CHAPTER III

RESULTS AND DISCUSSION

3.1 Scope of the investigation

The sequential investigation was carried out as follows.

1. Literature survey on related research
2. Synthesis of diethyl 3,4-dihydroxythiophene-2,5-dicarboxylate **3** by Hinsberg reaction
3. Synthesis of diethyl 3,4-dialkoxythiophene-2,5-dicarboxylates **4** via double nucleophilic substitutions, using diethyl 3,4-dihydroxythiophene-2,5-dicarboxylate **3** as the starting material
4. Synthesis of 3,4-dialkoxythiophene monomer **6**
5. Preparation of dibromothiophene **7** and tetrabromothiophene **8** derivatives from bromination of 3,4-dialkoxythiophene monomer **6**
6. To synthesize poly(3,4-dialkoxythiophene) derivatives from 3,4-dialkoxythiophene monomer **6**, dibromothiophene monomer **7** and tetrabromothiopheme monomer **8** by
    a. Oxidative polymerization
    b. Thermal polymerization
    c. Solid state polymerization (SSP)
7. To study the optical property of polythiophene **9** from both oxidative and thermal polymerization and polythiophene **10** from solid state polymerization

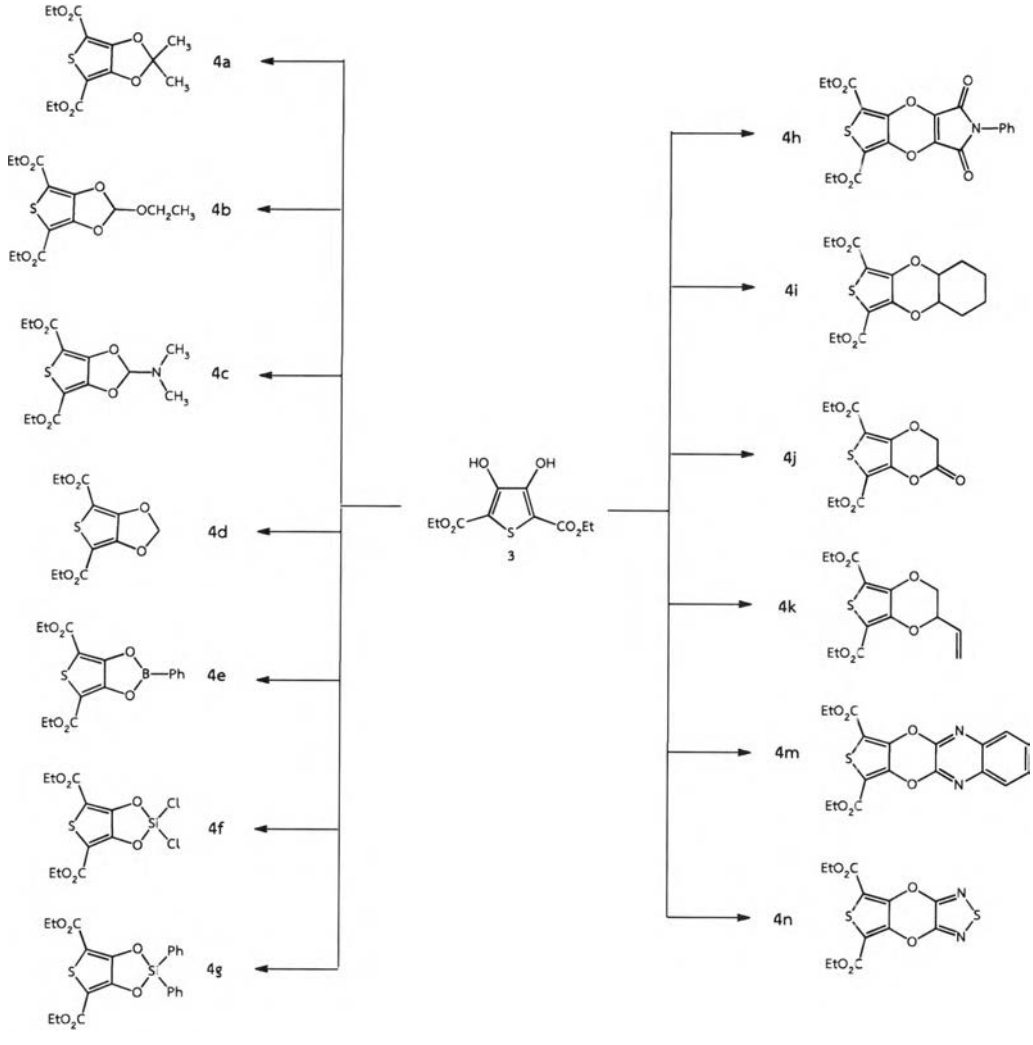
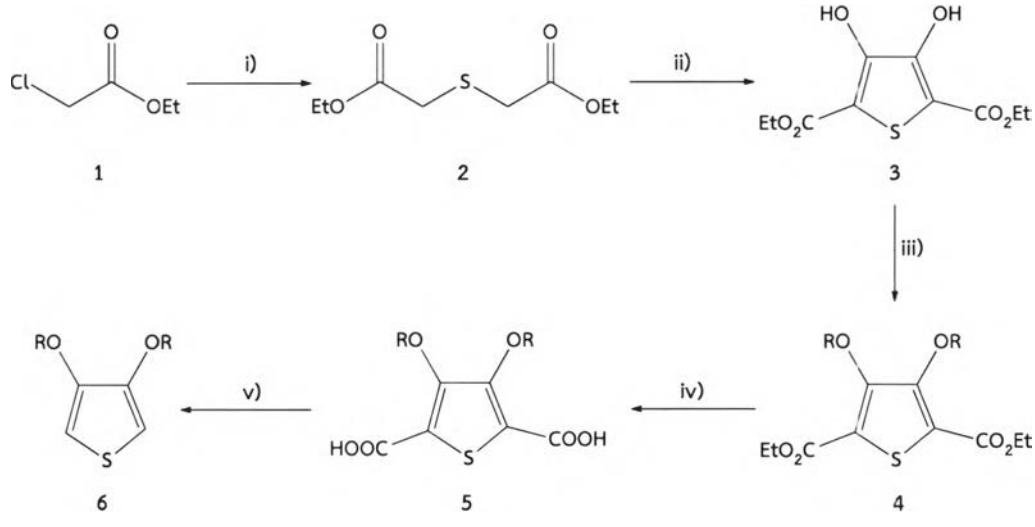


Figure 3.1 Synthesis diagram of diethyl 3,4-dialkoxythiophene-2,5-dicarboxylates **4**

