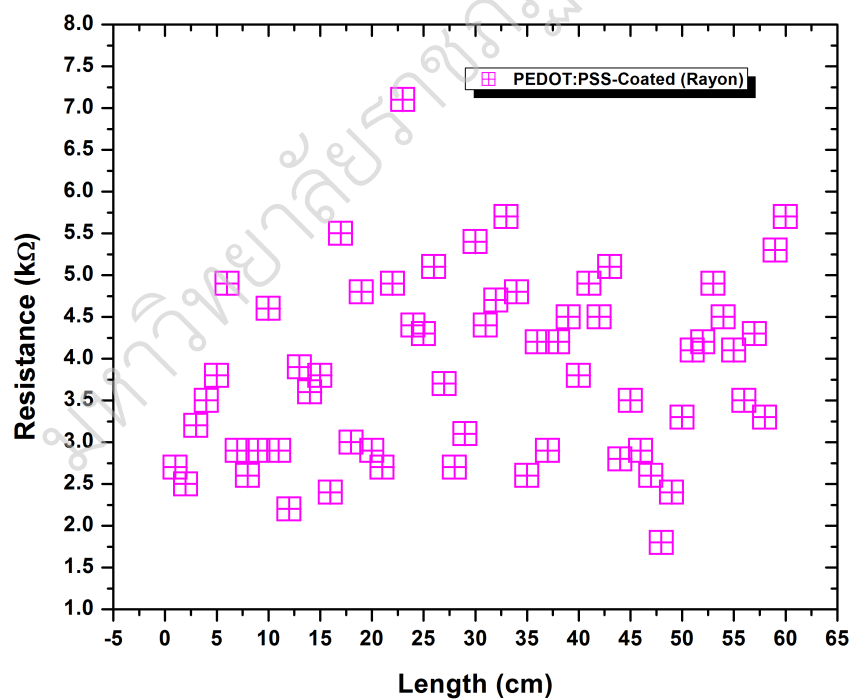


Figure 33 The measured electrical resistance of rayon yarns after dip-coating with PEDOT:PSS as a function of yarn length (0–60 cm).

Subsequently, the electrical resistance of the indigo-dyed (soft) yarn after dip-coating with PEDOT:PSS also was evaluated as a function of yarn length (0–60 cm). It was found that, the PEDOT:PSS-coated soft indigo yarn shows stable electrical conductivity with resistance values mostly between 2–7.5 k Ω . The data are scattered that indicating uneven coating due to the indigo-dyed surface. Despite this variability, the yarn remains consistently conductive across all lengths and no degradation over time is observed as shown in Figure 34.

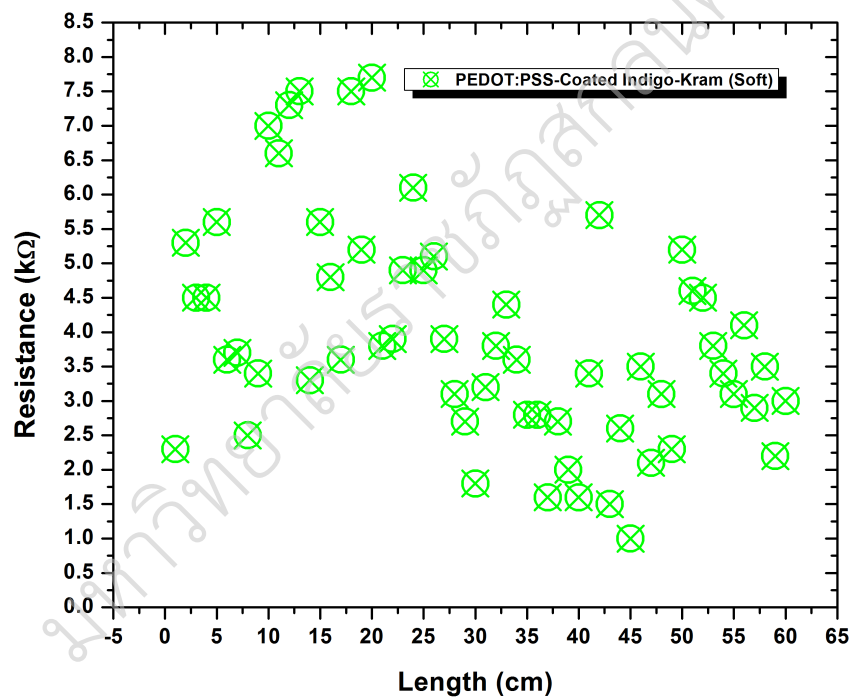


Figure 34 The measured electrical resistance of Indigo-Kram (Soft) yarns after dip-coating with PEDOT:PSS as a function of yarn length (0–60 cm).

In the last graph presents the electrical resistance of the intensive indigo-dyed yarn after coating with PEDOT:PSS and then measured across yarn lengths from approximately 0–60 cm. Consequence, the intensive indigo-dyed yarn coated with PEDOT:PSS (Figure 35) shows electrical resistance between 2–9

$k\Omega$ with significant variability due to heavy dye loading that interferes with uniform coating. Although the resistance varies widely, the yarn maintains consistent and stable conductivity over time, making it suitable for OTE-textile applications.

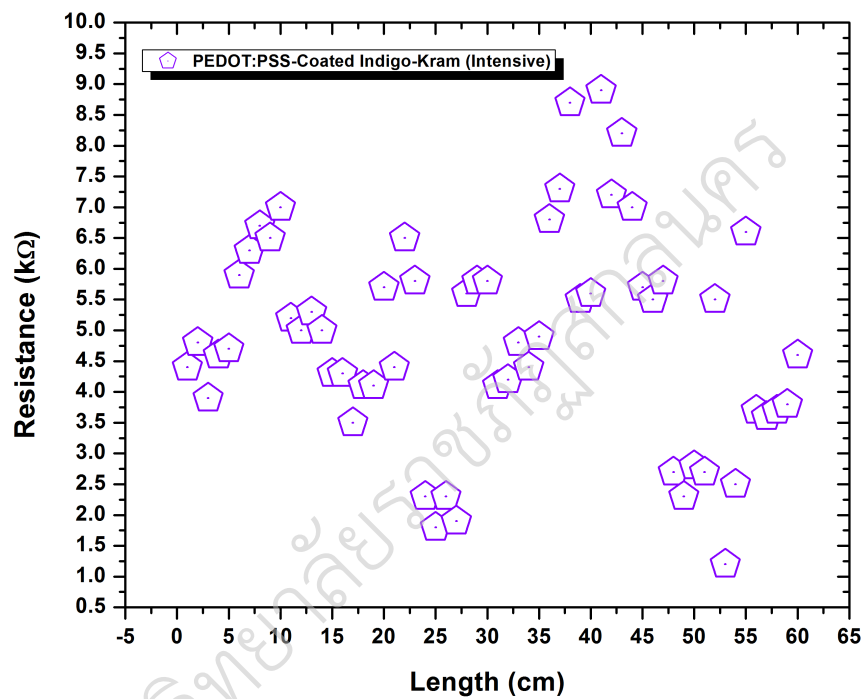


Figure 35 The measured electrical resistance of Indigo-Kram (Intensive) yarns after dip-coating with PEDOT:PSS as a function of yarn length (0–60 cm).

Hence, all of three yarn types showed a clear increase in electrical conductivity after PEDOT:PSS coating with higher dip-coating cycles producing progressively lower resistance and more stable conductive performance. The comparative summary table of the yarns coated as shown in Table 9.

Table 9 The comparative summary of the PEDOT:PSS-Coated yarns.

Sample Type	Resistance Range (k Ω)	Uniformity	Conductivity Stability	Influence of Indigo Dye
PEDOT:PSS-Coated Rayon	2.0-7	High uniformity	Stable	No interference; optimal PEDOT:PSS bonding.
PEDOT:PSS-Coated Indigo-Kram (Soft)	2.0-7.5	Moderate uniformity	Stable	Partial disruption of coating uniformity.
PEDOT:PSS-Coated Indigo-Kram (Intensive)	2.0-9.0	Low uniformity	Stable	Strong interference; most difficult coating environment.

Therefore, the increasing of indigo pigments correlates with increased resistance and greater measurement variability, confirming that dye concentration significantly affects coating uniformity and electrical performance.

2.3 Morphology and atomic composition characterizations

(1) Surface Morphology Analysis (SEM)

Figure 36(a) shown the SEM analysis undyed rayon yarn (Before Coating). The SEM image shows the surface morphology of undyed rayon fibers at a scale of 50 μm , revealing a bundle of smooth, elongated filaments. The individual rayon fibers appear uniform cylindrical and well-aligned with no visible surface coatings or particulate deposits. The surface texture is relatively smooth consistent with regenerated cellulose fibers and there is minimal fibrillation or surface damage indicating that the yarn structure is intact and has not undergone mechanical or chemical stress prior to coating. Accordingly, the fibers show clear separation between filaments suggesting a loosely packed yarn structure that provides good accessibility for subsequent coating processes such as dip coating.

No cracks, voids or morphological defects are observed and the filament diameters appear consistent throughout the bundle (typical rayon fiber diameter is approximately 10–20 μm based on the scale bar). Then, the morphology indicates a clean baseline substrate suitable for uniform PEDOT:PSS film formation.

Figure 36(b) shown the SEM analysis of Indigo-Kram (Soft) dyed yarn (before coating). The SEM image of the low-indigo dyed yarn (scale: 50 μm) shows a bundle of filaments with morphology similar to undyed rayon but with slight surface differences associated with the dyeing process. The fibers maintain a smooth, elongated and cylindrical appearance indicating that the low-indigo dyeing treatment did not significantly damage or deform the fiber structure. So, we compared to undyed rayon, the fiber surfaces appear slightly less smooth with minor surface irregularities and faint streaking patterns visible along the filament axes. These small variations are consistent with the deposition of a thin indigo layer or minor dye-induced swelling of the cellulose matrix. However, no major cracks, peeling or dye aggregates are observed, suggesting that the low-indigo application results in a uniform and mild coating effect. The yarn remains loosely packed and well-separated allowing good fiber accessibility for subsequent PEDOT:PSS coating. Filament diameters appear consistent and similar to the undyed sample and no structural defects such as fibrillation, micro-voids or roughening are evident. Therefore, the low-indigo dyed yarn preserves its structural integrity and remains an excellent substrate for conductive polymer deposition.

Figure 36(c) Shown the SEM analysis Indigo-Kram (Intensive) dyed yarn before dip-coating process. The SEM image of the intensive-indigo dyed yarn (scale: 50 μm) also shows a bundle of filaments with a generally smooth and

continuous morphology but with more noticeable surface changes compared to the undyed and low-indigo samples. The fibers remain elongated and cylindrical indicating that the structural integrity of the rayon has been preserved despite the stronger dyeing treatment. When we compared with the low-indigo sample, the fiber surfaces appear slightly rougher and more irregular, consistent with a heavier deposition of indigo particles or enhanced surface swelling. Subtle textural variations such as faint surface granularity and small adhered particles can be observing along some filaments. These features suggest that intensive dyeing introduces a denser and more uniform dye layer, which can alter surface smoothness but does not produce cracks or damage. Furthermore, the filament packing remains uniform although some fibers appear more tightly positioned possibly due to increased stiffness caused by higher dye uptake. Despite these changes, there is no evidence of fiber breakage fibrillation or structural defects that confirming the intensive indigo treatment primarily affects surface texture rather than the internal structure of the yarn. Then, the intensive-indigo dyed yarn exhibits the highest degree of surface modification among the three pre-coating samples. Therefore, this result providing a likely increase in surface energy and micro-texture that may improve adhesion during subsequent PEDOT:PSS coating.

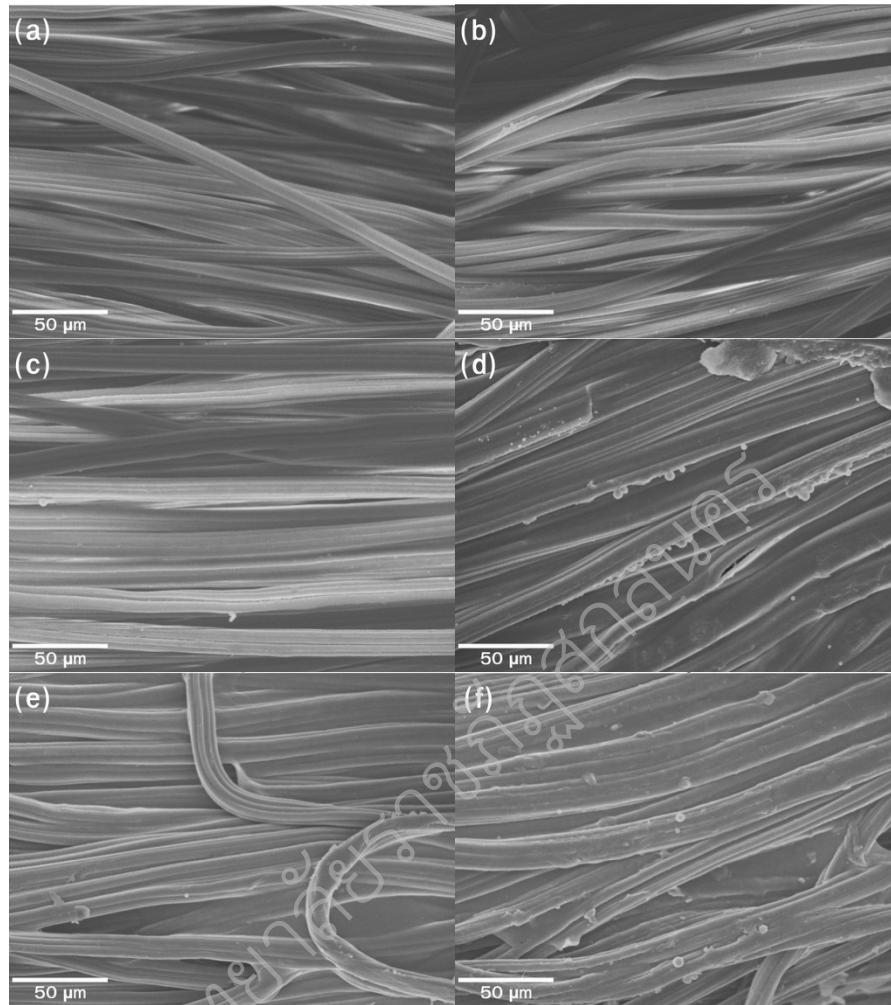


Figure 36 The SEM analysis of the yarns (before & after coating) (a) Rayon (b) Indigo-Kram (Soft) (c) Indigo-Kram (Intensive) (d) PEDOT:PSS-Coated Rayon (e) PEDOT:PSS-Coated Indigo-Kram (Soft) (f) PEDOT:PSS-Coated Indigo-Kram (Intensive).

Figure 36(d) shown the SEM analysis rayon yarn after PEDOT:PSS dip coating. The SEM image (scale: 50 μm) of the rayon yarn after dip coating with PEDOT:PSS shows clear evidence of polymer deposition across the fiber surfaces. Compared with the smooth, clean filaments observed before coating, the post-coating fibers exhibit irregular surface features, including small droplets, nodules, and thin film-like layers typical of dried PEDOT:PSS dispersion. A continuous but

non-uniform coating layer is visible along many filaments with localized accumulations where the polymer has formed beads or clusters. These features indicate that the PEDOT:PSS adhered effectively to the hydrophilic rayon substrate but dried in a way that produced micro-scale thickness variation. In addition, some areas show thicker deposits while other regions maintain visible fiber grooves, this suggesting partial but sufficient surface coverage. Importantly, the underlying fiber morphology remains intact with no signs of structural damage, cracking, or delamination. The coating conforms closely to the fiber contours, supporting good mechanical compatibility and potential durability under bending or textile movement. Then, the SEM image confirms that the dip-coated rayon yarn achieved successful surface deposition of PEDOT:PSS, forming a conductive layer characterized by bead-like aggregates and thin film spreading. This morphology is typical for PEDOT:PSS on cellulose-based substrates and is consistent with the improved electrical conductivity measured experimentally.

Figure 36(e) shown the SEM analysis Indigo-Kram (Soft) yarn after PEDOT:PSS dip coating. The SEM image (50 μm scale) of the low-indigo-dyed yarn after coating with PEDOT:PSS shows a noticeably smoother surface compared with the uncoated version, indicating successful adhesion of the conductive polymer layer. Unlike the rayon sample, which displayed bead-like aggregates, the low-indigo fibers exhibit a more uniform and continuous coating, suggesting that the indigo dye layer enhances polymer wetting and distribution. The fiber surfaces appear covered with a thin PEDOT:PSS film that follows the natural contours of the cellulose filaments. Only minimal particulate residues or coating clusters are observed and the polymer layer does not obscure the underlying fiber structure this indicates thin well-spread deposition rather than thick accumulation. Moreover, the improved uniformity may result from the interaction

between indigo pigments and PEDOT:PSS which enhances surface compatibility and spreading behavior. This results shown no structural damage, fractures or delamination are visible demonstrating that the dip-coating process did not compromise the mechanical integrity of the yarn. Additionally, the coated fibers retain distinct morphological boundaries which is favorable for maintaining textile flexibility. Consequently, the SEM image confirms that PEDOT:PSS forms a smooth, evenly distributed coating on low-indigo-dyed rayon fibers likely contributing to stable and consistent electrical conductivity across the yarn.

Figure 36(f) shown the SEM micrograph (50 μm scale) of the intensive-indigo-dyed yarn after PEDOT:PSS coating reveals a moderately uniform polymer layer distributed across the fiber surfaces. Compared with the low-indigo coated sample, the coating here appears slightly less continuous with more visible clusters and small spherical droplets of PEDOT:PSS present along the filament surfaces. These small nodules are indicative of localized polymer accumulation which commonly occurs when the substrate surface has higher surface roughness or greater dye saturation. The underlying fiber morphology remains visible showing that the coating forms a thin, conformal layer without excessively masking the natural cellulose structure. Nevertheless, the more pigmented fibers in the intensive-dyed yarn result in a coating surface that appears slightly more textured and irregular compared with low-indigo fibers. This suggests that the higher indigo content may influence polymer nucleation, leading to a more particulate-like deposition. Despite these small aggregates, there is no evidence of coating delamination, cracking or fiber damage confirming that the dip-coating process maintained the mechanical integrity of the yarns and fiber alignment remains clear and the coating is adhered consistently along the filament length. As a results, the SEM image indicates that PEDOT:PSS forms a

stable but somewhat more heterogeneous coating on intensive-indigo-dyed fibers, likely contributing to slightly higher resistance variability observed in the electrical measurements compared with low-indigo and undyed samples.

Consequence, the SEM analysis of the six yarn samples provided a clear comparison of how natural indigo dyeing and PEDOT:PSS dip-coating influenced fiber surface morphology. The undyed rayon yarn showed the smoothest and cleanest fiber surfaces with tightly aligned filaments and no visible debris serving as a baseline for coating adhesion. In comparison, the low-indigo dyed yarn exhibited only slight surface deposits from the dye while still maintaining a smooth overall morphology that remained favorable for uniform coating. Likewise, the intensive-indigo dyed yarn presented a noticeably rougher texture with more dye granules and uneven patches indicating that higher dye content increased surface heterogeneity. After dip coating with PEDOT:PSS distinct differences emerged among the three yarn types. The undyed rayon fibers displayed a relatively uniform and continuous polymer layer with small spherical PEDOT:PSS nodules that confirming strong adhesion on the clean cellulose surface. The low-indigo yarn also showed a well-distributed and smooth coating with minimal aggregation and good conformity to the fiber contours suggesting that the thin dye layer did not interfere with coating uniformity. In contrast, the intensive-indigo yarn displayed a more heterogeneous polymer deposition, characterized by localized clusters, droplets and a more textured coating surface. This indicates that the thicker and more uneven indigo layer influenced polymer nucleation and prevented fully uniform coating formation. The summary of SEM observations as shown in Table 10.

Table 10 Summary of SEM Observations for All Yarns Before and After PEDOT:PSS Coating.

Sample	Surface Morphology	Coating Uniformity	Visible Defects	Overall Interpretation
(a) Rayon	Smooth, clean cellulose fibers; tightly packed and well-aligned.	-	None; no debris.	Baseline morphology with clean surfaces ideal for polymer adhesion.
(b) Indigo-Kram (Soft)	Fibers smooth with minor surface deposits from natural dye; good alignment.	-	Small dye particles.	Dye layer thin; minimal effect on surface roughness.
(c) Indigo-Kram (Intensive)	Fibers show more surface texture and dye accumulation; slightly rougher surface.	-	More dye granules and uneven patches.	Higher indigo concentration increases roughness and may affect coating uniformity.

Table 10 (Continued)

Sample	Surface Morphology	Coating Uniformity	Visible Defects	Overall Interpretation
(d) PEDOT:PSS-Coated Rayon	Smooth fibers coated with thin polymer layer; visible small spherical PEDOT:PSS droplets.	Moderate-high uniformity	Small polymer nodules but no cracks.	Good overall coating uniformity and strong adhesion due to clean substrate.
(e) PEDOT:PSS-Coated Indigo-Kram (Soft)	Polymer layer well-distributed and more continuous than intensive sample; fiber alignment remains intact.	High uniformity	Very few aggregates; smooth surface.	Dye layer promotes adhesion; coating is consistent and stable.
(f) PEDOT:PSS-Coated Indigo-Kram (Intensive)	Coating present but more heterogeneous; polymer droplets and clusters visible; textured surface.	Moderate uniformity	More particulate deposition and uneven distribution.	Higher dye concentration creates a less uniform coating explaining greater resistance variability.

Summaries, the SEM results demonstrate that coating uniformity decreases as indigo concentration increases with the undyed and low-indigo yarns providing the most favorable surfaces for PEDOT:PSS adhesion. These morphological differences correspond well with the electrical conductivity results where the intensive-indigo coated yarns exhibited greater variability and slightly higher resistance.

(2) Energy Dispersive X-ray Spectroscopy (EDX)

The EDX spectra of the six yarn samples demonstrated clear elemental differences before and after PEDOT:PSS coating with sulfur emerging as the key indicator of polymer deposition. We were explained as below:

Figure 37(a) shown the EDX spectra of the uncoated rayon yarn show that the material contains with primarily carbon (50.92 wt%) carbon is the major backbone of cellulose this level is typical for untreated rayon fibers and oxygen (49.08 wt%) which is consistent with the chemical composition of regenerated cellulose, oxygen comes from the hydroxyl ($-OH$) groups in cellulose and this proportion also aligns with known cellulose chemistry. No additional elements were detected, confirming the absence of impurities, dyes or surface treatments. Furthermore, the platinum peaks visible in the spectrum originate from the conductive sputter coating applied during SEM preparation and do not represent the fiber composition. The elemental mapping image further shows a uniform distribution of C and O across the fiber surface that indicating a clean and homogeneous cellulose structure prior to coating. Figure 37(b) shown the EDX analysis of the Indigo-Kram (Soft) yarns prior to coating shows that the surface consists mainly of carbon (46.87 wt%) and oxygen (53.13 wt%) characteristic of regenerated cellulose fibers. Compared with the uncoated rayon sample, the slightly decreased carbon content and increased oxygen proportion

may be attributed to mild surface oxidation or the presence of trace organic dye residues from the indigo dyeing process. No inorganic elements or dyeing salts were detected, indicating the absence of any significant mineral contamination. Accordingly, Figure 37(c) shown the EDX spectrum of the intensive-indigo yarns before coating and shows a composition dominated by carbon (46.87 wt%) and oxygen (53.13 wt%) corresponding to the cellulose structure of rayon fibers. Compared with the pristine rayon sample, the slightly reduced carbon content and increased oxygen proportion may be attributed to mild oxidation or the presence of trace organic dye residues from the intensive indigo dyeing process. No inorganic elements or dye-related metals appear in the spectrum, indicating that the dyeing process does not introduce significant mineral impurities. In addition, the element mapping confirms a uniform distribution of C and O across the yarn surface demonstrating that intensive indigo dyeing does not significantly alter the elemental surface composition.

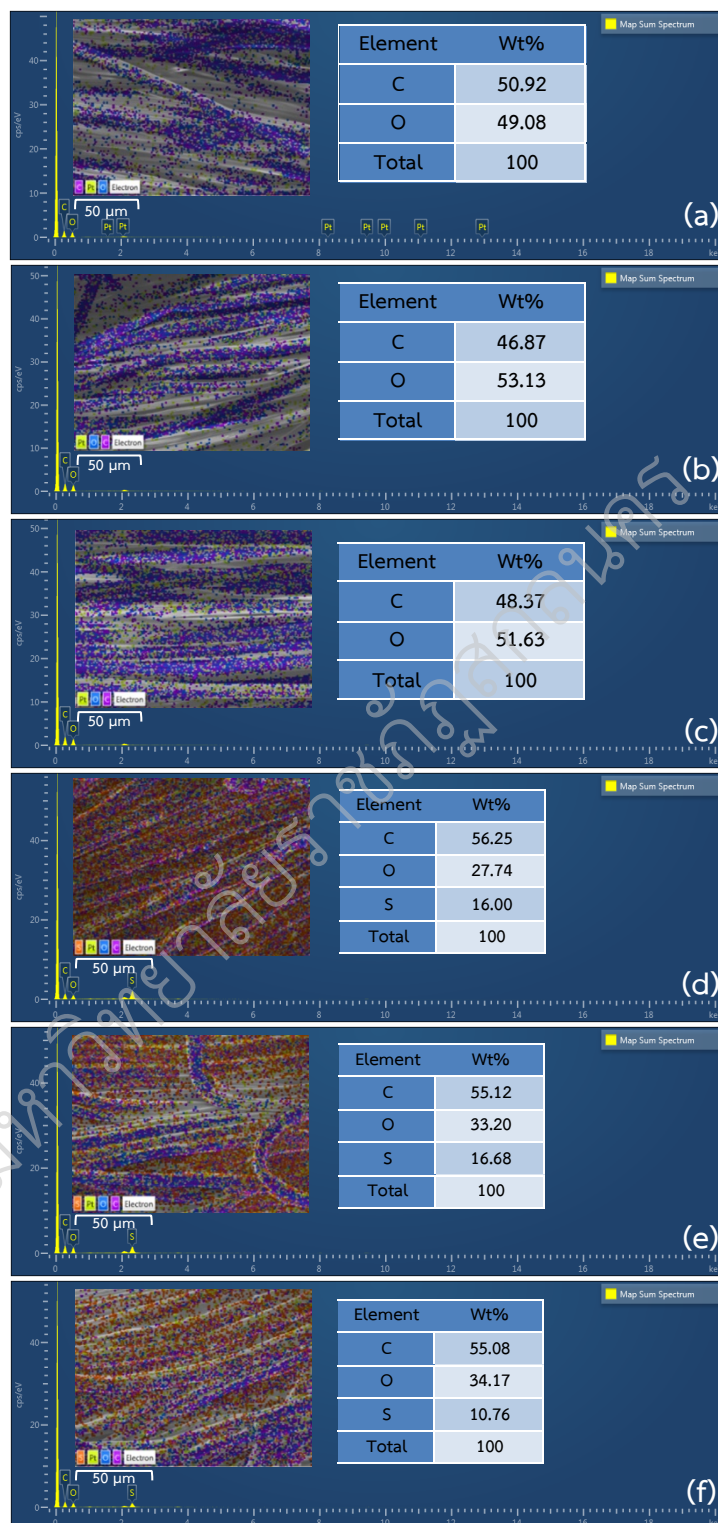


Figure 37 The EDX spectra and atomic composition of the yarns before & after coating with PEDOT:PSS.

