

**SUNLIGHT ASSISTED CROSS-COUPPLING REACTION OF
HEXLTHIOPHENE DERIVATIVES USING ROSE BENGAL**

BY

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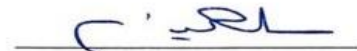
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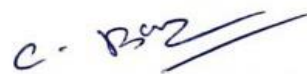


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[Dedication]

I dedicate this work to the woman whose unwavering love, boundless support, and enduring encouragement have been the guiding lights of my academic journey—my dearest Mom.

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In the name of Allah, the Most Gracious, the Most Merciful. All praise and thanks are due to Allah (SWT), the Most Compassionate, for His unwavering guidance and blessings throughout the challenging yet rewarding journey of completing this thesis.

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TABLE OF CONTENTS,

ACKNOWLEDGEMENTS.....	V
TABLE OF CONTENTS, ...	VI
LIST OF TABLES.....	IX
LIST OF FIGURES.....	X
LIST OF ABBREVIATIONS.....	XII
ABSTRACT	XIII
ملخص الرسالة	XIV
CHAPTER 1 INTRODUCTION.....	1
1.1 Background	1
1.2 Statement of the problem.....	15
1.3 Significance of the Study	16
1.4 Research Objectives	17
CHAPTER 2 LITERATURE REVIEW	18
2.1 Rose Bengal.....	18
2.2 Biological Application of Rose Bengal.....	18
2.3 Sun Energy	21
2.4 Photochemistry.....	21
2.5 Arylthiophene	22
2.6 Diary sulfide	25
2.7 N-Heterocycles.....	25

CHAPTER 3 RESEARCH METHODOLOGY	30
3.1 Chemicals and Reagents	30
3.2 Materials	30
3.3 Experimental Setup	31
3.3.1 Reaction Performed	33
3.3.2 Optimization of the reaction conditions	35
3.3.3 General Procedure for the Synthesis of 3-H ₂ PT (1c)	35
3.3.4 General Procedure for the Synthesis of 3-H ₂ ,5DPT (2c)	36
3.4 Characterization	37
3.5 Instrumental Analysis	37
3.5.1 Liquid Chromatography Mass Spectrometry.....	37
3.5.2 Fluorescence Study.....	38
CHAPTER 4 RESULTS AND DISCUSSION.....	40
4.1 Synthesis of Biphenyl Derivatives	40
4.2 Synthesis of 3-H ₂ PT and 3-H ₂ ,5DPT.....	46
4.2.1 Effect of No Rose	46
4.2.2 Effect of solvent	49
4.2.3 Effect of Bases and Solvent.....	52
4.2.4 Effect of Irradiation Time.....	57
4.2.5 Effect of Catalyst Loading	58
4.2.6 Effect of Base Concentrations.....	59
4.3 Comparison Study between Sunlight and Lamp-Assisted Reaction.....	61
4.4 Comparison Study between Rose Bengal and Other Dyes	65
4.5 Previously Synthesized Thiophene Compounds.....	67
4.6 Fluorescence Study of Rose Bengal (RB)	67

4.6.1	Effect of Rose Bengal Concentration on Fluorescence Intensity	68
4.6.2	Effect of Irradiation Time on Fluorescence Intensity	70
4.6.3	Effect of 2-B3HT on Rose Bengal	72
4.6.4	Effect of 2,5-DB3HT on Rose Bengal	74
CHAPTER 5 CONCLUSION AND RECOMMENDATIONS.....		76
5.1	Conclusion	76
5.2	Recommendations	77
APPENDIX.....		79
NMR of Starting Materials		79
REFERENCES.....		83
VITAE		90

LIST OF TABLES

<u>Table 1.1</u>	Physical Properties of Rose Benga	7
<u>Table 4.1</u>	LC-MS Data of Biphenyl	42
<u>Table 4.2</u>	Influences of Bases and Solvent on 3-H ₂ PT.....	55
<u>Table 4.3</u>	Influences of Bases and Solvent on 3-H ₂ ,5DPT.....	56
<u>Table 4.4</u>	Influences of Irradiation time on 3-H ₂ PT and 3-H ₂ ,5DPT.....	57
<u>Table 4.5</u>	Influences of Catalyst Loading on 3-H ₂ PT and 3-H ₂ ,5DPT.....	58
<u>Table 4.6</u>	Influences of amount of base on 3-H ₂ PT and 3-H ₂ ,5DPT.....	60
<u>Table 4.7</u>	Irradiation Source comparison on 3-H ₂ PT	63
<u>Table 4.8</u>	Irradiation Source comparison on 3-H ₂ ,5DPT.....	64
<u>Table 4.9</u>	Previously synthesized Thiophene compounds	67

LIST OF FIGURES

<u>Figure 1.1</u>	Suzuki Cross-Coupling Mechanism	2
<u>Figure 1.2</u>	Examples of Organic dyes	6
<u>Figure 1.3</u>	Energy Transfer Mechanism	8
<u>Figure 1.4</u>	SET Mechanism	9
<u>Figure 1.5</u>	Rose Oxidative Reaction mechanism	10
<u>Figure 1.6</u>	Applications of Conjugated Polymers in Optoelectronics	12
<u>Figure 1.7</u>	Applications of Conjugated Polymers in Bioelectronics.....	13
<u>Figure 1.8</u>	Industrial Applications of Conjugated Polymers	14
<u>Figure 2.1</u>	Rose Bengal Loaded Formulations Applications in Skin Diseases	20
<u>Figure 3.1</u>	Experimental Setup for the Study	32
<u>Figure 3.2</u>	LC-MS Instrumentations	38
<u>Figure 4.1</u>	¹ H NMR for Biphenyl Formation Without Rose Bengal	43
<u>Figure 4.2</u>	¹ H NMR for Biphenyl Formation Without Sunlight	44
<u>Figure 4.3</u>	¹ H NMR for Biphenyl Formation	45
<u>Figure 4.4</u>	¹ H NMR for 3-H ₂ ,5DPT Formation Without Rose Bengal	47
<u>Figure 4.5</u>	¹ H NMR for 3-H ₂ PT Formation Without Rose Bengal	48
<u>Figure 4.6</u>	¹ H NMR for 3-H ₂ PT Formation Without Base	50
<u>Figure 4.7</u>	¹ H NMR for 3-H ₂ ,5DPT Formation Without Base	51
<u>Figure 4.8</u>	¹ H NMR for 3-H ₂ PT Formation	53
<u>Figure 4.9</u>	¹ H NMR for 3-H ₂ ,5DPT Formation	54
<u>Figure 4.10</u>	Fiber illuminator experimental setup for the study	61
<u>Figure 4.11</u>	Chart of RB with two other dyes	66
<u>Figure 4.12</u>	Fluorescence Emission Spectra of RB Concentrations	69
<u>Figure 4.13</u>	Fluorescence Emission Spectra of RB in Sunlight	71

<u>Figure 4.14</u>	Fluorescence Emission Spectra of RB in with 2-B3HT.....	73
<u>Figure 4.15</u>	Fluorescence Emission Spectra of RB in with 2,5-DB3HT.....	75

LIST OF ABBREVIATIONS

RB	:	Rose Bengal
EY	:	Eosin Yellow
MB	:	Methylene Blue
DFT	:	Density Function Theory
LCMS	:	Liquid Chromatography Mass Spectrometry
$\lambda_{\max}$	:	Maximum wavelength
τ_f	:	Lifetime of Fluorescence
ϕ_f	:	Quantum Conversion of Fluorescence
ϕ_{ISC}	:	Quantum Conversion of Intersystem Crossing
G.S	:	Ground State
E.S	:	Excited State
SCE	:	Standard Calomel Electrode
S ₁	:	First Singlet State
T	:	Triplet State
SET	:	Single Electron Transfer
EnT	:	Energy Transfer
R2R	:	Roll-to-Roll
OLED	:	Light Emitting Diodes
OPV	:	Organic Photovoltaics
2-B3HT	:	2-Bromo-3-Hexylthiophene
2,5-DB3HT	:	2,5-Dibromo-3-Hexylthiophene
2,5-DB3MT	:	2,5-Dibromo-3-MethylThiophene
2-P3HT	:	2-Phenyl-3-Hexylthiophene
2,5-DP3HT	:	2,5-Diphenyl-3-Hexylthiophene

ABSTRACT

Full Name : [Mukhtar Adeola raji]
Thesis Title : [Sunlight-Assisted Cross Coupling Reaction of Hexylthiophene Derivatives Using Rose Bengal]
Major Field : [Chemistry]
Date of Degree : [December 2023]

This study focused on the use of sunlight as a means of energy to assess the feasibility of using it in the synthesis of organic compounds in the presence of RB as the catalyst. To understand the activity of Rose Bengal in sunlight, a Coupling reaction of halogenated benzene (Bromobenzene and Iodobenzene) and phenylboronic acid and its derivatives was designed. The results obtained showed that the best time for the reaction was 1hr, with the best coupling reaction been between phenylboronic acid and Iodobenzene.

A metal-free sunlight assisted cross-coupling involving hexylthiophenes and phenylboronic acid to afford aryl hexylthiophenes using a certain amount of catalyst (Rose Bengal) as photocatalyst was conducted. Different reaction conditions were explored to achieve the optimum Conversion. The reaction was successful with a maximum Conversion of 86 and 82% for both 3-hexyl-2-phenylthiophene and 3-hexyl-2,5-diphenylthiophene respectively.

After optimization, the catalyst was compared to other organic dyes and a different source of light was used for the study.

ملخص الرسالة

الاسم الكامل: مختار ادبولا راجي

عنوان الرسالة: تفاعل الاقتران المتقاطع بمساعدة ضوء الشمس لمركبات هيكسيل ثيوفين باستخدام روز البنغال

التخصص: كيمياء

تاريخ الدرجة العلمية: ديسمبر ألفين و ثلاثة و عشرون |

كعامل RB ركزت هذه الدراسة على استخدام ضوء الشمس كوسيلة للطاقة في تخليق المركبات العضوية باستخدام محفز. لفهم نشاط نبات الورد البنغالي في ضوء الشمس، تم تصميم تفاعل اقتران للبنزين المهلجنة (بروموبنزين ويودوبنزين) وحمض الفينيلبورونيك ومشتقاته. أظهرت النتائج أن أفضل وقت للتفاعل هو ساعة واحدة، وأن أفضل تفاعل اقتران كان بين حمض الفينيل بورونيك واليودوبنزين.

ساعد ضوء الشمس الخالي من المعادن في الاقتران المتقاطع الذي يشتمل على هيكسيل ثيوفين وحمض فينيل بورونيك لتزويد أريل هيكسيل ثيوفين باستخدام كمية معينة من المحفز كمحفز ضوئي. تم استكشاف ظروف التفاعل المختلفة لتحقيق العائد الأمثل. كان التفاعل ناجحًا بأقصى إنتاجية 86 و 82 % لكل من 2-فينيل-3-هكسيل ثيوفين و 5،2-ثنائي فينيل-3-هكسيل ثيوفين على التوالي. بعد التحسين، تمت مقارنة المحفز بالأصباغ العضوية الأخرى وتم استخدام مصدر مختلف للضوء للدراسة.

CHAPTER 1

INTRODUCTION

1.1 Background

One of the most important and basic developments in modern organic synthesis for the creation of carbon-carbon bonds is undoubtedly the Suzuki-Miyaura cross coupling reaction for biaryl compounds, which produces the synthetic building blocks of several natural products and compounds of biological significance [1]. The first pioneer of cross-coupling reaction with palladium catalyst was Akira Suzuki in the late 1970s. This discovery earned him the noble prize award, which he shared with his colleagues, namely, Eiichi Negishi and Richard F. Heck for their contributions to the development of this reaction in the field of organic chemistry. Furthermore, after their discovery, much research has been conducted using expensive noble metals. The classical method of the reaction involves the reaction between organoboron and organohalides in the presence of a base and a metal catalyst (palladium) (Fig 1.1). Despite the success of this reaction in the synthesis of biaryl compounds for various industrial and pharmaceutical applications, it suffers from few drawbacks which include expensive and limited availability of the catalyst, longer reaction time, limited utilization of functional/ sterically encumbered substrates [2]. Although other noble metals have been utilized to replace the palladium catalyst, the problem of efficiency, catalyst loading, and selectivity of the other metals limits their

applications[3], which gives the palladium catalyst much advantage over the other metals
therefore, the reaction is often carried out in the presence of a palladium catalyst [4].

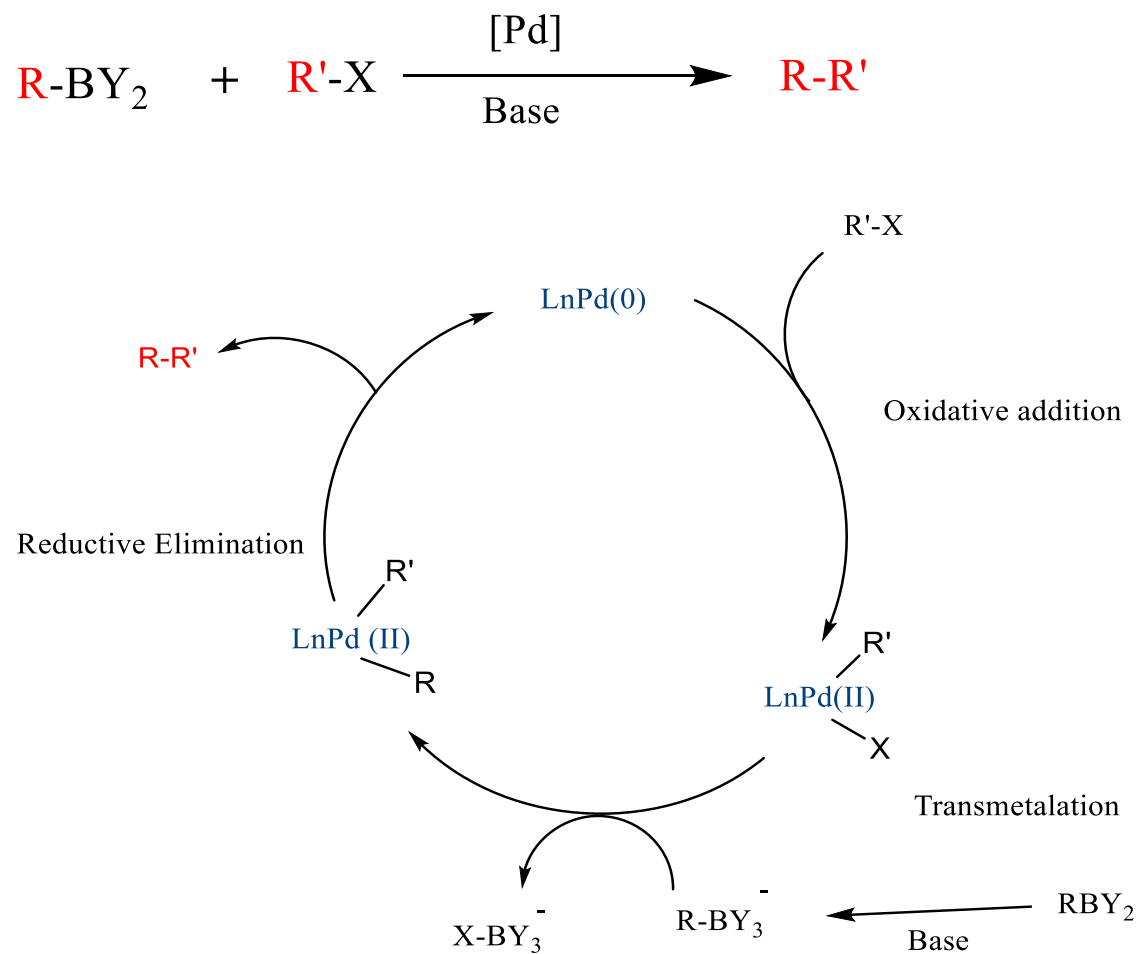


Fig: 1.1: Suzuki Coupling General Mechanism [1]

Where $\text{BY}_2 = \text{B(OH)}_2, \text{B(OR)}_2$

$\text{X} = \text{I, Br, Cl}$

$\text{R} = \text{Aryl or Alkenyl}$

R' = Aryl, alkenyl, benzyl.

[Pd] = Pd(PPh₃)₄, Pd(PPh₃)₂Cl₂.

Base = NEt₃, NaOEt, Na₂CO₃

Although, one of its limitations (longer reaction time) was sorted out using high temperature. Consequently, the extreme use of temperature and pressure to drive the reaction due to longer reaction rates also dimmed its beauty. These limitations lead to the discovery of photocatalysis in coupling reaction. However, some other techniques were used to solve the problem of longer reaction time such as microwave, ultrasound, and ball milling. These techniques all have the advantage of fastening the rate of reactions. Still, they couldn't solve the problem associated with the use of the metal catalyst and cost for setting up, and these techniques are difficult to scale up for industrial applications. Using less expensive equipment in photocatalysis, easier to scale-up for industrial applications offers an alternate solution over other techniques mentioned above for carbon-carbon coupling reactions [2]. This method proceeds through a radical-based pathway, which is governed by photogenerated electron-hole pairs at room temperature [3].

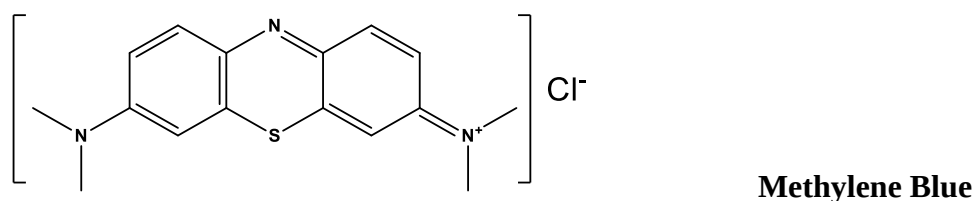
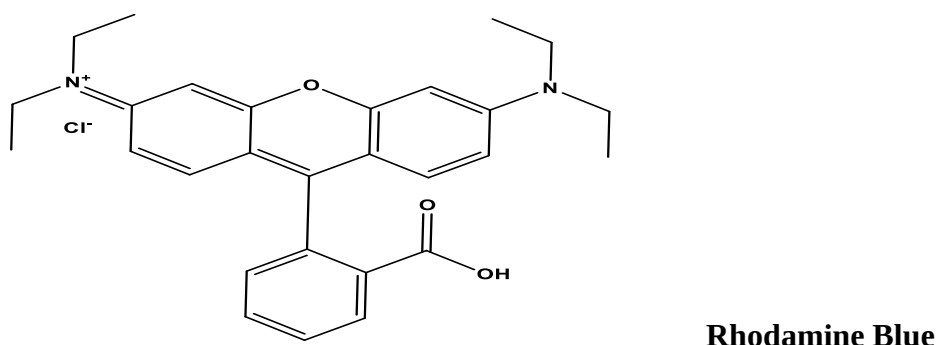
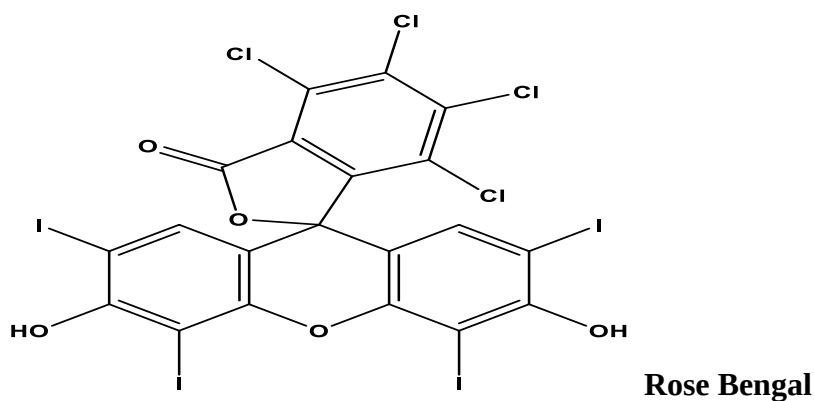
Over the past few years, the discipline of organic synthesis has seen a remarkable uptick in utilizing visible light-mediated photo-redox catalysis for the creation of safer and more effective procedures [4]. Creating carbon-carbon/carbon-halogen bonds in heterocyclic compounds can generally be explored using photo-redox catalysts, which offer an alternate route. Due to its abundant natural supply and environmentally safe energy source, visible light has caught the interest of numerous chemists willing to exploit it as a promoter in organic synthesis.[5]. Honda-Fujishima pioneered photocatalysis, employing a titania

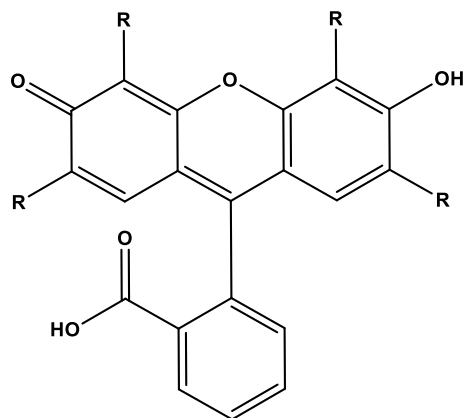
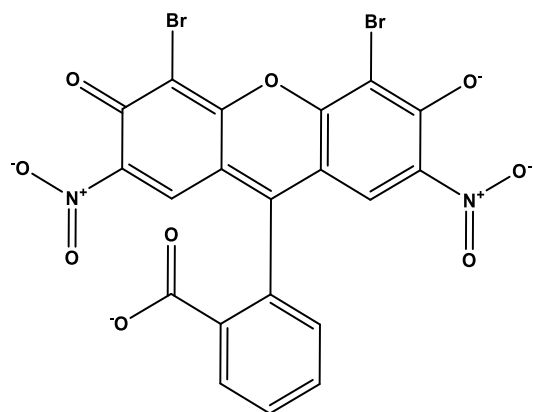
semiconductor and visible light to split water [6]. Since then, several transition metal complexes have been used as photo-catalysts [7]. The most often pathways (light-induced energy transfer pathways) employed during reaction for such catalysts are the single electron transfer (SET) and energy transfer (ET) [8]–[10].

As the source of constant solar light for the Earth, the sun is referred to as a super "energy warehouse." The amount of solar energy that, on average, reaches the surface of the Earth every hour is sufficient to supply all the energy people need today for an entire year[11], [12]. Saudi Arabia is strategically located due to its location in the so-called sun belt and extensive desert terrain; this location has been advantageous to the country as it has helped it to rise to the top of the list in terms of solar PV energy producers. It has been reported that the amount of thermal energy from the sunlight reaching Saudi Arabia is about 2200 kWh/m² [13], and attempts to produce renewable energy in the nation using PV cells and direct sunlight are worthwhile. This available energy which is free and unlimited motivated us in carrying out the experiment in sunlight. Moreover, as side from the use of solar energy in other applications such as in solar panels, sunlight assisted cross coupling reaction hasn't been conducted based on our knowledge in the kingdom.