3.2 Monomer synthesis

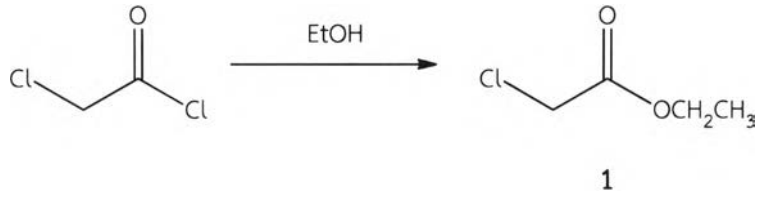
3,4-Dialkoxythiophenes were synthesized according to the double Williamson synthesis of the intermediate 3,4-dihydroxythiophene, as shown in **scheme 3.1**



Scheme 3.1 Reagents and conditions: i) $Na_2S.9H_2O$, acetone, 80 °C, 3 h; ii) NaOEt, 0.5 h, $(CO_2Et)_2$, reflux, 2.5 h, conc. HCl; iii) alkyl halides reagent, reflux; iv) NaOH, EtOH, reflux; v) Cu_2O, quinoline, DMSO, reflux

3.2.1 Ethyl chloroacetate 1

Ethyl chloroacetate was synthesized up to 99% yield from the reaction of chloroacetyl chloride and ethanol through bimolecular nucleophilic acyl substitutions as shown in **scheme 3.2**. Compound **1** was characterized by NMR and IR spectroscopy. ^1H NMR spectrum clearly showed the quartet and triplet signals of the new ethyl group of compound **1** at 4.21 ppm and 1.23 ppm **(Figure A.1, Appendix A)**. ^{13}C NMR spectrum showed the ethyl carbons at 62.2 ppm and 14.1 ppm **(Figure A.2, Appendix A)**. IR spectrum showed the carbonyl group at 1725 cm^{-1} **(Figure A.3, Appendix A).**



1

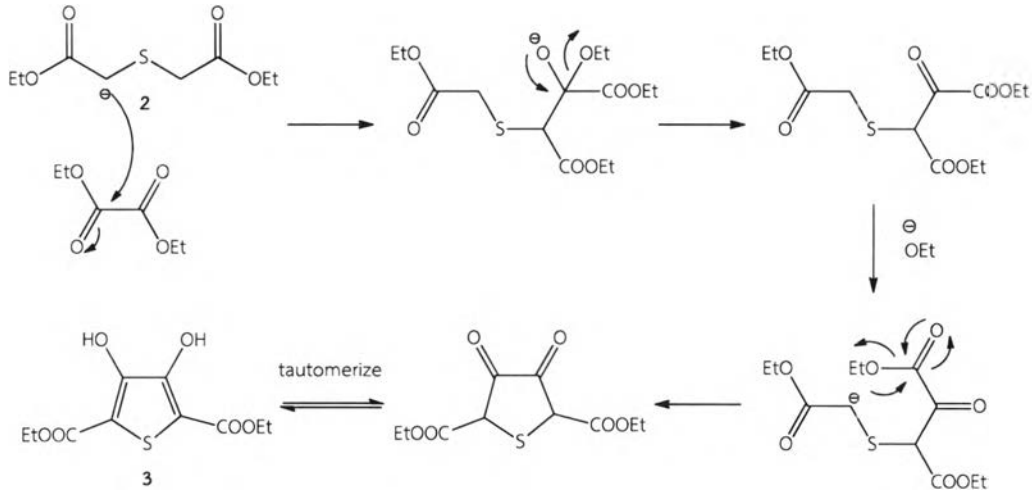
Scheme 3.2 Synthesis of compound **1**

3.2.2 Diethyl thioglycolate 2

Diethyl thioglycolate **2** was prepared as pale yellow liquid in 49% yield. from the reaction of compound **1** and sodium sulfide nonahydrate through double necleophilic substitution reaction **(Scheme 3.1)**. Compound **2** was characterized by NMR, IR and MS spectroscopy. ^{1}H NMR spectrum showed the singlet signal of methylene group at 3.39 ppm and the quartet and triplet signals of ethyl groups at 4.20 ppm and 1.30 ppm respectively **(Figure A.4, Appendix A)**. ^{13}C NMR spectrum appeared the carbonyl carbon at 169.5 ppm **(Figure A.5, Appendix A)**. In IR spectrum showed the carbonyl group band at 1790 cm^{-1} **(Figure A.6, Appendix A)**. The formation of compound **2** was supported by the mass value from MS in positive mode at 229.05 amu $[M+Na]^{+}$ **(Figure A.7, Appendix A).**

3.2.3 Diethyl 3,4-dihydroxythiophene-2,5-dicarboxylate 3

Diethyl 3,4-dihydroxythiophene-2,5-dicarboxylate **3** was made from Hinsberg reaction [47] of compound **2** and diethyl oxalate. The mechanism is the consecutive Claisen condensation reactions to generate a diketone intermediate, which tautomerizes to the dihydroxythiophene **(Scheme 3.3)**.



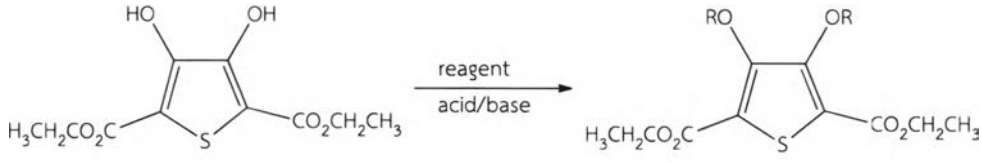
Scheme 3.3 Mechanism of Hinsberg reaction

Compound **3** was obtained as a pale yellow powder in 63% yield. ^{1}H NMR spectrum exhibited the broad singlet of OH at 9.37 ppm **(Figure A.8, Appendix A)**. ^{13}C NMR spectrum exhibited the carbonyl carbon and the two carbons of the thiophene ring at 165.5 ppm, 151.6 ppm and 107.1 ppm respectively. IR spectrum showed very strong broad OH stretching at 3292 cm^{-1} **(Figure A.9, Appendix A).** Mass spectrum indicated the molecular ion peak in the positive mode at 259.02 amu $[M-H]^{+}$ **(Figure A.10, Appendix A).**

3.2.4 Diethyl 3,4-dialkoxythiophene-2,5-dicarboxylates 4

Compound **4** was synthesized through double nucleophilic substitutions of compound **3** and various reagents. The reagents and conditions of the reactions were listed in **table 3.1**