Figure 37(d) shown the EDX spectrum of rayon yarns after dip-coating with PEDOT:PSS reveals a significant shift in elemental composition compared with the uncoated fibers with increased carbon (56.25 wt%) and the appearance of sulfur (16.00 wt%) which is the characteristic element of the PEDOT and PSS components. The oxygen content decreases to 27.74 wt% reflecting partial masking of the cellulose surface by the conductive polymer layer. The strong sulfur peak provides direct evidence of successful PEDOT:PSS deposition. In Figure we have seen elemental mapping shows a uniform distribution of sulfur across the fiber surface indicating consistent and well-adhered coating coverage. These results confirm the formation of a continuous conductive PEDOT:PSS film on the rayon yarns. Following Figure 37(e) shown the EDX mapping of the Indigo-Kram (Soft) yarn after dip-coating and then that shows clear evidence of PEDOT:PSS deposition of sulfur and get detected at 16.68 wt% while carbon increases to 55.12 wt% and oxygen falls to 33.20 wt% compared with the uncoated fiber. The sulfur distribution is uniform across the mapped area indicating continuous polymer coverage. These compositional shifts corroborate SEM observations of a smooth, conformal PEDOT:PSS film and explain the measured improvement and stability in electrical conductivity. Lastly, Figure 37(f) the EDX spectrum of the intensive-indigo yarns after dip-coating with PEDOT:PSS shows the presence of three main elements: carbon (C), oxygen (O) and sulfur (S). Carbon (55.08 wt%) and oxygen (34.17 wt%) dominate the composition reflecting the organic nature of both the cellulose-based rayon substrate and the PEDOT:PSS polymer coating. The presence of sulfur (10.76 wt%) is a clear indicator of successful PEDOT:PSS deposition as sulfur originates from the sulfonate groups in PSS and the thiophene rings in PEDOT. Therefore,

the elemental distribution confirms that the conductive polymer layer is uniformly incorporated onto the yarn surface.

As a results, after coating with PEDOT:PSS all of the yarns showed higher sulfur signals smoother polymer-covered surfaces and became electrically conductive compared to the uncoated samples. The indigo-dyed yarns, especially the intensive-indigo type still showed surface residues that made the coating slightly less uniform than on plain rayon.

2.4 Thermoelectric properties measurement

The conductive polymer coated yarns are attractive materials for wearable thermoelectric applications because they are flexible, lightweight and easily integrated into e-textiles. The PEDOT:PSS conductive polymer is widely used due to its good electrical conductivity and stable Seebeck response at room temperature. Then, to evaluate how different yarn substrates influence thermoelectric behavior, so PEDOT:PSS was coated onto the rayon, soft-indigo and intensive-indigo yarns. The thermoelectric properties of the coated yarns were then measured and compared.

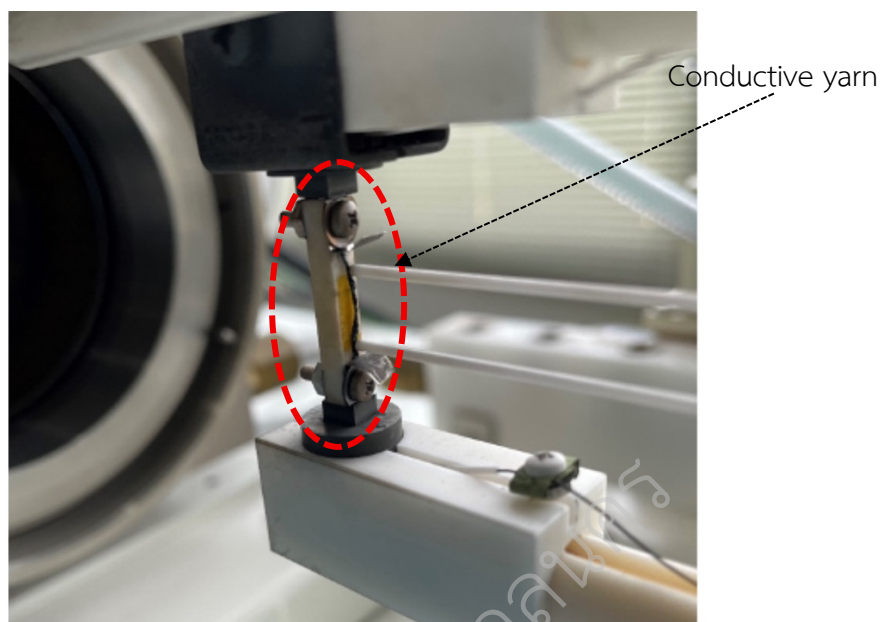


Figure 38 Thermoelectric measurement setup for PEDOT:PSS-Coated yarn.

Figure 38 shown the thermoelectric measurement setup used to evaluate the PEDOT:PSS-coated yarns. The yarn sample is clamped vertically between two metallic electrodes: the upper clamp and lower clamp provide both electrical contact and mechanical support. The lower block contains the temperature-controlled stage which applies a controlled heat source to create a temperature gradient along the yarn but in experiment we were setup at room temperature including to textiles wearing in natural environment. As the temperature difference develops between the two ends of the yarn, then the system measures the resulting thermoelectric voltage (Seebeck voltage) through the electrical contacts. This setup allows accurate determination of the Seebeck coefficient, resistivity and power factor of the coated yarns under controlled conditions.

As a results, among the three PEDOT:PSS coated yarns, the PEDOT:PSS-Coated Indigo-Kram (Soft) yarn shows the best thermoelectric performance with the highest Seebeck coefficient equal $21.75 \mu\text{V K}^{-1}$, the electrical resistivity $0.074 \text{ m}\Omega \text{ m}$ and the highest power factor equal $6.39 \mu\text{W m}^{-1} \text{ K}^{-2}$. Accordingly, the

PEDOT:PSS-Coated Indigo-Kram (Intensive) yarn has moderate performance power factor equal $4.75 \mu\text{W m}^{-1} \text{K}^{-2}$, electrical resistivity $0.067 \text{ m}\Omega \text{ m}$ and Seebeck coefficient equal $17.86 \mu\text{V K}^{-1}$ while PEDOT:PSS-Coated Rayon shows the lowest power factor equal $2.99 \mu\text{W m}^{-1} \text{K}^{-2}$, electrical resistivity $0.094 \text{ m}\Omega \text{ m}$ and Seebeck coefficient equal $16.72 \mu\text{V K}^{-1}$ at room temperature. This indicates that surface chemistry and dye residues of the low-indigo yarn create better PEDOT:PSS film formation or charge transport, leading to improved thermoelectric efficiency. The comparative with other work as shown in Table 11.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

Table 11 Comparison TE of PEDOT:PSS-Coated yarns with previously reported textile-based thermoelectric materials.

Methods	Type of Fabric	Formulations	S ($\mu\text{V K}^{-1}$)	Temp. (K)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	Ref.
Coating treatment	Polyester	PEDOT:PSS/DMSO	16	390	0.045	Du, Cai Chen, Wang, Shen, Donelson, & Lin (2015)
Dip coating	Cotton yarn & Polyester yarn	WPU/PEDOT:PSS/MWCNT/DMSO	10	300	~1.41	Wu & Hu (2016)
Drop casting & Printed	Embedded in textiles	Tellurium-PEDOT:PSS	114.97	-	284	Bea, Kang, Jang, & Cho (2016)
Dip coating	Polyester	PEDOT:PSS/Colloidal graphite/DMSO	22	398	~0.025	Du, Xu, Wang, & Lin (2017)
Impregnated & Drop deposition	Cotton yarn	PEDOT:PSS	10.3	40	3.2×10^{-3}	Pope & Lekakou (2019)

Table 11 (Continued)

Methods	Type of Fabric	Formulations	S ($\mu\text{V K}^{-1}$)	Temp. (K)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	Ref.
Dyeing & Roll-to-Roll	Silk sewing thread	PEDOT:PSS/EG/ DMSO	P-type ~14.3 (PEDOT:PSS coat threads) N-type ~0.3 (Silver-plated threads)	65	1.2	Lund, Tian, Darabi, & Müller (2020)
Wet-spinning & De- doping	PEDOT: PSS fiber was embroidered to thermoelectric fabric module	PEDOT:PSS wet- spinning into aqueous sulfuric acid	~15-30	-	30	Kim, et al., (2020)
Low-Temp. interfacial polymerization & Coating	Nonwoven fabrics	PEDOT: Tos	16.15	300	-	Zhang, et al., (2020)

Table 11 (Continued)

Methods	Type of Fabric	Formulations	S ($\mu\text{V K}^{-1}$)	Temp. (K)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	Ref.
Coating	Cotton yarn	PEDOT:PSS/DMSO/ILs	28	-	24.7	Li, et al., (2021)
Robust coating	Polyester yarn	PEDOT/CNT/Bi ₂ Te ₃	47.1	300	12.3	Ding, Wu, Gao, wang, Chen, & Li (2023)
Rapid and cost-effective wet-spinning	PEDOT:PSS fiber sewing on fabric	PEDOT:PSS/DMSO/H ₂ S O ₄	18	300	30.8	Wu, et al., (2024)
Coating	Wool fabric+Rayon yarn	PEDOT:PSS-Coated Rayon	16.72	300	2.99	This work
Coating	Wool fabric+Indigo-Kram (Soft) yarn	PEDOT:PSS-Coated Indigo-Kram (Soft)	21.75	300	6.39	This work
Coating	Wool fabric+Indigo-Kram (Intensive) yarn	PEDOT:PSS-Coated Indigo-Kram (Intensive)	17.86	300	4.75	This work

*WPU = Waterborne Polyurethane.

*MWCNT = Multi-Walled Carbon Nanotubes.

*IL = Ionic Liquid.

In table we were compared with previously reported textile-based thermoelectric materials, the PEDOT:PSS-coated yarns developed in this work exhibit a moderate Seebeck coefficient and a competitive power factor relative to other polymer-based systems. The Seebeck values of 16.72–21.75 $\mu\text{V/K}^{-1}$ fall within the typical range reported for PEDOT:PSS-based textile coatings (10–30 $\mu\text{V/K}^{-1}$) and are comparable to those achieved using surface treatments such as DMSO, EG, or ionic liquids. The power factors obtained (2.99–6.39 $\mu\text{W m}^{-1} \text{K}^{-2}$) are lower than high-performance composites like PEDOT/CNT/ Bi_2Te_3 or Te–PEDOT:PSS systems but are significantly higher than those of early PEDOT:PSS-coated cotton or polyester yarns reported in 2015–2017. Thus, this work demonstrates that simple dip-coating of yarns particularly the low-indigo (soft) yarn can produce thermoelectric properties competitive with multi-step chemically modified or composite textile systems reported in the literature.

Furthermore, the differences in thermoelectric performance among the three coated yarns arise from variations in their surface morphology, dye composition and coating interaction with PEDOT:PSS. The low-indigo (soft) yarn exhibits the highest Seebeck coefficient (21.75 $\mu\text{V/K}^{-1}$) and the highest power factor (6.39 $\mu\text{W m}^{-1} \text{K}^{-2}$) this suggesting that its surface chemistry facilitates a more uniform PEDOT:PSS deposition and improved charge transport pathways. Indigo dye residues and the softness of the fiber bundle may promote better wetting during dip-coating resulting in thicker or more continuous conductive layers. In contrast, the intensive-indigo yarn shows a slightly lower Seebeck value (17.86 $\mu\text{V/K}^{-1}$) and a moderate power factor (4.75 $\mu\text{W m}^{-1} \text{K}^{-2}$). This result indicate the heavier indigo pigmentation likely limits PEDOT:PSS penetration into the fiber structure, producing a coating that is more surface restricted and less interconnected. This can increase resistance and reduce effective carrier mobility. Additionally, the rayon yarn although chemically smooth and hydrophilic displays the lowest performance (power factor = 2.99 $\mu\text{W m}^{-1} \text{K}^{-2}$). Its relatively uniform fiber surface may result in a thinner conductive layer with less microstructural anchoring which reduces electrical conductivity even though the Seebeck

coefficient remains comparable. However, rayon lacks the residual dyes or surface roughness that may enhance PEDOT:PSS adhesion on the indigo-dyed yarns. Finally, the results indicate that fiber surface chemistry, roughness and dye pigments strongly influence PEDOT:PSS coating quality, which in turn affects resistivity and thermoelectric efficiency. The low-indigo yarn appears to achieve an optimal balance of coating adhesion and conductive pathway formation, leading to the best thermoelectric output among the samples studied.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

Textiles Thermoelectric module results

3.1 Physical properties of the module

The PEDOT:PSS-coated Rayon module (Figure 39) is a lightweight flexible textile thermoelectric device composed of five yarn legs connected in series on a wool fabric as a substrate. The module shows good coating adhesion, structural stability and clean electrical pathways though the measured resistance of the module $\sim 300 \text{ k}\Omega$ reflects the thin PEDOT:PSS coating and long conduction path. Its design is optimized for applying vertical temperature gradients and demonstrates characteristics consistent with wearable thermoelectric energy harvesting modules.

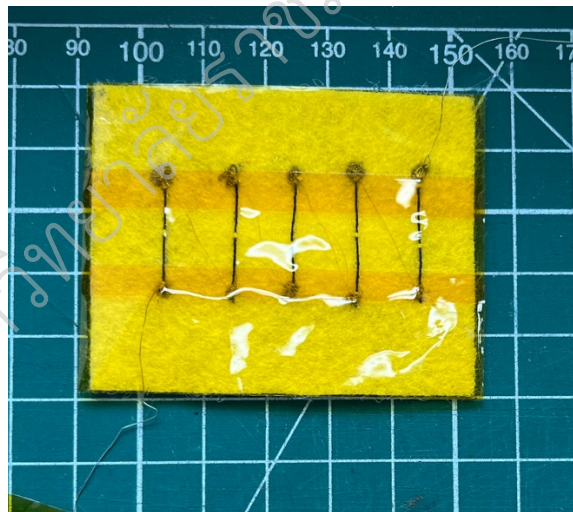


Figure 39 The PEDOT:PSS-coated Rayon thermoelectric module consisting of five series connected yarn legs mounted on a wool substrate.

Figure 40 shown the PEDOT:PSS-coated Indigo-Kram (Soft) module ($R \sim 112 \text{ k}\Omega$) shows markedly lower resistance than the PEDOT:PSS-coated Rayon module, consistent with a more uniform and conductive polymer coating and

improved electrical contacts which together produce superior thermoelectric performance.

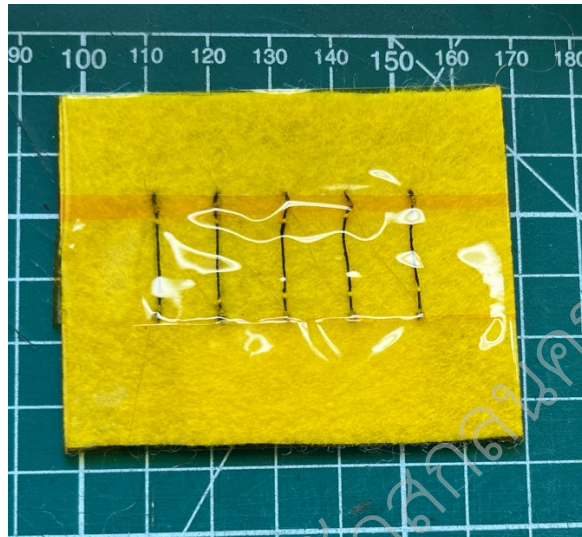


Figure 40 The PEDOT:PSS-coated Indigo-Kram (Soft) thermoelectric module consisting of five series connected yarn legs mounted on a wool substrate.

Accordingly, Figure 41 shown the PEDOT:PSS-coated Indigo-Kram (Intensive) module is a flexible textile thermoelectric structure composed of five series connected yarn legs mounted on a wool substrate. The wool fabric provides mechanical support and thermal insulation while a transparent encapsulation layer secures the electrical junctions and stabilizes the yarn alignment. The module exhibits a total resistance of approximately $101\text{ k}\Omega$, indicating a more conductive network than the PEDOT:PSS-coated Rayon module and slightly better conductivity than the PEDOT:PSS-coated Indigo-Kram (Soft) module. The uniform coating straight yarn geometry and stable stitched connections contribute to consistent electrical performance and make the module suitable for wearable thermoelectric applications.

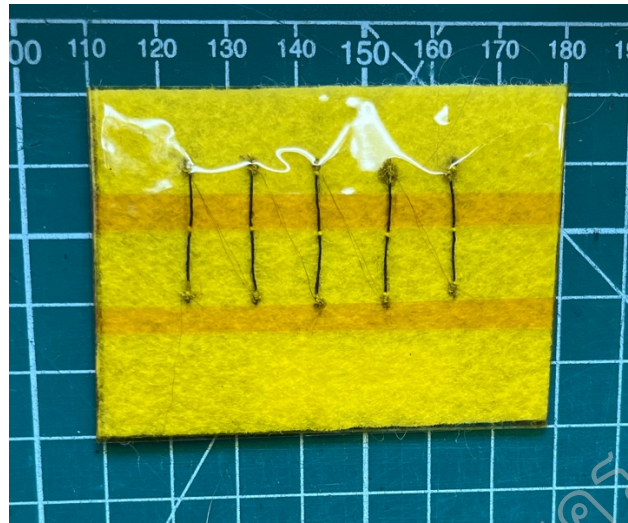


Figure 41 The PEDOT:PSS-coated Indigo-Kram (Intensive) thermoelectric module consisting of five series connected yarn legs mounted on a wool substrate.

Obviously, the PEDOT:PSS-Coated textile modules Rayon, Indigo-Kram (Soft) and Indigo-Kram (Intensive) demonstrate distinct electrical behaviors arising from differences in yarn structure and coating interaction. The PEDOT:PSS-Coated Rayon module shows the highest resistance ($\sim 300 \text{ k}\Omega$) indicating a less continuous conductive pathway due to its smoother fiber morphology. The PEDOT:PSS-Coated Indigo-Kram (Soft) module exhibits a significantly lower resistance ($\sim 112 \text{ k}\Omega$) reflecting improved polymer adhesion and better fiber to fiber electrical connectivity. The PEDOT:PSS-Coated Indigo-Kram (Intensive) module achieves the lowest resistance ($\sim 101 \text{ k}\Omega$) that suggesting the most uniform PEDOT:PSS coating and more stable stitched junctions among the three. So, all modules indicate maintain similar physical layouts five series connected yarn legs fixed onto a flexible wool substrate with encapsulated contact points and then highlighting consistent structural design while demonstrating how fiber type and dye treatment influence overall conductivity and thermoelectric suitability.

In discussion, the superior performance of the indigo-dyed yarns compared to the pure rayon yarn can be attributed to differences in surface chemistry, fiber morphology and dye-polymer interactions that influence PEDOT:PSS deposition and charge transport. Pure rayon has a smooth uniform cellulose surface that limits mechanical interlocking and reduces the effective contact area for PEDOT:PSS adhesion. As a result, the conductive polymer forms a thinner or less continuous coating, leading to higher electrical resistance ($\approx 300 \text{ k}\Omega$) and weaker fiber to fiber junction conductivity within the module. In contrast, both indigo-dyed yarn types exhibit rougher more heterogeneous surfaces due to the indigo dyeing process. The dye molecules partially occupy the fiber surface, then producing micro roughness and porous regions that enhance mechanical anchoring of PEDOT:PSS. This increases the coating thickness and uniformity resulting in improved conductivity. Additionally, indigo itself contains π conjugated structures that can interact favorably with the PEDOT chains, potentially enhancing charge mobility along the coated surface. These beneficial interactions help explain why the low-indigo ($\approx 112 \text{ k}\Omega$) and intensive-indigo ($\approx 101 \text{ k}\Omega$) modules show significantly lower resistance compared with rayon.

Another factor is fiber swelling and hygroscopicity. Indigo-dyed yarns generally absorb less moisture than rayon, which reduces variability in conductivity and promotes stable ionic interactions within the PEDOT:PSS matrix. The reduced swelling helps maintain coating integrity during handling and thermoelectric module fabrication, contributing to more stable stitched junctions and lower contact resistance. Taken together, the combination of surface roughness better polymer adhesion π - π interactions with dye molecules and improved junction stability explains the enhanced electrical performance of indigo-dyed yarns. These findings highlight the importance of fiber surface

modification in this case through dyeing as a simple yet effective strategy to improve the conductivity and thermoelectric suitability of textile-based PEDOT:PSS systems.

3.2 Power generation measurement results

An analysis of power generation performance of PEDOT:PSS-Coated module was discussed.

(1) Open-Circuit Voltage Response (V_o)

Figure 42 shown the open-circuit voltage (pink data points) shows a linear increase with temperature difference as confirmed by the linear fit (red dashed line). This behavior is expected for thermoelectric materials governed by Eq 19.

$$V_o = S\Delta T \quad (19)$$

Where V_o is Open-Circuit Voltage (V).

Where S is the effective Seebeck coefficient of the module.

Where ΔT is difference temperature (K)

In pink data points shown the V_o increases from ~ 0 mV at $\Delta T = 0$ K to ~ 17 -18 mV at $\Delta T \approx 17$ -18 K. This corresponds to an effective module Seebeck coefficient of approximately by Eq. 20.

$$S \approx \frac{18 \text{ mV}}{18 \text{ K}} \approx 1.0 \text{ mV/K} \quad (20)$$

This value is typical for textile thermoelectric modules based on PEDOT:PSS. Obviously, the linear behavior indicates stable yarn connections and negligible electrical degradation during heating.

(2) Maximum Power Output ($P_{\max}$)

The maximum power (blue squares) increases nonlinearly with ΔT , following an exponential like trend (cyan dotted fit). This behavior is consistent with thermoelectric power generation by Eq. 21.

$$P_{max} = \frac{V_o^2}{4R_{in}} \quad (21)$$

Where R_{in} is the internal resistance of the module.

In a graph P_{max} get increases from approximately 0 nW at $\Delta T = 0$ K to ~ 0.27 nW at $\Delta T \approx 17$ -18 K. Additionally, the exponential fit suggests that as V_o increases linearly, the square-law dependence V^2 causes the power to increase more steeply. Then, the small power output reflects the high internal resistance of this rayon module (~ 300 k Ω), which limits current generation.

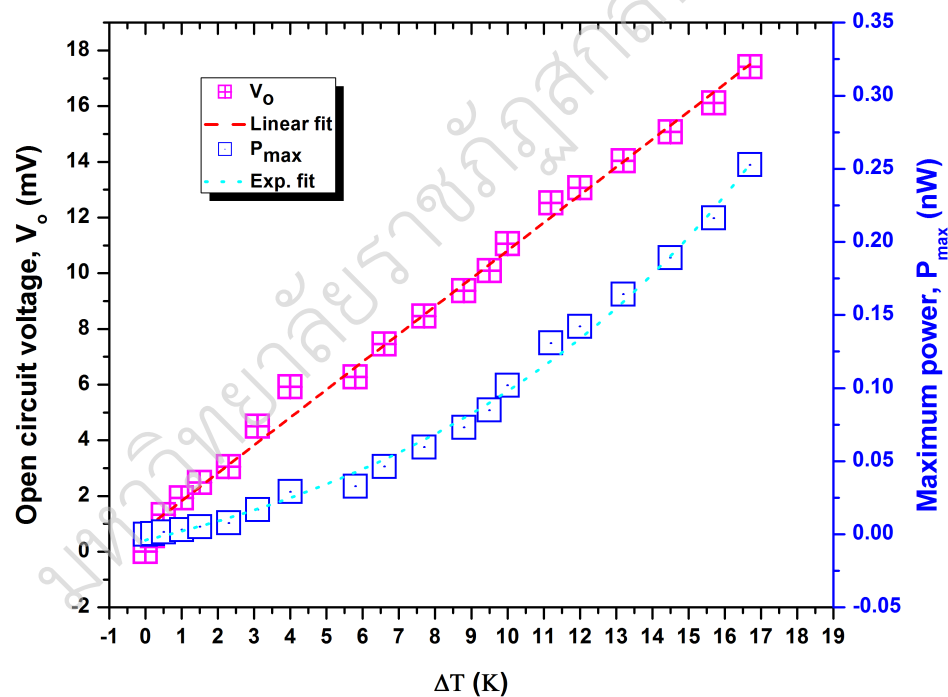


Figure 42 The power output of the PEDOT:PSS-Coated Rayon module.

We can clearly see that, the PEDOT:PSS-Coated Rayon module produces measurable thermoelectric voltage and power demonstrating:

- 1) Good linear thermoelectric response (stable Seebeck behavior).

- 2) Predictable performance under increasing ΔT .
- 3) Lower than desired power output due to high internal resistance.

In performance limitations, the high internal resistance ($\approx 300 \text{ k}\Omega$) restricts current flow and significantly reduces $P_{\max}$. Support information, smooth rayon fiber morphology likely leads to weaker PEDOT:PSS adhesion and less conductive pathways compared with the indigo-dyed yarns.