The most crucial component of organic processes produced by visible light is photocatalyst because photocatalysts absorb visible light and are activated either by energy transfer (EnTs) or single electron transfer (SET), unlike the organic molecules, which rely solely on the photocatalyst due to their inability to absorb visible light by themselves [14]. Aside from palladium and other noble metals experimented on, many other metal complexes have been synthesized and used as photocatalysts giving excellent photocatalytic properties. However, despite their great photocatalytic properties, the issues

of expensiveness, limited availability of the metal complexes, and toxicity haven't been resolved [15]. These limitations led researchers to discover other materials that could offer a better advantage. As of recent, the use of organic dyes (organo-photocatalyst) has gained much recognition from chemists as an option for metal-free organic synthesis. They offer solutions to the limitation of transition metals and metal complexes that are non-toxic, inexpensive, environmentally friendly, and ease separations from products [16], [17]. Many organic dyes, including Rose Bengal, Methylene Blue, Eosin Yellow, Eosin Blue, and Rhodamine Blue depicted in Fig 1.1 below, among many others, have been experimented on [14].





Eosin Blue

R = Br; Eosin Yellow : R = H; Fluorescein

Fig 1.2: Examples of organic dyes.

Among the above-listed dyes, the use of RB as a photoactive catalyst has gained much recognition in recent times; this is because of its redox potential, which falls within the range of redox potential of most organic compounds, which helps in the photo-induced electron transfer quickly. When Rose Bengal (RB) absorbs light, it gets activated to the excited state singlet Rose Bengal (RB*) with a half-life of 10^{-6} - 10^{-9} s. This excited singlet state either converts to a longer triplet state with a half-life of 10^{-3} s by intersystem crossing or returns to the ground state. The excited Rose Bengal exhibits both reducing and oxidizing properties when compared to the ground-state Rose Bengal. The values of the redox potential of both the measured ground state (GS) and excited state (ES) are shown in Table 1 below [16], [18], [19].

Table 1.1: Physical properties of Rose Bengal [14]

$\lambda_{\max}$ (nm)		549
τ_f (ns)		0.50
ϕ_f		0.09
Φ_{ISC}		0.77
Excited state energy (ev)	$E_{0,0}^{S_1}$	2.17
	$E_{0,0}^{T_1}$	1.80
G.S redox potential (V vs SCE)	$E_{1/2}^{red}$	-0.99
		-0.78
	$E_{1/2}^{oxid}$	+0.84
E.S redox potential (V vs SCE): S_1	$E_{red}^{S_1}$	+1.18
	$E_{oxid}^{S_1}$	-1.33
E.S redox potential (V vs SCE): T	$E_{red}^{T_1}$	+0.81
	$E_{oxid}^{T_1}$	-0.96

Single electron transfer (SET) and photoinduced electron transfer (EnT) are the two forms of induced reaction observed in Rose Bengal-mediated photocatalysis or any sort of photocatalyst, with the former being the most observed process when compared to the latter. However, the latter occurs mainly through singlet oxygen sensitizer. Upon light absorption, the ground state Rose Bengal (RB) gets activated to excited Rose Bengal (RB*) which generates reactive substrate or reagent by transferring energy to the substrate or

reagent. In some cases, triplet excited Rose Bengal ($^3\text{RB}^*$) is generated from singlet excited Rose Bengal ($^1\text{RB}^*$) through intersystem crossing, which then transfers energy to the substrate or reagent, as shown in fig 1.3 [14].

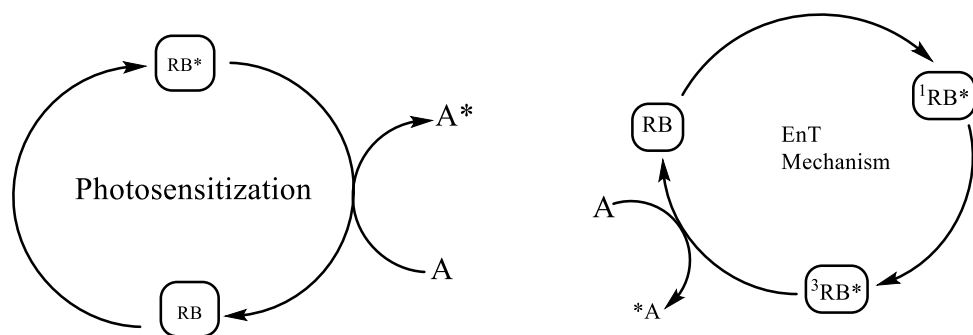


Fig 1.3: Energy Transfer [14]

A = substrates, reaction intermediates, oxygen.

A = oxygen

On the other hand, SET proceeds either through oxidative or reductive quenching (Quenching of reactive Rose Bengal). This implies that excited Rose Bengal can either accept or lose electrons either to the substrate or from substrate A, thereby creating free radicals during the process, as shown in Fig 1.4 [14].

The reactant is first oxidized in the first quenching of active RB (Reductive quenching). In this state, the excited Rose Bengal (RB^*) is transformed to Rose Bengal radical anion ($\text{RB}^{\bullet-}$) through the transfer of electron, with the immediate alteration of A to intermediate radical cation ($\text{A}^{\bullet+}$), which is then followed by the oxidation of Rose Bengal radical anion ($\text{RB}^{\bullet-}$) by B subsequently result in the of formation of $\text{B}^{\bullet-}$ and ground state Rose Bengal [14].

Meanwhile, in the oxidative quenching, the reactant is first reduced. In this state, the excited Rose Bengal (RB^*) is converted to Rose Bengal radical cation ($\text{RB}^{\bullet+}$) through the

transfer of electron, with the immediate alteration of A to intermediate radical anion (A^{*-}), which is then followed by the reduction of Rose Bengal radical cation (RB^{*+}) by B subsequently result in the of formation of B^{*+} and ground state Rose Bengal.

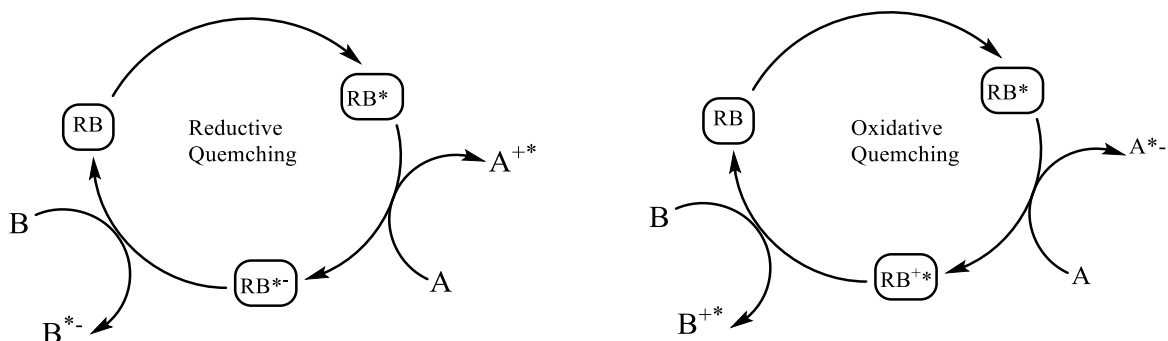


Fig 1.4: SET mechanism [14].

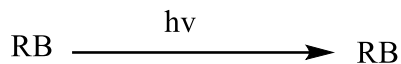
A = Reagent, Substrates, reaction intermediates

A = Reagent, Substrates, oxygen.

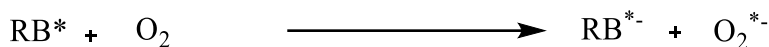
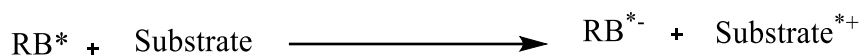
B = Reagent, oxygen.

B = Reagent, reaction intermediates.

However, another ambiguous photocatalytic mechanism of Rose Bengal occurs during oxidative carbon-carbon or formation of carbon-hetero atom as shown below. In the first scenario, the substrate gets oxidized via reductive quenching with Rose Bengal which in turn reduces the oxygen into peroxide radical with immediate oxidation as shown in Fig 1.5. While in the second process, triplet oxygen is converted to singlet oxygen by Rose Bengal followed by oxidation of the substrate via single electron transfer (SET) producing peroxy radical as indicated in Fig 1.5[14].



i) SET through RB*



ii) SET through $^1\text{O}_2$

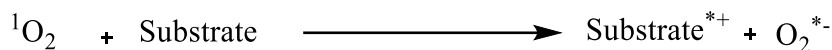
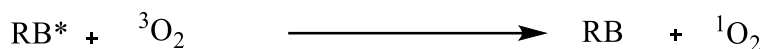
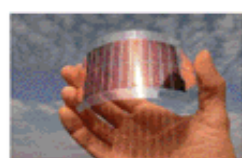


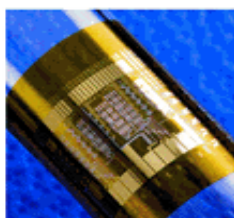
Fig 1.5: Proposed Rose Bengal oxidative reaction mechanisms [14]

The building blocks of many medications are heterocycles called thiophene scaffolds[20]. Thiophene has anti-inflammatory and analgesic[21], anti-microbial[22], anti-diabetes mellitus[23], anti-hypertensive[24], anti-psychotic[25], anti-allergic[26], anti-gonadotropin releasing hormone antagonist[27], and anti-tumor properties[26]. They have been observed to exhibit noticeable optical, electrical, and redox capabilities as well as notable supramolecular behavior either on the solid surface or in bulk. Additionally, to create a variety of configurations, this compound of interest can change selectively at either position 1,2 or the sulfur atom in the ring. For instance, adding lengthy alkyl sidechains position 1 or 2 ensures self-assembly capability and processability of the solution while incorporating α -linked thiophene units into oligomers results in an effective conjugation along the main chain backbone. Due to their high polarizability, the soft Sulphur atom present in the ring can induce charge-transport properties as well as electron donating effect

as its well known in all thiophene derivatives [28]. Furthermore, thiophenes can collectively combine with itself or other substrates under favorable conditions to form conjugated polymers. Due to their special combination of electrochemical, optical, conducting, and/or semiconducting properties, these polymers are recognized to belong to the class of semiconducting materials which are widely applicable in a range of different electronics. They offer a cheaper route to inorganic materials as they can be manufactured into lightweight and flexible devices and can be solution processed to enable for roll-to-roll (R2R) manufacturing [29]. Conjugated polymers' synthetic tunability enables considerable optimization of their electrical and physical properties. Through synthetic alteration, their properties, such as crystallinity and solubility, and electrical properties, such as light absorption and charge transport, can be modified. This has made it possible for them to find successful application in gadgets like organic light-emitting diodes (OLED), organic field effect transistors, and organic photovoltaics (OPV) and bioelectronics as shown in figure 1.6 and 1.7 which will be the applications that are predominantly explored in this perspective [30]–[33].

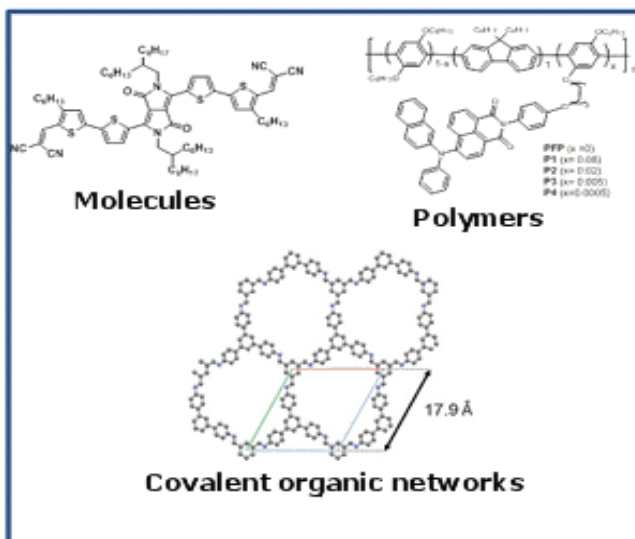


Organic solar cells (OSCs)

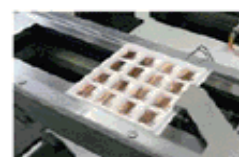


Field effect transistors (OFETs) for organic electronics

ORGANIC MATERIALS FOR OPTOELECTRONICS



Organic light-emitting diodes (OLEDs)



Batteries



Sensors

Fig 1.6: Showing some applications of conjugated polymers in optoelectronic [34], [35].

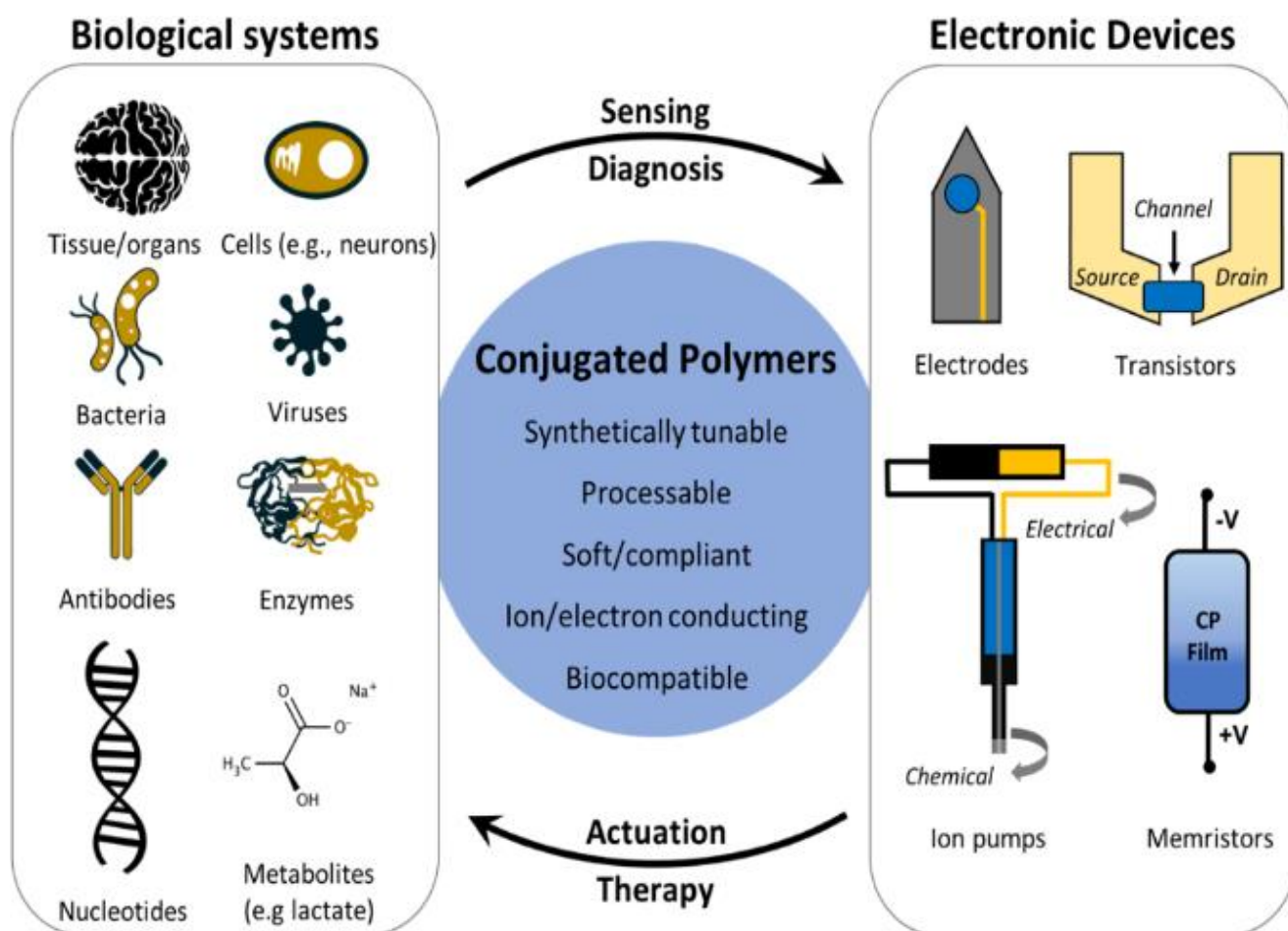


Fig 1.7: Some applications of conjugated polymers in optoelectronic and bioelectronics[34], [35].

In recent advances, conjugated polymers have been studied to be applicable in industrial processes such as photocatalytic degradation of organic dyes, water splitting, CO₂ photo-reduction, and light-activated organic transformations, as depicted in Fig 1.8 [36].

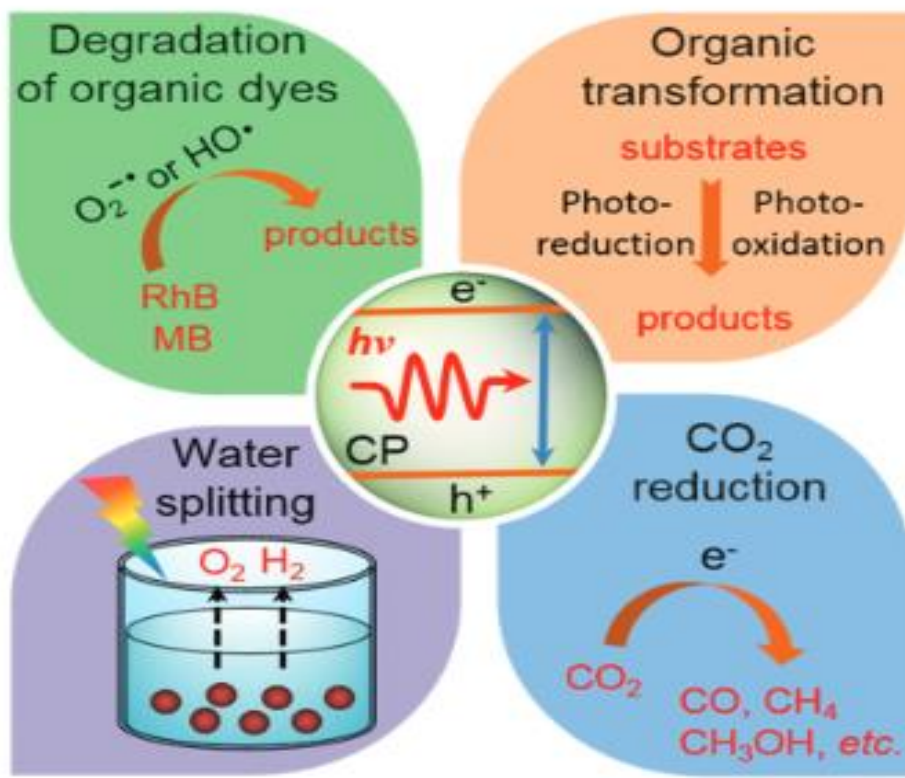


Fig 1.8: A summary of the various industrial applications of conjugated polymers.

This research aims to utilize Rose Bengal as photocatalyst for the synthesis of 3-hexyl-2-phenylthiophene and 3-hexyl-2,5-phenylthiophene derivatives instead of the generally used metal complexes as catalyst. As far as we are concerned, Rose Bengal has yet to be used as a photocatalyst towards the synthesis of 3-hexyl-2-phenylthiophene and 3-hexyl-2,5-diphenylthiophene derivatives but has been applied towards Friedel-Crafts alkylation of indoles in the presence of nitroalkenes mediated by Visible light[37].

1.2 Statement of the problem

The photocatalyst is regarded as an essential component of visible light-induced organic reactions because they absorb visible light and get stimulated either through electron transfer or energy transfer (EnTs), unlike the organic molecules, which rely solely on the photocatalyst due to their inability to absorb visible light by themselves [14]. Aside from palladium experimented on, many other metal complexes have been bought commercially/synthesized and used as photocatalysts, which in turn gave excellent photocatalytic properties. However, despite their great photocatalytic properties, the issues of expensiveness, separations as mentioned earlier, and toxicity haven't been resolved [15]. These limitations led researchers to discover other materials that could offer a better advantage. The use of organic dyes as an alternative to this metal catalyst has been extensively studied. Reports have shown that these dyes could be used in place of metal complexes due to their environmentally friendliness and are less expensive when compared with metal catalyst. RB as an organic dye is synthetic chemistry's most studied and used compound.

1.3 Significance of the Study

The significance of this research is to utilize RB as a photocatalyst to synthesize 3-Hexyl-2-phenylthiophene and 3-Hexyl-2,5-diphenylthiophene and compare it to other organic dyes. These compounds are commonly used as host materials in organic light emitting devices (OLED), building blocks for synthesizing other thiophene-based organic semiconductors, among many other applications. This area of research is in line with energy and environmentally friendly synthesis, which are strategically important areas in the kingdom.

1.4 Research Objectives

The key objective of this research is to develop a simple and efficient synthetic approach using solar energy to synthesize important organic compounds by primarily focusing on the catalytic activity of RB and its application in the synthesis of diaryl-thiophene derivatives.

- To assess the feasibility of using sunlight for coupling reactions
- To synthesize 3-hexyl-2-phenylthiophene and 3-hexyl-2,5-diphenylthiophene under different optimizing conditions.

|

CHAPTER 2

LITERATURE REVIEW

2.1 Rose Bengal

In the 19th century, Rose Bengal was produced as a wool colorant from fluorescein (a dianionic compound that belongs to the group of xanthene dye). It is a violet, water-soluble dye which is chemically known as 3', 4', 5', 6'-tetrachloro-2,4,5,7-tetraiodo-fluorescein [38]. Aside from being an organic dye applied towards the synthesis of organic compounds, it possesses inherent cytotoxicity concerning various cancer and cells [39]–[43], microbial cells [44], applications towards photodynamic due to their Sono-photodynamic properties [45]–[49] and sonodynamic therapies [49]–[51].

2.2 Biological Application of Rose Bengal

In recent times, the scientific community has focused their attention on the use of Rose Bengal, especially in relation to its role in dealing with skin disease. As a result of their inherent cytotoxicity, Rose Bengal has been recognized to be a prospective chemotherapeutic in the treatment of cutaneous melanoma both at early and metastatic stages [39], [52], [53].

Currently, research is still going on, and scientists are focused on enhancing the efficiency of Rose Bengal in dermatology by developing advanced drug delivery systems to eradicate

the drawbacks of Rose Bengal, such as scarce permeation of biological membranes and low bioavailability (1,28), as depicted in the figure below. Rose Bengal is easily analyzed using Ultraviolet-visible and fluorescence methods due to the conjugated system present in their structure. The maximum wavelength of absorption and emission of RB in water and other solvents have been reported to be 546nm and 567nm, respectively [54].