Table 3.1 Various conditions for the synthesis of compound **4**



3 **4**

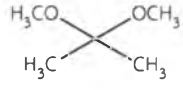
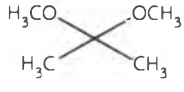
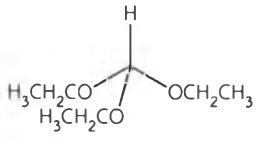
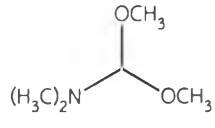
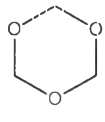
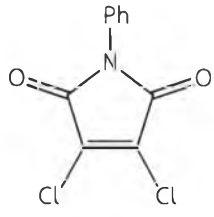
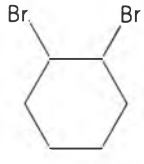
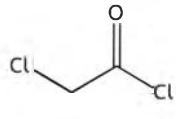
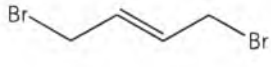
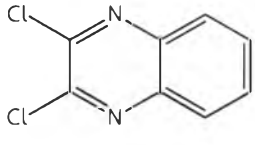
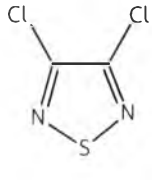
Entry	Reagent (equiv)	Acid/Base (equiv)	Solvent	Expected product[a]	%yield
1	 (1.2)	PTSA (0.2)	Toluene	**4a**	-
2	 (excess)	Sulfuric acid (0.1)	-	**4a**	-
3	 (4.8)	PTSA (0.2)	Toluene	**4b**	-
4	 (1.2)	PTSA (0.2)	Toluene	**4c**	-
5	 (11)	PTSA (0.5)	Toluene	**4d**	-[b]
6	$PhB(OH)_2$ (1)	Sulfuric acid (0.1)	Toluene	**4e**	-[b]
7	$SiCl_4$ (3.3)	-	CH_2Cl_2	**4f**	-[b]

Table 3.1 (Continued)

Entry	Reagent (equiv)	Acid/Base (equiv)	Solvent	Expected product[a]	%yield
8	Ph_2SiCl_2 (4.2)	TEA (5.5)	CH_2Cl_2	**4g**	-[b]
9	 (1.1)	NaH (2.5)	DMF	**4h**	-
10	 (5.5)	TEA (5.5)	ACN	**4i**	-[b]
11	 (2)	TEA (5)	CH_2Cl_2	**4j**	16.7
12	 (1.5)	K_2CO_3 (3), DMAP (0.1)	DMF	**4k**	53.2
13	 (0.25)	NaH (2.5)	NMP	**4m**	61.1
14	 (0.5)	K_2CO_3 (2.5)	DMSO	**4n**	9.4

[a] See **Figure 3.1**

[b] Compound **3** was recovered.