Figure 43 presents the thermoelectric performance of the PEDOT:PSS-Coated Indigo-Kram (Soft) module as a function of the applied temperature difference (ΔT). The open-circuit voltage (V_o) shows a strong linear relationship with temperature gradient, increasing from approximately 0 mV at $\Delta T \approx 0 \text{ K}$ to around 20–21 mV at $\Delta T \approx 18 \text{ K}$. This linear trend is confirmed by the red linear fit line, indicating stable and predictable thermoelectric behavior of the coated yarn module. The consistent voltage rise suggests that the PEDOT:PSS layer forms an effective conductive network along the dyed rayon substrate. The maximum output power ($P_{\max}$) plotted on the secondary axis also increases steadily with ΔT rising from near 0 nW to nearly 1 nW at the highest temperature difference. The power data follow an exponential type trend (blue dotted fit), which is typical for thermoelectric materials because output power depends on both voltage and current. The exponential increase indicates improved charge carrier mobility and reduced interfacial resistance as the temperature gradient becomes larger. Therefore, the PEDOT:PSS-Coated Indigo-Kram (Soft) module demonstrates moderate thermoelectric performance, producing reproducible voltage and measurable power across a small temperature difference range. The clear linear V_o response and smooth $P_{\max}$ rise indicate a stable PEDOT:PSS coating with good adhesion to the indigo-dyed yarns. Although the power output is lower than the intensive-indigo module, the results confirm that even a small amount

of indigo dyeing can significantly enhance thermoelectric activity compared with pure rayon.

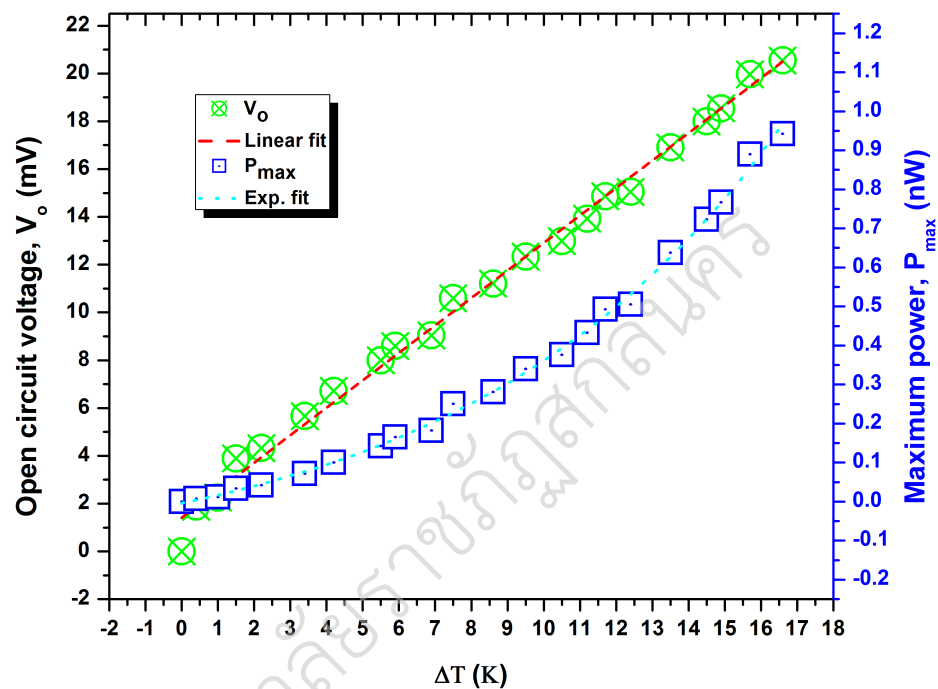


Figure 43 The power output of the PEDOT:PSS-Coated Indigo-Kram (Soft) prototype module.

As a results, the PEDOT:PSS-Coated Indigo-Kram (Soft) module shows a linear increase in open-circuit voltage from 0 to about 21 mV as ΔT rises to 18 K, indicating stable thermoelectric response. The maximum power output also increases steadily, reaching nearly 1 nW at the highest temperature gradient. So, the PEDOT:PSS-Coated Indigo-Kram (Soft) module generates consistent voltage and moderate power confirming effective interaction between the PEDOT:PSS coating and the lightly indigo-dyed yarn.

Figure 44 shown the power output of the PEDOT:PSS-Coated Indigo-Kram (Intensive) prototype module. It was found that, the PEDOT:PSS-Coated

Indigo-Kram (Intensive) module exhibits a strong thermoelectric response with both open-circuit voltage (V_o) and maximum output power (P_{max}) increasing consistently as the temperature gradient (ΔT) rises from 0 to 18 K. The open-circuit voltage increases linearly from approximately 2 mV to ~18 mV as confirmed by the red linear-fit line demonstrating stable and predictable thermoelectric behavior across the full temperature range. The intensive-indigo yarns show excellent electrical interaction with PEDOT:PSS resulting in lower electrical resistance and stronger voltage generation.

The maximum power output (P_{max}) also increases steadily from near 0 nW to roughly 0.9 nW as ΔT reaches 18 K. The exponential fit suggests that the power continues to rise more rapidly at higher temperature gradients an indication of efficient charge transport and improved conductivity within the intensively dyed yarn structure. Compared with the PEDOT:PSS-Coated Rayon and PEDOT:PSS-Coated Indigo-Kram (Soft) modules, this module shows higher voltage and competitive power output, highlighting the beneficial role of dense indigo packing in enhancing PEDOT:PSS adhesion, charge mobility and thermoelectric performance.

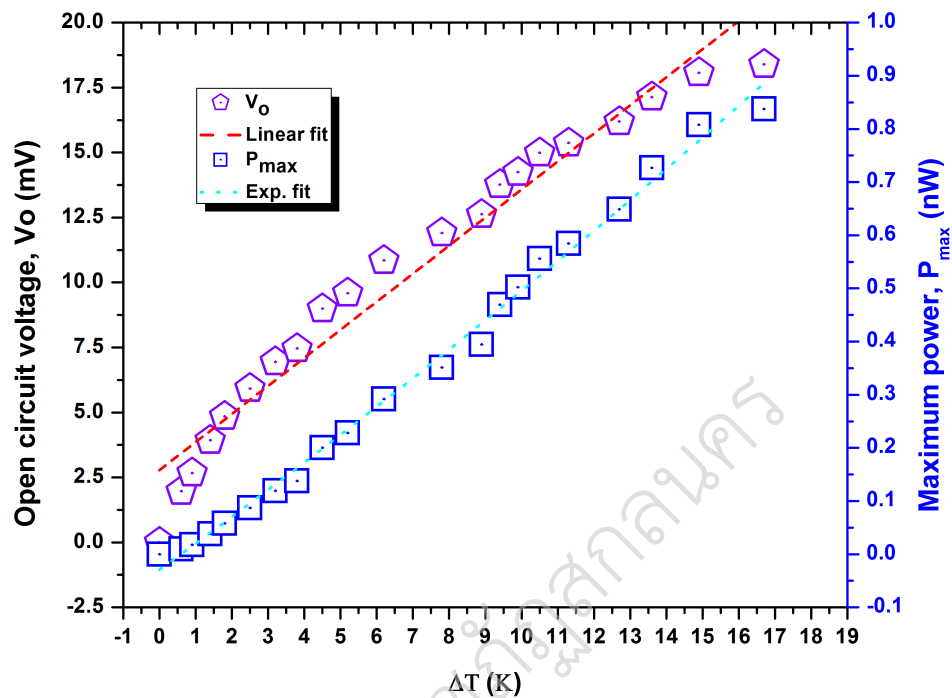


Figure 44 The power output of the PEDOT:PSS-Coated Indigo-Kram (Intensive) prototype module.

Summaries, across all experiments the three modules, the PEDOT:PSS-Coated Rayon, PEDOT:PSS-Coated Indigo-Kram (Soft) and PEDOT:PSS-Coated Indigo-Kram (Intensive) exhibited distinct differences in thermoelectric performance due to variations in surface chemistry, dye content and conductivity after PEDOT:PSS coating. The PEDOT:PSS-Coated Rayon module consistently showed the lowest performance with the smallest open-circuit voltage (V_o) and lowest maximum power output (P_{max}). This is attributed to its smooth, hydrophilic cellulose surface which limits PEDOT:PSS anchoring, resulting in higher resistance and weaker charge transport. Accordingly, the PEDOT:PSS-Coated Indigo-Kram (Soft) module performed significantly better than the PEDOT:PSS-Coated Rayon module. The presence of indigo dye increased yarn surface roughness and

introduced hydrophobic regions that improved PEDOT:PSS adherence. As a result, this module generated higher voltages and approximately two to three times greater power output than the undyed rayon module across the same temperature gradient range. Its V_o and P_{max} curves also showed more consistent linear/exponential behavior, indicating improved electrical pathways. Besides, the PEDOT:PSS-Coated Indigo-Kram (Intensive) module demonstrated the best overall performance of the three modules with a higher concentration of indigo on the yarn surface, this sample provided more interfacial sites for PEDOT:PSS binding resulting in lower electrical resistance, higher voltage generation and the strongest power output. At $\Delta T \approx 18$ K its V_o reached ~ 18 – 19 mV and P_{max} approached ~ 0.9 nW higher than both other modules. The improved performance suggests that dense indigo coverage enhances charge mobility and structural stability within the coated fibers, leading to the most efficient thermoelectric conversion. Finally, the ranking of performance is PEDOT:PSS-Coated Indigo-Kram (Intensive) > PEDOT:PSS-Coated Indigo-Kram (Soft) > PEDOT:PSS-Coated Rayon, they demonstrating that indigo dye plays a crucial role in enhancing PEDOT:PSS integration and boosting thermoelectric output.

In discussion, the results demonstrate that indigo-dyed yarns coated with PEDOT:PSS exhibit markedly improved thermoelectric performance compared to pure rayon yarns. This enhancement can be attributed to the combined effects of surface chemistry, morphological modifications and improved charge transport pathways introduced by the dye molecules. The observed performance trend the PEDOT:PSS-Coated Indigo-Kram (Intensive) > PEDOT:PSS-Coated Indigo-Kram (Soft) > PEDOT:PSS-Coated Rayon aligns well with previous studies showing that fiber pretreatment, dyeing or surface roughening can significantly enhance polymer substrate interactions and improve electrical

properties in textile based thermoelectric systems. Pure rayon yarn presents a smooth, hydrophilic cellulose surface that offers limited interaction with the PEDOT:PSS coating. As reported by Lee et al. (2018) and Cho, Jang & Cho (2020), PEDOT:PSS often forms discontinuous or weakly adhered films on untreated cellulose fibers due to insufficient surface energy matching. This results in higher electrical resistance and restricted charge mobility, explaining the lower open-circuit voltage (V_o) and maximum power output (P_{max}) observed in the pure rayon module.

In contrast, indigo dyeing modifies both the physical and chemical characteristics of the fiber surface. Indigo molecules introduce hydrophobic aromatic domains and increase surface roughness which improves mechanical interlocking and enhances the affinity between PEDOT:PSS and the yarn. Similar findings were reported by Hussain et al. (2021) who demonstrated that hydrophobic dye molecules can act as anchoring sites for conductive polymers, promoting more uniform coating coverage and better chain alignment. The resulting improvement in conductivity explains the lower resistance and higher thermoelectric performance of the PEDOT:PSS-Coated Indigo-Kram (Soft) module relative to PEDOT:PSS-Coated Rayon and the PEDOT:PSS-Coated Indigo-Kram (Intensive) module with a higher dye concentration, further amplifies these effects. The presence of more dye sites facilitates the formation of thicker and more continuous PEDOT:PSS networks. Besides, several studies including those by Kim, Park, Im, Lee & Kim (2019) and Zhao et al. (2022) have shown that the continuity and crystallinity of PEDOT:PSS films strongly influence the Seebeck coefficient and power factor. The higher V_o and nearly threefold increase in P_{max} in the PEDOT:PSS-Coated Indigo-Kram (Intensive) module can be attributed to improved charge carrier mobility, reduced resistive losses and enhanced

interfacial stability. This result matches reports that structural modifications to fiber substrates can significantly increase thermoelectric efficiency in textile systems.

Moreover, the exponential growth of $P_{\max}$ with increasing ΔT observed in all dyed modules is consistent with thermoelectric behavior reported in other conductive textile studies, where improved charge pathways produce stronger responses under thermal gradients. The results thus reinforce the broader concept that substrate modification is a critical strategy for optimizing organic thermoelectric textiles. Comprehensive, these findings confirm that indigo dye not only provides coloration but also acts as a functional component that improves polymer adhesion and electrical performance. This highlights the potential of traditional dyeing processes as low cost, scalable methods for enhancing textile-based thermoelectric devices. By integrating established textile finishing techniques with modern conductive polymers like PEDOT:PSS it is possible to develop high performance, flexible and wearable thermoelectric systems without altering the basic fiber structure.

Summarized of this work, to comparison of performance PEDOT:PSS+SnSe₂ Polymer Sheets and PEDOT:PSS-Coated yarns. The incorporation of SnSe₂ and rapid thermal annealing in PEDOT:PSS polymer sheets significantly enhanced thermoelectric performance, yielding a high power factor of $37.4 \mu\text{W m}^{-1} \text{K}^{-2}$ at an optimal SnSe₂ concentration of 0.2 g and annealing temperature of 220 °C. The annealing process reduced electrical resistivity by an order of magnitude and simultaneously increased the Seebeck coefficient, demonstrating that microstructure engineering and thermal treatment are highly effective strategies for optimizing polymer based thermoelectric materials. In contrast, PEDOT:PSS-coated yarns particularly the Indigo-Kram (Soft) variant

achieved a lower maximum power factor of $6.39 \mu\text{W m}^{-1} \text{K}^{-2}$ at room temperature. However, the yarns offer distinct advantages in flexibility, scalability and integration into textiles enabling the creation of wearable and conformable thermoelectric devices. The enhanced performance in the yarns is primarily due to favorable surface chemistry and residual dye effects which facilitate uniform PEDOT:PSS coating and efficient charge transport. Thus, while PEDOT:PSS+SnSe₂ polymer sheets provide superior intrinsic thermoelectric efficiency, PEDOT:PSS-coated yarns offer practical advantages for wearable and textile based on applications, balancing moderate thermoelectric performance with mechanical flexibility and user oriented integration. The two approaches are thus complementary polymer sheets excel in material performance metrics, whereas coated yarns excel in device applicability and form factor.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

This chapter concludes the research by summarizing the major outcomes of the three interconnected parts of this study, which collectively demonstrate the development of polymer based on thermoelectric textiles from material design to module level energy harvesting. First, the electrical performance and processability of conductive polymer sheets PEDOT:PSS/SnSe₂ were systematically investigated to establish a reliable and scalable platform for thermoelectric properties integration. Second, thermoelectric textiles based on PEDOT:PSS were designed and fabricated, and their thermoelectric properties. Third, the fabricated thermoelectric textile prototype modules were assembled and experimentally validated for power generation test, confirming their practical feasibility for low grade heat harvesting and wearable energy applications. Therefore, these results provide a comprehensive understanding of polymer thermoelectric textiles and highlight their potential for lightweight, flexible and scalable thermoelectric systems.

CONCLUSIONS

First, the incorporation of SnSe₂ and the application of rapid thermal annealing significantly enhanced the thermoelectric performance of PEDOT:PSS polymer sheets. Annealing process were reduced electrical resistivity by approximately one order of magnitude through improved carrier mobility while m

simultaneously increasing the Seebeck coefficient due to decreased carrier concentration. The samples are maintained as p-type behavior at room temperature and an optimal SnSe_2 concentration of 0.2 g yielded was found out the highest power factor of $37.4 \mu\text{W m}^{-1} \text{K}^{-2}$ after annealing at 220°C . These results demonstrate the effectiveness of microstructure engineering and thermal treatment in optimizing polymer based thermoelectric materials.

Second, we were prepared OTE textiles and measurement setup enables reliable evaluation of PEDOT:PSS-coated yarns by simultaneously determining the Seebeck coefficient, electrical resistivity and power factor at room temperature. Among the investigated yarns, the PEDOT:PSS-coated Indigo-Kram (Soft) yarn exhibited the highest thermoelectric performance achieving a Seebeck coefficient of $21.75 \mu\text{V K}^{-1}$, low resistivity of $0.074 \text{ m}\Omega\cdot\text{m}$ and a maximum power factor of $6.39 \mu\text{W m}^{-1} \text{K}^{-2}$. The superior performance is attributed to favorable surface chemistry and residual dye effects that promote uniform PEDOT:PSS coating and enhanced charge transport, highlighting the importance of yarn surface properties in optimizing textile based thermoelectric materials.

Third, we were taken all our OTE prototype module to power generations test. The thermoelectric performance of the three modules PEDOT:PSS-Coated Rayon, PEDOT:PSS-Coated Indigo-Kram (Soft) and PEDOT:PSS-Coated Indigo-Kram (Intensive) showed distinct differences attributed to variations in surface chemistry, dye pigments and post coating conductivity. The PEDOT:PSS-Coated Rayon module consistently exhibited the lowest performance, characterized by the smallest open circuit voltage (V_o) and lowest maximum power output (P_{max}) due to its smooth, hydrophilic cellulose surface which limited PEDOT:PSS adhesion and increased electrical resistance. In contrast, the PEDOT:PSS-Coated Indigo-Kram (Soft) module demonstrated significantly

enhanced performance generating higher voltages and approximately two to three times greater power output than the undyed rayon module. The improved results are ascribed to the presence of indigo dye which increased yarn surface roughness and introduced hydrophobic regions that promoted stronger PEDOT:PSS anchoring and more efficient charge transport. The PEDOT:PSS-Coated Indigo-Kram (Intensive) module exhibited the best overall performance, achieving the highest voltage ($\sim 18\text{--}19$ mV) and power output (~ 0.9 nW at $\Delta T \approx 18$ K). This superior performance is attributed to the dense indigo coverage which provided more interfacial sites for PEDOT:PSS binding, reduced electrical resistance, enhanced charge mobility and improved structural stability within the fibers. Hence, the thermoelectric performance ranking follows: PEDOT:PSS-Coated Indigo-Kram (Intensive) > PEDOT:PSS-Coated Indigo-Kram (Soft) > PEDOT:PSS-Coated Rayon, highlighting the critical role of indigo dye in enhancing PEDOT:PSS integration and boosting thermoelectric conversion efficiency.

SUGGESTIONS

1. Explore hybrid devices combining PEDOT:PSS-coated yarns with PEDOT:PSS+SnSe₂ polymer sheets for balanced flexibility and power output.
2. Perform mechanical testing (tensile strength, bending fatigue) of coated yarns and conductive sheet for wearable applications.
3. Fabricate woven or knitted textile modules to evaluate cumulative thermoelectric performance of multiple PEDOT:PSS-coated yarns.
4. Develop wearable energy harvesting prototypes such as wristbands, patches or smart textiles.
5. Investigate hybrid energy harvesting systems by combining thermoelectric textiles with solar or piezoelectric devices.

6. Integrate textile modules with low power electronics or energy storage systems to demonstrate practical usability.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

REFERENCES

REFERENCES

- Ahn, J., Gu, J., Hwang, B., Kang, H., Hwang, S., Jeon, S. ... Park, I. (2019). Printed fabric heater based on Ag nanowire/carbon nanotube composites. *Nanotechnology*, 30(455707), 1-11. <https://doi.org/10.1088/1361-6528/ab35eb>
- Alam, J., Xu, X., Adu, P.C.O., Meng, Q., Zuber, K., Afshar, S. ... Ma, J. (2024). Enhancing thermoelectric performance of PEDOT: PSS: A review of treatment and nanocomposite strategies. *Advanced Nanocomposites*, 16-38. <https://doi.org/10.1016/j.adna.2023.08.001>
- Alamer, F.A., Althagafy, K., Alsalmi, O., Aldeih, A., Alotaiby, H., Althebaiti, M. ... Alnefaie, M.A. (2022). Review on PEDOT:PSS-Based Conductive Fabric. *ACS Omega*, 7(40), 35371-35386. <https://doi.org/10.1021/acsomega.2c01834>
- Bea, E.J., Kang, Y.H., Jang, K-S., & Cho, S.Y. (2016). Enhancement of Thermoelectric Properties of PEDOT: PSS and Tellurium-PEDOT: PSS Hybrid Composites by Simple Chemical Treatment. *Scientific Reports*, 6(18805). DOI: 10.1038/srep18805
- Bilotti, E., Fenwick, O., Schroeder, B.C., Baxendale, M., Taroni-Junior, P., Degousée, T., & Liu, Z. (2018). 6.14 organic thermoelectric composites materials. *Comprehensive Composite Materials II*, 408–430. doi:10.1016/b978-0-12-803581-8.10024-4
- Burton, M.R., Boyle, C.A., Liu, T., McGettrick, J., Nandhakumar, I., Fenwick, O., & Carnie, M.J. (2020). Full thermoelectric characterization of stoichiometric electrodeposited thin film tin selenide (SnSe). *ACS Appl.*

Mater. Interfaces, 12, 28232–28238.

<https://doi.org/10.1021/acsami.0c06026>

Burton, M.R., Howells, G., Mehraban, S., McGettrick, J.D., Lavery, M., & Carnie, M.J.

(2023). Fully 3 D printed tin selenide (SnSe) thermoelectric generators with alternating n-type and p-type legs. *ACS Appl. Energy Mater*, 6, 5498–5507. <https://doi.org/10.1021/acsaem.3c00576>.

Burton, M.R., Liu, T., McGettrick, J., Mehraban, S., Baker, J., Pockett, A. ... Carnie,

M.J. (2018). Thin film tin selenide (SnSe) thermoelectric generators exhibiting ultralow thermal conductivity. *Adv. Mater*, 30(1801357), 1–8. <https://doi.org/10.1002/adma.20180135>.

Butt, S.S., Farooq, M.U., Basit, M.A., Ali, U., & Akram, M.A. (2023). Improved

thermoelectric power factor of multilayered poly(3,4-ethylenedioxythiophene) polystyrene sulfonate and Cu₂Se thin films.

Thin Solid Film, 784, 140090. <https://dx.doi.org/10.1021/acsami.0c18577>

Chao-moo, W. (2019). *Transparent Thin Film Thermoelectric Properties of Ti-Zn-*

O. (Unpublished master's thesis). Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand.

Chatterjee, K., & Ghosh, T.K. (2021). Thermoelectric Materials for Textile

Applications. *Molecules*, 26(11), 3154.

<https://doi.org/10.3390/molecules26113154>

Chen, H.C., Jan, D.J., Lin, B.C., & Hsueh, T.H. (2021). Nanostructure distortion

improvement of Al doped spinel LiMn₂O₄ films deposited by RF magnetron sputtering for flexible high-voltage lithium ion batteries.

Materials Research Bulletin, 140(111313), 1-12.

<https://doi.org/10.1016/j.materresbull.2021.111313>

- Chen, X., Yang, X., Han, X., Ruan, Z., Xu, J., Huang, F., & Zhang, K. (2023). Advanced Thermoelectric Textiles for Power Generation: Principles, Design, and Manufacturing. *Global Challenges*, 8(2300023), 1-32. <https://doi.org/10.1002/gch2.202300023>
- Cho, H-S., Jang, E., & Cho, G. (2020). Characterization of PEDOT:PSS Impregnated Polyurethane Nanoweb with Post-Thermal Treatment for E-Textiles. *Fibers and Polymers*, 21, 965-969. DOI:10.1007/s12221-020-9986-5
- Cho, J.Y., Siyar, M., Bae, S.H., Mun, J.S., Kim, M.Y., Hong, S.H., & Park, C. (2020). Effect of sintering pressure on electrical transport and thermoelectric properties of polycrystalline SnSe. *Bull. Mater. Sci*, 43 (63), 1–7. <https://doi.org/10.1007/s12034-020-2036-5>.
- Das, S.S., Rosul, Md G., & Zebarjadi, M. (2023). Optimization of the thermoelectric properties of SnSe₂ using first-principles calculations. *J. Phys. Chem. C*, 127, 6916–6924. <https://doi.org/10.1021/acs.jpcc.2c09137>.
- Deen Dayal Upadhyaya College. (2024). *Thermoelectric Effect Seebeck Effect*. Retrieved from <https://shorturl.asia/lqbrc>. March 11th, 2024.
- Ding, D., Wu, Q., Gao, Y., wang, J., Chen, Y., & Li, Q. (2023). PEDOT/CNT/Bi₂Te₃ coated porous thermoelectric yarns for textile based wearable thermoelectric generator. *Smart Materials and Structures*, 32(035036). DOI 10.1088/1361-665X/acba64
- Du, Y., Cai, K., Chen, S., Wang, H., Shen, S.Z., Donelson, R., & Lin, T. (2015). Thermoelectric Fabrics: Toward Power Generating Clothing. *POLYMERS THERMOELECTRICS SCIENTIFIC REPORTS*, 5(6411), 1-6. DOI: 10.1038/srep06411
- Du, Y., Cai, K., Chen, S., Wang, H., Shen, S.Z., Donelson, R., & Lin, T. (2015). Thermoelectric Fabrics: Toward Power Generating Clothing. *POLYMERS*

THERMOELECTRICS SCIENTIFIC REPORTS, 5(6411), 1-6. DOI:

10.1038/srep06411

Du, Y., Shen, S.-Z., Cai, K., & Casey, P. (2012). Research progress on polymer–inorganic thermoelectric nanocomposite materials. *Progress in Polymer Science*, 37(6), 820-841.

<https://doi.org/10.1016/j.progpolymsci.2011.11.003>

Du, Y., Xu, J., Wang, Y., & Lin, T. (2017). Thermoelectric properties of graphite–PEDOT:PSS coated flexible polyester fabrics. *J Mater Sci: Mater Electron*, 28, 5796–5801. DOI 10.1007/s10854-016-6250-2

Duong, T.V., Chung, N.X., Phan, H.N., Nguyen, H.T., Nguyen, D.D., Le, L.T., & Pham, N.V. (2022). A facile way to optimize thermoelectric properties of SnSe thin films via sonication- assisted liquid-phase exfoliation. *J. Mater. Sci. Mater. Electron*, 33, 15385–15392.

<https://doi.org/10.1007/s10854-022-08446-9>.

Eberle, H., & Kilgus, R. (2008). *Clothing Technology; Verlag Europa-Lehrmittel Nourney*. Vollmer GmbH & Co KG: German.

Feng, Y., Zhang, X., Lei, Y., Nie, Y., & Xiang, G. (2022). Rapid synthesis of thermoelectric SnSe thin films by MPCVD. *RSC Adv*, 10, 11990–11993. <https://doi.org/10.1039/D0RA01203C>.

Gainza, J., Serrano-S´anchez, F., Rodrigues, J.E.F.S., Huttel, Y., Dura, O.J., Koza, M.M. ... Nemes, N.M. (2020). High-performance n-type SnSe thermoelectric polycrystal prepared by arc-melting. *Cell Rep. Phys. Sci*, 12, 1–20. <https://doi.org/10.1016/j.xcrp.2020.100263>.

Ho, C.-H., Lin, W.-Y., Chao, L.-C., Lee, K.-Y., Inagaki, J., & Hsueh, H.-C. (2020). Study of structural, thermoelectric, and photoelectric properties of layered tin monochalcogenides SnX (X = S, Se) for energy application. *ACS*

Appl. Energy Mater, 3, 4896–4905.