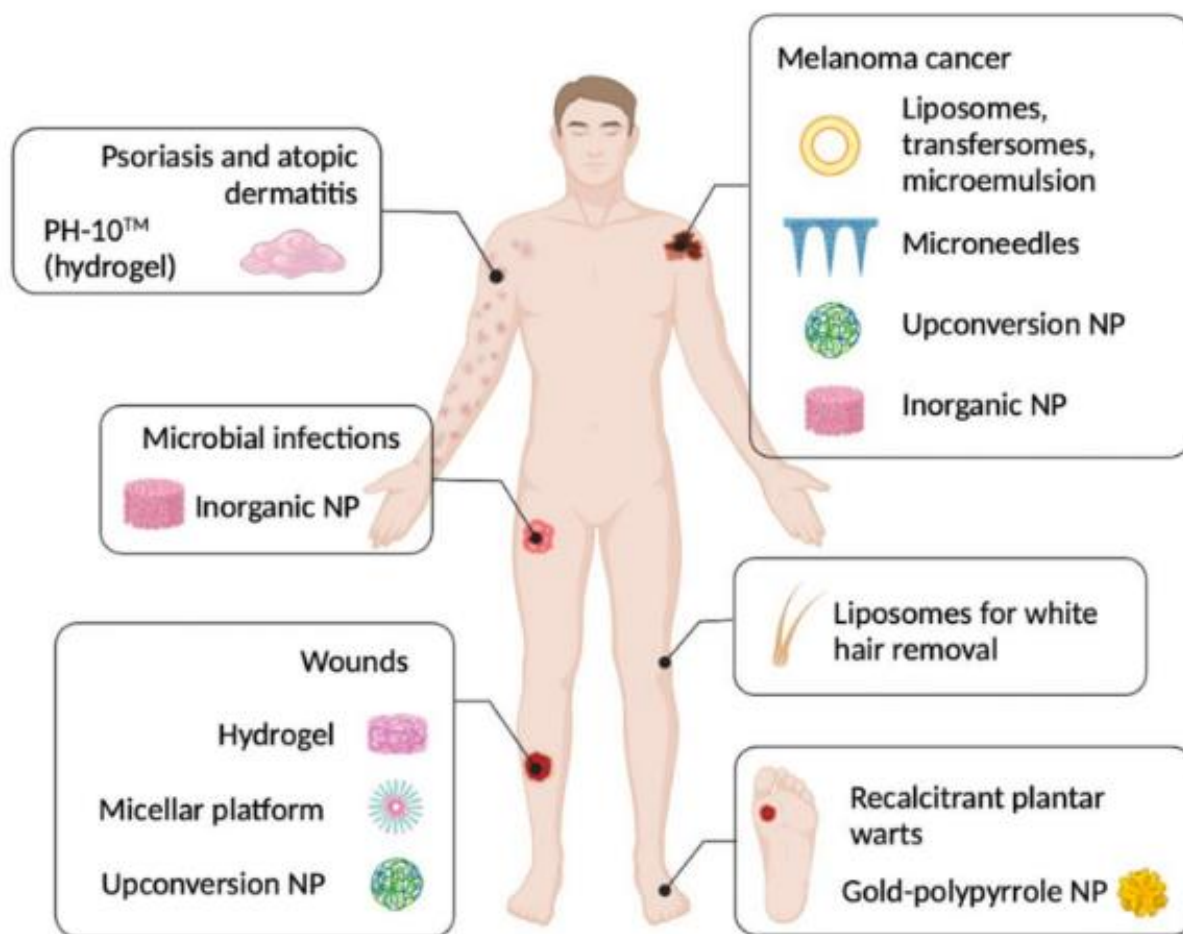


Fig 2.1: Showing a summary of Rose Bengal loaded formulation applications in dealing with skin diseases as obtained from previous literature [55]

2.3 Sun Energy

The largest energy source on earth is light from the sun [56]–[58]. The amount of energy (solar) reaching the earth has been recognized to have a magnitude more significant than that of electrical discharges and shockwaves resulting from the combination of geothermal sources, volcanoes and radioactivity when considering the early sun, which has lower luminosity [57], [58]. Furthermore, considering the non-existence of ozone and atmospheric oxygen, which protect the surface of the earth from UV photons in the present day, chemically important light, which is composed of high energy, would have been available on the surface of the earth [59]. Radiation reaching the earth comprises low entropy and high energy only to degrade into motion, thermal energy and heat which eventually is re-radiated back into space. Entropy is produced due to energy dispersal, which in turn gives rise to processes on large-scale including weather systems, ocean currents, etc [59]. Consequently, solar energy radiation can be utilized to create many complex compounds. One of the most widely used fields of chemistry, which involves the use of light, is photochemistry. Photochemistry has been applied to synthesize organic molecules and cellular molecules such as sugar, metabolites, lipids, amino acids, and nucleic acids [59].

2.4 Photochemistry

The trademark of metabolism is the production of organic compounds that can store energy in the form of chemicals in their bonds, which subsequently can be used in chemical reactions. In the present day, sugar is the primary fuel necessary for metabolism. One of

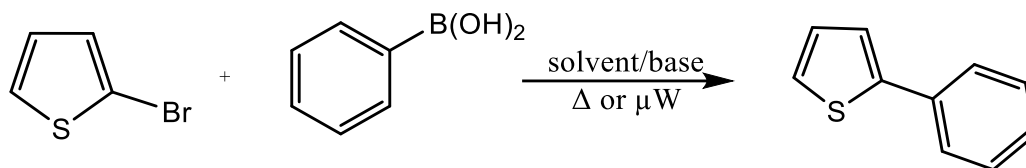
the prebiotically methods of sugar production is the formose reaction. This reaction produces a series of sugar compounds via several aldolic reactions of formaldehyde and glyceraldehyde [59]. Moreover, the photochemical synthesis of alkanes using UV light has been reported. In addition, the prebiotic photochemical synthesis of formaldehyde and glyceraldehyde has been investigated using CO₂ and H₂O gas-phase [59]. Also, another means of formaldehyde and glyceraldehyde synthesis is the photooxidation of alkanols using transition metal complexes as photosensitizers [60].

Another application of photochemistry is in biopolymer precursors. Biopolymers comprise amino acids, nucleotides, nucleosides, and nucleobases, which are prebiotically synthesized, including photochemically. Biopolymers have been recognized as the core center of life by performing essential functions of enzyme catalysis and storage of information. Proteins and nucleic acids are formed by several condensation reactions in which monomers are connected by forming amide bonds as seen in peptides or phosphodiester bonds as observed in oligonucleotides[59]. Several methods used in the synthesis of amino acids via photochemical means have been reported. One of the synthetic routes is the use of aqueous phase photochemistry in the synthesis of amino acids [59], [61]–[64]. This method involves passing UV light onto the organic precursors in the presence of nitrate salts [63].

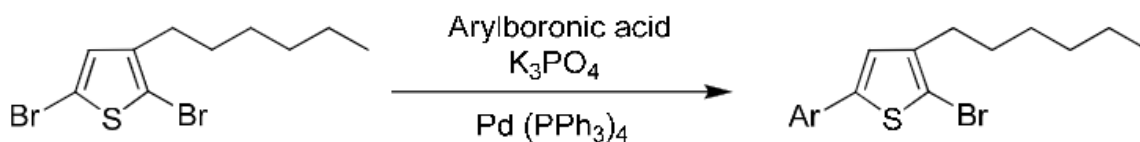
2.5 Arylthiophene

In a study, palladium (II) complex was used as a catalyst towards the coupling reaction of 2-B3HT and 2,5-DB3HT with phenylboronic acids and their derivatives. The catalyst was

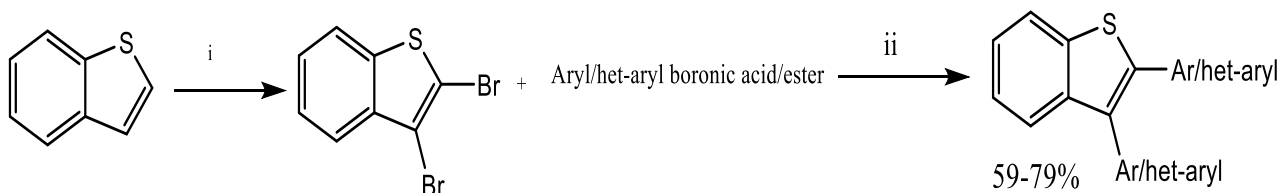
prepared from readily available materials. The synthesized palladium catalyst was observed to be effective under both conventional and microwave irradiation conditions[59], [65].



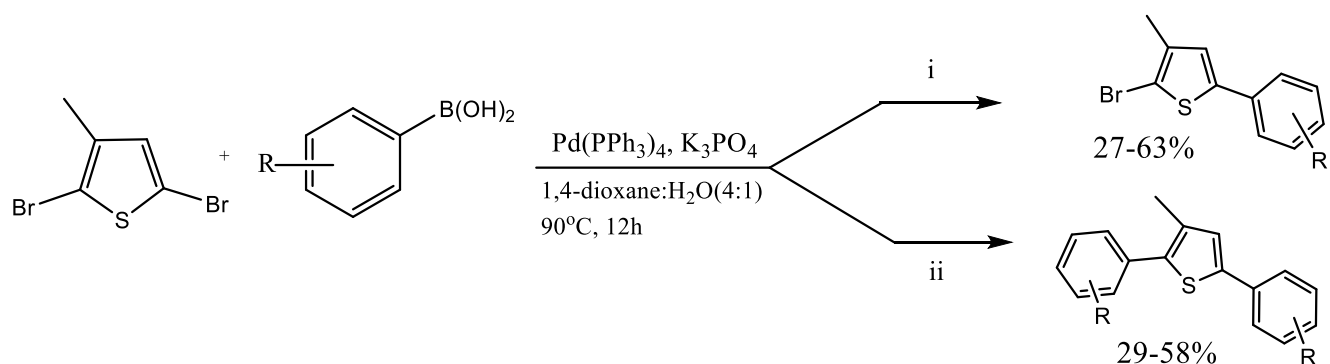
Another study investigated a cross-coupling reaction of several phenylboronic acids and their derivatives with 2,5-DB3HT. The products formed (thiophene compounds) were analyzed and their haemolytic, biofilm inhibition and anti-thrombolytic properties were studied, and they were observed to have excellent beneficial features[66]



The synthesis of several 2,3-diaryldibenzo[b]thiophene derivatives was investigated in the presence of triphenylphosphine palladium complex as the catalyst. The yield of the products ranges from 59%-79%. The synthesized products' biological applications such as biofilm inhibition and anti-thrombolytic activity were studied [67].

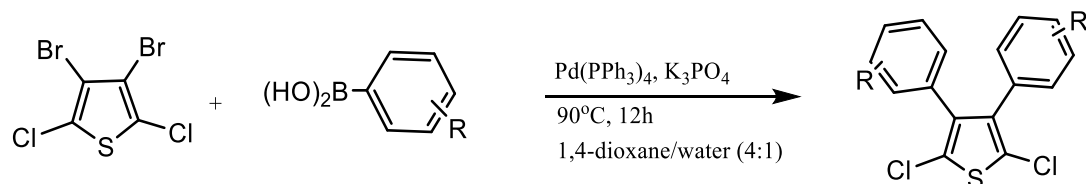


In another investigation, 2,5-DB3MHT was coupled with different aryl boronic acids to produce several derivatives of 2,5-DB3MHT in the presence of a triphenylphosphine palladium complex. The Density function theory (DFT) of the synthesized compounds was investigated alongside their pharmaceutical properties, such as antibacterial and antioxidant activities, among many others [68].



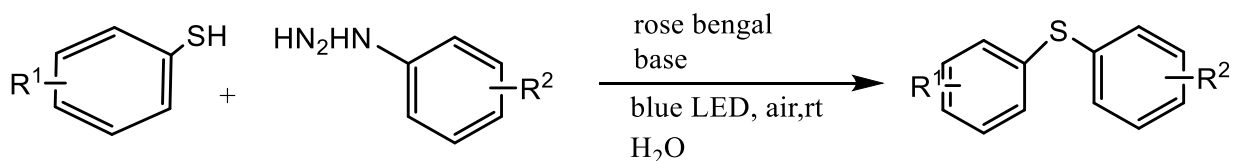
The regioselective Suzuki cross-coupling synthesis of various derivatives of 2-(bromomethyl)-5-aryl thiophene using a different classes of phenyl boronic acids with 2-B-5BMT. The synthesized products were further subjected to different biological studies, such as haemolytic and anti-thrombolytic activities [69].

In another study, the synthesis of 3,4-biaryl-2,5-dichlorothiophene derivatives using palladium catalyst via Suzuki cross-coupling reaction was reported. Many thiophene derivatives were formed as the product with 3,4-dibromo-2,5-dichlorothiophene and arylboronic acids as the starting materials with dioxane as the solvent and potassium phosphate as the base. The products were formed in moderate to good yield[70].



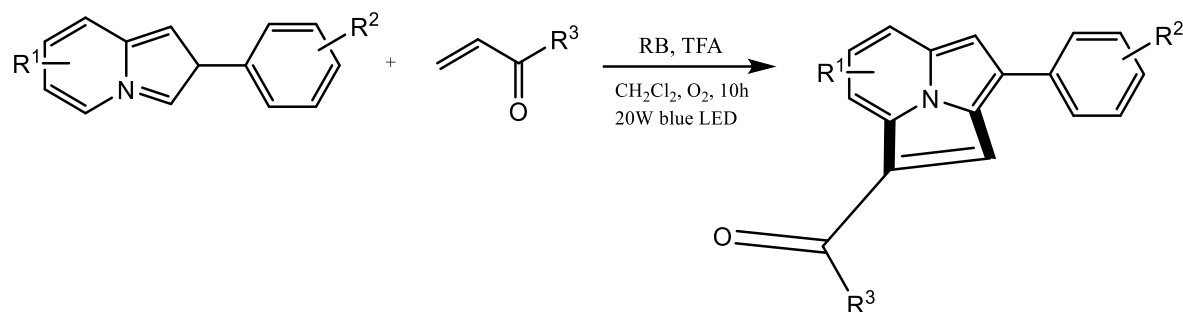
2.6 Diary sulfide

In another report, the use of Rose Bengal in visible light enhanced oxidative coupling of thiols and arylhydrazines to produce diary sulfides in the presence of air. The product was formed in good Conversions. In the previously reported literature, this reaction was carried out in the presence of transition metal-ligand complexes, while aryl halides were used in place of arylhydrazines. Due to the harsh conditions needed for the reaction to occur and the expensive nature of the transition metal complexes, RB became an alternative [71].

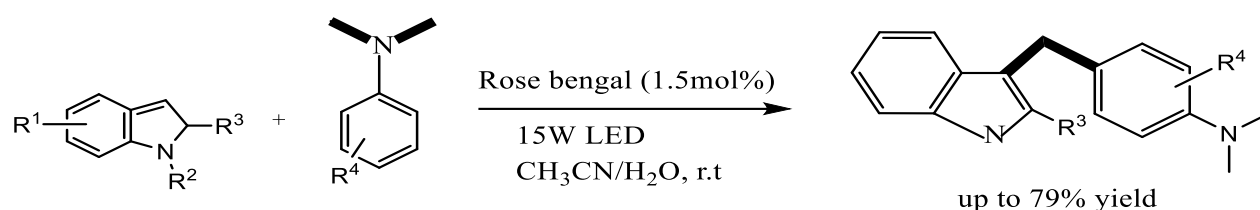


2.7 N-Heterocycles

The photosensitizing property of Rose Bengal was examined in a recent paper for intermolecular cyclization to create derivatives of Pyrrolo[2,1,5-cd] indolizine[72], as shown below. According to the authors, other photocatalysts contributed to the reaction's result, although with lower yield.

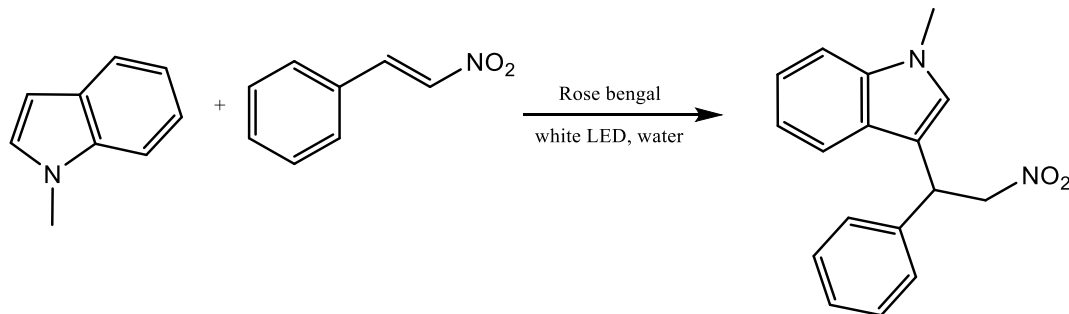


In 2018, research was made on Friedel-Crafts alkylation. The experiment involves using Rose Bengal as catalyst for the synthesis of alkylated indoles where N, N-dimethylanilines was utilized as the carbon source as shown below. Despite the authors' impressive yield in CH₃CN as the solvent, they used mixed acetonitrile/water solvents to demethylate tertiary amines quickly [73].

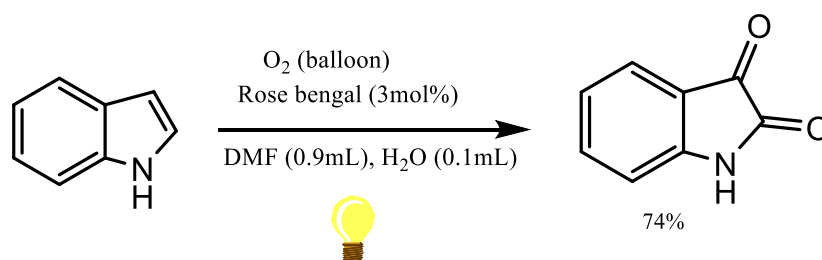


The use of water as a solvent in the functionalization of indoles has been reported. This experiment involves the Friedel-Crafts alkylation of an indole ring in a metal-free medium, as shown below. This method was found to be remarkably excellent even though the reaction was carried out without an oxidant, and the products were obtained in higher

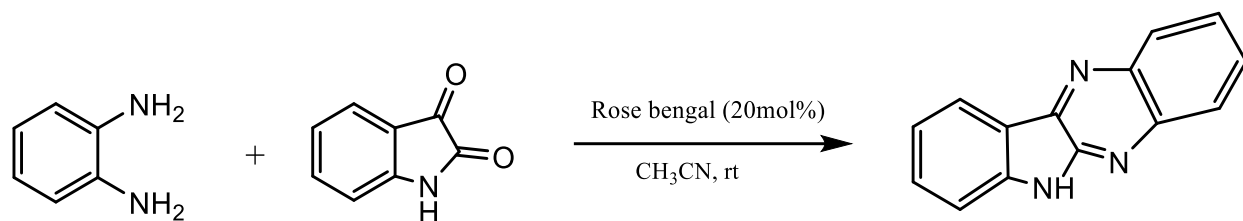
yield[37].



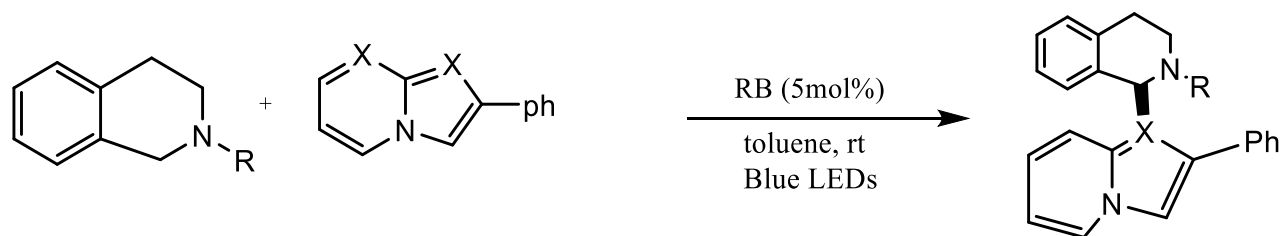
One of the up-and-coming fields which is still under investigation is the structural alteration of any heterocyclic ring for the possible synthesis of pharmacologic active molecules. In 2019, a study was made on the de-aromatization of pyrroles to imides and indoles to Isatin derivatives, as depicted below. This Isatin formed can undergo a wide range of structural changes, and it's also considered one of the preferred fundamentals in heterocyclic chemistry[74].



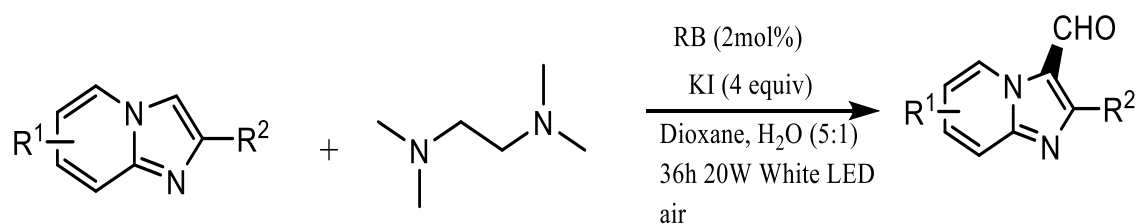
The photo-catalyzing reaction of phenylene 1,2-diamines with 1,2-dicarbonyls was studied to create quinoxaline derivatives. The described synthesis is more sustainable and demonstrates excellent atom economy compared to the previously reported traditional approaches. During the reaction, it was observed that Rose Bengal functions best in the presence of acetonitrile, although other solvent effects were studied [4].



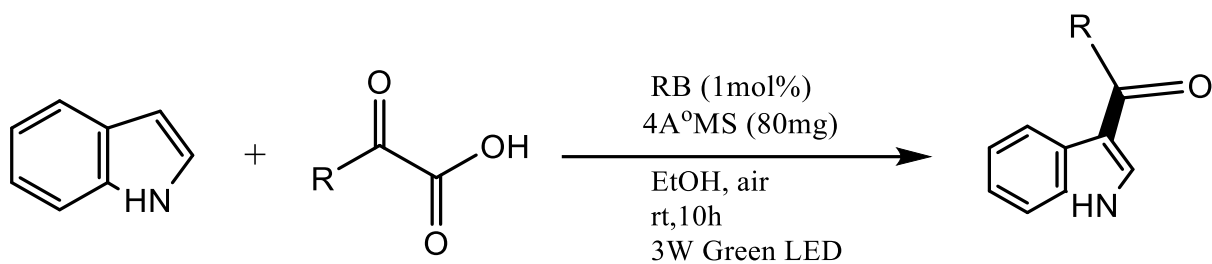
The use of visible in the synthesis of 3-substituted imidazopyridines derivatives was achieved using Rose Bengal as a catalyst as photosensitizer under aerobic conditions. The reaction involves the dehydrogenative coupling of imidazopyridines and tertiary amines such as tetrahydroisoquinoline and N-dimethyl anilines. In addition to this, the reaction was further applied to compounds such as indolizine, indole and pyrrole [75].



Similarly, the use of Rose Bengal in C-3 formylation of imidazo[1,2-*a*]pyridine with tetramethyl ethylenediamine (TMEDA) in the presence of air was reported. The reaction proceeds through energy transfer between the ground-state oxygen atom and the excited state Rose Bengal, which was contrary to previously reported literature [76].



In another study, α -oxocarboxylic acids were used in the C3-acylation of free (NH)-indoles and N-substituted indoles under visible with Rose Bengal being the photocatalyst. Many other catalysts were explored, including organic dyes, but none of them was sufficient for the reaction to proceed. The reaction pathway was observed to proceed via energy transfer. However, during the course of the experiment, it was observed that the reaction pathway of secondary amines proceeds via single electron transfer[77].