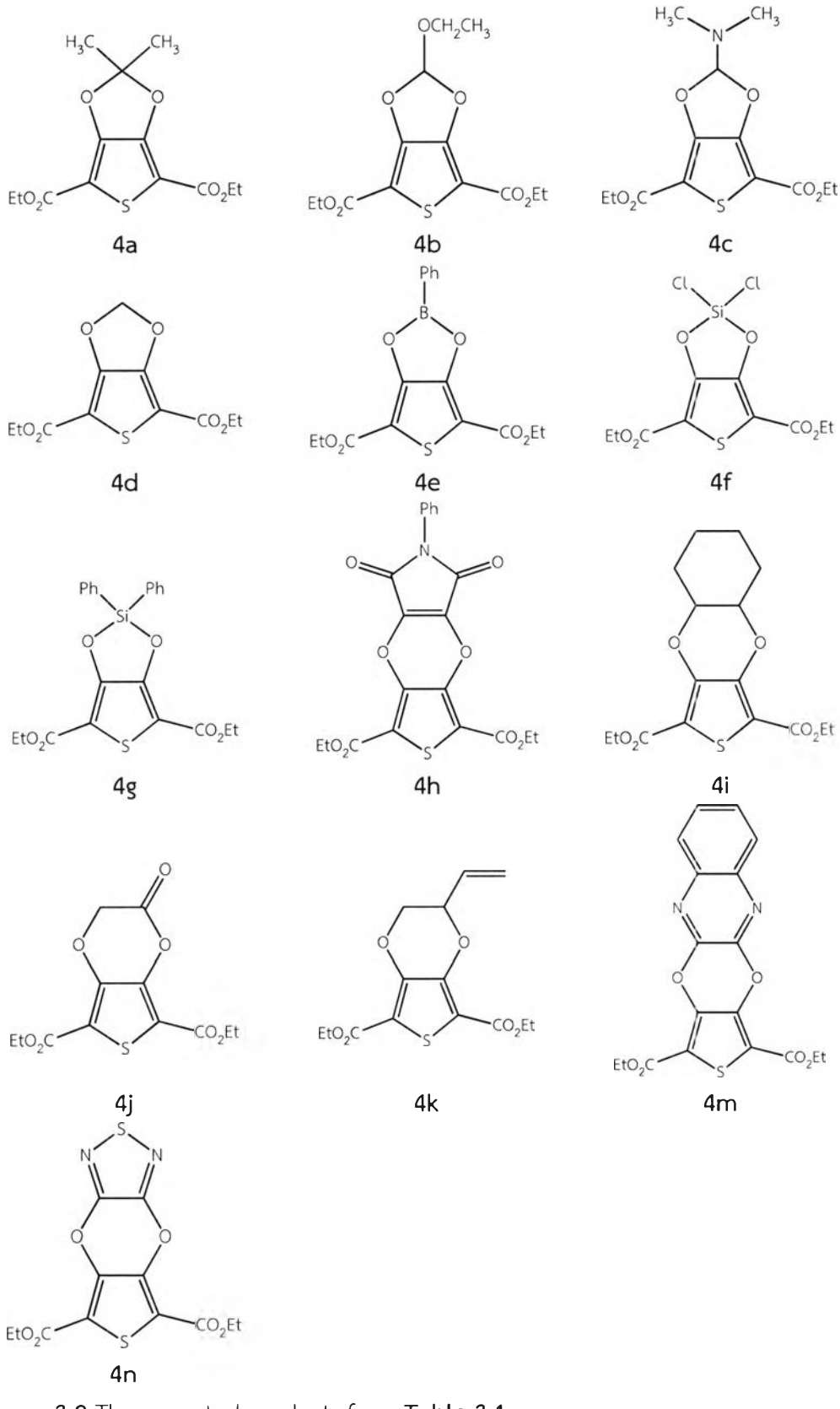


Figure 3.2 The expected products from **Table 3.1**

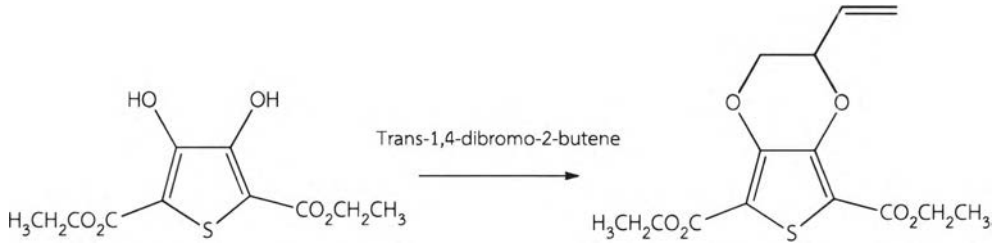
From the **table 3.1, entries 1 and 2**, the reaction did not give the desired product as expected, instead, only condensed side products from the hydrolyzed acetone released from 2,2-dimethoxypropane was detected. It was assumed that compound **3** did not react and decompose in these conditions. In **entries 3 and 4**, the reaction similarly gave unidentified products from side reactions of the reagents. In **entry 5**, compound **3** was recovered together with byproducts from hydroxymethylation reactions of toluene. In **entry 6**, the result also found only the starting material **3**. From these results, it could be concluded that acid is not a suitable catalyst. Compound **3** exhibited poor nucleophilic behavior in acid condition and rather inert.

In **entries 7, 8 and 9**, the silane and dichloroimide reagents seemed to react with compound **3**, but the expected product **4f, 4g** and **4h** were probably not stable during workup process, and were assumed to convert back to the starting material **3**. In **entry 10**, compound **3** did react with the reagent but too many products were observed and could not be isolated and identified.

Compound **4j** was prepared as white powder in 16.7% **(Entry 11)**. A part of compound **4j** may be lost during column chromatography purification. Identification of the compound **4j** was achieved through NMR, IR and MS. In ^{1}H NMR spectrum, the hydrogen signal of OH of compound **3** was absent and appeared the new singlet signal of methyl group at ethylene bridge **(Figure A.12, Appendix A)**. In the ^{13}C NMR, the carbonyl carbon and the methyl carbon at ethylene bridge appeared at 170.8 ppm and 60.2 ppm respectively **(Figure A.13, Appendix A)**. IR spectrum exhibited no strong broad band of -OH group at 3293 cm^{-1} **(Figure A.14, Appendix A)**. In the mass spectrum, the molecular ion peak appears in the positive mode at 324.09 $[M+Na]^{+}$ **(Figure A.15, Appendix A)**. Unfortunately, compound **4j** was not stable at room temperature and slowly converted back to the starting material **3**.

In **table 3.1 entry 12,** the desired product **4k** was synthesized in good yield **(Table 3.2, Entries 3 and 4)** through double nucleophilic substitutions using compound **3**, trans-1,4-dibromo-2-butene and base.

Table 3.2 Various conditions for the synthesis of compound **4k**



3 **4k**

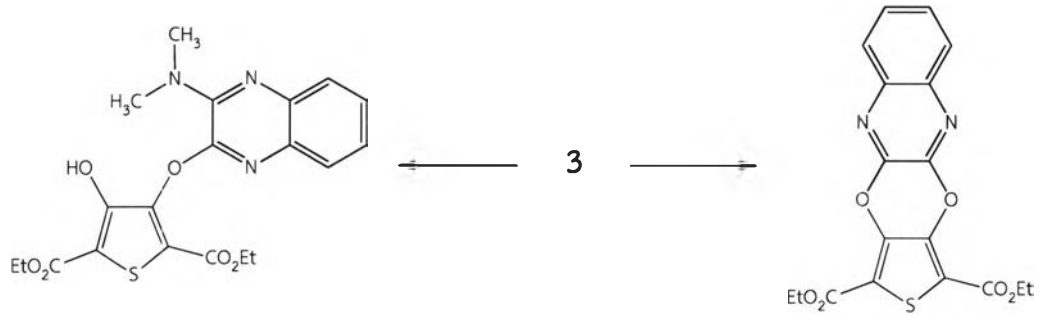
Entry	Trans-1,4-dibromo-2-butene (equiv.)	Base (3 equiv.)	Time (h)	Product (%yield)
1	1.7	TEA	3	12.5
2	1.5	K_2CO_3	3	58.2
3	1.5	K_2CO_3*	1	53.2

*added DMAP 0.1 equiv.

From **table 3.2 (Entry 1)**, it could be seen that TEA was a poor choice of base to make compound **4k**. Changing the base to K_2CO_3 improved the yield of compound **4k** dramatically. An addition of DMAP has helped the rate of the reaction, with small effect on the yield. ^1H NMR spectrum of **4k** was characterized by the appearance of a multiplet signal at 5.87 ppm and the doublet signals at 5.54 and 5.39 ppm assigned to the vinyl group **(Figure A.16, Appendix A)**. The vinyl carbon appeared at 130.5 and 120.4 ppm in ^{13}C NMR spectrum **(Figure A.17, Appendix A)**. IR spectrum showed no strong broad band of -OH group at 3293 cm^{-1} **(Figure A.18, Appendix A)**. The mass spectrum of compound **4k** showed the molecular ion peak $[M+Na]^+$ at m/z 335.27 **(Figure A.19, Appendix A)**.

Compound **4m (Table 3.1, Entry 13)** was synthesized from compound **3** and 2,3-dichloroquinoxaline to obtain a pale yellow powder in good yield as shown in **table 3.3.**

Table 3.3 Various conditions for the synthesis of compound **4m**



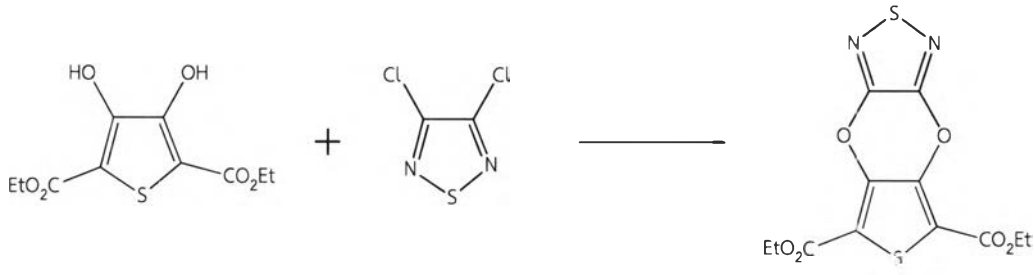
4l **4m**

Entry	2,3-dichloroquinoxaline (equiv.)	Base (equiv.)	Solvent	Time (h)	Product (%yield)
1	1.1	NaH (5)	THF:DMF (9:1)	49	**4l** (10.0)
2	1.2	K_2CO_3 (5)	DMF	4	**4m** (6.2)
3	0.5	K_2CO_3 (5)	DMF	4	**4m** (16.1)
4	0.25	K_2CO_3 (2.5)	DMF	3	**4m** (27.9)
5	0.25	NaH (2.5)	NMP	3	**4m** (61.1)