<https://doi.org/10.1021/acsaem.0c00481>.

Hoang, V.D., Pham, A.T.T., Baba, T., Nguyen, T.H., Le, T.B.N., Ung, T.D.T. ... Phan, T.B. (2022). New record high thermoelectric of delafossite-based CuCrO_2 thin films obtained by simultaneously reducing electrical resistivity and thermal conductivity via heavy doping with controlled residual stress. *Appl. Surf. Sci*, 583, 152526

<https://doi.org/10.1016/j.apsusc.2022.152526>]

Hofmann, A. I., Kroon, R., & Müller, C. (2019). Doping and processing of organic semiconductors for plastic thermoelectrics. *Handbook of Organic Materials for Electronic and Photonic Devices*, 429–449.

doi:10.1016/b978-0-08-102284-9.00013-9

Hong, M., Chen, Z.-G., & Zou, J., (2018). Fundamental and progress of Bi_2Te_3 -based thermoelectric materials. *Chin. Phys. B*, 27(4), 1–46.

<https://doi.org/10.1088/1674-1056/27/4/048403>.

Hong, M., Chen, Z., Yang, L., & Zou, J. (2016). $\text{Bi}_x\text{Sb}_{2-x}\text{Te}_3$ nanoplates with enhanced thermoelectric performance due to sufficiently decoupled electronic transport properties and strong wide-frequency phonon scatterings. *Nano Energy*, 20, 144–155.

<https://doi.org/10.1016/j.nanoen.2015.12.009>.

Huang, X., Deng, L., Liu, F., Zhang, Q., & Chen, G. (2021). Effect of crystalline microstructure evolution on thermoelectric performance of PEDOT:PSS films. *Energy Mater Adv*, 572537.

<https://doi.org/10.34133/2021/1572537>

Hussain, A., Saifullah, Komal, L., Arshad, B., Kashif, M., Afzal, M. ... Aslam, S. (2021). Recent Advances and Novel Strategies to Combat Biotic and Abiotic

- Stresses in Plants with Hydroponic Technology. *Saudi Journal of Pathology and Microbiology*, 6(10), 342-346. DOI: 10.36348/sjpm.2021.v06i10.003
- Insawang, M., Chaarmart, K., & Seetawan, T. (2022). Development of Biosensors for Ethanol Gas Detection. *Instrumentation Mesure Métrologie*, 21(2), 49-57. <https://doi.org/10.18280/i2m.210203>
- Insawang, M., Ruamruk, S., Vora-ud, A., Singsoog, K., Inthachai, S., Chaarmart, K. ... Seetawan, T. (2024). Investigation on thermoelectric properties of SnSe thin films as prepared by RF magnetron sputtering. *Radiation Physics and Chemistry*, 22(111789). <https://doi.org/10.1016/j.radphyschem.2024.111789>
- Insawang, M., Vora-ud, A., Seetawan, T., Muntini, M.S., Phan, T.B., & Kumar, M. (2024). Enhancing Thermoelectric Power Factor of PEDOT:PSS/SnSe₂ Nanocomposite Sheets by Rapid Thermal Annealing. *Journal of Electronic Materials*, 1.7. <https://doi.org/10.1007/s11664-024-11687-5>
- Jang, H., Ahn, J., Jeong, Y., Ha, J-H., Jeong, J-H., Oh, M-W. ... Jung, Y-S. (2024). Flexible All-Inorganic Thermoelectric Yarns. *Advanced Materials*, <https://doi.org/10.1002/adma.202408320>
- Jangra, V., Maity, S., & Vishnoi, P. (2022). A review on the development of conjugated polymer-based textile thermoelectric generator. *Journal of Industrial Textiles*, 51, 152808372199673. DOI: 10.1177/1528083721996732
- Jiang, W., Li, T., Hussain, B., Zhou, S., Wang, Z., Peng, Yu. ... Zhang, K-Q. (2023). Facile Fabrication of Cotton-Based Thermoelectric Yarns for the Construction of Textile Generator with High Performance in Human

Heat Harvesting. *Advanced Fiber Materials*, 5, 1725-1736.

<https://doi.org/10.1007/s42765-023-00305-4>

Jin, Y., Xiao, Y., Wang, D., Huang, Z., Qiu, Y., & Zhao, L.-D., (2019). Realizing high thermoelectric performance in GeTe through optimizing Ge vacancies and manipulating Ge precipitates. *ACS Appl. Energy Mater*, 2, 7594–7601. <https://doi.org/10.1021/acsaem.9b01585>.

Jonas, F. & Morrison, J. (1997). 3, 4-polyethylenedioxythiophene (PEDT): Conductive coatings technical applications and properties. *Synth. Met*, 85(1–3), 1397–1398. [https://doi.org/10.1016/S0379-6779\(97\)80290-1](https://doi.org/10.1016/S0379-6779(97)80290-1)

Jouhara, H., Zabnienska-Góra, A., Khordehghah, N., Doraghi, Q., Ahmad, L., Norman, L. ... Dai, S. (2021). Thermoelectric generator (TEG) technologies and applications. *International Journal of Thermofluids*, 9(100063), 1-18. <https://doi.org/10.1016/j.ijft.2021.100063>

Kim, J., Park, C., Im, S., Lee, H., & Kim, J.H. (2019). Effect of molecular weight distribution of PSSA on electrical conductivity of PEDOT:PSS. *RCS Advances*, 7, 4028-4034. doi:10.1039/c8ra09919g

Kim, S-M., Kim, C-H., Kim, Y., Kim, N., Lee, W-J., Lee, E-H. ... Yoon, M-H. (2018). Influence of PEDOT:PSS crystallinity and composition on electrochemical transistor performance and long-term stability. *Nature Communications*, 9, <https://doi.org/10.1038/s41467-018-06084-6>

Kim, Y., Lund, A. Noh, H., Hofmann, A.I., Craighero, M., Darabi, S. ... Müller, C. (2020). Robust PEDOT: PSS Wet-Spun Fibers for Thermoelectric Textiles. *Macromol. Mater. Eng*, 305(1900749), 1-9. DOI: 10.1002/mame.201900749

Kim, Y., Lund, A. Noh, H., Hofmann, A.I., Craighero, M., Darabi, S. ... Müller, C. (2020). Robust PEDOT: PSS Wet-Spun Fibers for Thermoelectric Textiles.

Macromol. Mater. Eng. 305(1900749), 1-9. DOI:

10.1002/mame.201900749

- Kushwaha, A.K., Kalita, H., Suman, S., Bhardwaj, A., & Ghosh, R. (2021). Two-dimensional (2D) thermoelectric materials. In: *Thermoelectricity and Advanced Thermoelectric Materials*. Elsevier, Amsterdam, 233–260. <https://doi.org/10.1016/B978-0-12-819984-8.00006-0>.
- Li, M., Zeng, F. Luo, M., Qing, X., Wang, W., Lu, Y. ... Wang, D. (2021). Synergistically Improving Flexibility and Thermoelectric Performance of Composite Yarn by Continuous Ultrathin PEDOT: PSS/DMSO/Ionic Liquid Coating. *ACS Appl. Mater. Interfaces*, 13, 50430–50440. <https://doi.org/10.1021/acsami.1c15946>
- Li, X., Liu, C., Wang, T., Wang, W., Wang, Z., Jiang, Q. ... Xu, J. (2017). Preparation of 2D - MoSe₂/PEDOT:PSS composite and its thermoelectric properties. *Mater. Res. Exp.* 4, 116410. DOI 10.1088/2053-1591/aa99f9
- Li, Y., Zeng, J., Zhao, Y., Wang, C., Zhang, C., Cheng, T. ... Chen, X. (2022). Fabric-based flexible thermoelectric generators: Design methods and prospects. *Frontiers in Materials* 01 frontiersin, 1-5. DOI 10.3389/fmats.2022.1046883
- Liu, D., Yan, Z., Zhao, Y., Zhang, Z., Zheng, Y., Zhang, B. ... Xue, C. (2022). Enhanced performance of SnSe/PEDOT:PSS composite films by MWCNTs for flexible thermoelectric power generator. *J. Alloy. Compd.* 898, 162844. <https://doi.org/10.1016/j.jallcom.2021.162844>
- Liu, D., Yan, Z., Zhao, Y., Zhang, Z., Zheng, Y., Zhang, B. ... Xue, C. (2021). Facile MWCNTs-SnSe/PEDOT:PSS ternary composite flexible thermoelectric films optimized by cold-pressing. *J. Mater. Res. Tech.* 15, 4452. <https://doi.org/10.1016/j.jmrt.2021.10.075>

- Liu, J., Jia, Y., Jiang, Q., Jiang, F., Li, C., Wang, X. ... Xu, J. (2018). Highly Conductive Hydrogel Polymer Fibers toward Promising Wearable Thermoelectric Energy Harvesting. *CS Appl. Mater. Interfaces*, 10(50), 44033–44040. <https://doi.org/10.1021/acsami.8b15332>
- Liu, X., Du, Y., Meng, Q., Dou, Y., Jin, M., Xu, J., & Shen, S.Z. (2020). Free-standing single-walled carbon nanotube/SnSe nanosheet/Poly (3,4-Ethylenedioxythiophene): Poly (4-styrenesulfonate) nanocomposite films for flexible thermoelectric power generators. *Adv. Eng. Mater*, 22, 2000605. <https://doi.org/10.1002/adem.202000605>
- Lund, A., Darabi, S., Hultmark, S., Ryan, J.D., Andersson, B., Ström, A., & Müller, C. (2018). Roll-to-Roll Dyed Conducting Silk Yarns: A Versatile Material for E-Textile Devices. *Electronic Textiles*, 3(1800251), 1-6. DOI: 10.1002/admt.201800251
- Lund, A., Tian, Y., Darabi, S., & Müller, C. (2020). A polymer-based textile thermoelectric generator for wearable energy harvesting. *Journal of Power Sources*, 480(228836), 1-11. <https://doi.org/10.1016/j.jpowsour.2020.228836>
- Mameekul, A. (2024). *Design and Fabrication of Thermoelectric Solid-State Air Conditioner*. (Doctoral dissertation). Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand.
- Materials Explorer(a). (2025). *SnSe₂ mp-655*. Retrieved from <https://next-gen.materialsproject.org/materials/mp-665>. February 5th, 2025.
- Materials Explorer(b). (2025). *SnSe mp-691*. Retrieved from <https://shorturl.asia/RonBL>. February 6th, 2025.
- Mathcentre. (2024). *Using proportional sets to calculate equivalent amounts, strengths and substitutes*. Retrieved from

<https://www.mathcentre.ac.uk/resources/uploaded/c1v1c2v2.pdf>.

February 6th, 2025.

Meng, K., Zhao, L.-M., Zhang, N.-Y., Zhang, Z.-F., Shen, W.-X., Zhang, Y.-W. ...

Jia, X.-P. (2022). Thermoelectric properties of n-type SiGe alloys with Sn incorporation. *Rare Met*, 41(12), 4156–4163.

<https://doi.org/10.1007/s12598-022-02085-z>.

Mulla, R. (2025). What's new in PEDOT:PSS thermoelectrics?. *Chemical Communications*, 59.

Müller, C., & Inganäs, O. (2012). *Bio-Based Materials as Templates for Electronic Devices*. Germany: Wiley-VCH Weinheim.

Nanotechnology in STEM. (2024). *Fundamental Principles of X-ray Powder Diffraction (XRD)*. Retrieved from <https://shorturl.asia/Alm0J>. August 10th, 2024.

Ossila enabling science. (2025). *What is PEDOT?*. Retrieved from <https://www.ossila.com/pages/what-is-pedot-pss>. January 30th, 2025.

Phakram Sakon Nakhon. (2023). *History of Kram fabric Sakon Nakhon*. Retrieved from <https://shorturl.asia/OS93o>. June 19th, 2023.

Phakram Sakon Nakhon. (2024). *History of Indigo Fabric or Indigo-dyed Fabric, Sakon Nakhon*. Retrieved from <https://www.phakram.com/story-kram-sakol/>. August 3rd, 2024.

Phononic. (2025). *How Thermoelectric Cooling Uses the Peltier Effect*. Retrieved from <https://shorturl.asia/KGpYL>. January 24th, 2025.

Physics Catalyst. (2024). *Seebeck effect*. Retrieved from <https://physicscatalyst.com/elec/seebeck-effect.php>. April 15th, 2024.

Pope, J., & Lekakou, C. (2019). Thermoelectric polymer composite yarn and an energy harvesting wearable textile. *Smart Mater. Struct*, 28(095006), 1-13. <https://doi.org/10.1088/1361-665X/ab1cc1>

- Qin, B., Wang, D., Hong, T., Wang, Y., Liu, D., Wang, Z. ... Zhao, L.-D. (2023). High thermoelectric efficiency realized in SnSe crystals via structural modulation. *Nat. Commun*, 14, 1–10.
<https://doi.org/10.1038/s41467-023-37114-7>.
- Rayon. (2024). *What is Rayon*. Retrieved from <https://shorturl.asia/1eayb>. July 1st, 2024
- Rehman,A., Ali, A., Ikram, S., Amami, M., & Mahmood, K. (2022). Characterization of polycrystalline SnSe₂ thin films for thermoelectric applications grown by single-stage horizontal tube furnace (SSHTF). *Optic Mater*, 133, 112797. <https://doi.org/10.1016/j.optmat.2022.112797>
- Rossella, F., Pennelli, G., & Roddaro, S. (2018). Chapter Six - Measurement of the Thermoelectric Properties of Individual Nanostructures. *Semiconductors and Semimetals*, 98, 409-444.
<https://doi.org/10.1016/bs.semsem.2018.02.001>
- Rout, N.K.C.S. (2021). Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications. *RSC Adv*, 11(10), 5659–5697. <https://doi.org/10.1039/d0ra07800j>
- Russ, B., Glaudell, A., Urban, J.J., Chabinyk, M.L., & Segalman, R.A. (2016). Organic thermoelectric materials for energy harvesting and temperature control. *Nature Reviews Materials*, 16050. DOI: 10.1038/natrevmats.2016.50
- Ryan, J.D., Mengistie, D.A., Gabrielsson, R.G., Lund, A., & Müller, C. (2017). Machine-Washable PEDOT: PSS Dyed Silk Yarns for Electronic Textiles. *American Chemical Society*, 9, 9045–9050. DOI: 10.1021/acsami.7b00530
- Salah, N., Abdullahi, S., Salah, Y.N., Alshahrie, A., & Koumoto, K. (2024). Suppressing the thermal conductivity to enhance the thermoelectric

- performance of SnSe₂ using the high-energy ball milling in a pressurised N₂ atmosphere. *J. Mater. Res. Tech*, 31, 1067-1069. DOI: 10.1016/j.jmrt.2024.06.150
- Sassi, S., Candolfi, C., Vaney, J.-B., Ohorodniichuk, V., Masschelein, P., Dauscher, A., & Lenoir, B. (2014). Assessment of the thermoelectric performance of polycrystalline p-type SnSe. *Appl. Phys. Lett*, 104, 212105 <https://doi.org/10.1063/1.4880817>.
- Seetawan, T., Vora-Ud, A., Ullah, F., Thang, P.B., Kumar, M., & Kim, H.J. (2022). Microstructural and thermoelectric properties of PbTe single crystals as grown by Czochralski method, *Materials Letters*, 324, 1-4. <https://doi.org/10.1016/j.matlet.2022.132798>
- Shi, W., Gao, M., Wei, J., Gao, J., Fan, C., Ashalley, E. ... Wang, Z. (2018). Tin Selenide (SnSe): Growth, Properties, and Applications. *Advanced Science*, 5(4), 1700602. DOI: 10.1002/advs.201700602
- Siam Generator. (2024). *Power Factor*. Retrieved from <https://shorturl.asia/S91Mi>. June 21st, 2024.
- Singh, K., Anwar, S., Dubey, P., & Mishra, S. (2023). Enhanced thermoelectric performance of mechanically hard nano-crystalline-sputtered SnSe thin film compared to the bulk of SnSe. *J. Mater. Sci. Mater. Electron*, 34, 1115. <https://doi.org/10.1007/s10854-023-10487-7>.
- Song, L., Zhang, J., & Iversen, B.B. (2019). Enhanced thermoelectric properties of SnSe thin films grown by single-target magnetron sputtering. *J. Mater. Chem. A*, 7, 17981–17986. <https://doi.org/10.1039/C9TA03252E>.
- Sun, T., Zhou, B., Zheng, Q., Wang, L., Jiang, W., & Snyder, G.L. (2020). Stretchable fabric generates electric power from woven thermoelectric fibers. *Nature Communications*, 11(572), 1-10.

<https://doi.org/10.1038/s41467-020-14399-6>

- Terasaki, I. (2011). Thermal conductivity and thermoelectric power of semiconductors. *Physics, Engineering*. DOI:10.1016/B978-0-44-453153-7.00070-5
- Thaowonkaew, S., Insawang, M., Vora-ud, A., Horprathum, M., Muthitamongkol, P., Maensiri, S. ... Seetawan, T. (2023). Effect of substrate rotation and rapid thermal annealing on thermoelectric properties of Ag-doped Sb₂Te₃ thin films. *Vacuum*, 211(111920), 1-8.
<https://doi.org/10.1016/j.vacuum.2023.111920>
- Tritt, T.M. (2002). Thermoelectric Materials: Principles, Structure, Properties, and Applications. *Encyclopedia of Materials: Science and Technology (Second Edition)*, 1-11. <https://doi.org/10.1016/B0-08-043152-6/01822-2>
- Truong, D.C., Thaowonkaew, S., Muthitamongkol, P., Horprathum, M., Kumar, M., Le, T.B.N. ... Phan, T.B. (2022). Relaxation of residual stress- controlled thermopower factor in transparent-flexible Ti-doped ZnO thin films. *Ceramic Inter*, 48, 2605. <https://doi.org/10.1016/j.ceramint.2021.10.043>
- Ubon Ratchathani University. (2025). *Field Emission Scanning Electron Microscope - Energy Dispersive X-ray Spectroscopy (FESEM-EDS)*. Refrigerant. Retrieved from <https://shorturl.asia/32ptm>. January 22nd, 2025.
- ULVAC Technologies. (2024). *Seebeck Coefficient/Electric Resistance Measurement System*. Retrieved from <https://shorturl.asia/EioA2>. June 21st, 2024.
- Urmila, K.S., Namitha, T.A., Rajani, J., Philip, R.R., & Pradeep, B. (2016). Optoelectronic properties and Seebeck coefficient in SnSe thin films. *J. Semiconduct*, 37, 093002. <https://doi.org/10.1088/1674-4926/37/9/093002>.

- Vora-Ud, A., Thaowonkaew, S., Khajornrit, J., Singsoog, K., Muthitamongkol, P., Chananonnawathorn, C. ... Seetawan, T. (2020). Rapid thermal annealing induced the c-axis (00 l) preferred orientation and the p-type thermoelectric properties of Bi-Sb-Te thin films. *Thin Solid Films*, 706, 138094. DOI: 10.1016/j.tsf.2020.138094
- Wang, L., & Zhang, K. (2022). Textile-based thermoelectric generators and their applications. *Energy Environ Mater*, 3, 67–79.
- Wu, Q., & Hu, J. (2016). Waterborne polyurethane based thermoelectric composites and their application potential in wearable thermoelectric textiles. *Composites Part B*, 107, 59-66.
<https://doi.org/10.1016/j.compositesb.2016.09.068>
- Wu, Q., & Hu, J. (2016). Waterborne polyurethane based thermoelectric composites and their application potential in wearable thermoelectric textiles. *Composites Part B*, 107, 59-66.
<https://doi.org/10.1016/j.compositesb.2016.09.068>
- Wu, Q., & Hu, J. (2017). A novel design for a wearable thermoelectric generator based on 3D fabric structure. *Smart Mater Struct*, 26.
- Wu, Q., & Hu, J. (2017). Thermoelectric Textile Materials. *Bringing Thermoelectricity into Reality*. DOI: 10.5772/intechopen.75474
- Wu, T., Shi, X-L., Liu, W-D., Li, M., Yue, F., Huang, P. ... Chen, Z-G. (2024). High Thermoelectric Performance and Flexibility in Rationally Treated PEDOT: PSS Fiber Bundles. *Advanced Fiber Materials*, 6, 607-618.
<https://doi.org/10.1007/s42765-024-00374-z>
- Xiao, R., Zhou, X., Zhang, C., Liu, X., Han, S., & Che, C. (2024). Organic Thermoelectric Materials for Wearable Electronic Devices. *Sensors*, 24(14), 4600. <https://doi.org/10.3390/s24144600>

- Xie, L., He, D., & He, J. (2021). SnSe the rising star thermoelectric material: a new paradigm in atomic blocks, building intriguing physical properties. *Mater. Horiz*, 7, 3–24. <https://doi.org/10.1039/d1mh00091h>.
- Xin, J., Basit, A., Li, S., Danto, S., Tjin, S., & Wei, L. (2021). Inorganic Thermoelectric Fibers: A Review of Materials, Fabrication Methods, and Applications. *Sensors*, 21(10), 3437. <https://doi.org/10.3390/s21103437>
- Yan, Z., Zhao, Y., Liu, D., Zhang, Z., Zheng, Y., Cui, J. ... Xue, C. (2020). Thermoelectric properties of flexible PEDOT:PSS-based films tuned by SnSe via the vacuum filtration method. *RSC Adv*, 71, 43840. <https://doi.org/10.1039/d0ra08458a>
- Yan, Z., Zhao, Y., Liu, D., Zhang, Z., Zheng, Y., Cui, J. ... Xue, C. (2020). Thermoelectric properties of flexible PEDOT:PSS-based films tuned by SnSe via the vacuum filtration method. *RSC Advances*, 71, 43840-43846. doi: 10.1039/d0ra08458a
- Yan, Z., Zhao, Y., Liu, D., Zhang, Z., Zheng, Y., Cui, J., Zhang, Y., & Xue, C. (2020). Thermoelectric properties of flexible PEDOT:PSS-based films tuned by SnSe via the vacuum filtration method. *RSC Adv*, 10, 43840–43846. <https://doi.org/10.1039/d0ra08458a>.
- Yang, L., Huh, D., Ning, R., Rapp, V., Zeng, Y., Liu, Y. ... Prasher, R.S. (2021). High thermoelectric figure of merit of porous Si nanowires from 300 to 700 K. *Nat. Commun*, 12(3926), 1–7. <https://doi.org/10.1038/s41467-021-24208-3>.
- Yu, P., Yu, X., Lu, W., Lin, H., Sun, L., Du, K. ... Liu, Z. (2016). Fast photoresponse from 1T tin diselenide atomic layers. *Adv. Funct. Mater*, 26, 137–145. <https://doi.org/10.1002/adfm.201503789>

- Zhang, Q.K., Ning, S.T., Qi, N., Chen, Z.Q., Tang, X.F., & Chen, Z.Y. (2019). Enhanced thermoelectric performance of a simple method prepared polycrystalline SnSe optimized by spark plasma sintering. *J. Appl. Phys*, 125, 225109 <https://doi.org/10.1063/1.5095197>.
- Zhang, X., Li, T.T., Jiang, Q., Wu, L., Ren, H-T., Peng, H-K. ... Lin, J-H. (2020). Worm-Like PEDOT: Tos coated polypropylene fabrics via low-temperature interfacial polymerization for high-efficiency thermoelectric textile. *Progress in Organic Coatings*, 149(105919). <https://doi.org/10.1016/j.porgcoat.2020.105919>
- Zhang, Y., Heo, Y-J., Park, M., & Park, S-J. (2019). Recent Advances in Organic Thermoelectric Materials: Principle Mechanisms and Emerging Carbon-Based Green Energy Materials. *Polymers*, 11(167), 1-22. DOI: 10.3390/polym11010167
- Zhao, J., Zhao, X., Guo, R., Zhao, Y., Yang, C., Zhang, L. ... Ren, Y. (2022). Preparation and Characterization of Screen-Printed Cu₂S/PEDOT:PSS Hybrid Films for Flexible Thermoelectric Power Generator. *Nanomaterials*, 12(14), 2430. <https://doi.org/10.3390/nano12142430>
- Zhao, L.-D., Lo, S.-H., Zhang, Y., Sun, H., Tan, G., Uher, C., & Kanatzidis, M.G. (2014). Ultralow thermal conductivity and high thermoelectric figure of merit in SnSe crystals. *Nature*, 508(7496), 373–377. <https://doi.org/10.1038/nature13184>.
- Zhao, Y., Liu, L., Zhang, F., Di, C-a., & Zhu, D. (2021). Advances in organic thermoelectric materials and devices for smart applications. *SmartMat*, 2, 426–445. DOI: 10.1002/smm2.1034
- Zheng, Y., Han, X., Yang, J., Jing, Y., Chen, X., Li, Q. ... Zhang, K. (2022). Durable, stretchable and washable inorganic-based woven thermoelectric

textiles for power generation and solid-state cooling. *Energy & Environment Science*, 6(15), 2371-2385.

Zhong, Y., Zhang, L., Linseis, V., Qin, B., Chen, W., Zhao, L., & Zhu, H. (2020). High quality textured SnSe thin films for self-powered, rapid-response photo thermoelectric application. *Nano Energy*, 72, 104742.

<https://doi.org/10.1016/j.nanoen.2020.104742>.