CHAPTER 3

Research Methodology

3.1 Chemicals and Reagents

Rose Bengal (RB) $\geq 90\%$, and boronic acids (phenylboronic acid, 4-hydroxyphenylboronic acid, 4-cyanophenylboronic acid) were acquired from Sigma Aldrich. Aryl halides (Bromobenzene, Iodobenzene) were acquired from Sigma Aldrich, 2-B3HT and 2,5-DB3HT were purchased from, Ethylacetate, Methanol, Acetonitrile, Tetrahydrofuran (THF) was purchased from Fluka, Dioxane, Dimethylformamide (DMF), Triethylamine, Sodium Carbonate was purchased from Sigma Aldrich, Potassium Carbonate was acquired from Fluka, Anhydrous Sodium Sulfate was procured from BDH chemicals. The solutions used were prepared using distilled water.

3.2 Materials

All the glassware used for this experiment was washed with distilled water, followed by rinsing with acetone and dried in the oven for 24hrs before use.

3.3 Experimental Setup

Visible light-mediated catalysis has become an overwhelming technique for the synthesis of organic compounds in recent times. The utilization of dyes (organic) to replace transition metal catalysts as photoredox catalysts has gained much attention due to their cheapness, nontoxicity, and synthetic resourcefulness. In this report, we investigated the photocatalytic activity of rose Bengal towards the synthesis of organic compounds via sunlight.

The experimental setup consists of a mirror for reflection, a 125ml flask, and a retort stand. The schematic diagram of the configuration is shown in (figure 3.1)



Fig 3.1: Sunlight experimental setup for the study (Static Mode).

3.3.1 Reaction Performed

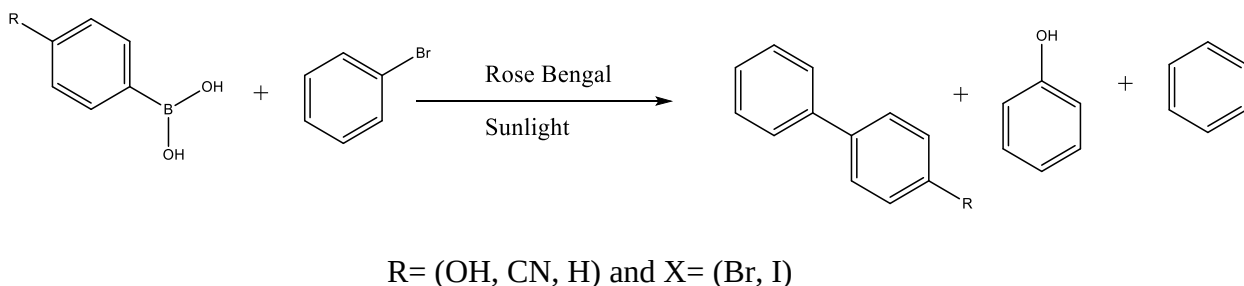
Reaction-1: Synthesis of Biphenyl.

A reaction was carried out to investigate the photocatalytic property of Rose Bengal. This investigation was carried out by reacting between bromobenzene and Iodobenzene with phenylboronic acid alongside its derivatives in sunlight for a certain period.

General Procedure

Suzuki cross-coupling reaction of aryl halides and phenylboronic acid alongside its derivatives was followed, where 0.5mmol of aryl halides was mixed with 0.6mmol phenylboronic acid and its derivatives in the presence of 0.75mol% of RB in 10ml of solvent contained in 125ml volumetric flask. The reaction mixture was in sunlight for 1-4hrs. After reaction, the crude samples were collected and analyzed using HPLC and LCMS. The crude samples were later extracted using ethyl acetate and dried over sodium sulfate (anhydrous) to eliminate any traces of water, which were later analyzed using NMR. The equation of the reaction is given as follows.

Scheme 1



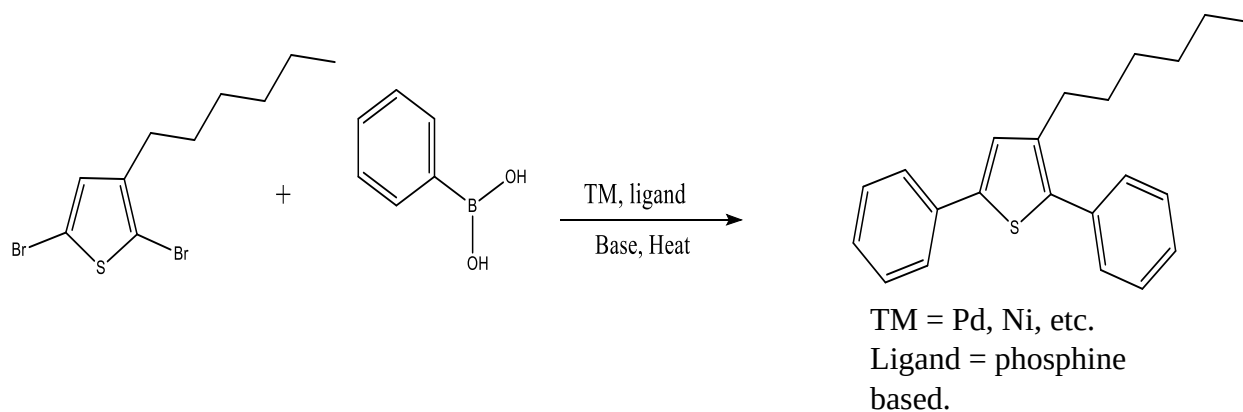
Reaction-2: Synthesis of Aryl hexylthiophene compounds

Thiophene scaffolds are an essential set of compounds utilized in different fields ranging from medical to industrial purposes. Among these compounds is Arylthiophene, previously synthesized by other authors (Scheme 1). We are exploring a new synthesis method using a cheap photocatalyst (dye) in sunlight.

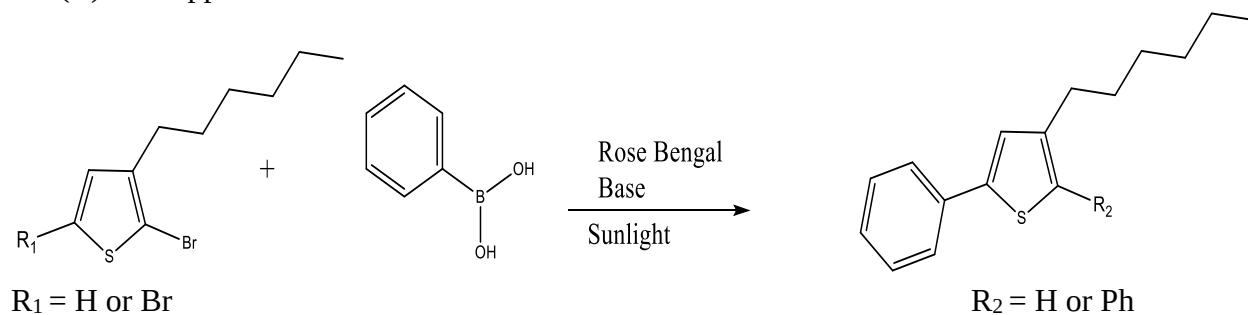
Scheme 2

Synthesis of Aryl hexylthiophene

(A) Previous Cross-Coupling Reaction



(B) Our Approach



3.3.2 Optimization of the reaction conditions

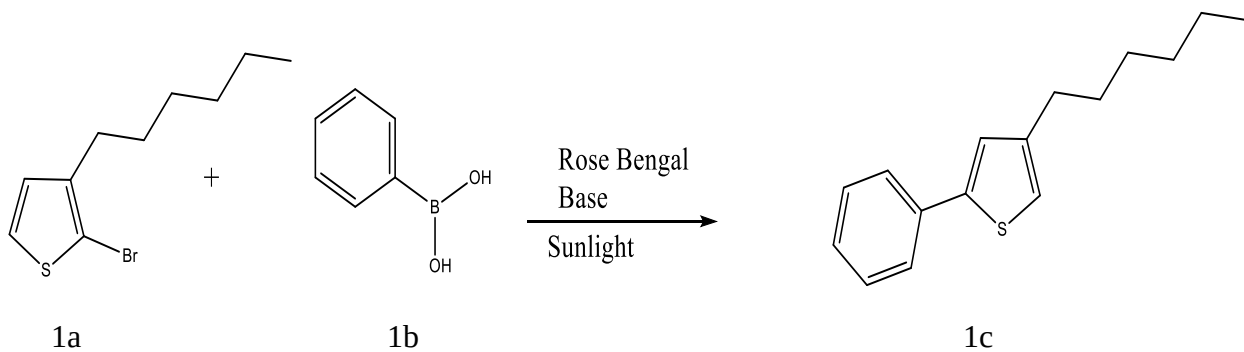
The optimization conditions needed for the reaction to take place were investigated. The investigation involves the reaction of phenylboronic acid with 2-BHT and 2,5-DBHT compounds under varying conditions of time, bases, solvents, and catalyst loading in the sun to achieve the condition with the highest Conversion.

3.3.3 General Procedure for the Synthesis of 3-H2PT (1c)

2-bromo-3-hexylthiophene (1mmol) and 1 mol% (Rose Bengal) were added to a flask containing organic solvents (10ml) and water (0.5ml) under ambient conditions. The mixture was stirred to completely dissolve the thiophene and the dye after which phenylboronic acid (1mmol) was added. The reaction mixture was then placed in the sun for a duration of 120 minutes, after which it was extracted using ethyl acetate and dried over sodium sulfate (anhydrous) to eliminate any traces of water.

Scheme 3

i) Synthesis of 3-hexyl-2-phenyl thiophene

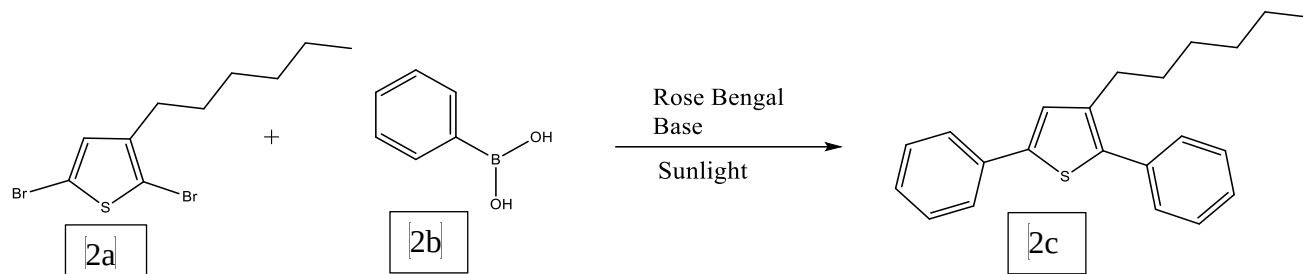


3.3.4 General Procedure for the Synthesis of 3-H2,5DPT (2c)

2,5-DBHT (1mmol) and Rose Bengal (1 mol%) were added to a flask containing organic solvents (10ml) and water (0.5ml) under ambient conditions. The mixture was stirred to completely dissolve the thiophene and the dye after which phenylboronic acid (2mmol) was added. The reaction mixture was then placed in the sun for a duration of 120 minutes, after which it was extracted using ethyl acetate and dried over anhydrous sodium sulfate to eliminate any traces of water.

Scheme 4

ii) Synthesis of 3-H2,5DPT



3.4 Characterization

^1H NMR and ^{13}C NMR were used to characterize the products obtained.

3.5 Instrumental Analysis

A JEOL Delta Aspect AM-600 NMR instrument was used to study ^1H -NMR and ^{13}C -NMR spectroscopic values in CHLOROFORM-*D* at 600 MHz. All analytical chemicals were obtained from BDH, Fluka and Sigma Aldrich for reaction.

3.5.1 Liquid Chromatography Mass Spectrometry

Shimadzu LCMS-8050 autosampler, PAL HTC-tx attached, Nexera X2/SPD-M30A Diode array detector, DGU-20A5R degassing unit, Nexera X2/LC-30AD, and Liquid Chromatography Mass Spectrometry (LCMS) Utilizing liquid chromatography with a Nexera X2 CTO-30A Column oven, the HPLC data were quantified and confirmed (Figure). All studies used Acetonitrile and water as the mobile phase ratios, with a flow rate of 1 ml/min and an injection volume of 1 μL . For each run, the Mass Spectrometer (MS) temperature was 400°C, and Column (Fig 3.2).

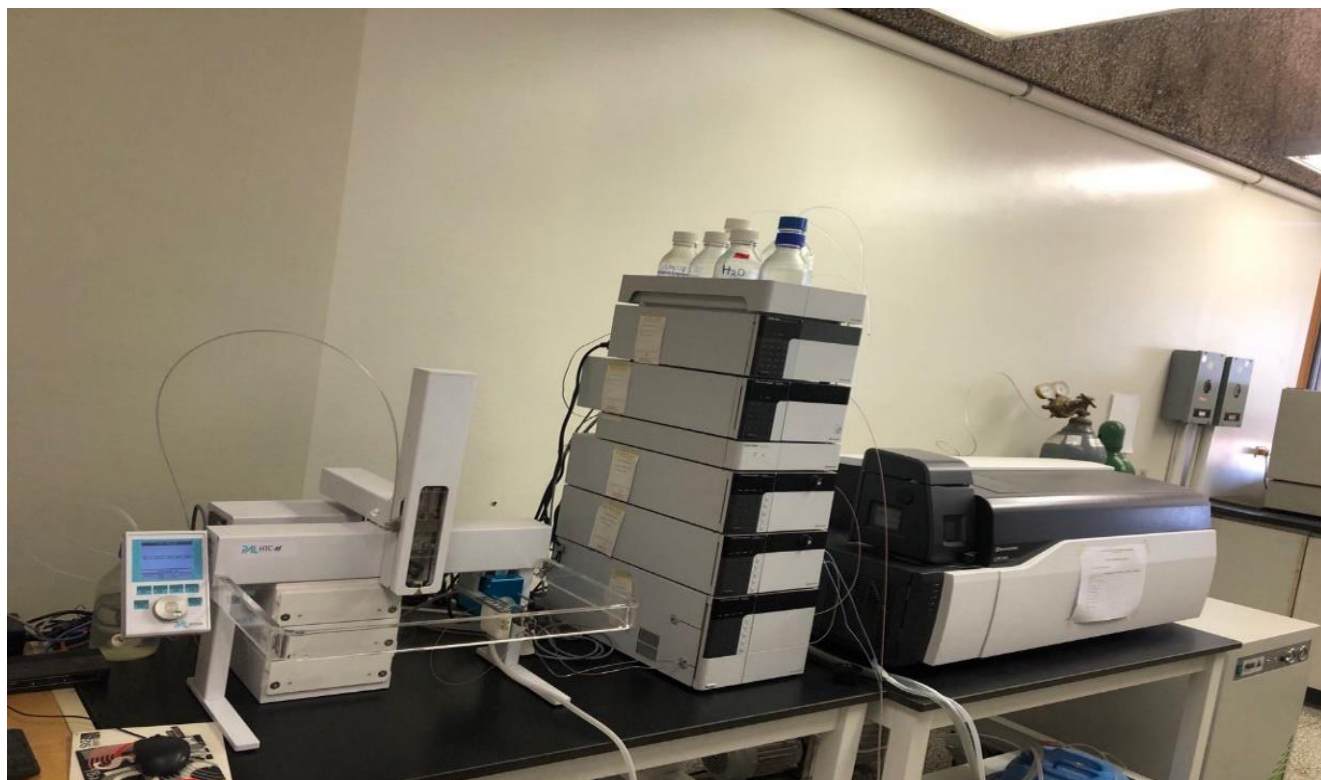


Fig 3.2: Diagram showing the LC-MS

3.5.2 Fluorescence Study

An FLS920 fluorescence spectrophotometer (Edinburgh Instruments, Livingston, UK) was used to measure each fluorescence emission spectrum. The emission wavelength was fixed at 280 nm, and the excitation wavelength ranged from 300 to 600 nm. Fluorescence measurements of the solutions were performed using a sub-micro quartz cuvette with a 10-mm path length (Cole-Parmer, Vernon Hills, IL, USA). Throughout the measurements, the spectra were obtained at room temperature.

The formulas below were used in the calculation of conversion.

$$\text{Conversion (\%)} = \frac{\text{Response of reactant after reaction}}{\text{Response of reactant taken}} \times 100$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Synthesis of Biphenyl Derivatives

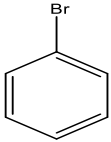
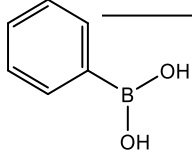
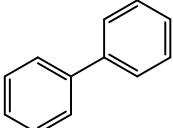
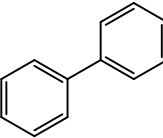
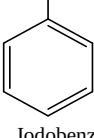
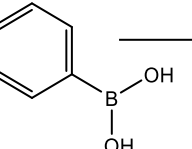
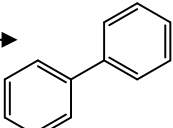
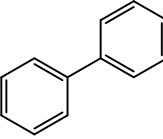
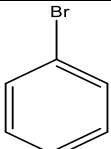
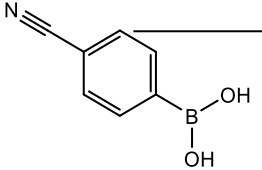
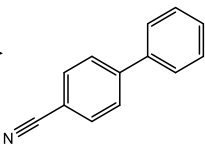
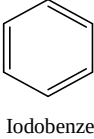
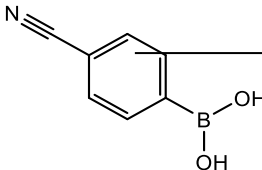
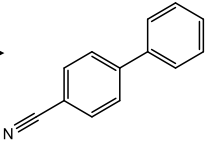
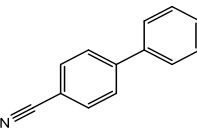
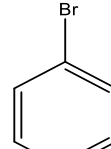
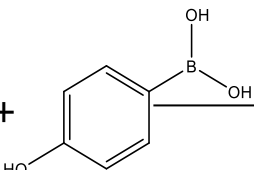
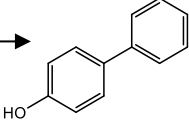
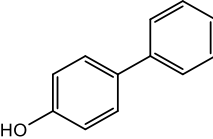
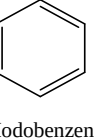
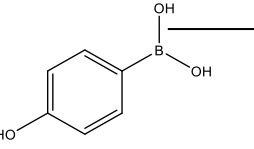
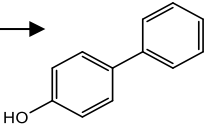
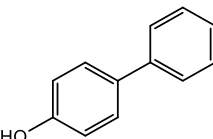
The synthesis of biphenyl and its derivative's using Rose Bengal was performed to investigate into the photocatalytic property of Rose Bengal in sunlight (Table 4.1). The results obtained reveal that no reaction occurs in the absence of Rose Bengal (Fig 4.1) and furthermore, the reaction was also monitored in the absence of sunlight (Fig 4.2) and an unresolved peak was obtained. Finally, in the presence of all the necessary conditions, the coupling of phenylboronic acid with Iodobenzene gave the better results in the formation of biphenyl (Fig 4.3) with a moderate Conversion of 39% at 1hr of irradiation time. This is because of the higher reactivity of Iodobenzene since it is larger in size than bromine, it is expected to be a better leaving group than bromine thereby enhancing electrophilic aromatic substitution reaction by coupling with the phenyl anion to give biphenyl. As the time progresses, the Conversion of the product is decreasing, this is due to photobleaching effect which arises due to prolong exposure of the dye in sunlight which eventually lowers its activity which in turn gives lower Conversion of biphenyl in contrast, the use of bromobenzene gave lower Conversion due to its small size when compared to iodine.

On the other hand, 4-Hydroxyphenylboronic acid and 4-Cyanophenylboronic acid both gave traces/no reaction as the product since both hydroxy and cyano group are both electron withdrawing groups attached to the phenyl ring, thereby reducing the

nucleophilicity of the phenyl ring after removal of the boronic group thereby giving a lower Conversion/no reaction.

Since the reduction in its nucleophilicity affects the instant formation of the product, the reaction will solely depend on the catalyst to drive the reaction faster. But due to long exposure of the dye in sunlight, degradation of the dye occurs which eventually lowers the Conversion or even deactivates the dye thereby giving no reaction. The reaction conditions for the monitoring reaction are displaced below.