In **table 3.3 entry 1,** mixture of solvent (THF:DMF, 9:1) and long reaction time found to yield compound **4l** in 10.0% yield, but did not observe the expected product **4m**. Compound **4l** was assumed to derive from side reaction of DMF and 2,3-dichloroquinoxaline, followed by reaction with compound **3**. **In entries 2-4,** changing the solvent and base lowered the reaction time but still gave the expected product **4m** in poor yield. In **entry 5,** combination of several changes together with decreasing the equivalent of 2,3-dichloroquinoxaline improved the yield to 61.1%. ^{1}H NMR spectrum showed doublet signals of aromatic at 7.92 and 7.68 ppm **(Figure A.23, Appendix A)**. ^{13}C NMR spectrum showed the aromatic carbons at 139.0 and 129.7 ppm **(Figure A.24, Appendix A)**. IR spectrum showed no strong broad band of -OH group at 3295 cm^{-1} **(Figure A.25, Appendix A).** The formation of compound **4m** was supported by the mass value from MS in positive mode at 386.98 $[M+H]^+$ **(Figure A.26, Appendix A)**.

In **table 3.1, entry 14**, the expected product **4n** was synthesized from compound **3** and 3,4-dichloro-1,2,5-thiodiazole in poor yields **(Table 3.4)**.

Table 3.4 Various conditions for the synthesis of compound **4n**



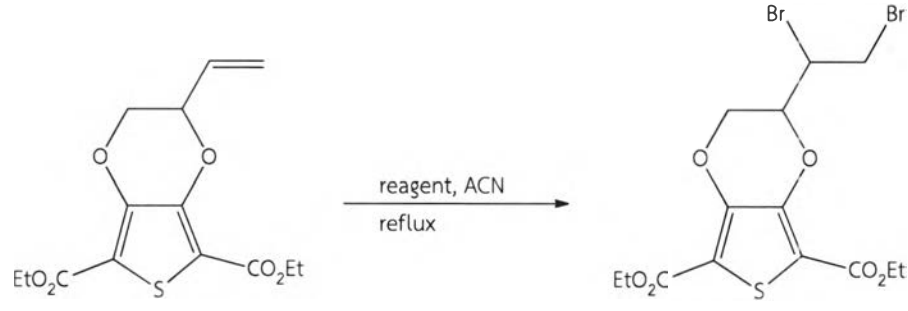
3 **4n**

Entry	3,4-dichloro-1,2,5-thiodiazole (equiv)	Base (2.5 equiv)	Solvent	Time (h)	Product (%yield)
1	1.2	K_2CO_3	DMF	6	1.4
2	0.5	K_2CO_3	DMSO	6	9.4
3	0.25	NaH	NMP	10	3.5

From **table 3.4**, it could be seen that none of the attempts on changing the reaction conditions could improve the yield of the product to a practical level. It is possible that the product not stable during workup and purification processes. The product may decompose back to compound **3** and 1,2,5-thiadiazole-3,4-diol. The unexpected byproduct may be washed away during workup process. The product **4n** was characterized by NMR, IR and MS spectroscopy. ^{1}H NMR spectrum of the product was close to that of the starting material except the absence of the singlet signal of OH group at 9.37 ppm **(Figure A.27, Appendix A)**. ^{13}C NMR spectrum matched well with the expected structure of the compound **4n (Figure A.28, Appendix A)**. IR spectrum showed no strong broad band of -OH group at 3293 cm^{-1} **(Figure A.29, Appendix A)**. In the mass spectrum, the molecular ion peak appeared in the positive mode at 342.96 $[M+H]^+$ **(Figure A.30, Appendix A)**.

In an attempt to demonstrate a downstream functionalifation, compound **4k** was brominated at reflux to provide compound **4p** according to **table 3.5** [50].

Table 3.5 Various conditions for the synthesis of compound **4p**



4k **4p**

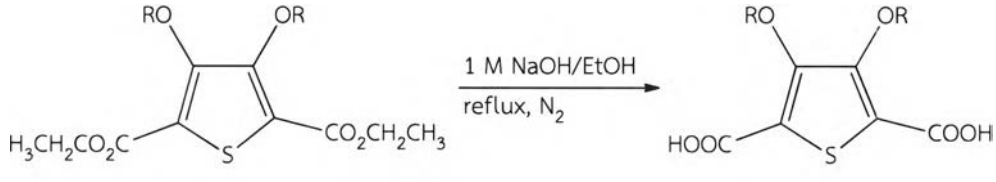
Entry	Reagent (equiv)	Time (h)	Product (%yield)
1	Pyridinium tribromide (1.5)	6	14.5
2	Pyridinium tribromide (3.0)	3	89.4
3	*N*-bromosuccinimide (6.0)	10	54.3

In **table 3.5**, at least 3 equivalents of pyridinium tribromide were needed to complete the reaction and raise the yield to 89.4% **(Entries 1 and 2)**. Changing the reagent to NBS produced lower yield of **4p** even with extended reaction time and higher equivalent **(Entry 3).** In ^{1}H NMR spectrum of compound **4p**, the signals of vinyl group of its precursor **4k** were absent and replace with new multiplet signals at 4.70, 4.66 and 3.93 ppm **(Figure A.31, Appendix A)**. The ^{13}C NMR spectrum matched well with the expected structure of the compound **4p (Figure A.32, Appendix A)**.

3.2.5 3,4-Dialkoxythiophene-2,5-dicarboxylic acid 5

The synthesis of 3,4-dialkoxythiophene-2,5-dicarboxylic acid was outlined in **scheme 3.1** [48]. Compound **5k** was synthesized from hydrolysis of diethylester **4k** to obtain the product in 92.5% yield. The expected dicarboxylic acid product was obtained in pure form after acidification with no further purification needed. The ^{1}H NMR and ^{13}C NMR spectra of the product were quite similar to those of the starting material except the absence of the signals of the ethyl groups **(Figure A.34, A.35, Appendix A)**. IR spectra showed the characteristic strong carbonyl C=O stretching peak and strong broad band of carboxylic O-H stretching **(Figure A.36, Appendix A)**.