Zhu, T., Bai, H., Zhang, J., Tan, G., Yan, Y., Liu, W. ... Tang, X. (2020). Realizing high thermoelectric performance in Sb-doped Ag₂Te compounds with a low- temperature monoclinic structure. *ACS Appl. Mater. Interfaces*, 12, 39425–39433. <https://doi.org/10.1021/acsami.0c10932>.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

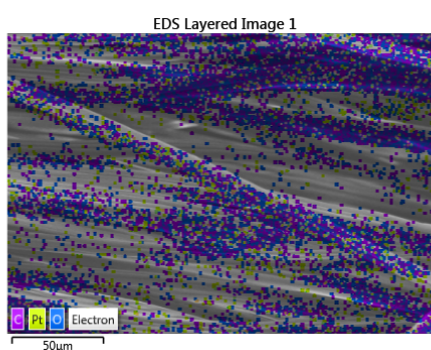
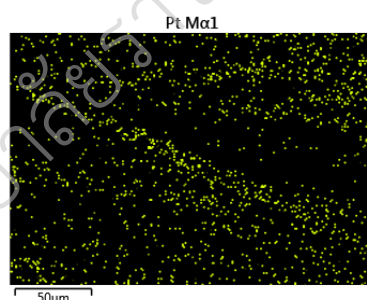
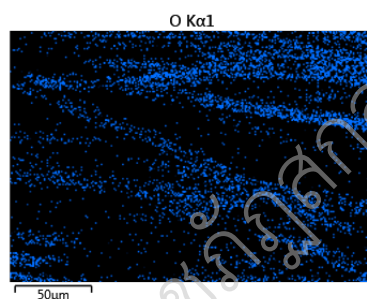
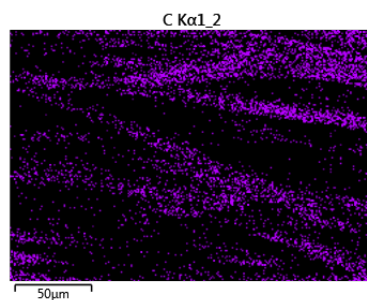
มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

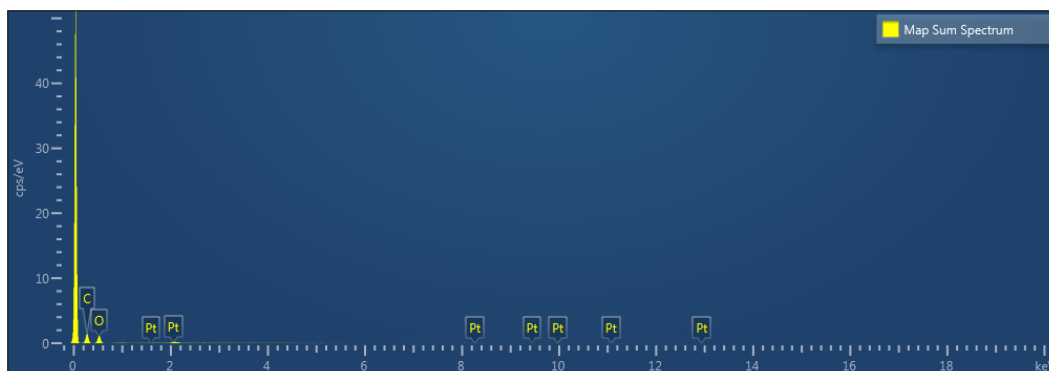
APPENDICE

APPENDICE A

DATA OF OUTCOMES

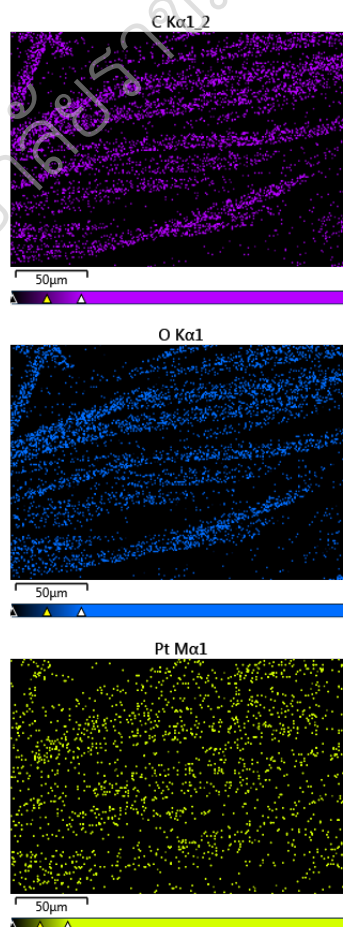
EDX spectra and Atomic composition of the yarns before & after coating with PEDOT:PSS.

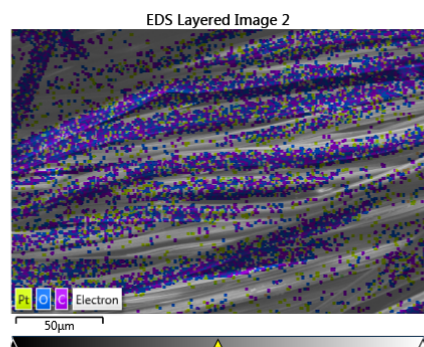




Element	Wt%	Wt% Sigma
C	50.92	0.73
O	49.08	0.73
Total:	100.00	

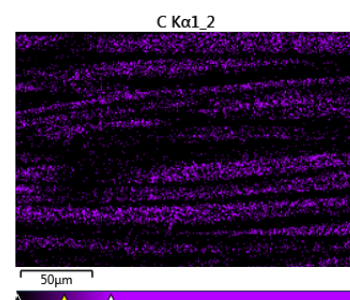
Rayon yarn.





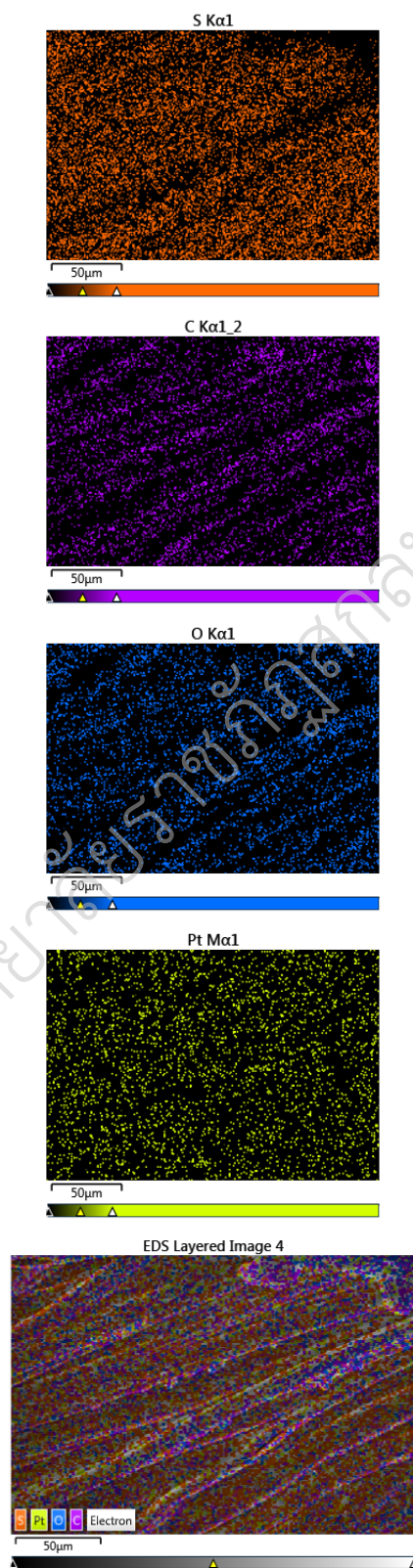
Element	Wt%	Wt% Sigma
C	46.87	0.71
O	53.13	0.71
Total:	100.00	

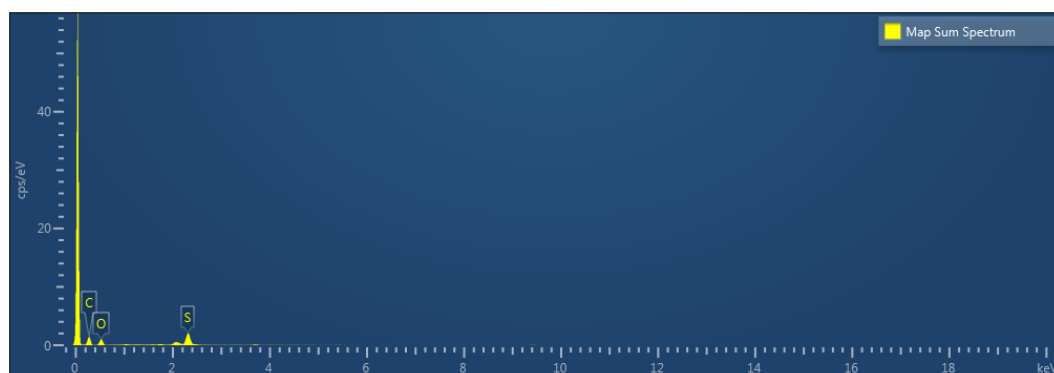
Indigo-Kram (Soft) yarn.





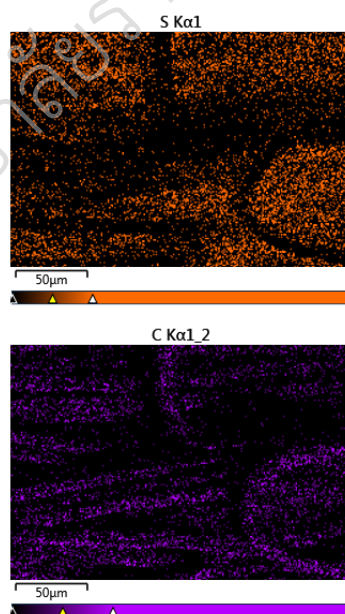
Indigo-Kram (Intensive) yarn.

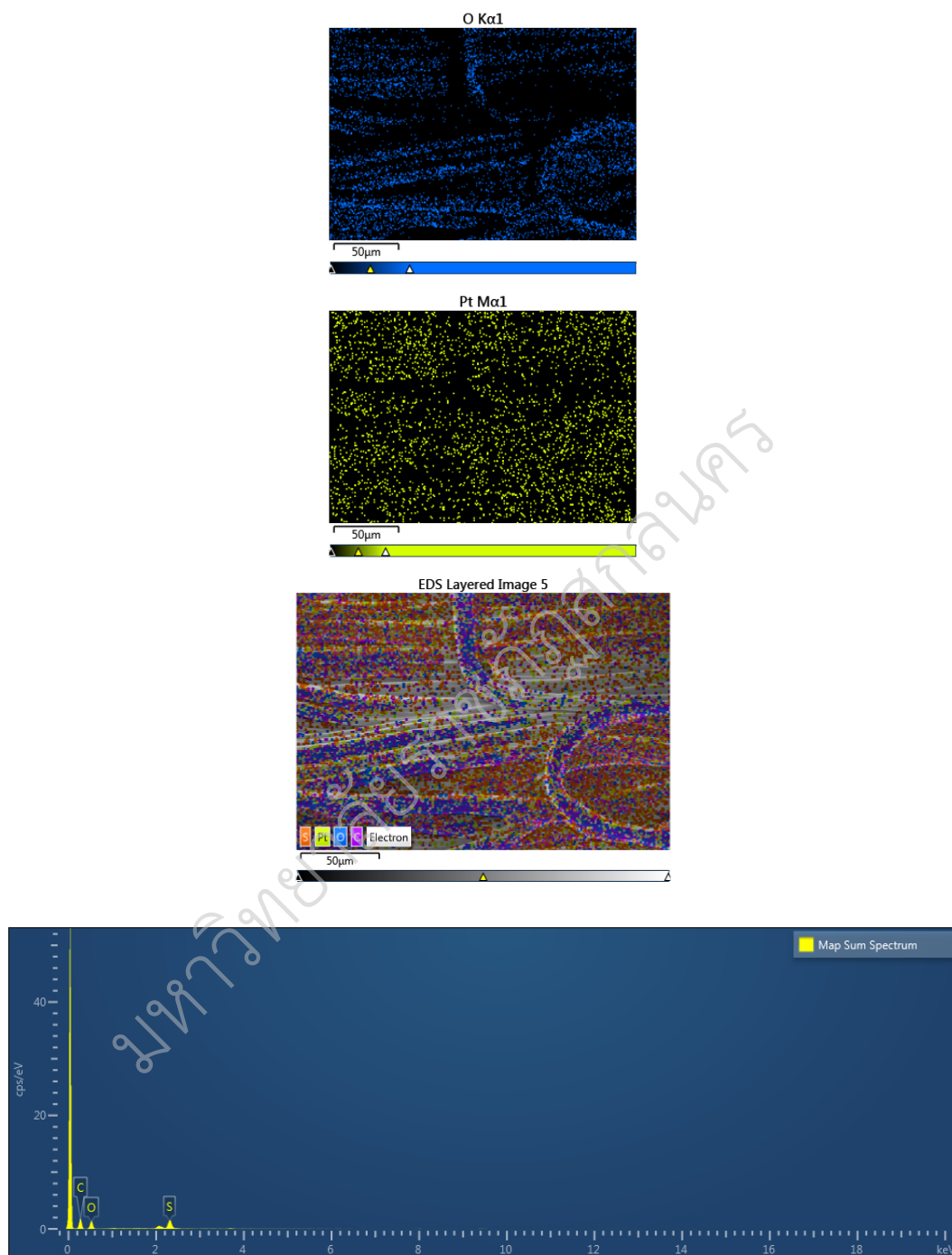




Element	Wt%	Wt% Sigma
C	56.25	0.73
O	27.74	0.64
S	16.00	0.32
Total:	100.00	

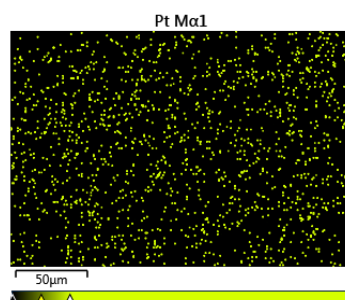
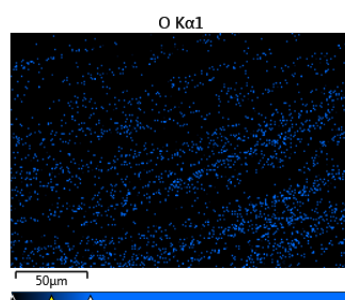
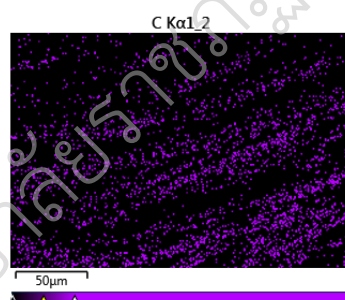
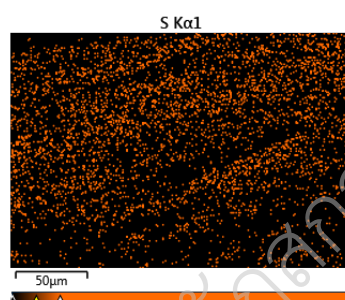
PEDOT:PSS-Coated Rayon yarn.

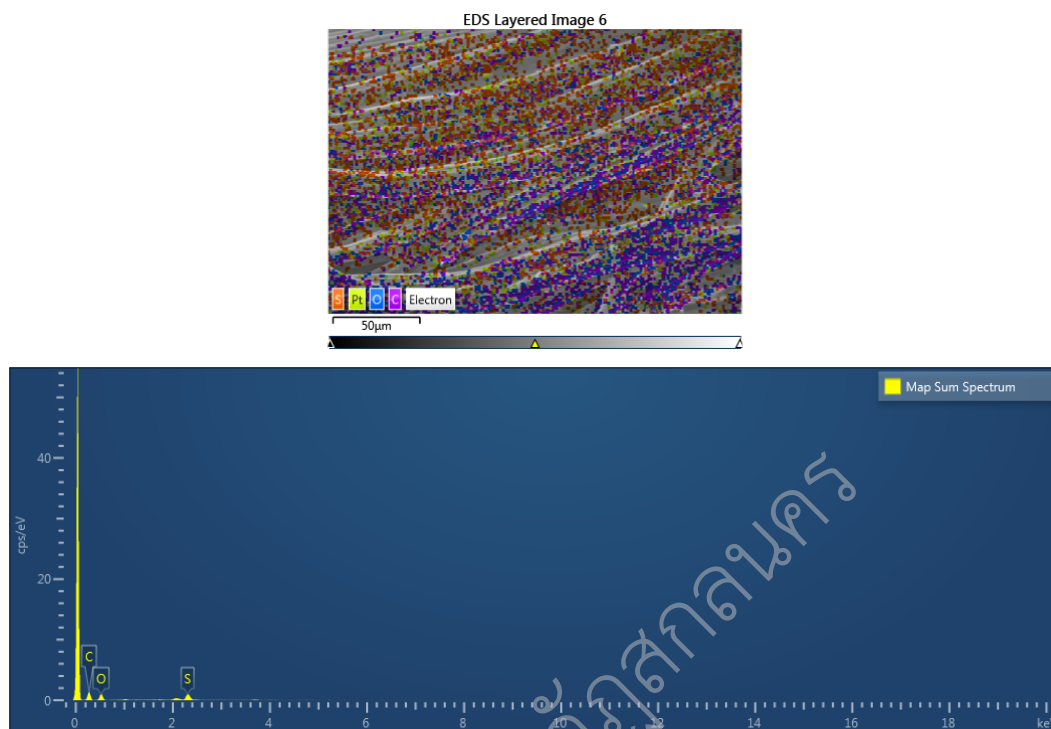




Element	Wt%	Wt% Sigma
C	55.12	0.68
O	33.20	0.63
S	11.68	0.26
Total:	100.00	

PEDOT:PSS-Coated Indigo-Kram (Soft) yarn.





Element	Wt%	Wt% Sigma
C	55.08	0.87
O	34.17	0.82
S	10.76	0.32
Total:	100.00	

PEDOT:PSS-Coated Indigo-Kram (Intensive) yarn.

Power output of the OTE modules.

PEDOT:PSS-Coated Rayon Module data.

dT	Vo(mV)	Pmax (nW)
0	0	0
0.2	0.5712	0.00027189
0.5	1.325	0.00146302
1	1.928	0.00309765
1.5	2.483	0.00513774
2.3	3.043	0.00771654
3.1	4.498	0.01686
4	5.912	0.02912645
5.8	6.268	0.03273985
6.6	7.454	0.04630176
7.7	8.453	0.05954434
8.8	9.363	0.07305481
9.5	10.089	0.08482327
10	11.054	0.10182576
11.2	12.524	0.13070881
12	13.06	0.14213633
13.2	14.034	0.16412763
14.5	15.066	0.18915363
15.7	16.11	0.21627675
16.7	17.412	0.25264812

PEDOT:PSS-Coated Indigo-Kram (Soft) Module data.

dT	Vo(mV)	Pmax (nW)
0	0	0
0.4	1.873	0.007831
1	2.254	0.01134
1.5	3.892	0.033812
2.2	4.323	0.041715
3.4	5.66	0.071508
4.2	6.713	0.10059
5.5	7.994	0.142643
5.9	8.595	0.164897
6.9	9.034	0.182172
7.5	10.593	0.250472
8.6	11.211	0.28055
9.5	12.337	0.339736
10.5	12.984	0.376304
11.2	13.923	0.432701
11.7	14.861	0.492967
12.4	15.042	0.505049
13.5	16.905	0.6379
14.5	17.995	0.722813
14.9	18.536	0.766927
15.7	19.967	0.889913
16.6	20.545	0.942181

PEDOT:PSS-Coated Indigo-Kram (Intensive) Module data.

dT	Vo(mV)	Pmax (nW)
0	0	0
0.6	1.969	0.009596
0.9	2.669	0.017633
1.4	3.926	0.038152
1.8	4.847	0.058152
2.5	5.923	0.086836
3.2	6.946	0.119423
3.8	7.461	0.137788
4.5	8.99	0.20005
5.2	9.594	0.227834
6.2	10.852	0.2915
7.8	11.907	0.350932
8.9	12.624	0.394469
9.4	13.768	0.469203
9.9	14.24	0.501925
10.5	14.987	0.555966
11.3	15.367	0.584517
12.7	16.188	0.648642
13.6	17.134	0.726668
14.9	18.067	0.807962
16.7	18.396	0.837655

APPENDICE B

INTERNATIONAL CONFERENCES WORKSHOPS AND PUBLICATIONS

INTERNATIONAL CONFERENCES

1. **Insawang M.**, Singsoog, K., Chaarmart, K., Seetawan, T., & Vora-ud, A.

“Thermoelectric Properties of SnSe Films as Prepared by RF Magnetron Sputtering Method” The 6th International Conference on Applied Physics and Materials Applications (ICAPMA 2023) on December 6-9th, 2023 at Garden Cliff Resort and Spa in Pattaya, Thailand.

2. **Insawang M.**, Vora-ud, A., Muntini, M.S., Phan, T.B., Kumar, M., & Seetawan, T.

“Thermoelectric properties PEDOT:PSS+SnSe₂ polymer composite as prepared by wet chemical method” 8th Southeast Asia Conference on Thermoelectric (SACT2024) on November 20-22nd, 2024. Bali, Indonesia.

WORKSHOPS

1. e-Asia Workshop on Thermoelectrics of Low-Dimensional and Topological Materials 2024. **Contributed Talk** “Investigation on Thermoelectric Properties of SnSe Thin Films as Prepared by RF Magnetron Sputtering” on August 6-7th, 2024 at Graha Widya Bhakti Building, B.J. Habibie Science and Technology Park Serpong, Jakarta, Indonesia.

2. The Asian Workshop on Laboratory Development for Smart Electronics 2024. **Contributed Talk** “Investigation on Thermoelectric Properties of SnSe Thin Films as Prepared by RF Magnetron Sputtering” on September 12-13th, 2024 at Suttabongkot Meeting Room (Building 11) Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand.

3. Workshop on Innovation Development for Sustainable Local Development in the Northeastern Region. **Exhibition** “PEDOT:PSS+Indigo-Kram yarns for Organic

Thermoelectric Textiles” on June 5th, 2025 at Jamjury auditorium 1 Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand.

4. Knowledge Transfer of Innovation and Technology of Alternative Energy

Workshop 2025. **Training** “PEDOT:PSS+Indigo-Kram yarns for Organic

Thermoelectric Textiles” on June 5th, 2025 at Building 21 Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand.

5. Science in action for Sustainable Community. **Training & Exhibition**

“PEDOT:PSS+Indigo-Kram yarns for Organic Thermoelectric Textiles” on August 18-19th, 2025 at Jamjury auditorium 1, 2 Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand.

PUBLICATIONS

FIRST AUTHOR

Insawang, M., Ruamruk, S., Vora-ud, A., Singsoog, K., Inthachai, S., Chaarmart, K. ...

Seetawan, T. (2024). Investigation on thermoelectric properties of SnSe thin films as prepared by RF magnetron sputtering. *Radiation Physics and Chemistry*, 22(111789).

<https://doi.org/10.1016/j.radphyschem.2024.111789>

Insawang, M., Vora-ud, A., Seetawan, T., Muntini, M.S., Phan, T.B., & Kumar, M.

(2024). Enhancing Thermoelectric Power Factor of PEDOT:PSS/SnSe₂ Nanocomposite Sheets by Rapid Thermal Annealing. *Journal of Electronic Materials*, 1.7. <https://doi.org/10.1007/s11664-024-11687-5>

CO-AUTHOR

- Thaowonkaew, S., **Insawang, M.**, Vora-ud, A., Horprathum, M., Muthitamongkol, P., Maensiri, S. ... Seetawan, T. (2023). Effect of substrate rotation and rapid thermal annealing on thermoelectric properties of Ag-doped Sb_2Te_3 thin films. *Vacuum*, 211(111920), 1-8.
<https://doi.org/10.1016/j.vacuum.2023.111920>
- Vora-ud, A., Pham, A.T.T., Truong, D.C., Thaowonkaew, S., Lai, H.T., Le, T.B.N., Tran, N.M.Q., **Insawang, M.** ... Phan, T.B. (2023). Transparent-flexible thermoelectric module from In/Ga co-doped ZnO thin films. *Chemical Engineering Journal*, 465(142954), 1-13.
- Muntini, M.S., Putri, N.R.I.S., **Insawang, M.**, Boonkirdram, S., Horprathum, M., Seetawan, T., & ., Vora-ud, A. (2024). Thermoelectric of Iron-Antimony-Titanium Thin Films Fabricated Through DC Magnetron Sputtering. *Journal of Electronic Materials*, 1-8. <https://doi.org/10.1007/s11664-024-11695-5>
- Faridah, N., Vora-ud, A., **Insawang, M.**, & Muntini, M.S. (2024). Investigation on Flexible Thin Film Thermoelectric of Tin Selenide prepared by RF Magnetron Sputtering. *Journal of Physics: Conference Series*, 3034, 1-7.
[doi:10.1088/1742-6596/3034/1/012009](https://doi.org/10.1088/1742-6596/3034/1/012009)
- Rahayu, I., Vora-ud, A., **Insawang, M.**, Pramono, Y.H., & Muntini, M.S. (2024). Thermoelectric Properties of Molybdenum Disulfide Thin Film as Prepared by RF Magnetron Sputtering and Rapid Thermal Annealing Process. *Journal of Physics: Conference Series*, 3034, 1-7.
[doi:10.1088/1742-6596/3034/1/012008](https://doi.org/10.1088/1742-6596/3034/1/012008)
- Rahayu, I., **Insawang, M.**, Muntini, M.S., Pramono, Y.H., Pham, A.T.T., Park, S. ... Vora-ud, A. (2026). Thermoelectric properties of MoS_2 thin films

prepared by RF magnetron sputtering. *Vacuum*, 243(114817), 1-8.

<https://doi.org/10.1016/j.vacuum.2025.114817>

Limwichean, S., Sriporaya, K., Vora-ud, A., Chittinan, D., **Insawang, M.,**

Wongdamnern, N. ... Kasayapanand, N. (2025). Thermoelectric power generation based on the Pd-doped Bi₂Te₃ thin film flexible modules. *J Mater Sci: Mater Electron*, 36(2039), 1-11.

<https://doi.org/10.1007/s10854-025-16125-8>

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

CONFERENCES I



THERMOELECTRIC PROPERTIES OF SnSe FILMS AS PREPARED BY RF MAGNETRON SPUTTERING METHOD

Mekhala Insawang^{1,2}, Kunchit Singsoog², Kongphope Chaarmart³, Tosawat Seetawan^{1,2} and Athorn Vora-ud^{1,2,*}

¹Program of Physics, Faculty of Science and Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand.

²Center of Excellence on Alternative Energy, Research and Development Institute, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand.

³Program of Electrical and Electronics, Faculty of Industrial Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Rd., Mueang District, Sakon Nakhon, 47000, Thailand

*Email: athornvora-ud@snru.ac.th

Abstract

SnSe (Tin Selenide) is a p-type thermoelectric with an indirect band gap of ~0.9 eV and a direct band gap of ~1.3 eV, which reported a maximum dimensionless Figure of Merit (ZT) value around 3.1 at 783 K. In this work, we studied the thermoelectric properties of SnSe thin films onto SiO₂/Si-wafer as prepared by the RF magnetron sputtering technique. The sputtering conditions were used with a base pressure below 5.5×10^{-4} Pa and a working pressure of about 0.93 Pa with the Ar gas (99.999% UHP purity) as a flow rate of 40 sccm. The RF sputtering power was applied at 80W with a sputtering time of 30 min. After thin film deposition, as-deposited thin films were annealed by the rapid thermal annealing (Mila5000, Advanced-Riko) method at a temperature 250-450 °C. The crystal structure, morphology and film thickness, and atomic composition of SnSe thin films were carried by X-ray diffraction (XRD-6100, Shimadzu), the field emission scanning electron microscope (FE-SEM; SU8030, Hitachi), and energy-dispersive X-ray spectroscopy (EDX; SU8030, Hitachi), respectively. Thermoelectric properties (electrical resistivity (ρ) and Seebeck coefficient (S)) were measured by ZEM-3 method (Ulvac-Riko). At room temperature, the maximum power factor of $0.35 \text{ mWm}^{-1} \text{ K}^{-2}$ ($\rho = 202 \text{ m}\Omega \text{ m}$ and $S = 165 \text{ }\mu\text{VK}^{-1}$) could be found on the thin film annealed 400 °C sample.