Table 4.1: showing the conversion and Conversion obtained using LC-MS

Aryl halide	Coupling Partner	Expected Product	Formed Product	Substrate Conversion (%)	Yield (%)	Time (hr.)
 Bromobenzene	 Phenylboronic acid	 Biphenyl	 Biphenyl	47	27	1
				27	19	2
				2	Traces	4
 Iodobenzene	 Phenylboronic acid	 Biphenyl	 Biphenyl (1hr, 4hrs)	62	39	1
				52	34	2
				29	17	4
 Bromobenzene	 4-Cyanophenylboronic acid	 4-Cyanobiphenyl	Not Formed	48	Traces	1
				42		2
				27		4
 Iodobenzene	 4-Cyanophenylboronic acid	 4-Cyanobiphenyl	 4-Cyanobiphenyl (2hrs and 4hrs)	59	Traces	1
				45		2
				53		4
 Bromobenzene	 4-Hydroxyphenylboronic acid	 4-Hydroxybiphenyl	 4-Hydroxybiphenyl (4hrs)	49	Traces	1
				47		2
				31		4
 Iodobenzene	 4-Hydroxyphenylboronic acid	 4-Hydroxybiphenyl	 4-Hydroxybiphenyl (2hrs)	17	Traces	1
				11		2
				30		4

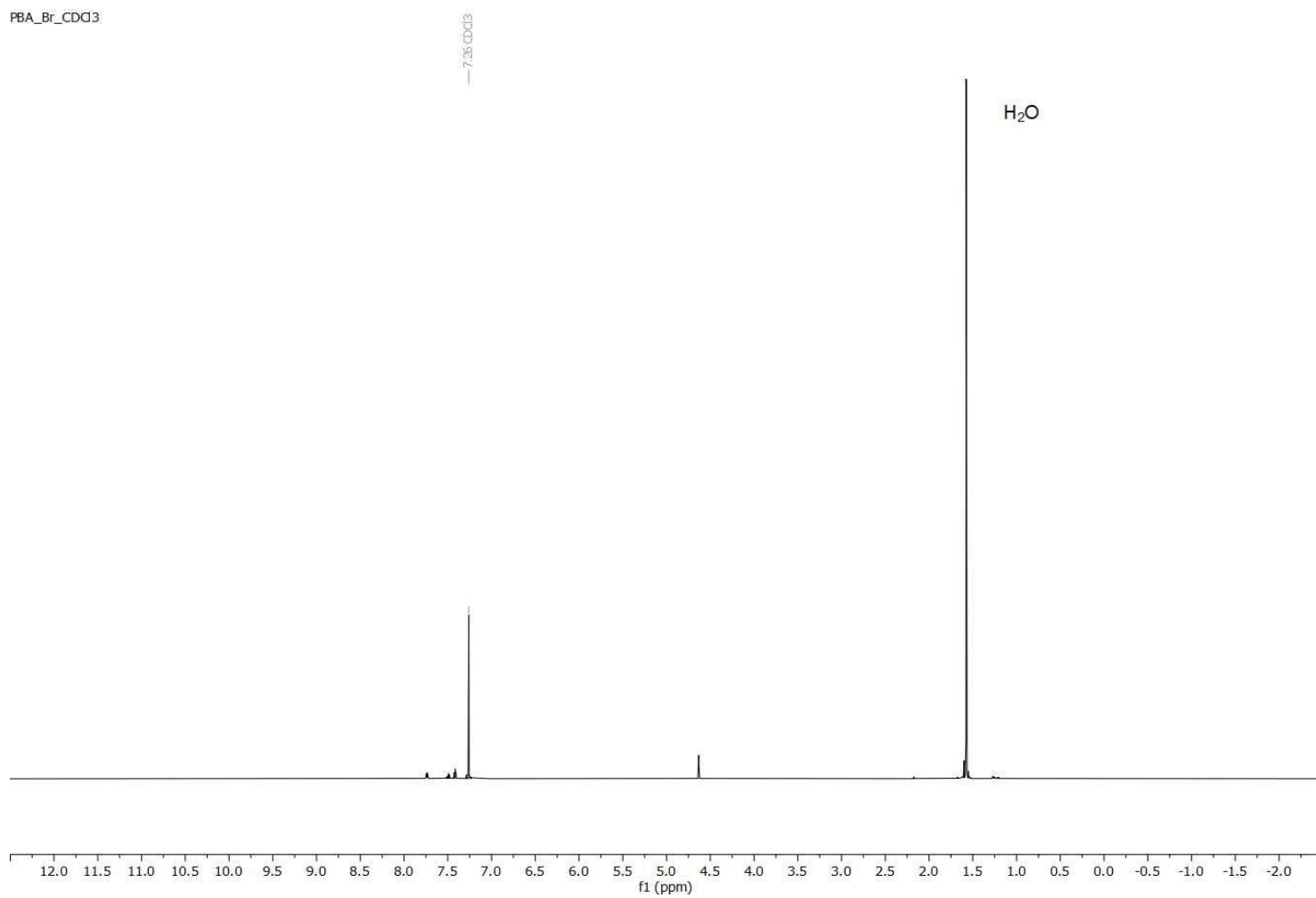


Fig 4.1: ^1H NMR spectra for the formation of biphenyl without Rose Bengal

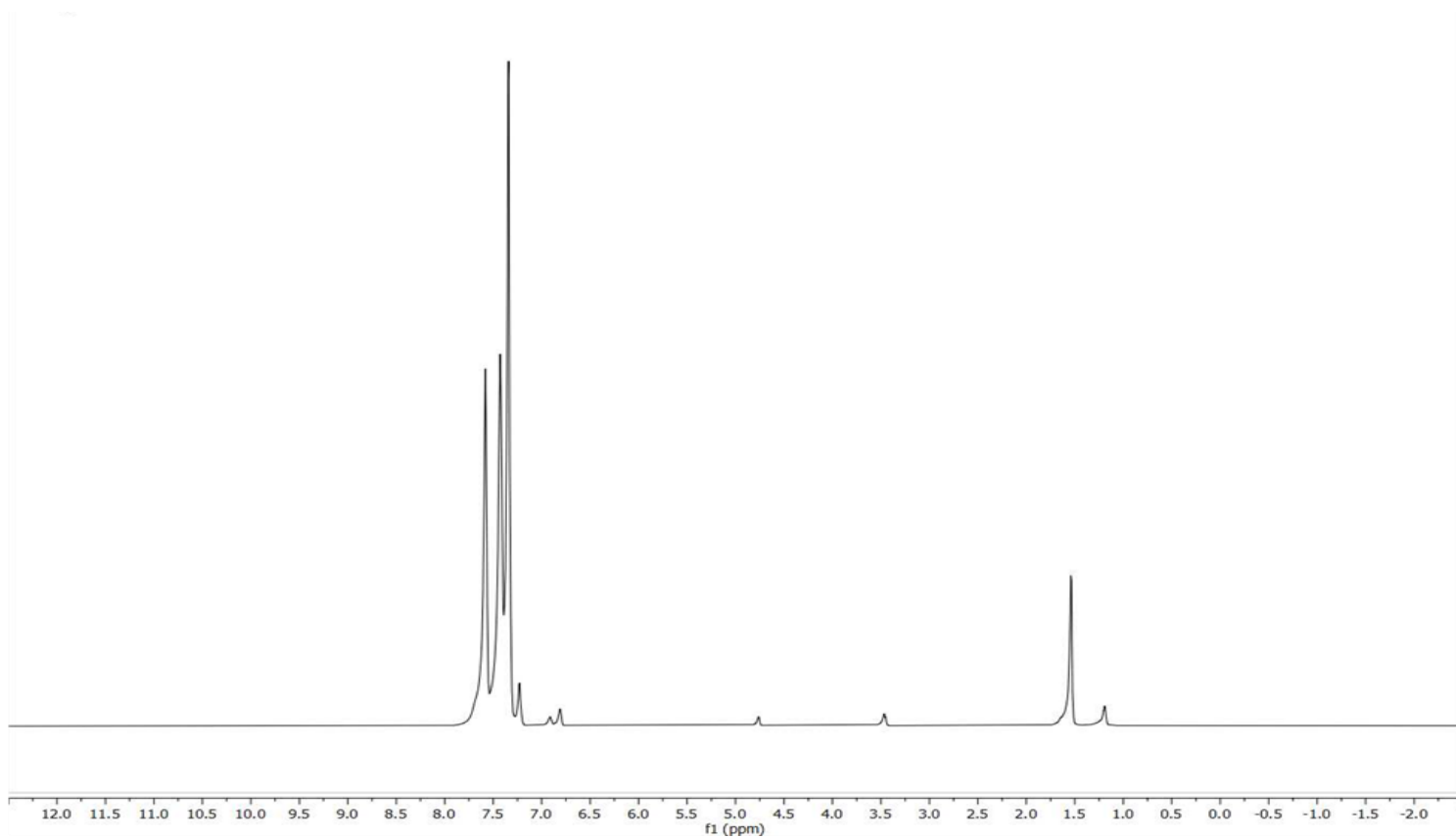


Fig 4.2: ^1H NMR spectra for the formation of biphenyl without Sunlight

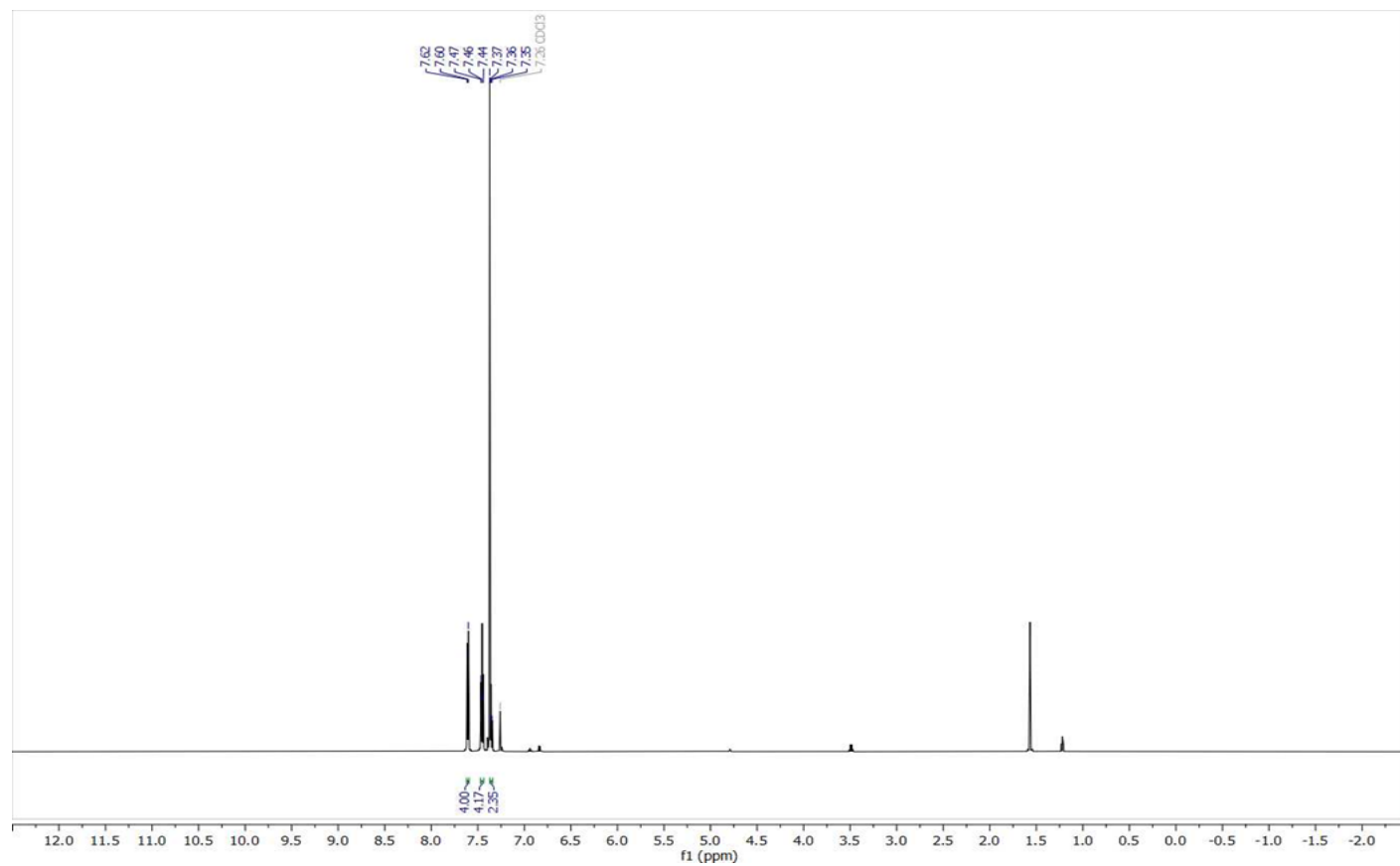


Fig 4.3: ^1H NMR spectra for the formation of biphenyl with Rose Bengal

4.2 Synthesis of 3-H₂PT and 3-H₂,5DPT

The results obtained from the reaction of 2-B₃HT and 2,5-DB₃HT with phenylboronic acids are shown below.

4.2.1 Effect of No Rose

The synthesis of compounds 1c and 2c was carried using the static mode as depicted in fig (3.1). The first optimized condition was carried out without the catalyst (Rose Bengal), and it was observed that the reaction did not proceed without the catalyst, as depicted in (Fig 4.4 and 4.5) respectively. Suzuki coupling reaction is a catalytic cycle reaction effective in the presence of a catalyst. However, the absence of a catalyst inhibits the catalytic cycle from taking place, thereby giving no Conversion despite the presence of sunlight. It indicated that the presence of the sun alone without the catalyst cannot drive the reaction to completion.

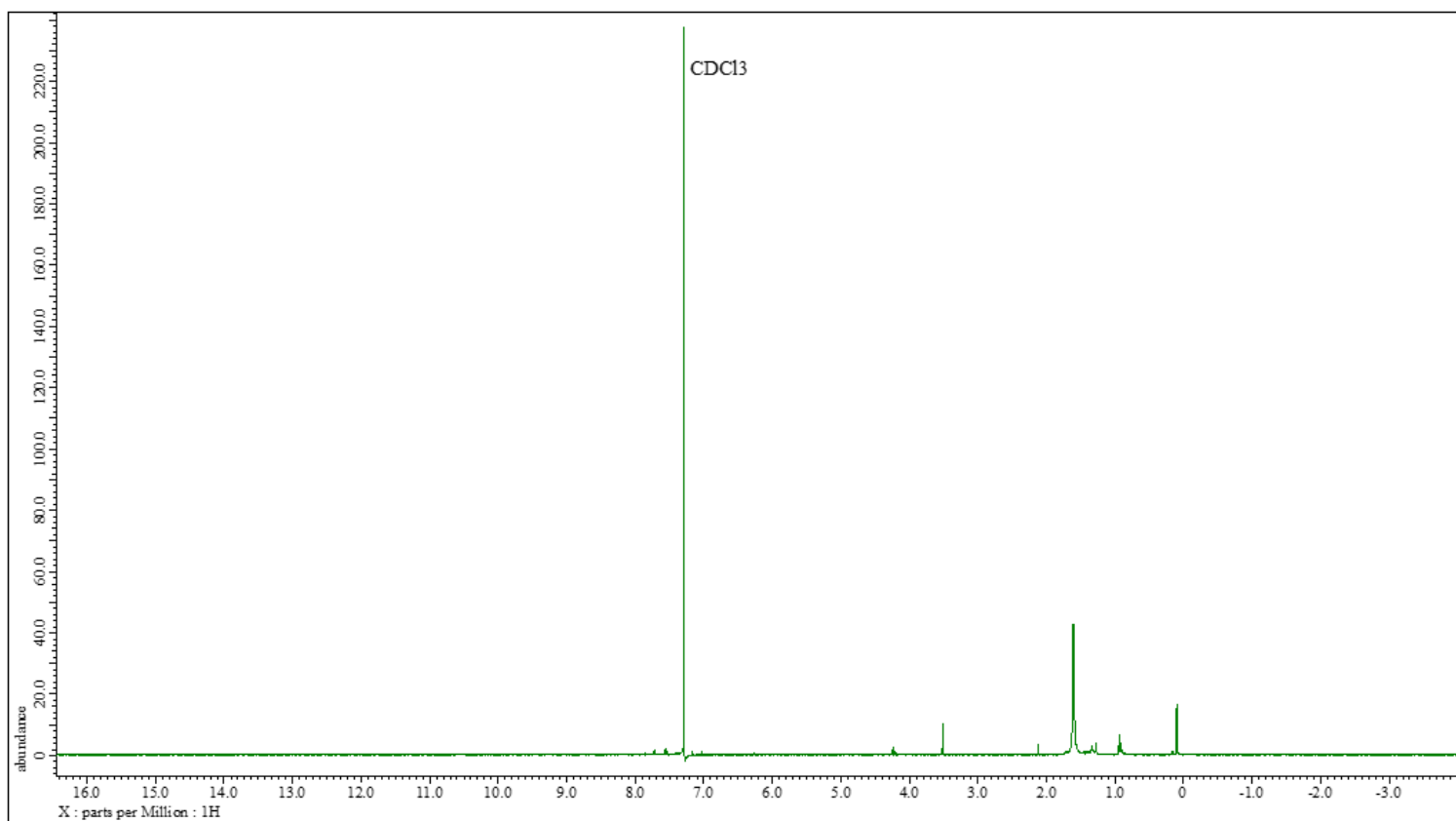


Fig 4.4: ^1H NMR spectra for the formation of 3-hexyl-2,5-diphenyl thiophene without Rose Bengal

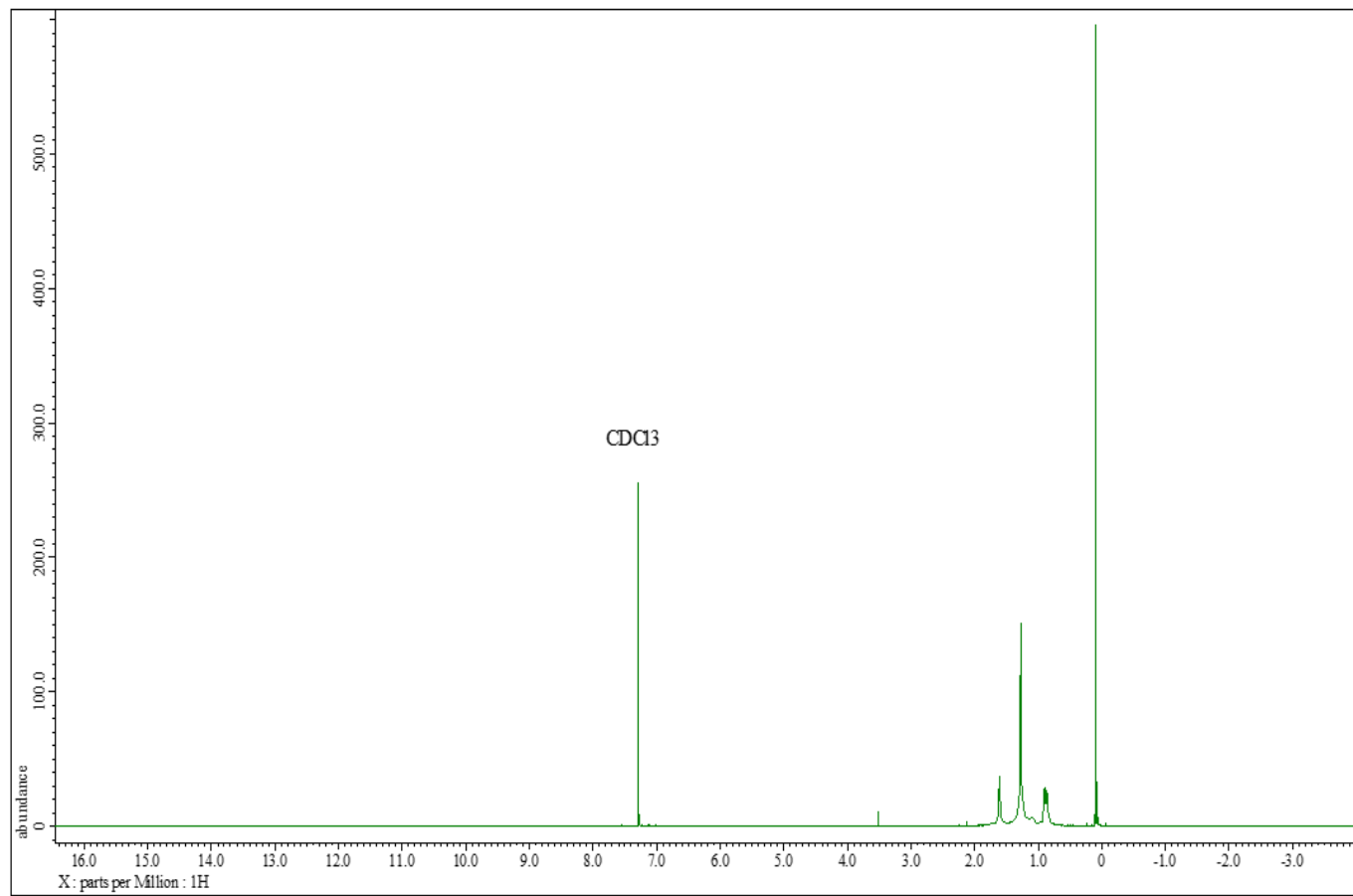


Fig 4.5: ^1H NMR spectra for the formation of 3-hexyl-2-phenyl thiophene without Rose Bengal

4.2.2 Effect of solvent

The solvent effect was the first optimization condition performed on the percentage Conversion of 3-hexyl-2-phenylthiophene (3-H2PT) and 3-hexyl-2,5-diphenylthiophene (3-H2,5DPT). No reaction was observed (Figures 4.6 and 4.7) because of the absence of base which will completely convert the weak boronic acid into reactive species. It indicated that the presence of a base plays a vital role in the formation of the product.

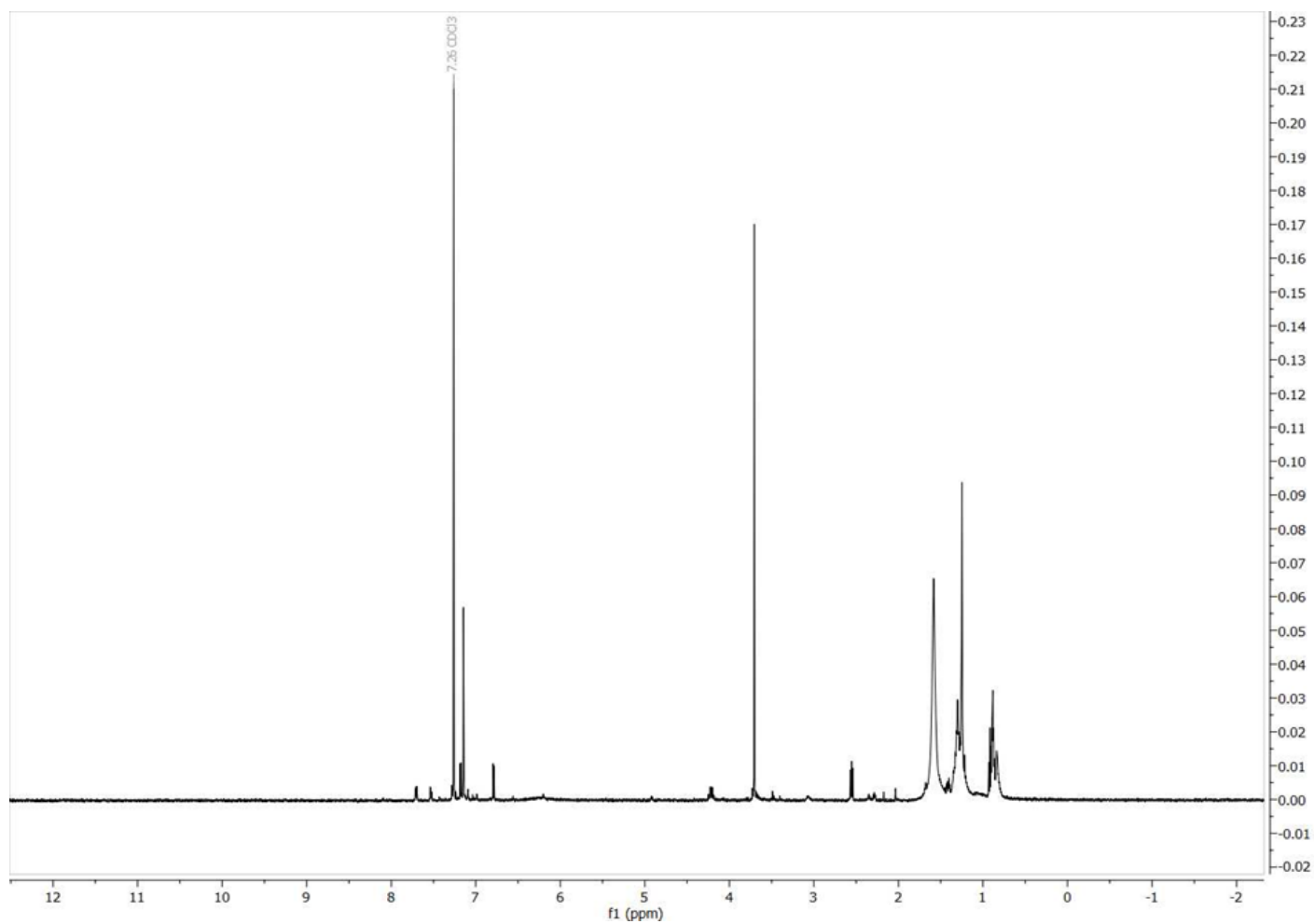


Fig 4.6: ^1H NMR spectra for the formation of 3-hexyl-2-phenylthiophene without Base