Unfortunately, the hydrolysis of diethylester **4m** and **4p** did not obtain the expected products **(5m and 5p)**. Compound **4m** may decompose tc give the diacid **5q** and quinoxaline-2,3-diol during hydrolysis process **(Entry 2)**. The diacid **5q** and quinoxaline-2,3-diol may be lost during workup process.



4 5

Scheme 3.4 Hydrolysis of diethylester derivatives **4**

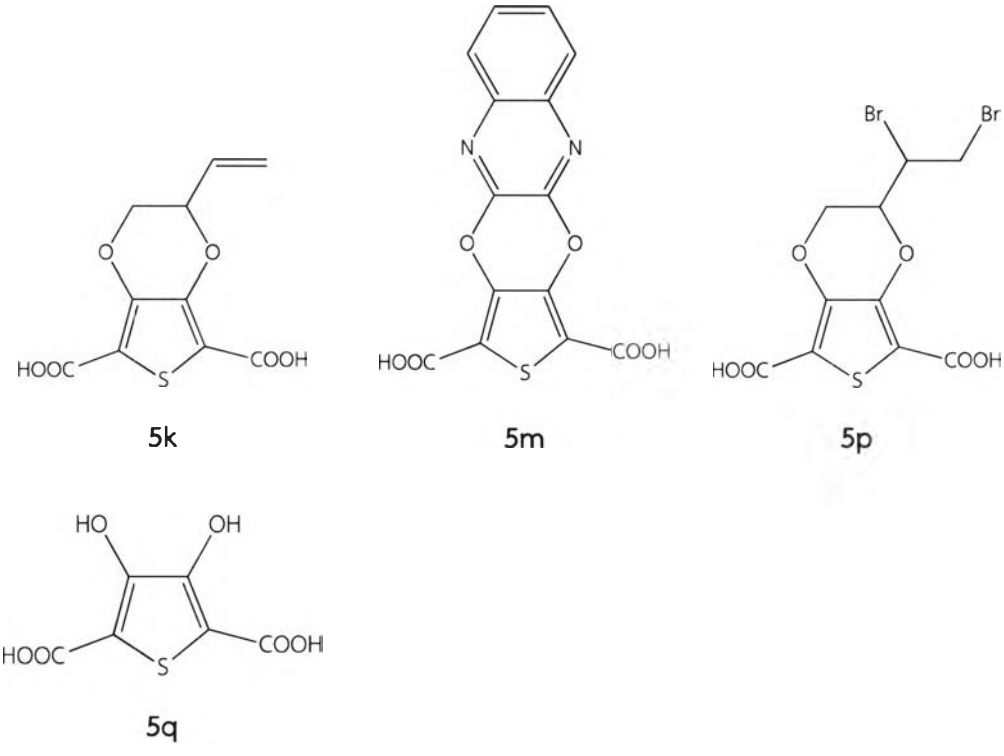
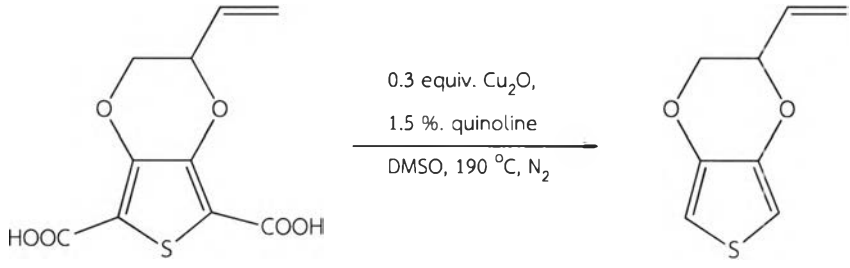


Figure 3.3 Structure of 3,4-diakoxythiophene-2,5-dicarboxylic acid **5**

3.2.6 3,4-Dialkoxythiophene derivative 6

The decarboxylation procedure was modified from existing protocols to minimize the amount of quinoline solvent, that was very hard to eliminate from the obtained product [48, 51]. The 3,4-dialkoxythiophene **6** was prepared through this procedure on 3,4-dialkoxythiophene-2,5-dicarboxylic acid **5** using copper(I) oxide and 1.5% quinoline in DMSO **(Scheme 3.5)**. Compound **5k** was obtained the expected product **6** in 59.5% yield. It was assumed that part of compound **6** may be lost during the repeated aqueous washes the leftover DMSO solvent and column chromatography purification.



5k **6**

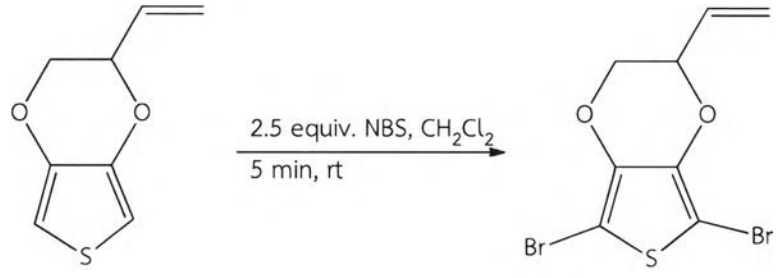
Scheme 3.5 Decarboxylation of the diacid compound **5k**

Compound **6** was structurally confirmed by the presence of the singlet of α-protons of thiophene ring at 6.35 and 6.33 ppm in ^1H NMR spectrum and also the disappearance of the carboxyl functional group signals from both ^1H NMR and ^{13}C NMR spectra **(Figure A.37, A.38, Appendix A)**. The carbonyl stretching peaks were no longer observed in their IR spectrum **(Figure A.39, Appendix A)**.

3.2.7 Brominations of thiophene derivatives

3.2.7.1 5,7-Dibromo-2-vinyl-2,3-dihydrothieno[3,4-b][1,4]dioxin 7

Bromination of thiophene derivatives using *N*-bromosuccinimide (NBS) was modified from the method by Kellogg and coworkers [49]. The synthesis of compound **7** was shown in **scheme 3.6** through bromination of compound **6** obtaining the expected product as pale yellow liquid in excellent yield (96.0%).