Keyword: Thermoelectric thin film, magnetron sputtering, rapid thermal annealing, SnSe



CONFERENCES II



WORKSHOPS I



WORKSHOPS II



Philosophy Doctoral of Physics Curriculum

This is to certify that

Miss Mekala Insawang

has been contributed Talk in Topic: "Investigation on thermoelectric properties of SnSe thin films as prepared by RF magnetron sputtering" on the "Asian Workshop on Laboratory Development for Smart Electronics" as supported by the Reinventing University Project, the Policy and Planning Division, Sakon Nakhon Rajabhat University.

September 12, 2024

T. Seetawan

Prof. Dr. Tosawat Seetawan
Vice President of
Sakon Nakhon Rajabhat University

Athorn

Assoc. Prof. Dr. Athorn Vora-ud
Chair of Philosophy Doctoral
of Physics Curriculum



WORKSHOPS III



WORKSHOPS IV



WORKSHOPS V



FULL PAPER

Radiation Physics and Chemistry 222 (2024) 111789



Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Investigation on thermoelectric properties of SnSe thin films as prepared by RF magnetron sputtering

Mekhala Insawang^{a,b}, Surasak Ruamruk^{a,b}, Athorn Vora-ud^{a,b,*}, Kunchit Singsoog^b, Sakorn Inthachai^c, Kongphope Chaarmart^d, Sarawoot Boonkirdram^d, Mati Horprathum^e, Melania Suweni Muntini^f, Sungkyun Park^g, Thang Bach Phan^{h,i}, Tosawat Seetawan^{a,b}

^a Program of Physics, Faculty of Science and Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand

^b Center of Excellence on Alternative Energy, Research and Development Institute, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand

^c Program of Mechanical and Industrial Engineering, Faculty of Industrial Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand

^d Program of Electrical and Electronics, Faculty of Industrial Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand

^e National Electronics and Computer Technology Center, 114 Thailand Science Park, Paholyothin Road, Klong 1, Klong Luang, Pathumthani, 12120, Thailand

^f Instrumentation and Electronic Laboratory, Department of Physics, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia

^g Department of Physics, Pusan National University, Busan, 46241, Republic of Korea

^h Center for Innovative Materials and Architectures, Ho Chi Minh City, 700000, Viet Nam

ⁱ Vietnam National University, Ho Chi Minh City, 70000, Viet Nam

ARTICLE INFO

Handling Editor: Dr. Chris Chantler

Keywords:

Thermoelectric thin film
Magnetron sputtering
Vacuum thermal annealing
SnSe

ABSTRACT

In this work, we investigated the thermoelectric properties of SnSe (Tin Selenide) thin films onto SiO₂/Si-wafer substrates as prepared by RF (radio frequency) magnetron sputtering technique. The sputtering conditions used base pressure below 5.5×10^{-4} Pa and working pressure at 0.93 Pa within the Ar atmosphere as a flow rate fixed 40 sccm. The RF sputtering power was applied at 80 W and sputtering time for 30 min. After thin film deposition, as-deposited thin films were annealed by the vacuum annealing method at 300–450 °C. The crystal structure, morphology and film thickness, and atomic composition of SnSe thin film were carried out by X-ray diffraction (XRD), the field emission scanning electron microscope (FE-SEM), and energy-dispersive X-ray spectroscopy (EDS) techniques, respectively. The thermoelectric properties (electrical resistivity; ρ) and Seebeck coefficient; S) were measured by the ZEM-3 method to calculate the power factor (PF) value. The results showed that the as-deposited thin films had improved the crystallography of SnSe from amorphous to crystalline phases after thin films were annealed at a temperature range of 300–400 °C. At room temperature, the maximum power factor of $0.35 \text{ mW m}^{-1} \text{ K}^{-2}$ ($\rho = 202 \text{ m}\Omega \text{ m}$ and $S = 165 \text{ }\mu\text{V K}^{-1}$) could be found to estimate the dimensionless Figure of Merit (ZT) values around 0.44 for annealing thin film sample at 400 °C.

1. Introduction

In a world that is becoming ever more concerned with climate change and an ever-dwindling supply of fossil fuels, there needs to be a transition toward green and sustainable energy sources [1]. The carbon peaking and carbon neutrality goals have put forward higher, and more urgent requirements to improve the current energy efficiency and develop more green energy technologies [2]. Harvesting this wasted

energy could contribute to energy efficiency targets, helping to reduce the need for fossil fuels, causing a reduction in greenhouse gas emissions, and helping to tackle climate change [3]. Thermoelectric (TE) technology realizes the direct conversion between heat and electricity, playing an increasingly significant role in the current global energy development strategy [2]. It works on the principle of the Seebeck effect, Peltier effect, and Thomson effect. TE materials can convert a considerable amount of unwanted waste heat energy compared to the

* Corresponding author. Program of Physics, Faculty of Science and Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Road, Mueang District, Sakon Nakhon, 47000, Thailand.

E-mail address: athornvora-ud@snru.ac.th (A. Vora-ud).

<https://doi.org/10.1016/j.radphyschem.2024.111789>

Received 6 February 2024; Received in revised form 2 April 2024; Accepted 24 April 2024

Available online 28 April 2024

0969-806X/© 2024 Elsevier Ltd. All rights reserved.

Table 1The ZT and PF values of different TE materials variously.

Methods	Materials	ZT	Temp. (K)	PF ($Wm^{-1} K^{-2}$)	Ref.
Czochralski	PbTe single crystals	0.41	300	P-type 1.91×10^{-3} N-type 0.063×10^{-3}	[8]
MSS + CP	Bi_2Te_3 (n)	0.91	350	–	[9]
MSS + CP	$Bi_{0.5}Sb_{1.5}Te_3$ (p)	1.2	363	–	
SG + SPS	$Bi_2Te_{2.7}Se_{0.3}$ (n)	0.55	300	–	
RMAS	$Bi_4Sb_{2-x}Te_3$ nanoplates	1.2	325	28.3×10^{-4}	[10]
Precipitates	$Ge_{0.94}Bi_{0.06}Te$	1.9	723	35×10^{-6}	[11]
Vacuum	Sb-doped $Ag_3Sb_2Te_{1-x}$	1.4	410	1.07×10^{-3}	[12]
Melting	SnSe poly crystal	1.8	816	10×10^{-6}	[13]
Arc melting	SnSe poly crystal	0.47	703	4.4×10^{-6}	[14]
Solvothermal	SnSe poly crystal	0.5	834	4×10^{-6}	[15]
Solid State Reaction	SnSe poly crystal	0.7	823	3.9×10^{-6}	[16]
Mechanical alloying	SnSe single-crystal	2.6	923	–	[17]
–	SnSe ₂ layer	1.1	950	0.49	[18]
SPS	Sn-doped SiGe	1.26	573	13×10^{-4}	[19]
–	Si-nanowires	0.71	700	–	[20]

*MSS = Microwave solvothermal *RMAS = Rapid Microwave-Assisted Solvothermal.

*CP = Cold pressing.

*SPS = Spark plasma sintering.

*SG = Solution grown.

dimensionless Figure of Merit (ZT). The higher ZT the value shown, the more efficient a material is at harvesting heat energy and converting it into useable electrical energy [3–4]. The combination of TE materials parameters is represented as defined by Eq. (1);

$$ZT = \frac{S^2 T}{\rho \kappa} = \frac{(PF) T}{\kappa} \quad (1)$$

Where S is the Seebeck coefficient, ρ is electrical conductivity, and T is the absolute temperature. Then, this ρ could be determined by Eq. (2);

$$\rho = \frac{1}{qn\mu} \quad (2)$$

where q is a carrier charge, n is the carrier concentration, and μ is the charge mobility. Furthermore, the high performance of TE materials requires a high power factor (PF) with low thermal conductivity. The power factor was defined by Eq. (3);

$$PF = \frac{S^2}{\rho} \quad (3)$$

Furthermore, PF the value corresponds to the total thermal conductivity (κ), which was described by Eq. (4);

$$\kappa = \kappa_e + \kappa_L \quad (4)$$

where κ_e and κ_L are electrical thermal and lattice thermal conductivities, respectively [5–7]. In addition, the κ_e as dependent on the temperature could be evaluated from the Wiedemann–Franz law as followed by Eq. (5);

$$\kappa_e = \sigma LT \quad (5)$$

The proportionality constant L , known as the Lorenz number, is equal to $2.44 \times 10^{-8} V^2 K^{-2}$ [8], and σ is electrical conductivity ($\sigma = 1/\rho$).

Various TE materials of telluride, selenides and homologous such as PbTe, Bi_2Te_3 , $Bi_{0.5}Sb_{1.5}Te_3$, $Bi_2Te_{2.7}Se_{0.3}$, $Bi_4Sb_{2-x}Te_3$, $Ge_{0.94}Bi_{0.06}Te$, Sb-doped $Ag_3Sb_2Te_{1-x}$, SnSe, SnSe₂, Sn-doped SiGe, and Si nanowires have also been reported in Table 1 [8–20]. Nevertheless, all of the above were presented in TE materials and exhibited significantly lower ZT

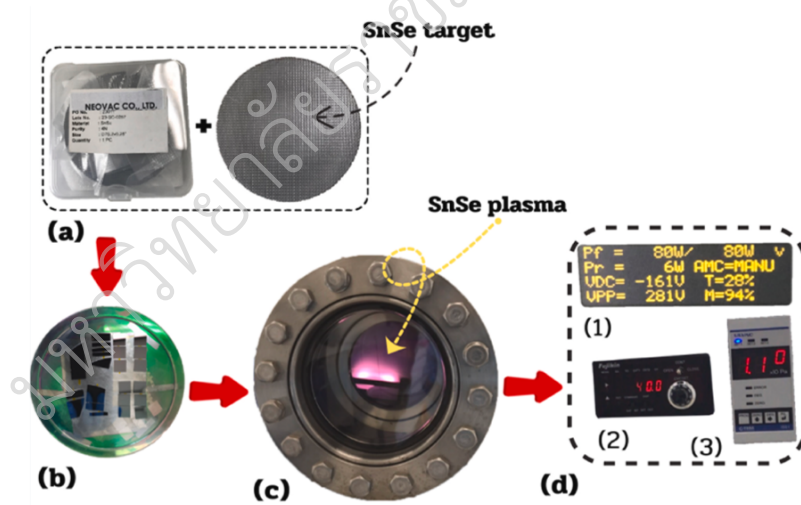


Fig. 1. The Schematic of SnSe thin film preparation with the RF sputtering process: (a) SnSe target, (b) SiO₂ substrates, (c) light plasma emitting during SnSe sputtered and (d) the conditions of (1) RF power apply, (2) Ar flow rate, and (3) working pressure.

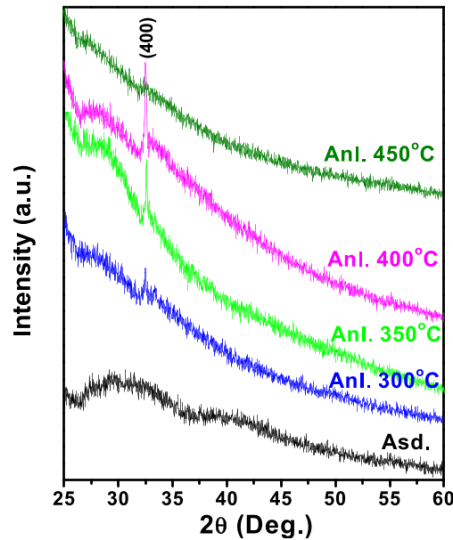


Fig. 2. Shows the XRD patterns of as-deposited and annealed SnSe thin films as depended the annealing temperature functions.

values than SnSe single-crystal. Among them, SnSe has a promising state of TE materials for the generation, SnSe full name tin selenide has attracted rapidly growing research interest for its high TE performance and the intrinsic layered structure that leads to strong anisotropy [21]. Besides that, SnSe, exhibited an outstanding ZT of 2.6 at 923 K [17] and then up to 3.1 along with its *c*-axis at 783 K [22–23]. It is well known that single crystalline SnSe materials are unsuitable for industrial company applications due to their difficulty in fabrication and brittle nature [4, 17]. Nowadays, thermoelectric thin-film architecture has the advantage

over bulk by further reducing thermal conductivity and increasing the figure of merit [4]. In the future, flexible thermoelectric devices will be great as micro-power units for self-powered wearable electronics and ultra-wide distributed wireless sensor networks [24–26].

In this work, we prepared the SnSe thin films onto SiO₂/Si-wafer substrates through the RF magnetron sputtering method toward annealing with the vacuum thermal annealing method at 300–450 °C temperature. The microstructure, surface morphology, thickness, composition, and thermoelectric properties of SnSe thin films as annealing temperature functions were investigated and reported.

2. Materials and method

SnSe thin films on SiO₂/Si-wafer substrates were prepared through the RF magnetron sputtering method from the SnSe target (NEOVAC, 99.99% purity). Before light film preparation, SiO₂/Si-wafer substrates were cleaned with a cleaning washer and water, then toward ultrasonic cleaner within methanol, acetone, and deionized solutions, respectively, each for 10 min, and finally dried with N₂ drying. The base pressure is below 5.5×10^{-4} Pa, and then the fixed working pressure is at 1.1 Pa within the Ar gas (UHP, 99.999% purity) flow rate at 40 sccm. The RF power was applied at 80 W, and the sputtering time was 30 min. As-deposited samples were annealed at 300–450 °C temperature by using a mini lamp furnace technique (MILA-3000, Advanced Riko) within a vacuum state for 1 h. The schematic of thin film preparation processes is illustrated in Fig. 1. The crystal structure, morphology and film thickness, and atomic composition of SnSe thin film were carried by X-ray diffraction (XRD-600, Shimadzu), the field emission scanning electron microscope (FE-SEM; SU8030, Hitachi), and energy-dispersive X-ray spectroscopy (EDX; SU8030, Hitachi), respectively. The electrical resistivity and Seebeck coefficient values were measured by the ZEM-3 method (Ulvac-Riko). To confirm electrical properties, the carrier concentration and mobility at room temperature were measured by the Hall Effect measurement (HMS-3000, Ecopia) based on the Van der Pauw method under a magnetic field of 0.55 T. Finally, the electrical thermal conductivity value was calculated from the Wiedemann-Franz law based on electrical properties to estimate the ZT values for all samples.

3. Results and discussion

Fig. 2 shows the XRD pattern results of as-deposited and annealed SnSe thin films at different annealing temperatures. The as-deposited

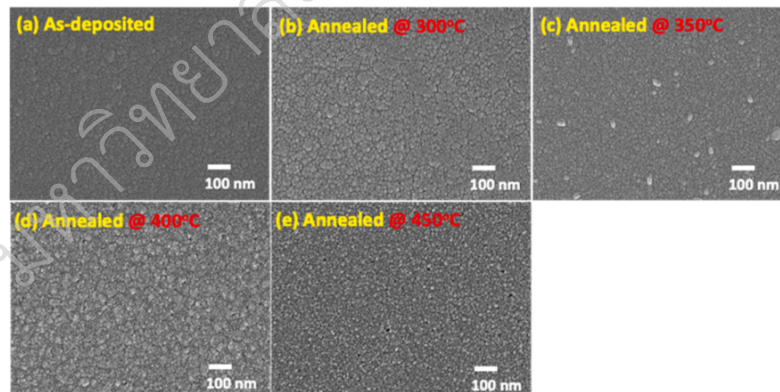


Fig. 3. FE-SEM images of SnSe thin film surfaces; (a) as-deposited, (b) annealed 300 °C, (c) annealed 350 °C, (d) annealed 400 °C, and (e) annealed 450 °C.

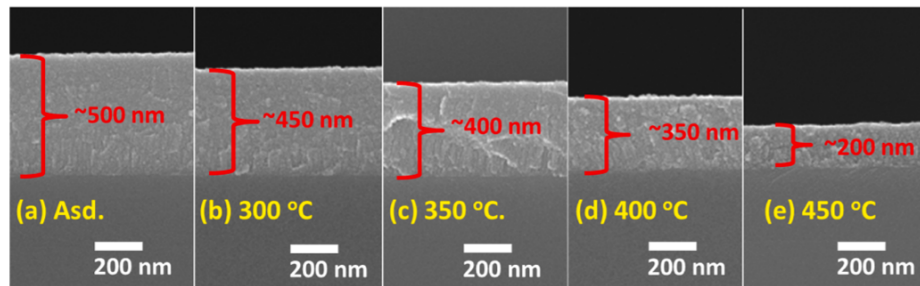


Fig. 4. FE-SEM images of cross-section SnSe thin film surfaces; (a) as-deposited, (b) annealed 300 °C, (c) annealed 350 °C, (d) annealed 400 °C, and (e) annealed 450 °C.

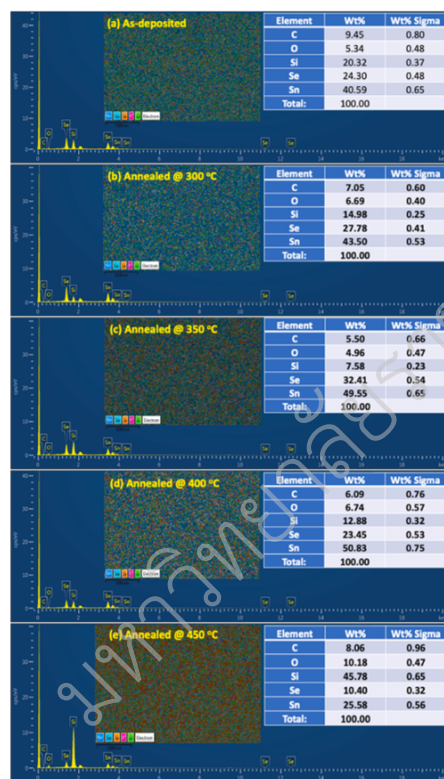


Fig. 5. EDX spectra and atomic composition analysis of SnSe thin films; (a) as-deposited, (b) annealed 300 °C, (c) annealed 350 °C, (d) annealed 400 °C, and (e) annealed 450 °C.

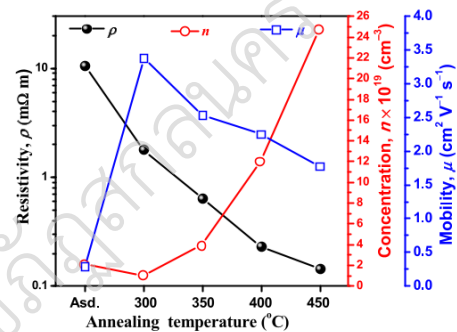


Fig. 6. The carrier concentration, mobility, and electrical resistivity as measured by hall effect method at room temperature of SnSe thin films as annealing temperature functions.

thin film showed the amorphous phase, then became the crystal phase after thin films were annealed at 300–400 °C. These results confirmed the crystal phase transferred with annealing temperatures as illustrated in the XRD peak (400) within the JCPDS card no. 32–1382). In contrast, the thin film became the amorphous phase when the thin film was annealed at a temperature of 450 °C. This result demonstrated that the limit of the SnSe phase as changed is 400 °C. The FE-SEM images of as-deposited and annealed SnSe thin film surfaces are displayed in Fig. 3. The as-deposited light film surface was different from the annealed narrow film surfaces due to between the amorphous and crystalline phases. Fig. 4 shows the FE-SEM images of cross-section SnSe thin film surfaces at different annealing temperatures. The temperature annealing affected reduced the thickness of the SnSe thin film. These results are caused by atomics thermal evaporation, which followed the EDX analysis results, as shown in Fig. 5.

Fig. 5 shows the EDX spectra with an inserted atomic composition of SnSe thin film samples for (a) as-deposited sample, (b) annealed at 300 °C sample, (c) annealed at 350 °C sample, (d) annealed at 400 °C sample, and (e) annealed at 450 °C sample. All samples were successfully identified as traced elements Sn and Se deposited into the substrate. Furthermore, all samples were significantly converted to atomic percentages to obtain the atomic composition. The results showed $\text{Sn}_{1.75}\text{Se}$, $\text{Sn}_{1.55}\text{Se}$, $\text{Sn}_{1.25}\text{Se}$, $\text{Sn}_{1.1}\text{Se}$, and $\text{Sn}_{1.3}\text{Se}$ composition as performed for as-deposited sample, annealed at 300 °C sample, annealed at 350 °C

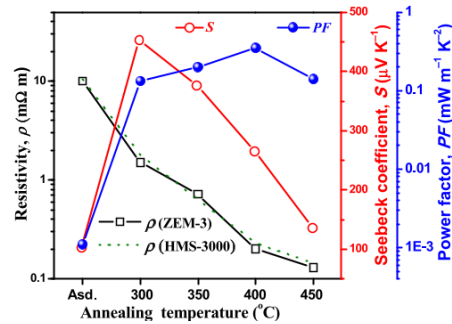


Fig. 7. Shows the resistivity, Seebeck coefficient, and PF value of SnSe thin films as annealed temperature functions.

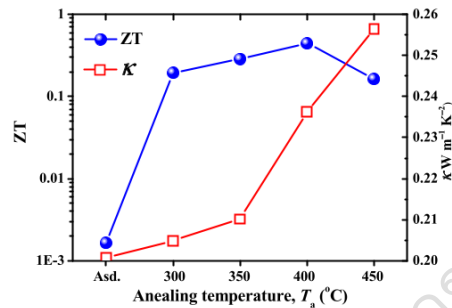


Fig. 8. Estimations for the ZT and total thermal conductivity values of SnSe thin films as annealed temperature functions.

sample, annealed at 400 °C sample, and annealed at 450 °C sample, respectively.

Fig. 6 shows the electrical properties (n and μ) as measured by the Hall effect method at room temperature of SnSe thin film samples concerning thin film annealing temperature. The carrier concentration and mobility values have been related to calculate the electrical resistivity values as follows Eq. (2). The result reveals a uniform trend in which the resistivity value decreases with the annealing temperature increasing. In addition, thermoelectric properties (S and ρ) as measured by ZEM-3 method at room temperature of SnSe thin film samples to be calculated the power factor values as followed Eq. (3), which concerning thin film annealing temperature are illustrated in Fig. 7. Focusing on the electrical resistivity part, the comparison of measured electrical resistivity values from the Hall Effect and ZEM-3 methods demonstrated that both methods show a similar trend of electrical resistivity variation. This signifies that the electrical conductivity of samples increased with the increase in annealing temperature. Based on the S graph, the trend of the Seebeck coefficient on p-type significantly falls along with the temperature rise. The highest Seebeck coefficient from 300 °C annealed or Sn_{1.55}Se sample is around 453 $\mu\text{V K}^{-1}$. Annealing treatment is expected to raise the power factor after resulting in resistivity and Seebeck coefficient in SnSe thin film. Then, the highest PF for all samples resulted in 0.35 $\text{mW m}^{-1} \text{K}^{-2}$, where ρ is 202 $\text{m}\Omega \text{m}$ and S is 165 $\mu\text{V K}^{-1}$ for annealed samples at 400 °C. The κ values were calculated based on the

Table 2

In comparing the thermoelectric properties of SnSe thin film in various synthesis.

Synthesis method	Materials	ZT	Temp. (K)	PF ($\text{mW m}^{-1} \text{K}^{-2}$)	Ref.
Sputtering	SnSe thin film	0.44	300	0.35	This work [3]
Thermal evaporation	SnSe thin film	0.055	501	0.11	[4]
RF magnetron sputtering	SnSe thin film	0.83	700	2.43	[28]
Sputtering	SnSe thin film	0.28	675	2.4	[31]
Chemical vapor transport	SnSe thin film	0.16	300	–	[32]
Sonication-assisted liquid-phase exfoliation	SnSe thin film	–	600	1.55	[33]
Vacuum filtration method	SnSe/PEDOT:PSS thin film	–	353	0.24	[34]
Chemical vapor deposition	SnSe thin film	0.15	550	3.2	[35]
MPCVD	SnSe thin film	0.35	600	3.98	[36]
Electrodeposited and delamination	SnSe thin film	0.4	675	5.8	[37]
Reactive evaporation	SnSe thin film	1.2	42	7.2	[37]

*MPCVD = Microwave plasma chemical vapor deposition.

Wiedemann-Franz law to calculate the κ of SnSe thin films, with lattice thermal conductivity fixed at 0.2 [4] as followed Eq. (4).

Fig. 8 displays the determined annealing temperature dependent on κ and ZT values for SnSe thin films. The total thermal conductivity was around 0.20–0.26 $\text{W m}^{-1} \text{K}^{-1}$, at room temperature. A maximum ZT value is 0.44 for the annealed samples at 400 °C. Among those methods and previously of SnSe thin-film, magnetron sputtering can deposit a progressive adherent and alter the structure by suitable adjusting the deposition parameters of a coating and provides a high degree of freedom to control the structure evolution over various substrates [4, 27]. Additionally, annealing temperature on the physical properties of SnSe thin film shows smoothness increases at elevated temperatures, superior thermoelectric performance, and promising versatile material with applications [28–30]. Therefore, the present work demonstrates the structural requirement to enhance the ZT and PF values of a SnSe thin film deposited by RF magnetron sputtering. Compared to other work, the ZT and PF values based on SnSe thin films were presented in Table 2.

4. Conclusion

The RF magnetron sputtering technique successfully prepared SnSe thin films onto SiO₂/Si-wafer substrates. Amorphous SnSe thin film (as-deposited) could be changed to a crystalline structure within the thermal annealing process during a temperature range of 300–400 °C. Atomic composition for all samples was significantly converted in atomic percentage to obtain the results of Sn_{1.75}Se, Sn_{1.55}Se, Sn_{1.25}Se, Sn_{1.1}Se, and Sn_{1.3}Se atomic composition as performed for as-deposited sample, annealed at 300 °C, 350 °C, 400 °C, and 450 °C samples, respectively. The annealing thin film sample at 400 °C, the maximum power factor of 0.35 $\text{mW m}^{-1} \text{K}^{-2}$ to be estimated at the ZT value of around 0.44, at room temperature.