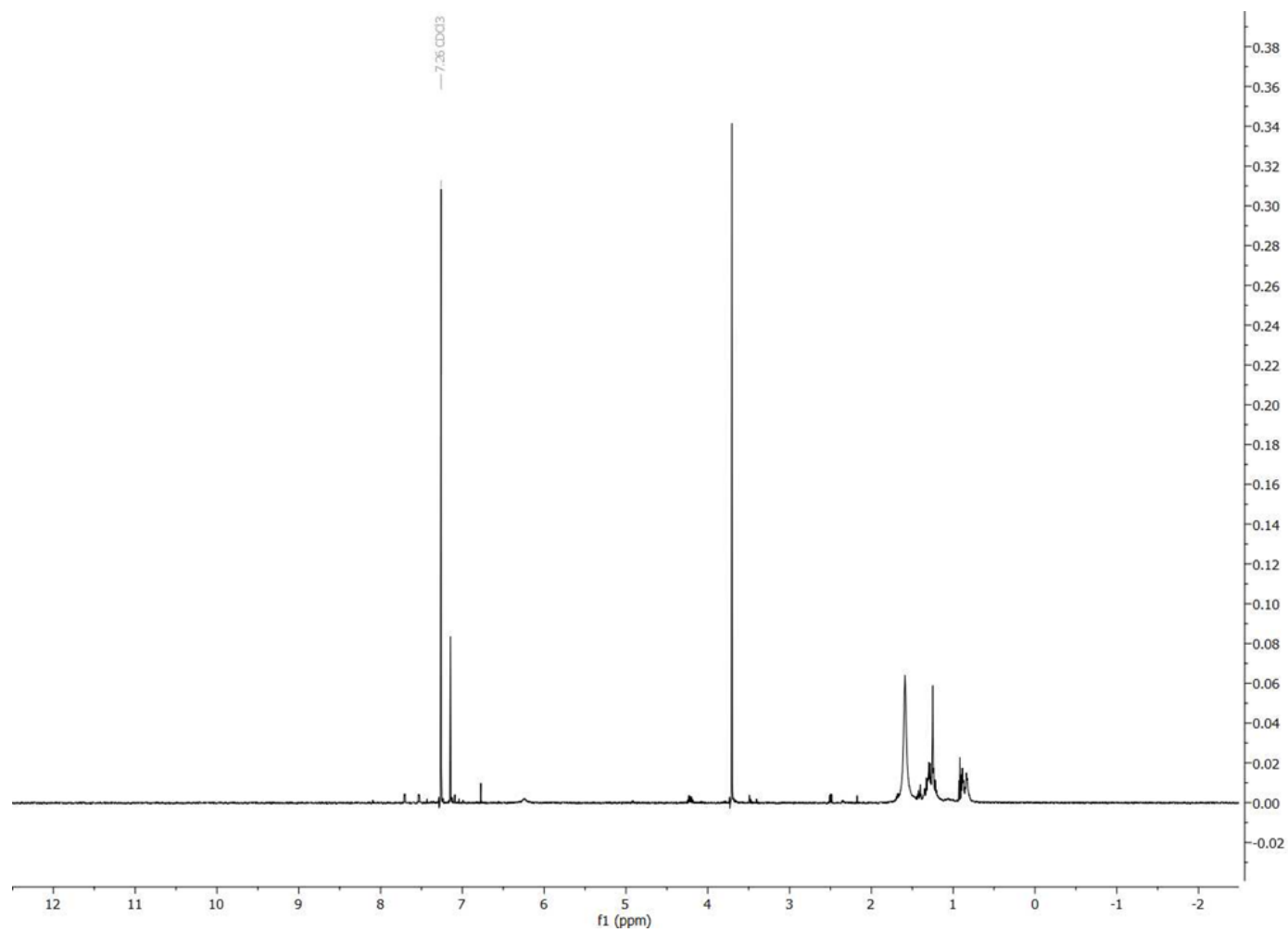


Fig 4.7: ^1H NMR spectra for the formation of 3-hexyl-2,5-diphenylthiophene without Base.

4.2.3 Effect of Bases and Solvent

One of the most important parameters that determine the conversion of the product formed is the type of base used during the reaction. Three bases were chosen for the experiment, which are Potassium Hydroxide (KOH), Potassium Carbonate (K_2CO_3) and Sodium Carbonate (Na_2CO_3). The main function of a base in this experiment is to increase the reactivity of boronic acid to form reactive species (borate anion) since aryl-boronic acids are generally weak acids. This reactive species will then serve as a nucleophile and react faster towards the hexylthiophene compound, forming the desired product (Fig 4.8 and 4.9).

As shown in table 4.2 and 4.3, respectively, it is observed that KOH, as a base on average, produced the lowest Conversion as compared to the other two; this is because of the high, strong, basic nature of KOH. This strong basicity is due to the complete ionization in solution thereby producing large amount of hydroxide ions which favors the conversion of phenylboronic acid into its organoborates anion by making it reactive towards the thiophene group. Still, this rapid conversion happens so fast that the phenyl anion produced tends to undergo homo-coupling, forming biphenyl as an unwanted side reaction, which in turn lowers the Conversion of the product. At the same time, K_2CO_3 and Na_2CO_3 are moderately strong bases and give better yield than KOH, but Na_2CO_3 is less basic than K_2CO_3 due to its small ionic radius and less polarizability as compared to K_2CO_3 . As such, sodium carbonate was observed to have the highest Conversion on average.

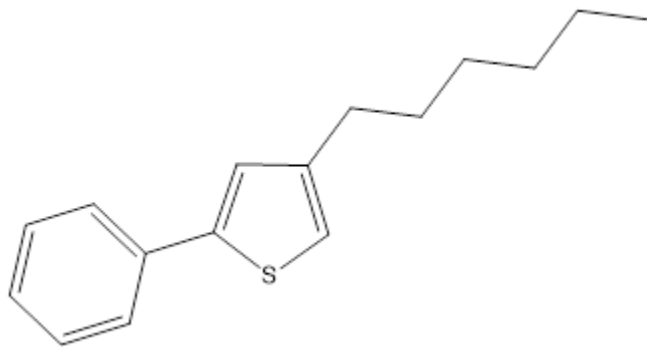
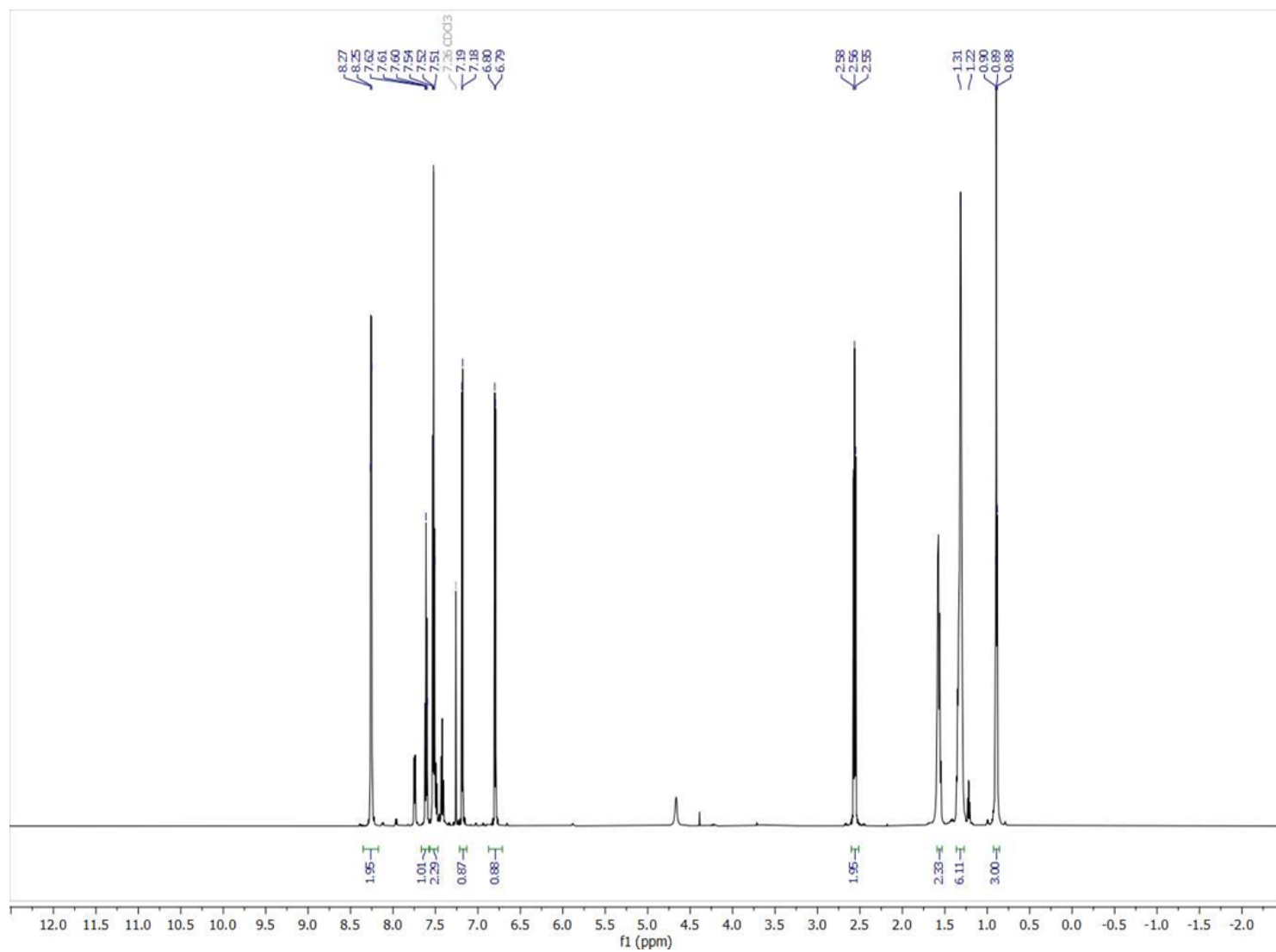


Fig 4.8: ^1H NMR spectra 3-hexyl-2-phenylthiophene



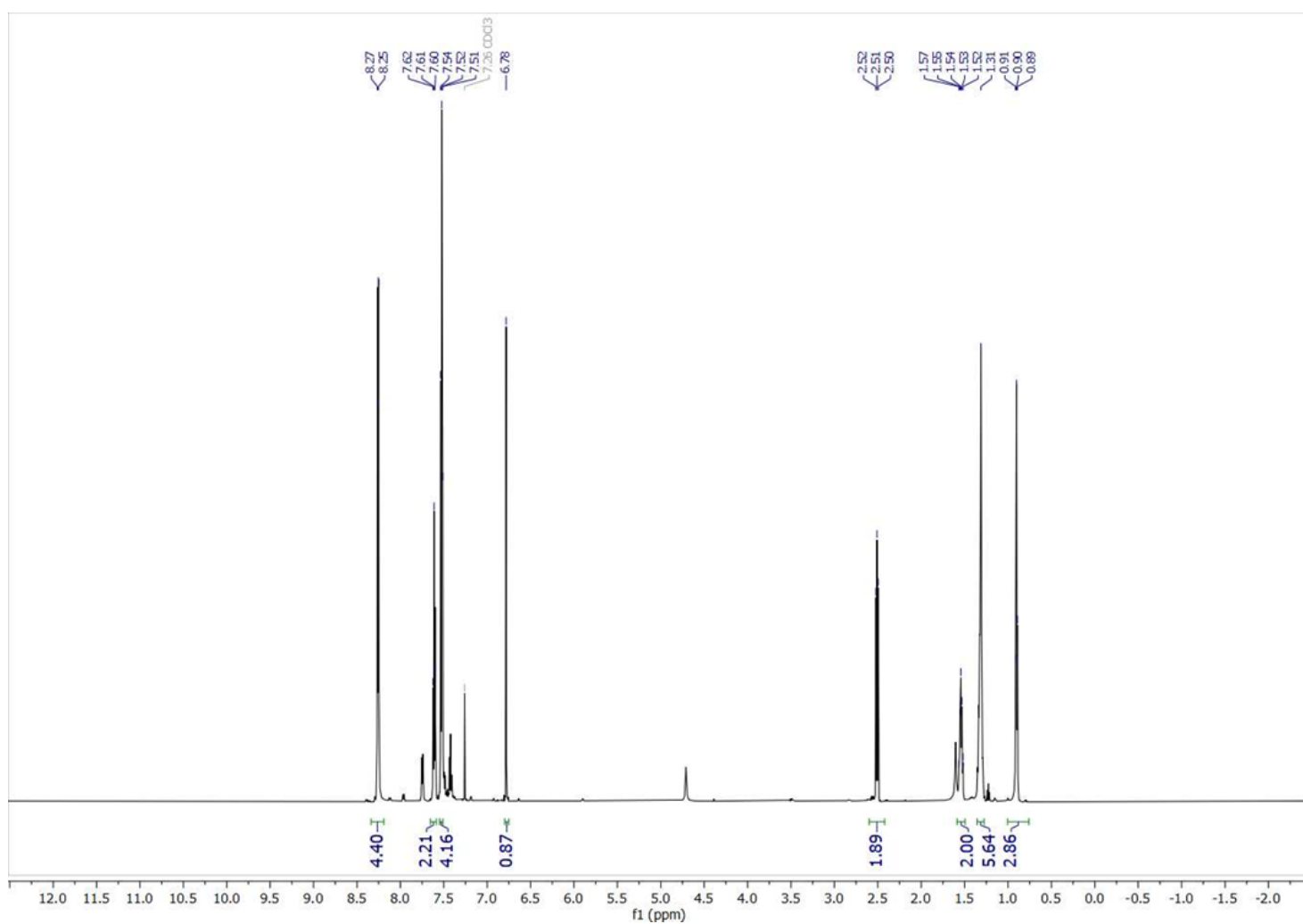
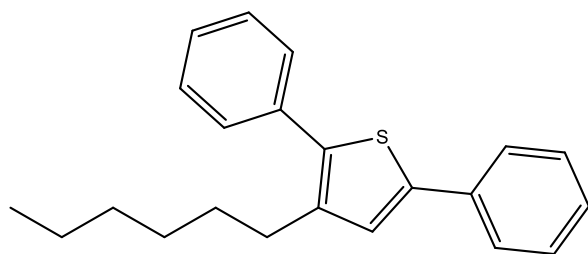


Fig 4.9: ¹H NMR spectra 3-hexyl-2,5-diphenylthiophene

Table 4.2: Influences of Bases and Solvents in Suzuki Cross-Coupling Reaction of 3-hexyl-2-phenylthiophene Catalyzed by Rose Bengal

Entry	Base	Solvent	Conversion (%)
1	KOH	THF	19.9
2	KOH	DMF	18.3
3	KOH	MeOH	17.6
4	KOH	Dioxane	26.2
5	KOH	H ₂ O	7.40
6	KOH	ACN	16.0
7	Na ₂ CO ₃	THF	37.2
8	Na ₂ CO ₃	DMF	37.0
9	Na ₂ CO ₃	MeOH	30.0
10	Na ₂ CO ₃	Dioxane	45.4
11	Na ₂ CO ₃	H ₂ O	28.4
12	Na ₂ CO ₃	ACN	32.6
13	K ₂ CO ₃	THF	33.1
14	K ₂ CO ₃	DMF	31.5
15	K ₂ CO ₃	MeOH	26.9
16	K ₂ CO ₃	Dioxane	33.9
17	K ₂ CO ₃	H ₂ O	22.0
18	K ₂ CO ₃	ACN	27.4

Reaction conditions: 1a (1mmol), 1b (1mmol), photocatalyst (1mol%), base (0.1M) solvent (10ml), sunlight for 2hrs

Table 4.3: Influences of Bases and Solvents in Suzuki Cross-Coupling Reaction of 3-hexyl-2,5-diphenylthiophene Catalyzed by Rose Bengal

Entry	Base	Solvent	Conversion (%)
1	KOH	THF	9.27
2	KOH	DMF	8.23
3	KOH	MeOH	6.50
4	KOH	Dioxane	14.5
5	KOH	H ₂ O	1.45
6	KOH	ACN	6.66
7	Na ₂ CO ₃	THF	34.4
8	Na ₂ CO ₃	DMF	35.6
9	Na ₂ CO ₃	MeOH	25.6
10	Na ₂ CO ₃	Dioxane	40.6
11	Na ₂ CO ₃	H ₂ O	24.9
12	Na ₂ CO ₃	ACN	29.0
13	K ₂ CO ₃	THF	31.2
14	K ₂ CO ₃	DMF	27.4
15	K ₂ CO ₃	MeOH	20.4
16	K ₂ CO ₃	Dioxane	31.6
17	K ₂ CO ₃	H ₂ O	19.1
18	K ₂ CO ₃	ACN	20.4

Reaction conditions: 1a (1mmol), 1b (1mmol), 2a (1mmol), 2b (2mmol), photocatalyst (1mol%), base (0.1M) solvent (10ml), sunlight for 2hrs

4.2.4 Effect of Irradiation Time

As shown in table 4.4, the effect of reaction time was conducted. It was observed that at the initial stage, the Conversion was less but gradually increased as time progressed, reaching a maximum of 2hrs and decreasing/remaining unchanged at the final stage. This is because at the beginning, when rose Bengal absorbs photons when exposed to sunlight, it gets excited, thereby leading to chemical reactions, but as time passes, it undergoes photodegradation. Photodegradation is a complex process that involves the production of singlet oxygen and super radicals, which eventually react with the dye and degrade it in the process. In addition, due to too much exposure to sunlight, this reactive species could possibly aid the formation of side reactions, lowering the Conversion of the products.

Table 4.4: Influences of irradiation time in Suzuki Cross-Coupling Reaction Catalyzed by Rose Bengal

Entry	Base	Time (hr.)	Conversion (%) (3-H2PT)	Conversion (%) (3-H2,5DPT)
1	Na ₂ CO ₃	1	32.2	25.6
2	Na ₂ CO ₃	2	45.4	40.7
3	Na ₂ CO ₃	3	40.5	36.0
4	Na ₂ CO ₃	4	33.5	28.4
5	Na ₂ CO ₃	5	27.7	24.6

Reaction conditions: 1a (1mmol), 1b (1mmol), 2a (1mmol), 2b (2mmol), photocatalyst (1mol%), base (0.1M) solvent (10ml), sunlight for 1-5hrs

4.2.5 Effect of Catalyst Loading

The effect of catalyst dosage was also studied, and the result is depicted in table 4.5. Since Rose Bengal is the catalyst used during the reaction, it is expected to have the optimal amount of catalyst to give the highest on the synthesis of our desired product. At lower concentrations, it is observed that the Conversion of the product keeps increasing but decreases as the concentrations become higher. This increase is associated with rose Bengal being a photosensitizer that works actively only when exposed to sunlight. So, as the amount increases, more interaction between the catalyst and the reactant is likely. But at a very high concentration, the excited dye molecules experience self-quenching due to proximity to each other, thereby deactivating each other, decreasing their activity, and there is a high chance of the formation of unwanted side reactions, which tend to compete with the desired reaction pathway.

Table 4.5: Influence of catalyst loading in Suzuki Cross-Coupling Reaction Catalyzed by Rose Bengal

Entry	Base	RB Loading (mol%)	Conversion (%) (3-H ₂ PT)	Conversion (%) (3- H ₂ ,5DPT)
1	Na ₂ CO ₃	1	45.4	40.7
2	Na ₂ CO ₃	2	48.4	50.1
3	Na ₂ CO ₃	3	63.6	54.5
4	Na ₂ CO ₃	4	51.6	62.4
5	Na ₂ CO ₃	5	44.7	49.2

4.2.6 Effect of Base Concentrations

The effect of sodium carbonate as the base was experimented on, and the result is depicted in table 4.6. The figure below indicates that the experiment's outcome greatly depends on the amount of base used during the experiment. These observations suggest that acid-base chemistry is a decisive factor affecting the outcome of the experiment.

As shown below, it is observed that there is an increase in the conversion of the product as the amount of base added increases, but a decrease in the conversion is observed as the concentration becomes too much.

If less base is used, then the amount of boronic acid converted to its respective borate will not be enough to react sufficiently with the thiophene compound, thereby lowering the conversion. As the amount of sodium carbonate increases, more of the borate anion is produced thereby reacting with enough of the thiophene compound. Still, at a very high concentration high amount of hydroxide is produced, over-base reaction is likely to occur where rapid conversion of the boronic acid into its corresponding borates occurs thereby enhancing formation of biphenyl which eventually reduces the amount of phenyl coupling with the thiophene compound which ultimately lowers the Conversion of the desired product.

Table 4.6: Influence of amount of base in Suzuki Cross-Coupling Reaction Catalyzed by Rose Bengal

Entry	Base	Base Loading (M)	Conversion (%) (3-H ₂ PT)	Conversion (%) (3-H ₂ ,5DPT)
1	Na ₂ CO ₃	0.1	63.4	62.4
2	Na ₂ CO ₃	0.2	70.7	63.1
3	Na ₂ CO ₃	0.3	86.7	82.2
4	Na ₂ CO ₃	0.4	66.2	48.3
5	Na ₂ CO ₃	0.5	49.3	38.0

Reaction conditions: 1a (1mmol), 1b (1mmol), 2a (1mmol), 2b (2mmol), photocatalyst (3mol%, 4mol%), base (0.1-0.5M) solvent (10ml), sunlight for 2hrs.

4.3 Comparison Study between Sunlight and Lamp-Assisted Reaction

To study the comparative study, a Cole Parmer Model 41500-55 Fiber Optic Illuminator 150W (fig) was used as the source of light.