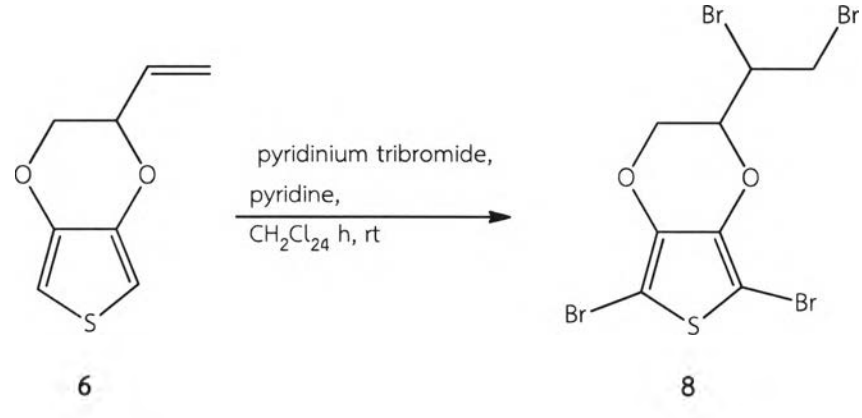
6 **7**

Scheme 3.6 Synthesis of compound **7**

The structure of compound **7** was confirmed by NMR spectroscopy. In ^{1}H NMR, the α-hydrogen signals on the thiophene ring at 6.35 and 6.33 ppm were absent after bromination **(Figure A.40, Appendix A)**. ^{13}C NMR spectrum matched well with the product structure **(Figure A.41, Appendix A)**.

3.2.7.2 5,7-Dibromo-2-(1,2-dibromoethyl)-2,3-dihydrothieno[3,4-b][1,4] dioxin 8

In **scheme 3.7**, pyridinium tribromide was replaced NBS as the brominating reagent on compound **6** [50]. The tetrabromo product **8** was observed as mixture of two stereoisomers, which could be separated by column chromatography to obtain the product **8** in 23.7% yield.

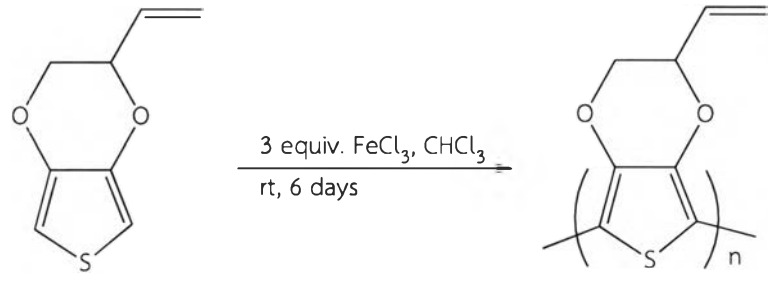


Scheme 3.7 Synthesis of compound **8**

Both isomers of compound **8** were characterized by NMR spectroscopy. In ^{1}H NMR, the α-hydrogen signals on the thiophene ring were absent and new multiplet signals appeared at 4.31, 4.01 and 3.85 ppm in one isomer **(Figure A.43, Appendix A)** and 4.35, 4.09 and 3.84 ppm in another **(Figure A.47, Appendix A)**. The ^{13}C NMR spectrum matched well with the expected structure of compound **8 (Figure A.44, A.48, Appendix A).** Unfortunately, the information is not sufficient to determine the configurations of these stereoisomers.

3.3 Polymer synthesis

3.3.1 Oxidative polymerization of compound 6



6 **9**

Scheme 3.8 Oxidative polymerization of compound **6**

The oxidative polymerization reported by Amou and coworkers [27] was applied on compound **6,** using $FeCl_3$ in chloroform at room temperature for 6 days **(Scheme 3.8)**. It gave a dark blue polythiophene **9** in 72.2% yield after exhaustive wash. Unfortunately the polymer could not be dissolved in any solvents and hence could not be characterized as solution. The polymer was analyzed by IR and UV-Vis spectroscopy. In IR spectrum, the polymer did not show any characteristic peaks that directly related to the structure **(Figure A.51, Appendix A)**. The optical property of **9** measured as pressed solid film, however, showed a characteristic absorption of conjugated polymer at long wavelength in the visible region with a maximum wavelength absorption (λ_{max}) at 552 nm **(Figure 3.5)**.

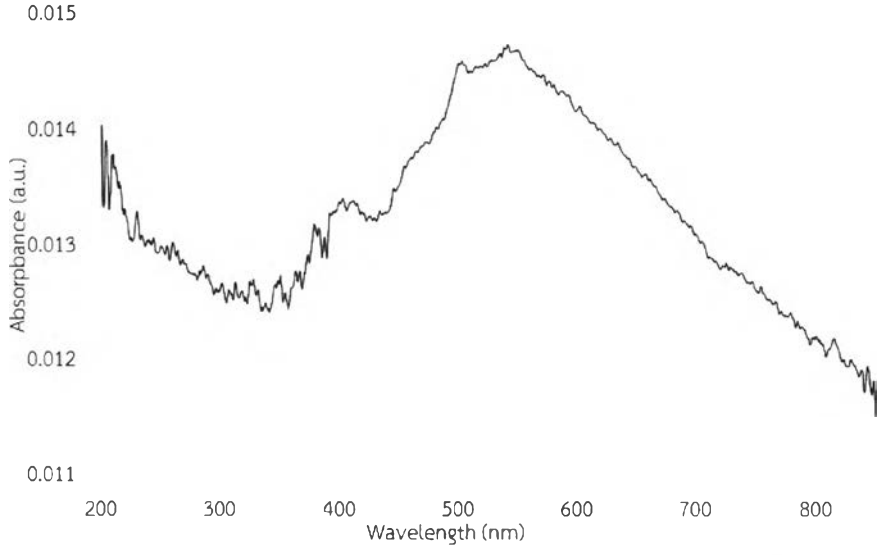
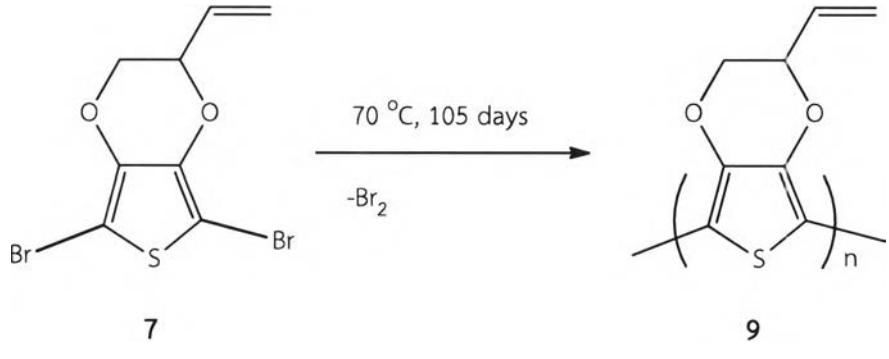