CRediT authorship contribution statement

Mekhala Insawang: Writing – original draft, Methodology, Investigation. **Surasak Ruamruk:** Investigation. **Athorn Vora-ud:** Writing – review & editing, Writing – original draft, Methodology, Investigation,

Conceptualization. **Kunchit Singsoog**: Data curation. **Sakorn Inthachai**: Data curation. **Kongphope Chaarmart**: Data curation, Conceptualization. **Sarawoot Boonkirdram**: . **Mati Horprathum**: Methodology. **Melania Suweni Muntini**: Supervision, Data curation, Conceptualization. **Sungkyun Park**: Methodology. **Thang Bach Phan**: Methodology. **Tosawat Seetawan**: Supervision, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Acknowledgments

The National Research Council of Thailand (NRCT) and Sakon Nakhon Rajabhat University financially supported this work through a Mid-Career Research Grant (N42A660826) and the Program Management Unit for Human Resources & Institutional Development Research and Innovation (PMU-B) (B16F650001).

References

- [1] Burton, M.R., Howells, G., Mehraban, S., McGettrick, J.D., Lavery, M., Carnie, M.J., 2023. Fully 3 D printed tin selenide (SnSe) thermoelectric generators with alternating n-type and p-type legs. *ACS Appl. Energy Mater.* 6, 5498–5507. <https://doi.org/10.1021/acsaem.3c00576>.
- [10] Hong, M., Chen, Z., Yang, L., Zou, J., 2016. $\text{Bi}_2\text{Sb}_{2-x}\text{Te}_{3+x}$ nanoplates with enhanced thermoelectric performance due to sufficiently decoupled electronic transport properties and strong wide-frequency phonon scatterings. *Nano Energy* 20, 144–155. <https://doi.org/10.1016/j.nanoen.2015.12.009>.
- [11] Jin, Y., Xiao, Y., Wang, D., Huang, Z., Qiu, Y., Zhao, L.-D., 2019. Realizing high thermoelectric performance in GeTe through optimizing Ge vacancies and manipulating Ge precipitates. *ACS Appl. Energy Mater.* 2, 7594–7601. <https://doi.org/10.1021/acsaem.9b01585>.
- [12] Zhu, T., Bai, H., Zhang, J., Tan, G., Yan, Y., Liu, W., Su, X., Wu, J., Zhang, Q., Tang, X., 2020. Realizing high thermoelectric performance in Sb-doped Ag_2Te compounds with a low-temperature monoclinic structure. *ACS Appl. Mater. Interfaces* 12, 39425–39433. <https://doi.org/10.1021/acsaami.0c10932>.
- [13] Gainza, J., Serrano-Sánchez, F., Rodríguez, J.E.F.S., Hüttel, Y., Durá, O.J., Kozá, M.M., Fernández-Díaz, M.T., Meléndez, J.J., Márkus, B.G., Simón, F., Martínez, J.L., Alonso, J.A., Nemes, N.M., 2020. High-performance n-type SnSe thermoelectric polycrystal prepared by arc-melting. *Cell Rep. Phys. Sci.* 12, 1–20. <https://doi.org/10.1016/j.xcrp.2020.100263>.
- [14] Zhang, Q.K., Ning, S.T., Qi, N., Chen, Z.Q., Tang, X.F., Chen, Z.Y., 2019. Enhanced thermoelectric performance of a simple method prepared polycrystalline SnSe optimized by spark plasma sintering. *J. Appl. Phys.* 125, 225109. <https://doi.org/10.1063/1.5095197>.
- [15] Sauti, S., Candolfi, C., Vaneý, J.-B., Oshorodilichuk, V., Masschelein, P., Dauscher, A., Lenoir, B., 2014. Assessment of the thermoelectric performance of polycrystalline p-type SnSe. *Appl. Phys. Lett.* 104, 212105. <https://doi.org/10.1063/1.4880817>.
- [16] Cho, J.Y., Siyar, M., Bae, S.H., Mun, J.S., Kim, M.Y., Hong, S.H., Park, C., 2020. Effect of sintering pressure on electrical transport and thermoelectric properties of polycrystalline SnSe. *Bull. Mater. Sci.* 43 (63), 1–7. <https://doi.org/10.1007/s12034-020-2036-5>.
- [17] Zhao, L.-D., Lo, S.-H., Zhang, Y., Sun, H., Tan, G., Uher, C., Kanatzidis, M.G., 2014. Ultralow thermal conductivity and high thermoelectric figure of merit in SnSe crystals. *Nature* 508 (7496), 373–377. <https://doi.org/10.1038/nature13184>.
- [18] Das, S.S., Rosul, Md G., Zebajadi, M., 2023. Optimization of the thermoelectric properties of SnSe_2 using first-principles calculations. *J. Phys. Chem. C* 127, 6916–6924. <https://doi.org/10.1021/acs.jpcc.2c09137>.
- [19] Meng, K., Zhao, L.-M., Zhang, N.-Y., Zhang, Z.-F., Shen, W.-X., Zhang, Y.-W., Wan, B., Fang, C., Chen, L.-C., Wang, Q.-Q., He, J.-L., Jia, X.-P., 2022. Thermoelectric properties of n-type SiGe alloys with Sn incorporation. *Rare Met.* 41 (12), 4156–4163. <https://doi.org/10.1007/s12598-022-02085-z>.
- [20] Qin, B., Wang, D., Hong, T., Wang, Y., Liu, D., Wang, Z., Gao, X., Ge, Z.-H., Zhao, L.-D., 2023. High thermoelectric efficiency realized in SnSe crystals via structural modulation. *Nat. Commun.* 14, 1–10. <https://doi.org/10.1038/s41467-023-37114-7>.
- [20] Yang, L., Huh, D., Ning, R., Rapp, V., Zeng, Y., Liu, Y., Ju, S., Tao, Y., Jiang, Y., Beak, J., Leem, J., Kaur, S., Lee, H., Zheng, X., Prasher, R.S., 2021. High thermoelectric figure of merit of porous Si nanowires from 300 to 700 K. *Nat. Commun.* 12 (3926), 1–7. <https://doi.org/10.1038/s41467-021-24208-3>.
- [21] Xie, L., He, D., He, J., 2021. SnSe, the rising star thermoelectric material: a new paradigm in atomic blocks, building intriguing physical properties. *Mater. Horiz.* 7, 3–24. <https://doi.org/10.1039/d1mh00091h>.
- [22] Hoang, V.D., Pham, A.T.T., Babu, T., Nguyen, T.H., Le, T.B.N., Ung, T.D.T., Hong, J., Bae, J.-S., Park, H., Park, S., Ohkubo, I., Mori, T., Tran, V.C., Phan, T.B., 2022. New record high thermoelectric of delafossite-based CuCrO_2 thin films obtained by simultaneously reducing electrical resistivity and thermal conductivity via heavy doping with controlled residual stress. *Appl. Surf. Sci.* 583, 152526. <https://doi.org/10.1016/j.apsusc.2022.152526>.
- [23] Kushwaha, A.K., Kalita, H., Suman, S., Bhardwaj, A., Ghosh, R., 2021. Two-dimensional (2D) thermoelectric materials. In: *Thermoelectricity and Advanced Thermoelectric Materials*. Elsevier, Amsterdam, pp. 233–260. <https://doi.org/10.1016/B978-0-12-819984-8.00006-0>.
- [24] Liu, Y., Zhang, Q., Huang, A., Zhang, K., Wan, S., Chen, H., Fu, Y., Zuo, W., Wang, Y., Cao, X., Wang, L., Lemmer, U., Jiang, W., 2024. Fully inkjet-printed Ag_2Se flexible thermoelectric devices for sustainable power generation. *Nat. Commun.* 15, 2141. <https://doi.org/10.1038/s41467-024-46183-1>.
- [25] Yang, D., Shi, X.-L., Li, M., Nisar, M., Mansoor, A., Chen, S., Chen, Y., Li, F., Ma, H., Liang, G.X., Zhang, X., Liu, W., Fan, P., Zheng, Z., Chen, Z.-G., 2024. Flexible power generators by Ag_2Se thin films with record-high thermoelectric performance. *Nat. Commun.* 15, 923. <https://doi.org/10.1038/s41467-024-45092-7>.
- [26] Ao, D.-W., Liu, W.-D., Chen, Y.-X., Wei, M., Jabar, B., Li, F., Shi, X.-L., Zheng, Z.-H., Liang, G.-X., Zhang, X.-H., Fan, P., Chen, Z.-G., 2022. Novel thermal diffusion temperature engineering leading to high thermoelectric performance in Bi_2Te_3 -based flexible thin-films. *Adv. Sci.* 9, 2103547. <https://doi.org/10.1002/advs.202103547>.
- [27] Duployer, B., Tenaillon, C., Thimont, Y., Lenormand, P., Barnabé, A., Presmanes, L., 2020. Preparation and study of CuBi_2O_4 thin films by RF magnetron sputtering. *Mater. Res. Bull.* 130, 110940. <https://doi.org/10.1016/j.materresbull.2020.110940>.
- [28] Song, L., Zhang, J., Iversen, B.B., 2019. Enhanced thermoelectric properties of SnSe thin films grown by single-target magnetron sputtering. *J. Mater. Chem. A* 7, 17981–17986. <https://doi.org/10.1039/C9TA03252E>.
- [29] Kumar, S., Banotra, A., Padha, N., Ahmed, S., 2022. Effect of substrate and annealing temperature on the physical properties of the thin films of SnSe_2 -SnSe alloy. *Opt. Mater.* 134, 113078. <https://doi.org/10.1016/j.optmat.2022.113078>.
- [30] Burton, M.R., Liu, T., McGettrick, J., Mehraban, S., Baker, J., Pockett, A., Watson, T., Fenwick, O., Carnie, M.J., 2018. Thin film tin selenide (SnSe) thermoelectric generators exhibiting ultralow thermal conductivity. *Adv. Mater.* 30 (1801357), 1–8. <https://doi.org/10.1002/adma.201801357>.
- [30] Kumar, M., Rani, S., Singh, Y., Gour, K., Singh, V.N., 2021. Tin-selenide as a futuristic properties and applications. *RSC Adv.* 11, 6477–6503. <https://doi.org/10.1039/D0RA09807H>.
- [31] Ho, C.-H., Lin, W.-Y., Chao, L.-C., Lee, K.-Y., Inagaki, J., Hsueh, H.-C., 2020. Study of structural, thermoelectric, and photoelectric properties of layered tin monochalcogenides SnX ($\text{X} = \text{S}, \text{Se}$) for energy application. *ACS Appl. Energy Mater.* 3, 4896–4905. <https://doi.org/10.1021/acsaem.0c00481>.
- [32] Duong, T.V., Chung, N.X., Phan, H.N., Nguyen, H.T., Nguyen, D.D., Le, L.T., Pham, N.V., 2022. A facile way to optimize thermoelectric properties of SnSe thin films via sonication-assisted liquid-phase exfoliation. *J. Mater. Sci. Mater. Electron.* 33, 15385–15392. <https://doi.org/10.1007/s10854-022-08446-9>.
- [33] Yan, Z., Zhao, Y., Liu, D., Zhang, Z., Zheng, Y., Cui, J., Zhang, Y., Xue, C., 2020. Thermoelectric properties of flexible PEDOT:PSS-based films tuned by SnSe via the vacuum filtration method. *RSC Adv.* 10, 43840–43846. <https://doi.org/10.1039/d0ra04588a>.
- [34] Zhong, Y., Zhang, L., Linseis, V., Qin, B., Chen, W., Zhao, L., Zhu, H., 2020. High-quality textured SnSe thin films for self-powered, rapid-response photothermoelectric application. *Nano Energy* 72, 104742. <https://doi.org/10.1016/j.nanoen.2020.104742>.
- [35] Feng, Y., Zhang, X., Lei, Y., Nie, Y., Xiang, G., 2022. Rapid synthesis of thermoelectric SnSe thin films by MPCVD. *RSC Adv.* 10, 11990–11993. <https://doi.org/10.1039/D0RA01203C>.
- [36] Burton, M.R., Boyle, C.A., Liu, T., McGettrick, J., Nandhakumar, I., Fenwick, O., Carnie, M.J., 2020. Full thermoelectric characterization of stoichiometric electrodeposited thin film tin selenide (SnSe). *ACS Appl. Mater. Interfaces* 12, 28232–28238. <https://doi.org/10.1021/acsaami.0c06026>.
- [37] Urmila, K.S., Namitha, T.A., Rajani, J., Phillip, R.R., Pradeep, B., 2016. Optoelectronic properties and Seebeck coefficient in SnSe thin films. *J. Semiconduct.* 37, 093002. <https://doi.org/10.1088/1674-4926/37/9/093002>.
- [4] Singh, K., Anwar, S., Dubey, P., Mishra, S., 2023. Enhanced thermoelectric performance of mechanically hard nano-crystalline-sputtered SnSe thin film compared to the bulk of SnSe. *J. Mater. Sci. Mater. Electron.* 34, 1115. <https://doi.org/10.1007/s10854-023-10487-7>.
- [5] Chen, Z.-G., Han, G., Yang, L., Cheng, L., Zou, J., 2012. Nanostructured thermoelectric materials: current research and future challenge. *Prog. Nat. Sci.: Mater. Int.* 22, 535–549. <https://doi.org/10.1016/j.pnsc.2012.11.011>.
- [6] Thaowonkaw, S., Insawang, M., Vora-ud, A., Horprathum, M., Muthitamongkol, P., Maensiri, M., Kumar, M., Phan, T.B., Seetawan, T., 2023. Effect of substrate rotation and rapid thermal annealing on thermoelectric properties of Ag-doped Sb_2Te_3 thin films. *Vacuum* 211, 1–8. <https://doi.org/10.1016/j.vacuum.2023.111920>.
- [7] Seetawan, T., Vora-Ud, A., Ullah, F., Thang, P.B., Kumar, M., Kim, H.J., 2022. Microstructural and thermoelectric properties of PbTe single crystals as grown by

M. Insawang et al.

Radiation Physics and Chemistry 222 (2024) 111789

- Czochralski method. Mater. Lett. 324, 1–4. <https://doi.org/10.1016/j.matlet.2022.132798>.
- [8] Franz, R., Wiedemann, G., 1853. Ueber die Wärme-Leitungsfähigkeit der metalle. Ann. Phys. 165, 497–531.
- [9] Hong, M., Chen, Z.-G., Zou, J., 2018. Fundamental and progress of Bi₂Te₃-based thermoelectric materials. Chin. Phys. B 27 (4), 1–46. <https://doi.org/10.1088/1674-1056/27/4/048403>.

มหาวิทยาลัยราชภัฏสุราษฎร์ธานี

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/387322793>

Enhancing Thermoelectric Power Factor of PEDOT:PSS/SnSe₂ Nanocomposite Sheets by Rapid Thermal Annealing

Article in *Journal of Electronic Materials* · December 2024

DOI: 10.1007/s11664-024-11687-5

CITATION

1

6 authors, including:



Mekhala Insawang

Sakon Nakhon Rajabhat University

9 PUBLICATIONS 41 CITATIONS

[SEE PROFILE](#)



Tosawat Seetawan

Sakon Nakhon Rajabhat University

195 PUBLICATIONS 1,298 CITATIONS

[SEE PROFILE](#)

READS

32



Athorn Vora-ud

Sakon Nakhon Rajabhat University

77 PUBLICATIONS 517 CITATIONS

[SEE PROFILE](#)



Thang Phan

Sungkyunkwan University

251 PUBLICATIONS 4,228 CITATIONS

[SEE PROFILE](#)

All content following this page was uploaded by Mekhala Insawang on 07 January 2025.

The user has requested enhancement of the downloaded file.



Enhancing Thermoelectric Power Factor of PEDOT:PSS/SnSe₂ Nanocomposite Sheets by Rapid Thermal Annealing

Mekhala Insawang^{1,2} · Athorn Vora-ud^{1,2} · Tosawat Seetawan^{1,2} · Melania Suweni Muntini³ · Thang Bach Phan^{4,5} · Manish Kumar⁶

Received: 26 May 2024 / Accepted: 9 December 2024
 © The Minerals, Metals & Materials Society 2024

Abstract

Organic/inorganic nanocomposite sheets of poly (3,4-ethylenedioxythiophene)-poly (styrenesul-fonate) (PEDOT:PSS) + SnSe₂ were synthesized by a wet chemical method followed by rapid thermal annealing (RTA) at 220°C for 1 h. The ratio of PEDOT:PSS to SnSe₂ was varied by increasing incorporation of SnSe₂ powder as 0.0 g, 0.1 g, 0.2 g, and 0.3 g in the same volume of polymer solution (3 mL). It was found that the as-prepared PEDOT:PSS + SnSe₂ nanocomposite sheets were amorphous, and that the roughness of the sheets increased with increasing amounts of SnSe₂ powder. All the nanocomposite sheets showed *p*-type thermoelectric behavior. After the RTA process, the nanocomposite sheets exhibited an increased thermoelectric power factor of 37.4 μW m⁻¹ K⁻² compared to 0.44 μW m⁻¹ K⁻² before RTA for the same filling factor of the SnSe₂ reinforcement.

Keywords Organic–inorganic composite · thermoelectric properties · PEDOT:PSS · SnSe₂

Introduction

Organic thermoelectric (OTE) materials are recently finding increasing interest owing to their advantages of being low-cost, non-toxic, and promising flexible applicability in various fields.^{1,5} For practical high-performance application, a high dimensionless figure-of-merit (*ZT*) value is required in OTE materials. The *ZT* value is defined by;

$$ZT = \frac{S^2 T}{\rho \kappa} \quad (1)$$

where *S* is the Seebeck coefficient, *ρ* is the electrical resistivity, *κ* is the total thermal conductivity and *T* is the absolute temperature.^{6,7} The *S* and *ρ* values mainly control the thermionic emission (TE) power factor (PF) in^{8,9}:

$$PF = \frac{S^2}{\rho} \quad (2)$$

The poly 3, 4-ethylenedioxythiophene-polystyrene sulfonate (PEDOT-PSS) polymer is a significant area of interest in the field of OTE^{10,11} with good electrical conductivity and extremely low thermal conductivity.¹² PEDOT-PSS has been reported to have a *ZT* value of 0.42 at room temperature.¹³

✉ Athorn Vora-ud
 athornvora-ud@snru.ac.th

¹ Program of Physics, Faculty of Science and Technology, Sakon Nakhon Rajabhat University, 680 Nittayo Rd., Mueang District, Sakon Nakhon 47000, Thailand

² Thin Films Research Laboratory, Center of Excellence on Alternative Energy, Research and Development Institute, Sakon Nakhon Rajabhat University, 680 Nittayo Rd., Mueang District, Sakon Nakhon 47000, Thailand

³ Instrumentation and Electronic Laboratory, Department of Physics, Institute Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia

⁴ Center for Innovative Materials and Architectures, Ho Chi Minh City 700000, Vietnam

⁵ Vietnam National University, Ho Chi Minh City 70000, Vietnam

⁶ Centre for Advanced Materials, Organisation for Science Innovations and Research, RS Science Park, Bah 283104, India

PEDOT:PSS has been intensively investigated owing to its solution process ability^{14–17} and easy tunability of its redox state (i.e., bipolar or neutral) that facilitates the optimization of the S and ρ values.^{18–22} Since incorporating a suitable reinforcement can induce remarkable enhancement in the desired properties in nanocomposites, it is imperative to investigate polymer nanocomposites of PEDOT:PSS with suitable reinforcements. In this direction, few works have been reported that improve organic-based TE material for practical use²² exhibiting the advantage of being customizable²³ by doping with several inorganic TE materials. Moreover, the annealing temperature at an optimized temperature of 220°C could enhance the PF of PEDOT:PSS films to around 162.5 times that of the pristine film before annealing within the crystalline microstructure evolution.²⁴

Among other inorganic TE materials, tin diselenide (SnSe_2) is a semiconductor material with a bulk bandgap of 1.0 eV²⁵ and which shows a mobility of $28 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in thin-film form.²⁶ SnSe_2 has additionally demonstrated a potential for applications in the fields of optoelectronics, photovoltaics, infrared optoelectronic devices, holographic recording systems, and memory-switching devices.²⁷ Moreover, the SnSe_2 material has been promoted for new 2-dimensional TE materials^{29–31} based on structure regulation^{28,29} and nano-particles,³⁰ etc. In the same way, the PEDOT:PSS has been reported to reduce the low-dimensional material

with annealing temperature.²⁴ Hence, the low-dimensional material coupling between PEDOT:PSS and SnSe_2 will be investigated in this work.

We prepared the organic/inorganic composite sheets (PEDOT:PSS + SnSe_2) through the hot plate and stirred methods based on the solution. The PEDOT:PSS + SnSe_2 composite sheets were annealed with rapid thermal annealing (RTA) at 220°C for 1 h. The microstructure, morphology, composition, and TE properties of PEDOT:PSS + SnSe_2 composite sheets investigated and reported here.

Experimental

PEDOT:PSS (Ossila PH1000) 1.0–1.3 wt% in water was used at 3 mL each to be mixed with several SnSe_2 powders (99.9%, APS < 100 nm) with 0.0 g, 0.1 g, 0.2 g, and 0.3 g. The mixing solutions were each converted into microsheets onto beakers via a hot plate at 40°C and stirred for 1 h. Then, the PEDOT:PSS + SnSe_2 polymer sheets onto beakers were stripped to obtain the sheet samples of PEDOT:PSS, PEDOT:PSS + SnSe_2 (0.1 g), PEDOT:PSS + SnSe_2 (0.2 g), and PEDOT:PSS + SnSe_2 (0.3 g). The sheet sample preparation process diagram is shown in Fig. 1. All the samples were annealed by an RTA process (Mila5000; Advanced Riko) under a vacuum state. The temperature was fixed at

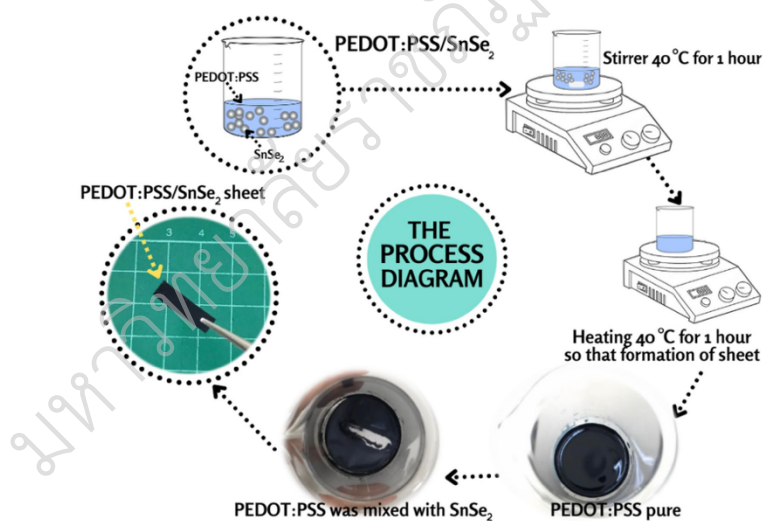


Fig. 1 Schematic of PEDOT:PSS/SnSe₂-based sheet preparation.

220°C with a heating step of 5°C/s for all the samples. After the RTA process, the microstructure of the SnSe₂ powder and polymer sheet samples was measured by x-ray diffractometer (XRD; 6100, Shimadzu) with CuK α 1 radiation in a 2θ range of 10–70°, with scan steps of 0.02°/1 s. The morphology, thickness, and atomic composition of all the sheet samples were evaluated by the field-emission scanning electron microscopy and energy-dispersive x-ray spectroscopy (FE-SEM/EDX; SU8030; Hitachi). The carrier concentration (n) and mobility (μ) were measured by the Hall effect measurement (HMS-3000, Ecopia) based on the Van der Pauw method under a magnetic field of 0.55 T. The field ρ and S of the annealed thin-film samples were measured by a ZEM-3 apparatus (ZEM-3; Advance Riko) under a helium atmosphere at room temperature to 100°C. The sheet sample size of $3.0 \times 15.0 \text{ mm}^2$ was cut and loaded onto the ZEM-3 thin film attachment.^{7,31,32}

Results and Discussion

The XRD patterns of the SnSe₂ powder and PEDOT:PSS + SnSe₂ polymer sheet samples are shown in Fig. 2. Figure 2a shows the XRD pattern of SnSe₂ powder

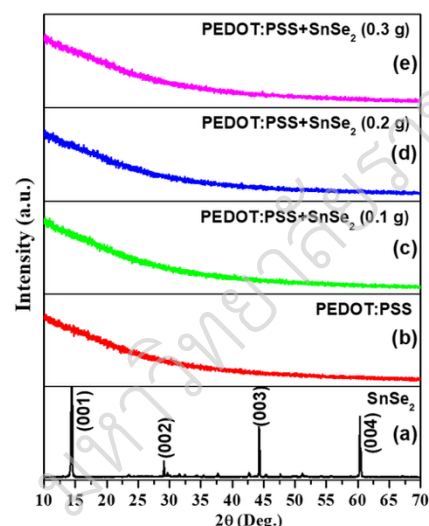


Fig. 2 XRD patterns of (a) SnSe₂ powder and (b–e) PEDOT:PSS sheets mixed with SnSe₂ powder of 0.0 g, 0.1 g, 0.2 g, and 0.3 g, respectively, before annealing.

which confirmed the single-crystal structure in hexagonal as aligned along the (001) plane (JCPDS#023-0602).³³ Figure 2b–e shows the XRD patterns of PEDOT:PSS + SnSe₂ within the SnSe₂ with added (b) 0.0 g, (c) 0.1 g, (d) 0.2 g, and (e) 0.3 g, which all indicate the amorphous phase of the polymers. Figure 3 shows the XRD pattern of the PEDOT:PSS + SnSe₂ annealed polymer sheet samples for (b) 0.0 g, (c) 0.1 g, (d) 0.2 g, and (e) 0.3 g. The effect of RTA can be seen in the composite phase of SnSe₂ with the major diffraction peaks of SnSe₂ (JCPDS#023-0602) appearing at $2\theta = 14.42^\circ$, 29.11° , 44.22° , and 60.24° corresponding to the (001), (002), (003), and (004) planes, respectively.