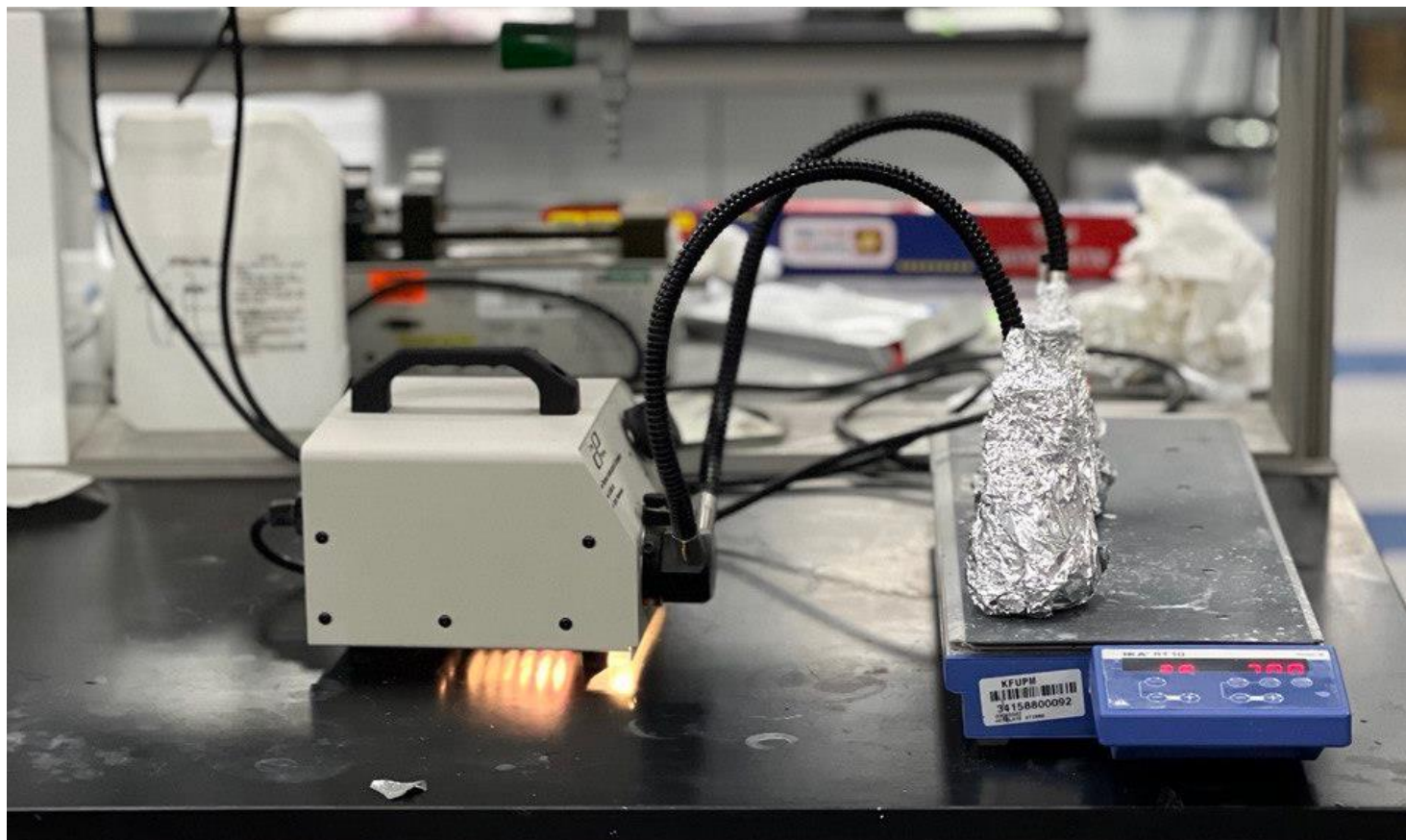


Fig 4.10: Fiber illuminator experimental setup for the study.

The source of light used in this lamp is halogen. Halogen lamps are generally known to tolerate a wide range of wavelengths compared to LED lamps. They are known to produce a variety of irradiation conditions such as mimic the sunlight to some instance. The study focused on the effect of base and solvent used in the sunlight-assisted reaction. The study still follows the same trend as the sunlight reaction where potassium hydroxide produces the lowest Conversion due to its strong basic nature, which tends to convert the phenylboronic acid to reactive species faster, thereby enhancing homocoupling reaction to giving biphenyl, which in turn lowers the Conversion of the desired product. As shown in Tables 8 and 9 below, there's a significant difference in the Conversion of sunlight assisted as compared to the light from the optical instrument used. This significant difference is due to the number of photons produced by light sources. Generally, Rose Bengal can only be active in the presence of light that produces photons; these photons tend to activate the dye, thereby producing reactive species such as singlet oxygen, which in turn react with the substrates of interest, thereby producing the product. Photons produced by sunlight are much higher than those produced by optical devices.

Furthermore, sunlight comprises several wavelengths, including those that will favor the photosensitization of the dye,. In contrast, optical fiber only comprises one wavelength, which might not favor the photosensitization of the dye.

Table 4.7: Comparison of the Influences of Base and Solvent in Suzuki Cross-Coupling Reaction Catalyzed by Rose Bengal using Optic Fiber Illuminator

Entry	Base	Solvent	Sun Conversion (%) ^{1c}	Lamp Conversion (%) ^{1c}
1	KOH	THF	19.9	7.64
2	KOH	DMF	18.3	6.24
3	KOH	MeOH	17.6	2.69
4	KOH	Dioxane	26.2	18.3
5	KOH	H ₂ O	7.40	0.87
6	KOH	ACN	16.0	4.55
7	Na ₂ CO ₃	THF	37.2	6.40
8	Na ₂ CO ₃	DMF	37.0	4.96
9	Na ₂ CO ₃	MeOH	30.0	2.81
10	Na ₂ CO ₃	Dioxane	45.4	27.0
11	Na ₂ CO ₃	H ₂ O	28.4	0.25
12	Na ₂ CO ₃	ACN	32.6	3.47
13	K ₂ CO ₃	THF	33.1	5.99
14	K ₂ CO ₃	DMF	31.5	4.83
15	K ₂ CO ₃	MeOH	26.9	3.72
16	K ₂ CO ₃	Dioxane	33.9	19.4
17	K ₂ CO ₃	H ₂ O	22.0	2.27
18	K ₂ CO ₃	ACN	27.4	3.84

Reaction conditions: 2a (1mmol), 2b (2mmol), photocatalyst (1mol%), base (0.1M) solvent (10ml), sunlight for 2hrs

Table 4.8: Comparison of the Influences of Base and Solvent in Suzuki Cross-Coupling Reaction Catalyzed by Rose Bengal using Optic Fiber Illuminator

Entry	Base	Solvent	Sun Conversion (%) ^{2c}	Lamp Conversion (%) ^{2c}
1	KOH	THF	9.27	3.60
2	KOH	DMF	8.23	3.00
3	KOH	MeOH	6.50	2.30
4	KOH	Dioxane	14.5	5.74
5	KOH	H ₂ O	1.45	1.92
6	KOH	ACN	6.66	2.65
7	Na ₂ CO ₃	THF	34.4	5.46
8	Na ₂ CO ₃	DMF	35.6	4.07
9	Na ₂ CO ₃	MeOH	25.6	3.06
10	Na ₂ CO ₃	Dioxane	40.6	27.4
11	Na ₂ CO ₃	H ₂ O	24.9	2.59
12	Na ₂ CO ₃	ACN	29.0	4.07
13	K ₂ CO ₃	THF	31.2	3.60
14	K ₂ CO ₃	DMF	27.4	3.00
15	K ₂ CO ₃	MeOH	20.4	2.62
16	K ₂ CO ₃	Dioxane	31.6	14.1
17	K ₂ CO ₃	H ₂ O	19.1	2.21
18	K ₂ CO ₃	ACN	20.4	2.65

Reaction conditions: 2a (1mmol), 2b (2mmol), photocatalyst (1mol%), base (0.1M) solvent (10ml), sunlight for 2hrs

4.4 Comparison Study between Rose Bengal and Other Dyes

To fully account for the difference in the photocatalytic activity of other dyes, a comparison study was carried out between Eosin Y and Methylene Blue compared to the optimized Rose Bengal. From the result obtained, it was discovered that Rose Bengal was much better amongst the two having a higher Conversion. This is because it has a high absorption coefficient in the visible light region and its high quantum Conversion of intersystem crossing (ϕ_{ISC}) when compared to the two dyes (fig 4.11), which are related directly to the quantum Conversion of singlet-oxygen production. Singlet oxygen is highly reactive and selective towards organic substrates.

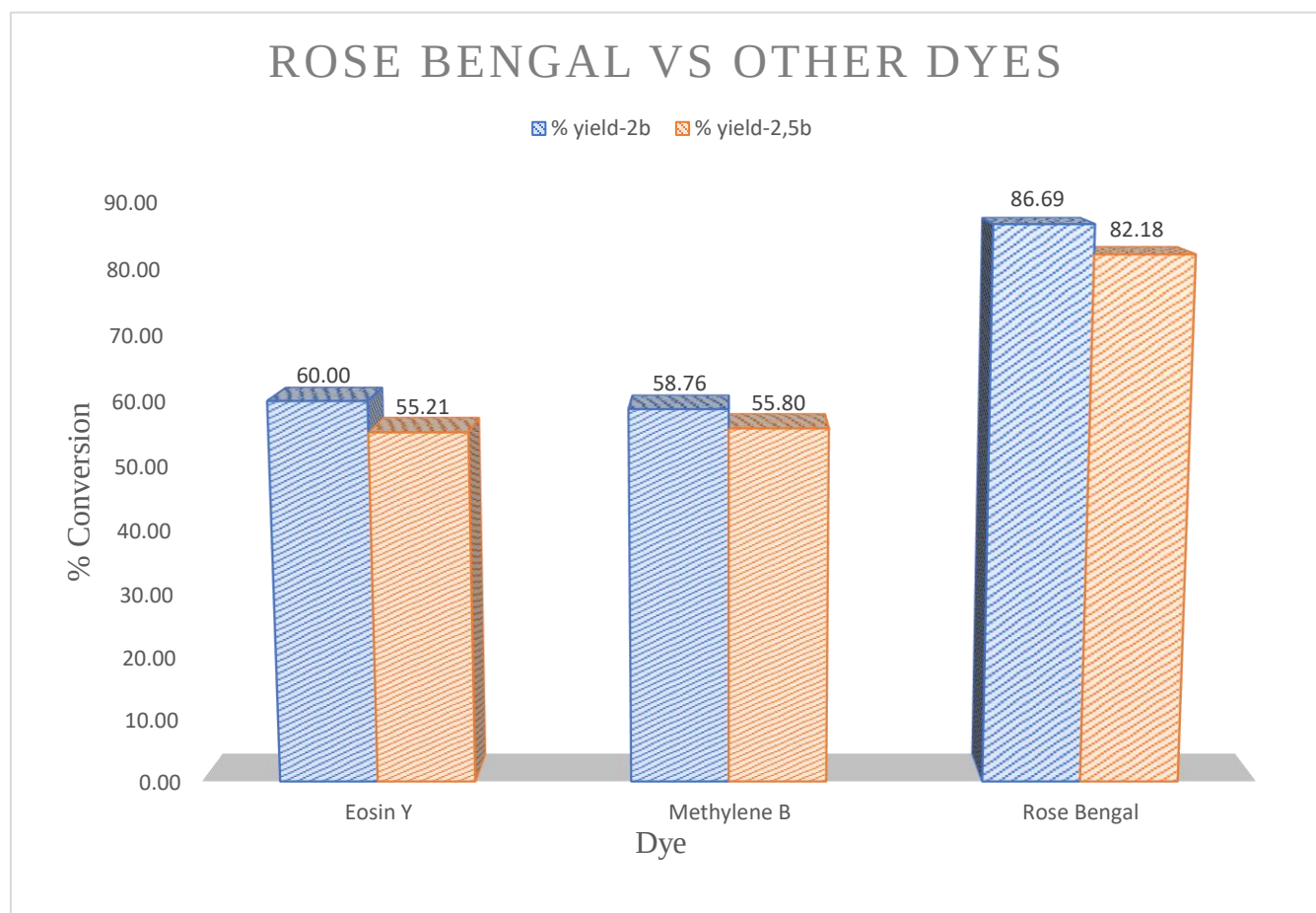


Fig 4.11: compared chart of RB and two other dyes

4.5 Previously Synthesized Thiophene Compounds

The table below presents a few thiophene synthesized using transition metal complexes.

Table 4.9: A comparison of Arylthiophene synthesis with transition metal complexes

Entry	Catalyst	Experimental conditions	Products	Yield (%)	Ref
1	palladium(II) formamidylypyrimidine-based complex	2-bromothiophene & 2,5-dibromothiophene, Microwave heating, catalyst, base, solvent (10ml)	2-phenyl thiophene & 2,5diphenylthiophene	68 ^a , 93 ^b	[26]
2	Tetrakis (Triphenylphosphine) palladium(0)	2,3-dibromobenzo[b]thiophene, Dioxane, 5mol% catalyst, K ₃ PO ₄ , 12h	2,3-diphenylbenzo[b]thiophene	62	[67]
3	Tetrakis (Triphenylphosphine) palladium(0)	2,5-Dibromo3-methyl thiophene, Dioxane 2.5ml, 5mol% catalyst, K ₃ PO ₄ , 12h	2-bromo-5-phenyl-3-methyl thiophene & 2,5diphenylthiophene	63 ^a , 58 ^b	[68]

4.6 Fluorescence Study of Rose Bengal (RB)

To fully understand the reaction mechanism of RB as a photocatalyst in the formation of our desired product, a fluorescence study was conducted on the Rose Bengal starting from the effect of concentration of RB on its intensity, effect of irradiation time on the dye itself and the quenching ability of the thiophene compound on the photocatalyst as illustrated as follows:

4.6.1 Effect of Rose Bengal Concentration on Fluorescence Intensity

To predict the mechanism of Rose Bengal, a few optimizing conditions are carried out on the dye itself. The first is the effect of Rose Bengal concentration as determined by the fluorescence machine. The result is depicted in Fig 4.12 below. As observed, the dye's intensity increases with a decrease in the dye's concentration, but the intensity decreases as the concentration becomes too low. This is because at higher concentrations, the dye molecules are closer to each other, thereby increases the chances of molecular interactions such as energy transfer or collisional quenching, which results in the release of excited-state energy in the form of heat rather than light emission, which in turn reducing the overall emission intensity which is not familiar with dye at lower concentrations. While at significantly lower concentrations, the dye molecules become too far apart, leading to other factors such as solvent interaction to interfere with the dye's intensity and the dye's electronic structure.

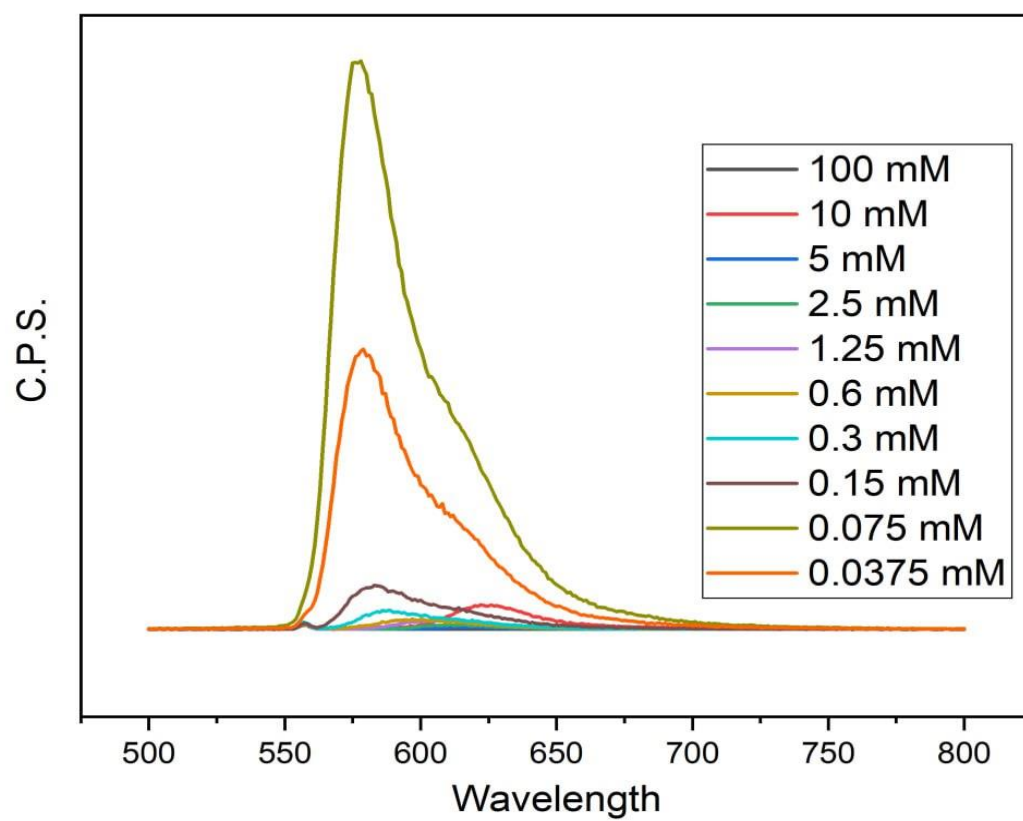


Fig 4.12: Fluorescence emission spectra of RB concentrations.

4.6.2 Effect of Irradiation Time on Fluorescence Intensity

Another condition studied is the effect of time on the rose Bengal, as depicted in fig 4.13 below. As seen, the dye intensity increases initially from 30min to 1hr but decreases as the irradiation time increases. The initial increase in intensity is due to absorption of light energy by the dye molecules which excite it to higher energy state, resulting in the possible formation of high energy intermediates. The intermediates then emit high energy, which is measured as intensity. The decrease in the intensity as time passes is due to photobleaching. This process is due to prolonged exposure of the dye to sunlight, which might lead to decreases in fluorescence intensity of the dye due to degradation or chemical changes of the dye by some reactive oxygen species (ROS). The longer the dye is exposed to sunlight the more this species are produced and the more the dye is degraded.

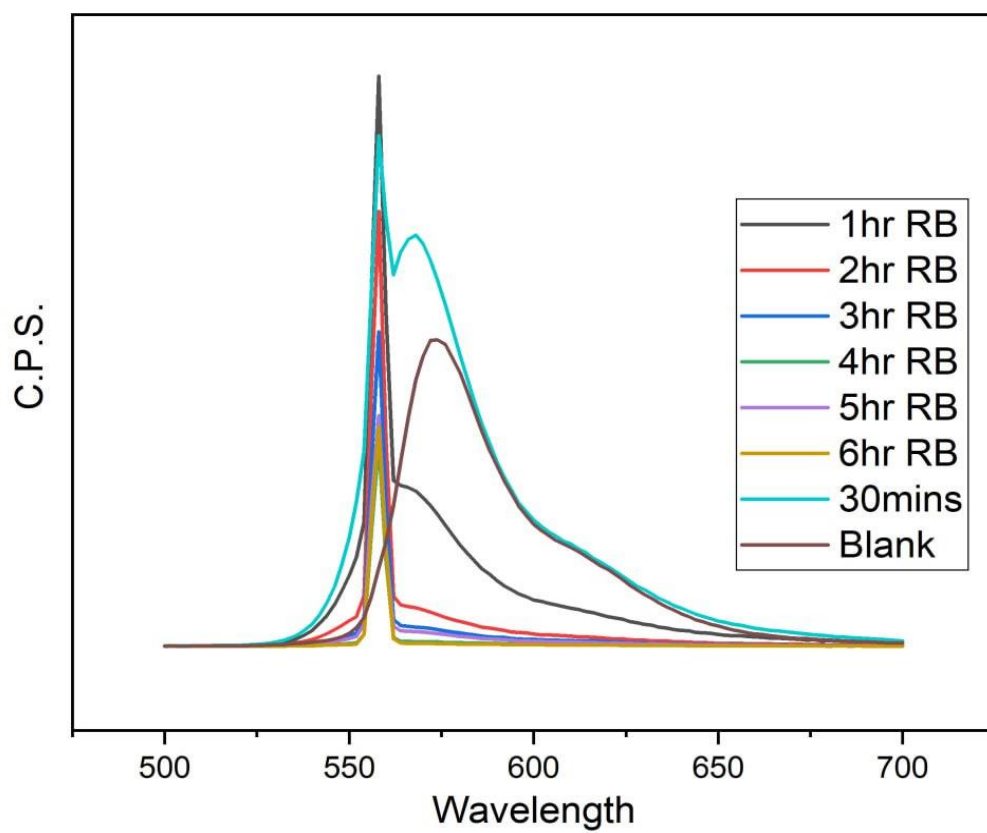


Fig 4.13: Fluorescence emission spectra of RB (0.075mM) in the presence of sunlight

4.6.3 Effect of 2-B3HT on Rose Bengal

As shown in fig 4.14, the effect of 2-bromo-3-hexylthiophene on rose Bengal was conducted. The fluorescence intensity decreases with an increase in the concentration of hexylthiophene. The reduction in the intensity, which is about 4 times the original, is due to the transfer of electrons from the excited Rose Bengal to the quencher, which eventually de-excites the rose Bengal without the emission of intensity. As the amount of 2-B3HT increases, the fluorescence intensity of the dye decreases due to an increase in the thiophene compound's quenching ability.

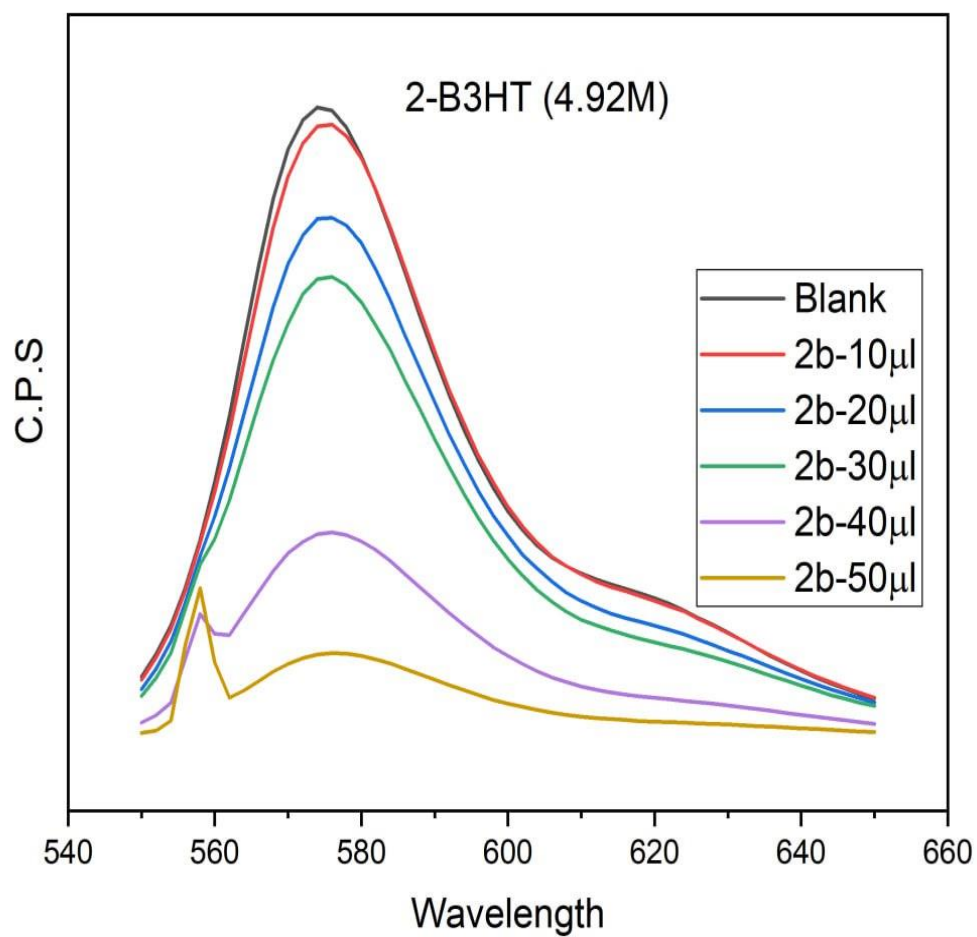


Fig 4.14: Fluorescence emission spectra of RB in the presence of 2-B3HT.

4.6.4 Effect of 2,5-DB3HT on Rose Bengal

The effect of 2,5-dibromo-3-hexylthiophene on Rose Bengal was carried out as shown in fig 4.15. As seen below, the fluorescence intensity of Rose Bengal does not decrease as expected, unlike as shown in Fig 4.14 above. This effect is a result of the presence of two bromine substituents on the thiophene compound, which tends to tamper with the electronic structure of the compound, thereby affecting the quenching ability of the compound towards the excited Rose Bengal. Another possible reason is the steric hindrance due to the bromine groups. The presence of the second bromine group imposes additional steric hindrance onto the compound, thereby affecting the proximity and the orientation of the bromine atoms towards the Rose Bengal, which affects the process of electron transfer.