Figure 3.4 UV absorption spectra of solid poly(2-vinyl-2,3-dihydrothieno[3,4-b][1,4] dioxine) **9**

3.3.2 Thermal polymerization of compound 7



Scheme 3.9 Thermal polymerization of compound **7**

Several dibromo derivatives of EDOT have been reported to polymerize thermally in solid state without adding any reagents. This solid state thermal polymerization as reported by Meng and coworkers is the basis for the current attempts to create new polymers using instead the liquid dibromo derivative **7** [35, 36]. Compound **7** was incubated at 70 °C for 105 days and finally gave an insoluble dark polymer **9** in good yield (68.4 %). The polymer was characterized by IR and UV

spectroscopy. IR spectrum showed broad CH stretching at 2924 cm^{-1} and the C=C stretching at 1681 cm^{-1} **(Figure A.52, Appendix A).** The optical property of **9** showed a maximum wavelength absorption (λ_{max}) at 668 nm **(Figure 3.6).** Comparing to previous polymerization, longer conjugation range of polymer was observed in this case.

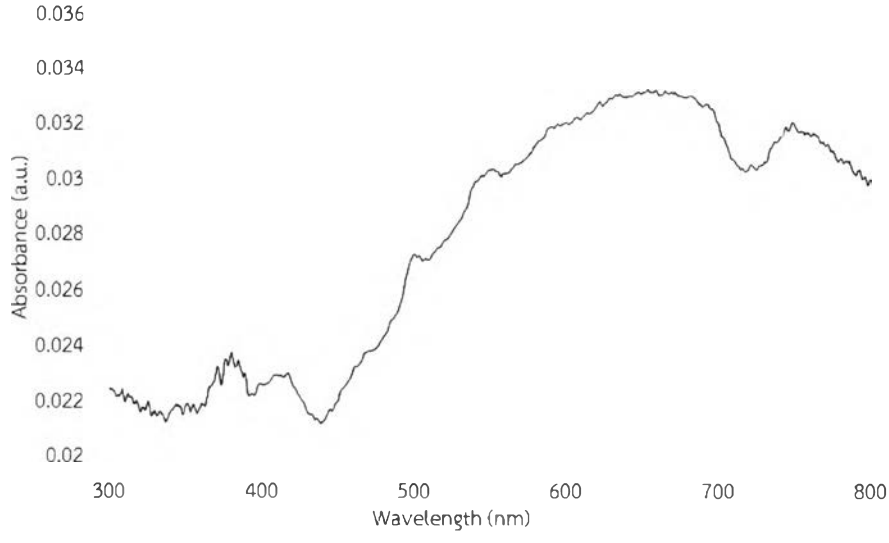
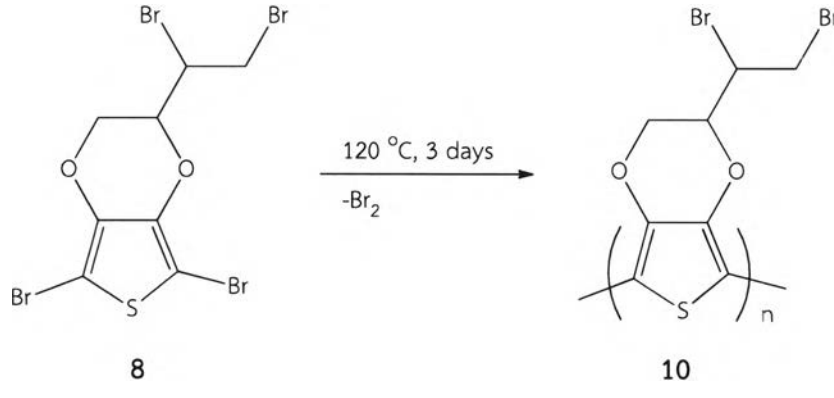


Figure 3.5 UV absorption spectra of solid poly(2-vinyl-2,3-dihydrothieno[3,4-b][1,4] dioxine) **9**

3.3.3 Solid state polymerization of compound 8



8 **10**

Scheme 3.10 Solid state polymerization of compound **8**

The expected polymer **10** was synthesized from tetrabromothiophene derivatives **8** through simple heating at 120 °C for 3 days **(Scheme 3.10)** [35, 36]. During the process, white solid of compound **8** slowly transformed to dark-blue solid of polymer **10** in 45.4% yield. The polymer was insoluble in all common solvents. IR spectrum of **10** did not show any signals characteristic to the product structure **(Figure A.53, Appendix A).** The optical property of polymer **10** showed a maximum wavelength absorption (λ_{max}) at 688 nm, indicating well-ordered highly conjugated polymer structure **(Figure 3.7).**

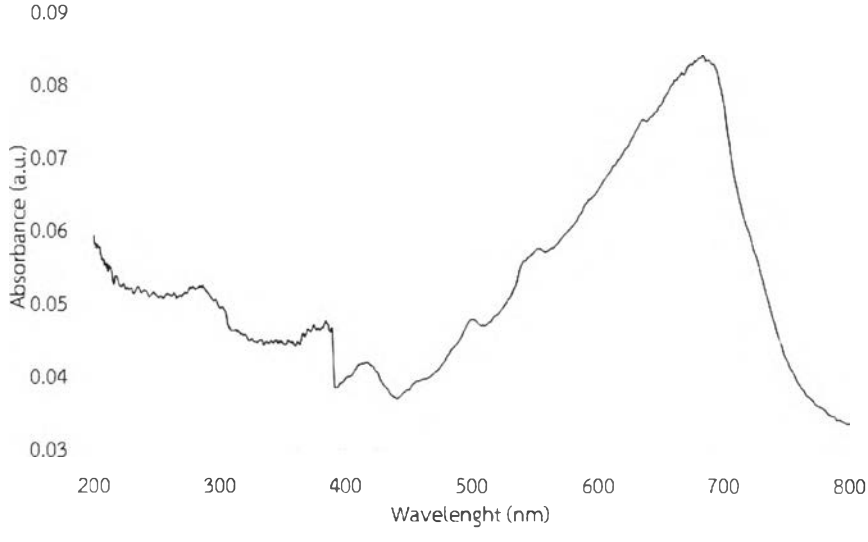


Figure 3.6 UV absorption spectra of solid poly(2-(1,2-dibromoethyl)-2,3-dihydrothieno[3,4-b][1,4]dioxine) **10**