The morphology and chemical composition of the PEDOT:PSS + SnSe₂ polymer sheets are shown in Fig. 4. Figure 4(1) shows SEM images of the amorphous surface morphology before annealing for PEDOT:PSS within the SnSe₂ with added (a) 0.0 g, (b) 0.1 g, (c) 0.2 g, and (d) 0.3 g. As a result, the surface morphology of the PEDOT:PSS polymer sheets was more homogenized and had very smooth roughness, and then the rough surface of the PEDOT:PSS + SnSe₂ polymer sheets was increased with

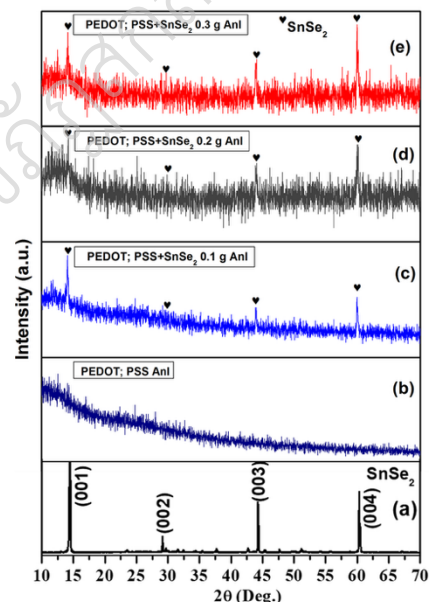


Fig. 3 XRD patterns of (a) SnSe₂ powder and (b–e) PEDOT:PSS sheets mixed with SnSe₂ powder of 0.0 g, 0.1 g, 0.2 g, and 0.3 g, respectively, after annealing.

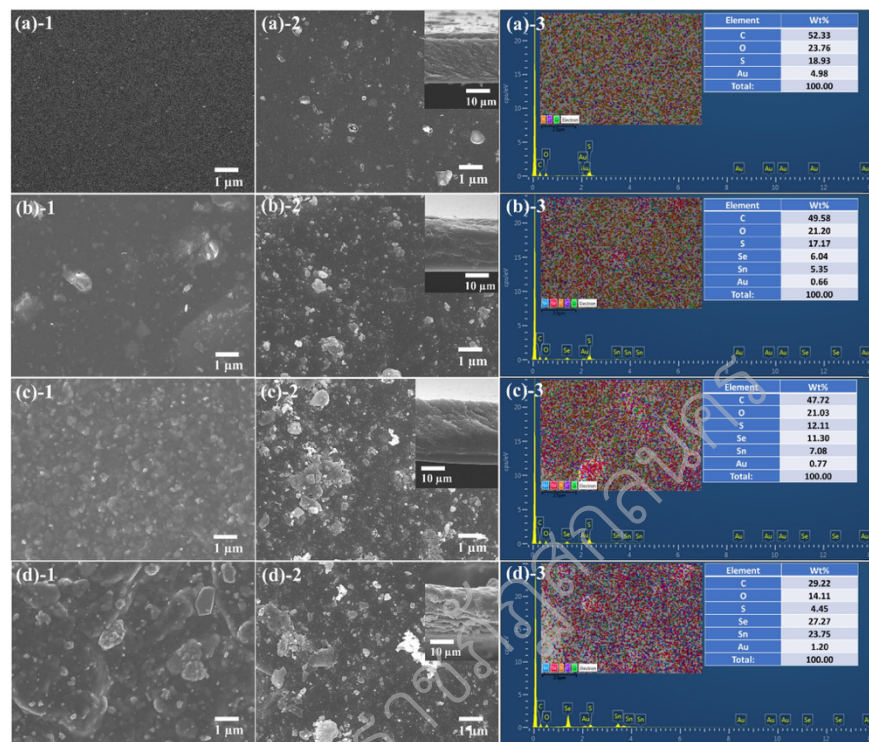


Fig. 4 SEM images of surface morphology before annealing (1), surface morphology after annealing and thickness (2) and EDX spectra with (insets) atomic mapping and composition (3) of PEDOT:PSS sheets mixed with SnSe₂ powder of (a) 0.0 g, (b) 0.1 g, (c) 0.2 g and (d) 0.3 g.

the concentration of added SnSe₂. Figure 4(2) shows SEM images of the composite surface morphology after annealing and cross-sections to obtain sheet thickness (insets) for PEDOT:PSS within the SnSe₂ with added (a) 0.0 g, (b) 0.1 g, (c) 0.2 g, and (d) 0.3 g. The results show the surface morphology of the SnSe₂ as mixed onto the PEDOT:PSS polymer sheet. These results agree with the XRD results of the composite phase of SnSe₂ as affected by the RTA process.

While all the sheet thicknesses are the same at around 30 μm, Fig. 4(3) shows EDX spectra and element mapping of the atomic composition in PEDOT:PSS + SnSe₂ within the SnSe₂ with added (a) 0.0 g, (b) 0.1 g, (c) 0.2 g, and (d) 0.3 g. The results indicate that the atomic composition in PEDOT:PSS + SnSe₂ polymer sheets is composed

of C, O, and S elements for PEDOT:PSS essential and C, O, S, Sn, and Se elements for PEDOT:PSS + SnSe₂. Then, the Au atomic composition was obtained from noble metal coating to especially helpful samples conducted during the SEM processing. Moreover, the atomic composition of Sn and Se has been increased with the increase in the concentration of SnSe₂ to confirm the composition of the PEDOT:PSS + SnSe₂ polymer sheets.

Figure 5 shows the n and μ values measured by the Hall effect method at room temperature of the PEDOT:PSS + SnSe₂ polymer sheets, indicating that the samples before annealing had very low mobility (0.014–0.15 cm² V⁻¹ s⁻¹). Then, after the annealing of the samples, the μ has reached a maximum of 1.84 cm² V⁻¹ s⁻¹ (PEDOT:PSS + SnSe₂ (0.2 g)). Hence, the reaching of μ

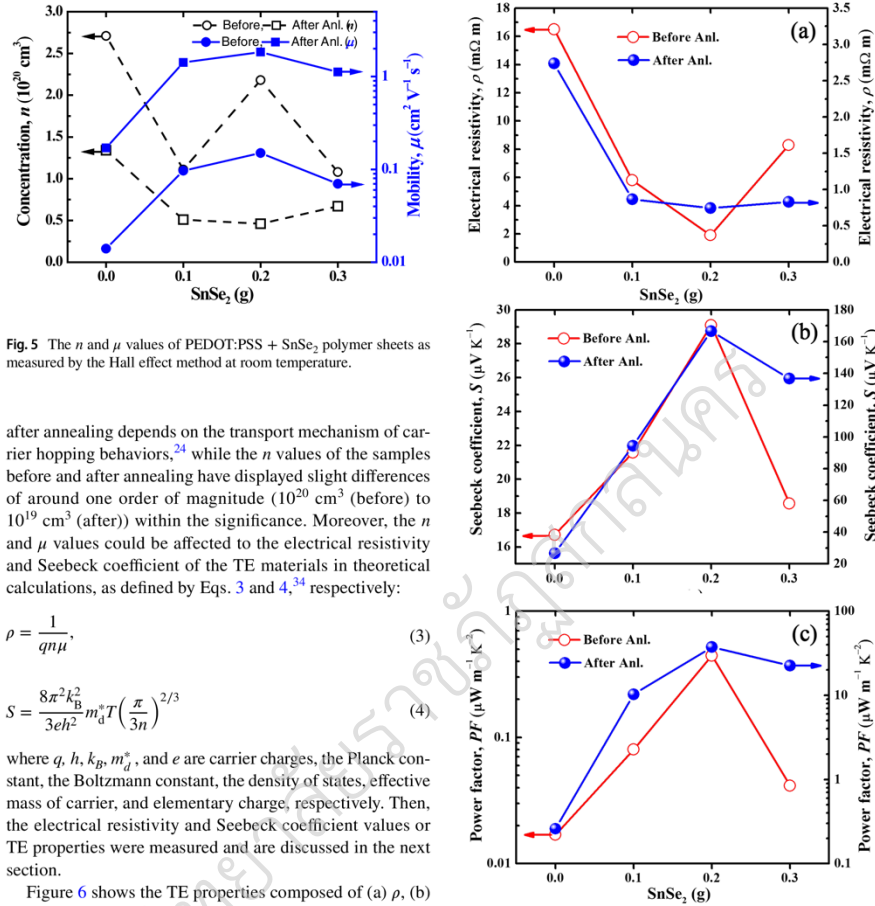


Fig. 5 The n and μ values of PEDOT:PSS + SnSe₂ polymer sheets as measured by the Hall effect method at room temperature.

after annealing depends on the transport mechanism of carrier hopping behaviors,²⁴ while the n values of the samples before and after annealing have displayed slight differences of around one order of magnitude (10^{20} cm^{-3} (before) to 10^{19} cm^{-3} (after)) within the significance. Moreover, the n and μ values could be affected to the electrical resistivity and Seebeck coefficient of the TE materials in theoretical calculations, as defined by Eqs. 3 and 4,³⁴ respectively:

$$\rho = \frac{1}{qn\mu}, \quad (3)$$

$$S = \frac{8\pi^2 k_B^2}{3eh^2} m_d^* T \left(\frac{\pi}{3n} \right)^{2/3} \quad (4)$$

where q , h , k_B , m_d^* , and e are carrier charges, the Planck constant, the Boltzmann constant, the density of states, effective mass of carrier, and elementary charge, respectively. Then, the electrical resistivity and Seebeck coefficient values or TE properties were measured and are discussed in the next section.

Figure 6 shows the TE properties composed of (a) ρ , (b) S , and (c) the PF of PEDOT:PSS + SnSe₂ polymer sheets at room temperature. The values of the samples before annealing were slightly decreased with a SnSe₂ concentration of 0.1 g and 0.2 g and then increased after a SnSe₂ concentration of 0.3 g. After the sample was annealed, the ρ values were slightly decreased and then trended stable with the SnSe₂ concentrations. The role of the RTA process induced the microstructure of SnSe₂ to decrease the ρ value by one order of magnitude (PEDOT:PSS + SnSe₂ (0.2 g); 1.91 m Ωm (before) and 0.74 m Ωm (after)) due to the mobility enhancement within the carrier hopping behaviors. While the S values for all samples indicated p -type

thermoelectricity, the S values of samples before annealing were slightly increased with a SnSe₂ concentrations of 0.1 g and 0.2 g and then increased after a SnSe₂ concentration of 0.3 g. After the sample was annealed, the S values suddenly increased with a SnSe₂ concentrations of 0.1 g and 0.2 g, and then they increased after a SnSe₂ concentration of 0.3 g. These results indicate that the increase in carrier mobility

Table 1 Comparison of PEDOT:PSS + SnSe₂ with other studies

Methods	Compositions	Temp. (K)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	References
Vacuum filtration	PEDOT:PSS/SnSe thin film	353	24.42	35
Vacuum filtration	PEDOT:PSS/SnSe nanosheet enhancing by SWCNT	380	109.9	36
Vacuum filtration	PEDOT:PSS/SnSe enhancing by MWCNTs	393	59.35	37
Cold-pressing & Vacuum filtration	PEDOT:PSS/SnSe- MWCNTs	393	166.5	38
Direct vacuum-filtration	PEDOT:PSS/MoSe ₂ nanosheets	300	48.6	39
Spin coating	PEDOT:PSS/Cu ₂ Se thin film	450	20.1	40
Wet chemical	PEDOT:PSS/SnSe ₂ polymer sheet	300	37.4	This work

MWCNTs multiwall carbon nanotubes, SWCNT single-walled carbon nanotube.

and the decrease in carrier concentration after annealing have been induced to enhance the Seebeck coefficient. As the same ρ values, the role of the RTA process has increased the S values by around one order of magnitude compared to before annealing (PEDOT:PSS + SnSe₂ (0.2 g); $29 \mu\text{V K}^{-1}$ (before) and $164 \mu\text{V K}^{-1}$ (after)). From the low ρ and high S values of PEDOT:PSS + SnSe₂ (0.2 g), the PF yielded a maximum of $37.4 \mu\text{W m}^{-1} \text{K}^{-2}$ after annealed at 220°C . In comparison, as listed in Table 1, the TE properties of the PEDOT:PSS + SnSe₂ polymer sheets are comparable to the literature on doped PEDOT:PSS polymer sheets.^{35–40} The enhanced TE power factor is affected by changes in the crystallography and morphology within the increased crystallinity of SnSe₂ due to rapid thermal annealing.

Conclusions

We prepared organic/inorganic composite sheets based on PEDOT:PSS and SnSe₂ nanopowder. The microstructure of the sheets showed the general amorphous structure of PEDOT:PSS and then led the composite with the SnSe₂ phase after annealing. TE properties of the composite PEDOT:PSS + SnSe₂ sheets showed a p -type thermoelectricity at room temperature. The ρ and S were increased with the increase in the concentration of SnSe₂. The PEDOT:PSS + SnSe₂ (0.2 g) sample showed the maximum PF of $0.44 \mu\text{W m}^{-1} \text{K}^{-2}$ (before annealing) and $37.4 \mu\text{W m}^{-1} \text{K}^{-2}$ (after annealing) at 220°C , which indicated that the effect of RTA could enhanced the PF by around two orders of magnitude.

Acknowledgments This work was financially supported by the National Research Council of Thailand (NRCT) and Sakon Nakhon Rajabhat University through Mid-Career Research Grant (N42A660826) and Program Management Unit for Human Resources & Institutional Development Research and Innovation (PMU-B) (B16F650001). Also, this work was financially supported by Vietnam National University Ho Chi Minh City (TX2025-50-01).

Conflict of interest The authors declare no conflict of interest.

References

1. A. Tripathi, Y. Lee, S. Lee, and Y.H. Woo, Recent advances in n -type organic thermoelectric materials, dopants, and doping strategies. *J. Mater. Chem. C* 10, 3 (2022).
2. B. Russ, A. Glauddell, J.J. Urban, L.M. Chabinye, and A.R. Segalman, Organic thermoelectric materials for energy harvesting and temperature control, *Nat. Rev. Mater.* 10, 16050 (2016).
3. H. Wang and C. Yu, *Thermoelectric Energy Conversion*, ed. R. Funahashi (Cambridge: Elsevier, 2021), p. 347.
4. H. Wang, and C. Yu, Organic thermoelectrics: materials preparation, performance optimization, and device integration. *Joule* 3, 53 (2019).
5. Y. Zhang, W. Wang, F. Zhang, K. Dai, C. Li, Y. Fan, G. Chen, and Q. Zheng, Soft organic thermoelectric materials: principles, current state of the art and applications. *Nano Micro Small* 18(12), 2104922 (2021).
6. P. Mele, D. Narducci, M. Ohta, K. Biswas, J. Morante, S. Saini, and T. Endo, *Thermoelectric Thin Films Materials and Devices*, 1st ed., (Dordrecht: Springer, 2010).
7. A. Vora-ud, M. Horprathum, P. Eiamchai, P. Muthitamongkol, C. Thanachayanont, W. Somkhunthot, and T. Seetawan, Power factor investigation of RF magnetron sputtered c -GeSbTe thin film. *Surf. Coat. Tech.* 291, 15 (2016).
8. T. Seetawan, V. Vora-Ud, F. Ullah, B.T. Phan, M. Kumar, and H.J. Kim, Microstructural and thermoelectric properties of PbTe single crystals as grown by Czochralski method. *Mater. Let.* 324, 1 (2022).
9. A. Vora-ud, M. Horprathum, M. Kumar, P. Muthitamongkol, C. Chananonawathorn, B. Saekow, I. Nualkham, S. Thaowonkaew, C. Thanachayanont, and T. Seetawan, Effect of Ag mixing in thermoelectric Ge₂Sb₂Te₃ thin films. *Mater. Let.* 234, 229 (2019).
10. E. Bihari, Y. Deng, T. Miyake, M. Saadaoui, G.G. Malliaras, and M. Rolandi, A Disposable paper breathalyzer with an alcohol sensing organic electrochemical transistor. *Sci. Rep.* 6, 27582 (2016).
11. X. Cao, M. Zhang, Y. Yang, H. Deng, and Q. Fu, Thermoelectric PEDOT:PSS sheet/SWCNTs composites films with layered structure. *Compos. Commun.* 27, 100869 (2021).
12. J.-Y. Kim, M.-H. Kwon, Y.-K. Min, S. Kwon, and D.-W. Ihm, Self-assembly and crystalline growth of poly(3,4-ethylenedioxythiophene) nanofilms. *Adv. Mater.* 19, 3501 (2007).
13. G.-H. Kim, L. Shao, K. Zhang, and K.P. Pipe, Engineered doping of organic semiconductors for enhanced thermoelectric efficiency. *Nat. Mater.* 12, 719 (2013).
14. J. Ouyang, Q. Xu, C.-W. Chu, Y. Yang, G. Li, and J. Shinar, On the mechanism of conductivity enhancement in poly

- (3,4-ethylenedioxythiophene): poly(styrene sulfonate) film through solvent treatment. *Polymer* 45, 8443 (2004).
15. Y. Wang, C. Zhu, R. Pfattner, H. Yan, L. Jin, S. Chen, F. Molina-Lopez, F. Lissel, J. Liu, N.I. Rabiah, Z. Chen, J.W. Chung, C. Linder, M.F. Toney, B. Murmann, and Z. Bao, A highly stretchable, transparent, and conductive polymer. *Sci. Adv.* 3, e1602076 (2017).
 16. S. Hwang, I. Jeong, J. Park, J.K. Kim, H. Kim, T. Lee, J. Kwak, and S. Chung, Enhanced output performance of all-solution-processed organic thermoelectrics: spray printing and interface engineering. *ACS Appl. Mater. Interfaces* 12, 26250 (2020).
 17. S.H. Kim, Y. Kim, H. Choi, J. Park, J.H. Song, H.W. Baac, M. Shin, J. Kwak, and D. Son, Mechanically and electrically durable, stretchable electronic textiles for robust wearable electronics. *RSC Adv.* 11, 22327 (2021).
 18. Z. Fan, D. Du, X. Guan, and J. Ouyang, Polymer films with ultra-high thermoelectric properties arising from significant Seebeck coefficient enhancement by ion accumulation on surface. *Nano Energy* 51, 481 (2018).
 19. N. Kim, S. Lienemann, I. Petsagkourakis, D.A. Mengistie, S. Kee, T. Ederth, V. Gueskine, P. Leclère, R. Lazzaroni, X. Crispin, and K. Tybrandt, Elastic conducting polymer composites in thermoelectric modules. *Nat. Commun.* 11, 1424 (2020).
 20. J. Dong, D. Gerlach, P. Koutsogiannis, P. Rudolf, and G. Portale, Boosting the thermoelectric properties of PEDOT:PSS via low-impact deposition of tin oxide nanoparticles. *Adv. Electron. Mater.* 7, 2001284 (2021).
 21. S. Tu, T. Tian, A.L. Oechsle, S. Yin, X. Jiang, W. Cao, N. Li, M.A. Scheel, L.K. Reb, S. Hou, A.S. Bandarenka, M. Schwartzkop, S.V. Roth, and P. Müller-Buschbaum, Improvement of the thermoelectric properties of PEDOT:PSS films via DMSO addition and DMSO/salt post-treatment resolved from a fundamental view. *Chem. Eng. J.* 429, 132295 (2022).
 22. M. Hokazono, H. Anno, and N. Tushima, Thermoelectric properties and thermal stability of PEDOT:PSS films on a polyimide substrate and application in flexible energy conversion devices. *J. Elect. Mater.* 43, 2196 (2014).
 23. X. Yan, Y. Zhao, G. Cao, X. Li, C. Gao, L. Liu, S. Ahmed, F. Altaf, H. Tan, X. Ma, Z. Xie, and H. Zhang, 2D organic materials: status and challenges. *Adv. Sci.* 10, 2203889 (2022).
 24. X. Huang, L. Deng, F. Liu, Q. Zhang, and G. Chen, Effect of crystalline microstructure evolution on thermoelectric performance of PEDOT : PSS films. *Energy Mater Adv.* 2021, 572537 (2021).
 25. P. Yu, X. Yu, W. Lu, H. Lin, L. Sun, K. Du, F. Liu, W. Fu, Q. Zeng, Z. Shen, C. Jin, Q.J. Wang, and Z. Liu, Fast photoresponse from 1T tin diselenide atomic layers. *Adv. Funct. Mater.* 26, 137–145 (2016).
 26. Y. Su, M.A. Ebrish, E.J. Olson, and S.J. Koester, SnSe, field-effect transistors with high drive current. *Appl. Phys. Lett.* 103, 263104 (2013).
 27. K.C. Zankat, P. Pataniya, G.K. Solanki, K.D. Patel, V.M. Pathak, N. Som, and K.P. Jha, Investigation of morphological and structural properties of *N* incorporated SnSe₂ single crystals. *Mat. Sci. Semicon. Proc.* 80, 137 (2018).
 28. X. Yang, H. Zhao, Y. Shen, C. Wang, H. Chen, T. Zhang, and X. Zheng, Effects of structural regulation on the thermoelectric properties of two-dimensional SnSe₂ films. *Appl. Mater. Today* 37, 102098 (2024).
 29. A. Rehman, A. Ali, S. Ikram, M. Amami, and K. Mahmood, Characterization of polycrystalline SnSe₂ thin films for thermoelectric applications grown by single-stage horizontal tube furnace (SHTF). *Optic Mater.* 133, 112797 (2022).
 30. N. Salah, S. Abdullahi, Y.N. Salah, A. Alshahrie, and K. Koumoto, Suppressing the thermal conductivity to enhance the thermoelectric performance of SnSe₂ using the high-energy ball milling in a pressurised N₂ atmosphere. *J. Mater. Res. Tech.* 31, 1067 (2024).
 31. A. Vora-Ud, S. Thaowonkaew, J. Khajornrit, K. Singsoog, P. Muthitamongkol, C. Chananonawathorn, N. Chanlek, M. Horprathum, S. Maensiri, and T. Seetawan, Rapid thermal annealing induced the *c*-axis (00 *l*) preferred orientation and the *p*-type thermoelectric properties of Bi-Sb-Te thin films. *Thin Solid Films* 706, 138094 (2020).
 32. A. Vora-ud, K. Chaarmart, W. Kasemsin, S. Boonkirdram, and T. Seetawan, Transparent thermoelectric properties of copper iodide thin films. *Physica B* 625, 413527 (2022).
 33. N.D. Boscher, C.J. Carmalt, R.G. Palgrave, and I.P. Parkin, Atmospheric pressure chemical vapour deposition of SnSe and SnSe₂ thin films on glass. *Thin Solid Films* 516, 4750 (2008).
 34. D.C. Truong, S. Thaowonkaew, P. Muthitamongkol, M. Horprathum, M. Kumar, T.B.N. Le, A.T.T. Pham, T. Seetawan, A. Vora-ud, and T.B. Phan, Relaxation of residual stress- controlled thermopower factor in transparent-flexible Ti-doped ZnO thin films. *Ceramic Inter.* 48, 2605 (2022).
 35. Z. Yan, Y. Zhao, D. Liu, Z. Zhang, Y. Zheng, J. Cui, Y. Zhang, and C. Xue, Thermoelectric properties of flexible PEDOT:PSS-based films tuned by SnSe via the vacuum filtration method. *RSC Adv.* 71, 43840 (2020).
 36. X. Liu, Y. Du, Q. Meng, Y. Dou, M. Jin, J. Xu, and S.Z. Shen, Free-standing single-walled carbon nanotube/SnSe nanosheet/ Poly(3,4-Ethylenedioxythiophene):Poly(4-styrenesulfonate) nanocomposite films for flexible thermoelectric power generators. *Adv. Eng. Mater.* 22, 2000605 (2020).
 37. D. Liu, Z. Yan, Y. Zhao, Z. Zhang, Y. Zheng, B. Zhang, P. Chi, and C. Xue, Enhanced performance of SnSe/PEDOT:PSS composite films by MWCNTs for flexible thermoelectric power generator. *J. Alloy. Compd.* 898, 162844 (2022).
 38. D. Liu, Z. Yan, Y. Zhao, Z. Zhang, Y. Zheng, B. Zhang, P. Chi, and C. Xue, Facile MWCNTs-SnSe/PEDOT:PSS ternary composite flexible thermoelectric films optimized by cold-pressing. *J. Mater. Res. Tech.* 15, 4452 (2021).
 39. X. Li, C. Liu, T. Wang, W. Wang, Z. Wang, Q. Jiang, F. Jiang, and J. Xu, Preparation of 2D MoSe₂/PEDOT:PSS composite and its thermoelectric properties. *Mater. Res. Exp.* 4, 116410 (2017).
 40. S.S. Butt, M.U. Farooq, M.A. Basit, U. Ali, and M.A. Akram, Improved thermoelectric power factor of multilayered poly(3,4-ethylenedioxythiophene) polystyrene sulfonate and Cu₂Se thin films. *Thin Solid Film* 784, 140090 (2023).

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

APPENDICE C

A BRIEF HISTORY OF RESEARCHER

A BRIEF HISTORY OF RESEARCHER

PERSONAL DATA:

Name	Mekhala Insawang
Academic Position	Ph.D. student
Date of Birth	June 1 st 1994
Place of Birth	Suphan Buri, Thailand
Nationality	Thai
Marital Status	Single

Address

- I Home: 114 No.9, Choengchoom Village, Choengchoom Subdistrict, Phanna Nikhom District, Sakon Nakhon Province, 47130 Thailand.
Tel. +66-9310-55015
mekhala.in61@snru.ac.th
- II Office: 680 Nittayo Road, Sakon Nakhon Rajabhat University, That Choeng Chum Subdistrict, Mueang District, Sakon Nakhon Province, 47000 Thailand.
Tel. 042-970021, 042-970094
Fax. 042-970022
saraban@snru.ac.th.

EDUCATION:

- 2008-2010 Junior high school: Banchoengchoom School, Choengchoom Sub-district Phanna Nikhom District, Sakon Nakhon Province, 47130 Thailand.
- 2011-2013 Senior high school: Banbuarajbumrung School,

Sawang Sub-district Phanna Nikhom District, Sakon
Nakhon Province, 47130 Thailand.

COLLEGE:

2013-2018 Bachelor of Science Degree in Biology (B.Sc.):
Sakon Nakhon Rajabhat University, Thailand.
Research Title: Diversity of fish at Bypass market,
Mueang Sakon Nakhon District, Sakon Nakhon Province.

GRADUATE SCHOOLS:

2018-2022 Master of Science Degree in Physics (M.Sc.):
Sakon Nakhon Rajabhat University, Thailand.
Thesis Title: Development of Biosensors for Ethanol Gas
Detection

2022–present Doctor of Philosophy Degree in Physics (Ph.D.):
Sakon Nakhon Rajabhat University, Thailand.
Dissertation Title: Development of Polymer and Textiles
Thermoelectric based on PEDOT:PSS