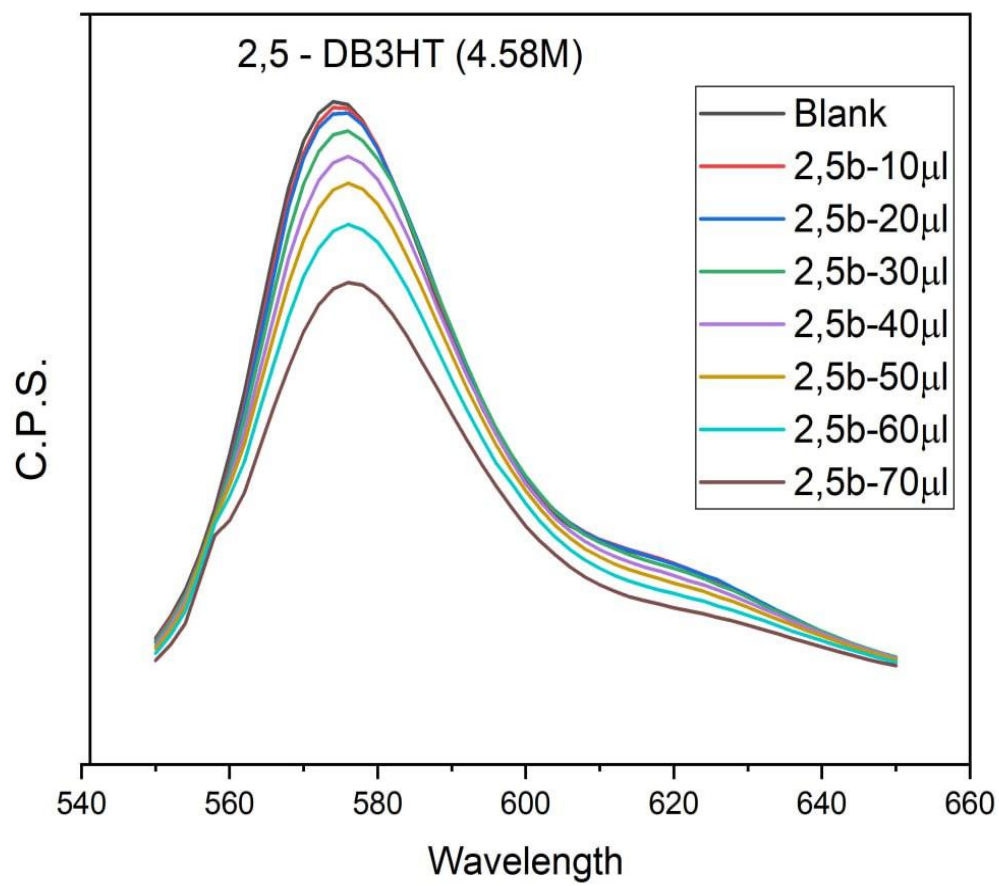


Fig 4.15: Fluorescence emission spectra of RB in the presence of 2,5-DB3HT

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study focused on using solar energy as a means of energy in synthesizing organic compounds using Rose Bengal as the catalyst. The study's objectives involved the investigation of the photocatalytic properties of RB using aryl halides and phenylboronic acid and its derivatives. After which, the catalyst was used in the synthesis of Arylthiophene compounds, which was the main objective of the work.

The coupling of Bromobenzene and Iodobenzene with phenylboronic acid was found to be successful in giving biphenyl with a Conversion of 39% at 1hr of sunlight irradiation using Iodobenzene. In contrast, the reaction with the derivatives of phenylboronic acid was found to proceed to give lower Conversion at some time and in some instances, no reaction was observed due to the electronegativity of the attached group.

After confirming that Rose Bengal can be used as a catalyst, the main objective of the work was experimented on. The work involves the reaction between 2-bromo-3-hexylthiophene and 2,5-dibromo-3-hexylthiophene with phenylboronic acid in sunlight to give 3-hexyl-2-phenylthiophene and 3-hexyl-2,5-diphenylthiophene. Several optimization conditions, such as the effect of time, base, solvent, and catalyst loading, were varied to obtain the maximum Conversion of the product. It was observed that the maximum Conversion was

found to be 86.7 and 82.2% for 3-hexyl-2-phenylthiophene and 3-hexyl-2,5-diphenylthiophene, respectively.

A comparative study was conducted on the efficiency of sunlight compared to an optical fiber illuminator. The reaction conditions used for the optical fiber illuminator are the same as those used during sunlight optimization (Effect of Bases). The result revealed that the reaction using the optical fiber gave the lowest Conversion irrespective of the base used due to lower intensity and photons that drive the reaction faster. Another comparative study was done on different organic dyes (Eosin Y and Methylene blue) under the same conditions as that of the Rose Bengal. It was observed that Rose Bengal gave a better Conversion as compared to the other dyes, which should prove again that Rose Bengal is a better photocatalyst.

5.2 Recommendations

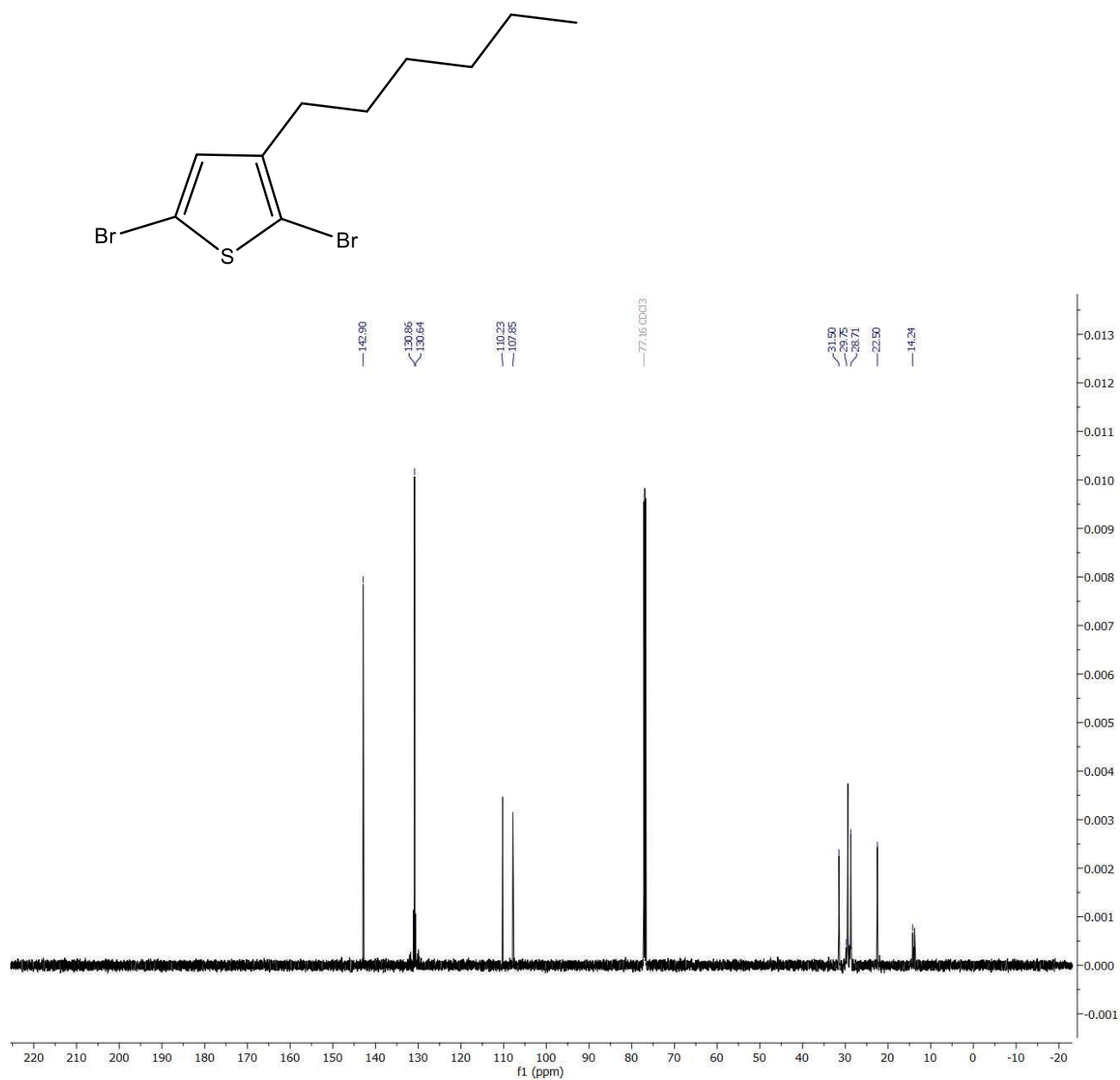
The progress of science strongly depends on recommendations made from experiment studies. From this work, the following are highly recommended.

1. Solar radiation has variability, irreproducibility, and high infrared (IR) content, making it challenging to harness for chemical reactions utilizing visible light.
2. Research in modest, more economical, and resourceful reactor designs is necessary to overcome the current barriers to the implementation of solar photochemistry.
3. Flow chemistry, with its uniform irradiation and integration with solar collectors, offers a promising solution to deliver solar photons to the reaction medium efficiently

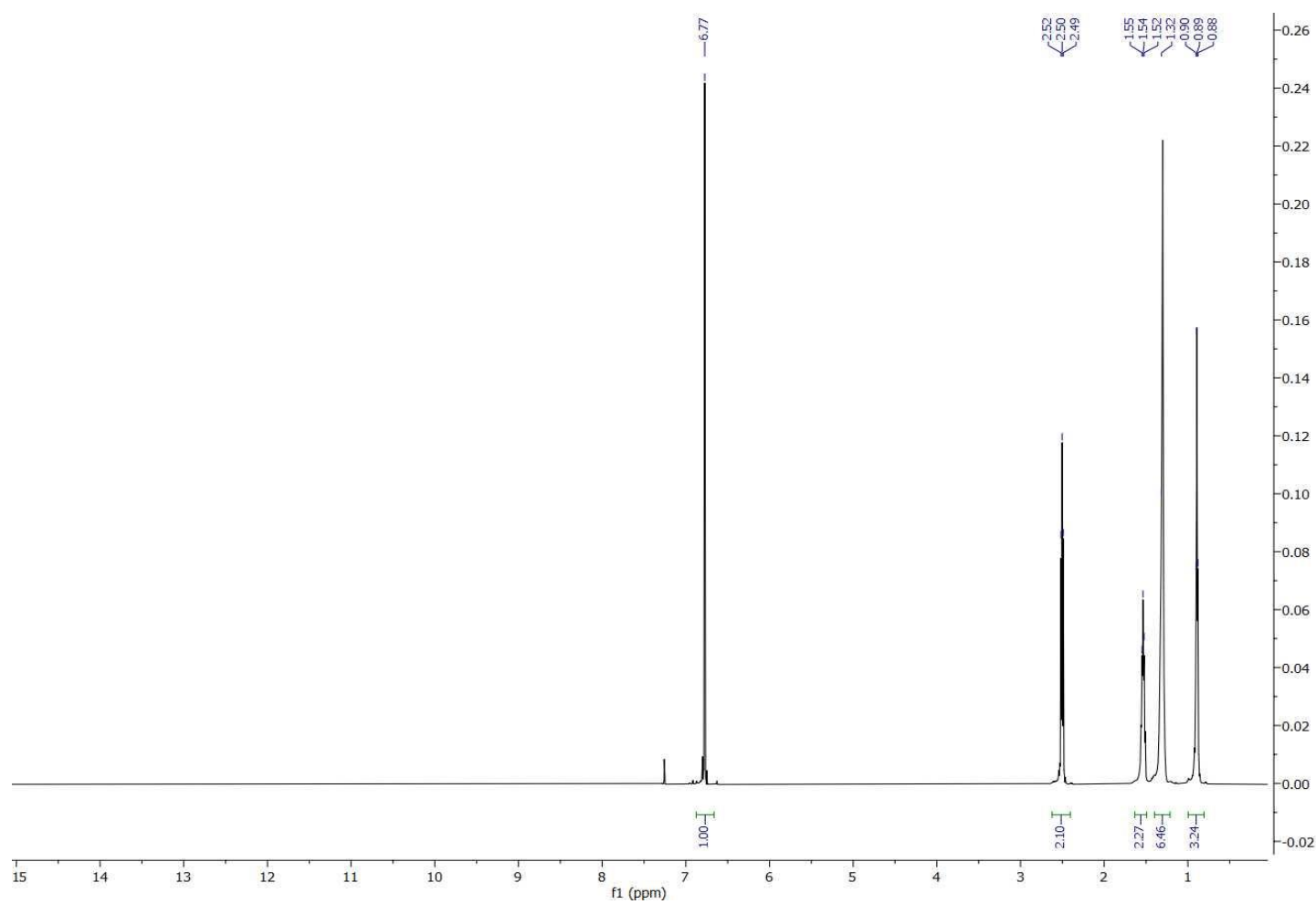
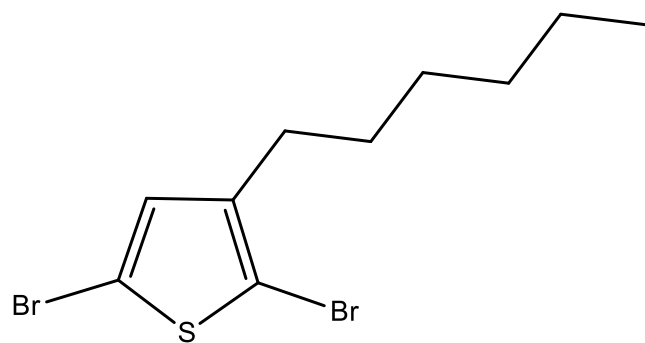
4. Future research should be performed on Rose Bengal towards organic synthesis regarding reuse, recovery, and recycling.
5. Combined organic dyes with metal complexes could be exploited for organic synthesis using visible light as well as Infrared (due to high content of infrared in the sun).

Appendix

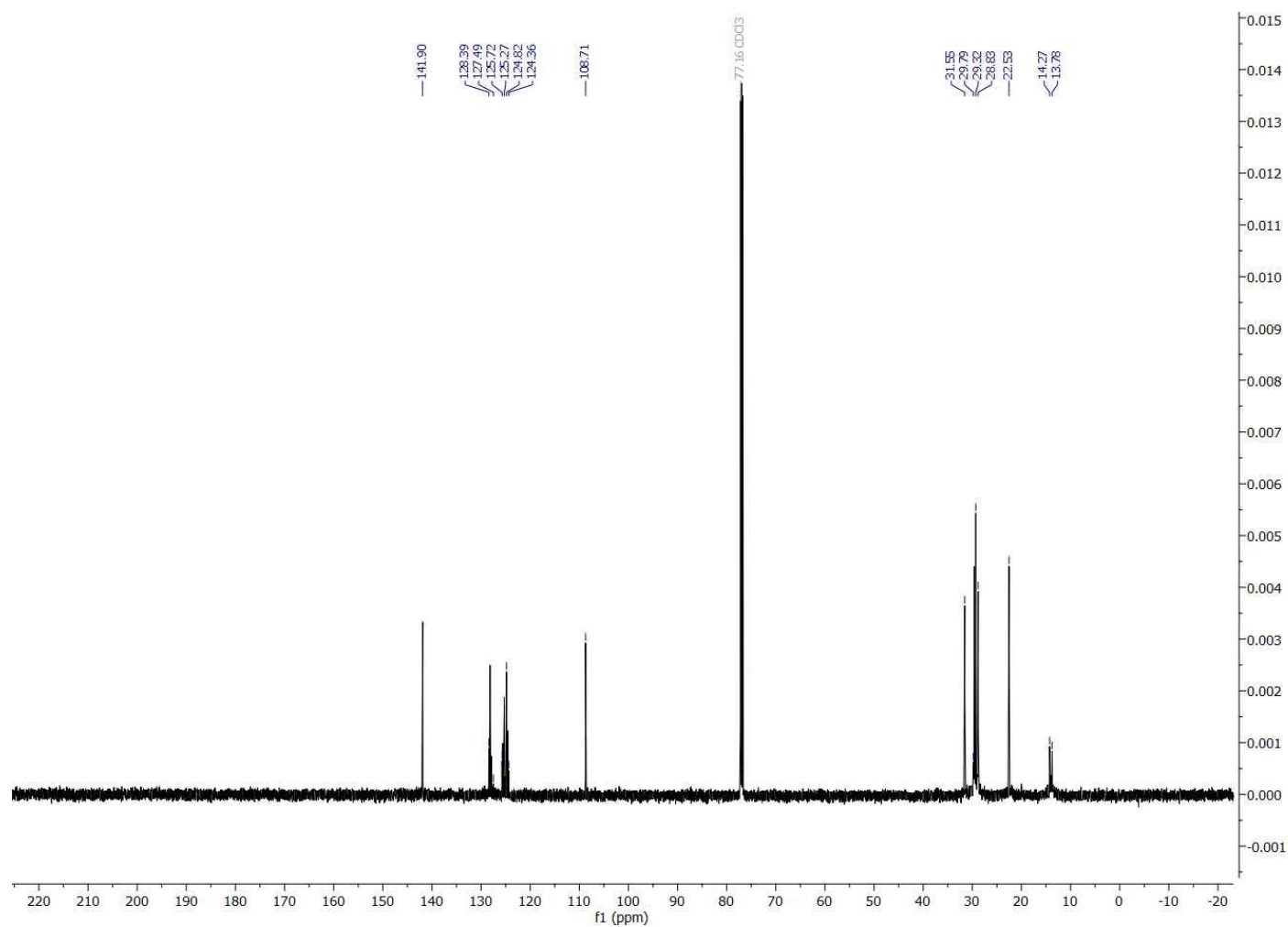
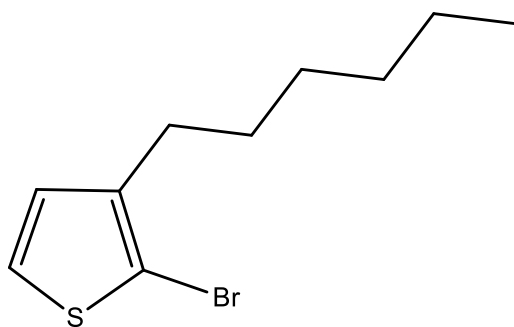
NMR of Starting Materials



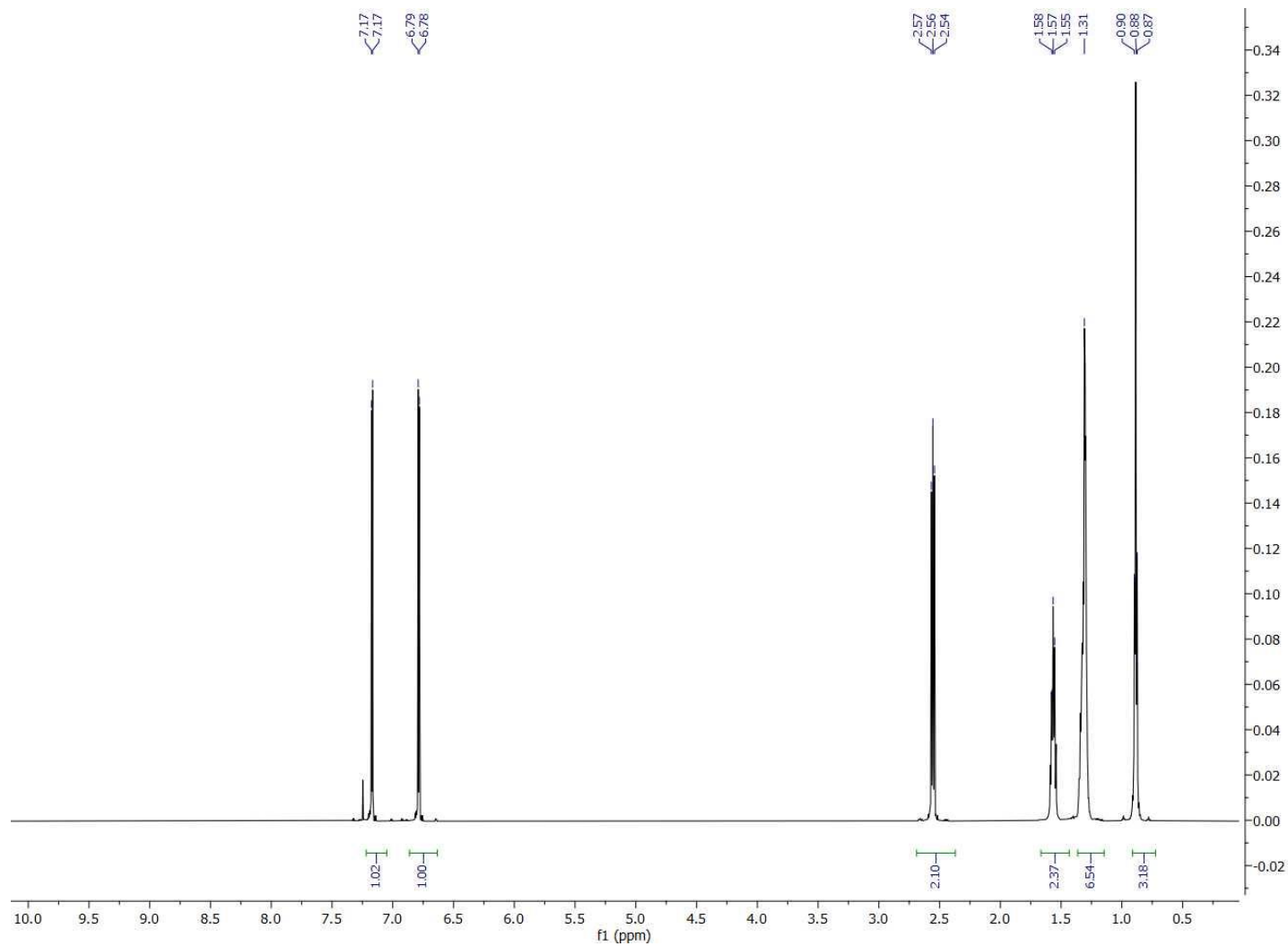
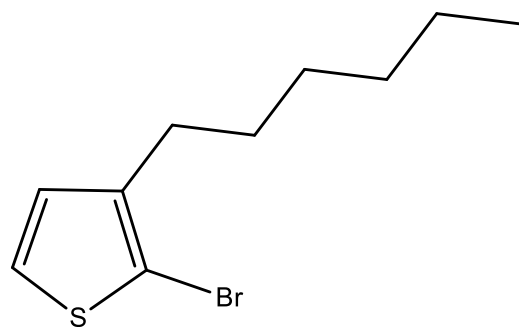
^{13}C NMR of 2,5-dibromo-3-hexylthiophene



¹H NMR of 2,5-dibromo-3-hexylthiophene



^{13}C NMR of 2-bromo-3-hexylthiophene



^1H NMR of 2-bromo-3-hexylthiophene

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