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A novel method for the oxidation of thiophenes. Synthesis of thiophene 1,1-dioxides containing electron-withdrawing substituents

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A novel method for the synthesis of thiophene 1,1-dioxides by oxidation of substituted thiophenes with trifluoroperoxyacetic acid was developed. The effect of the solvent nature on the course of the reaction was studied and optimum conditions for the oxidation of thiophenes containing various functional groups were found. Previously unknown thiophene dioxides were obtained.

Key words: thiophene 1,1-dioxides, trifluoroperoxyacetic acid, thiophenes with electron-withdrawing substituents.

Thiophene 1,1-dioxides are nonaromatic heterocyclic systems that exhibit the properties of conjugated electron-withdrawing dienes. The high reactivities of thiophene 1,1-dioxides have long attracted the attention of chemists; however, their synthetic potential was studied extensively only for a few representatives of this class. For unsubstituted thiophene dioxide and its halogen- and alkyl-containing derivatives, cycloaddition reactions[1—3] and 1,3-dipolar[4] and nucleophilic[5] transformations were investigated. The formation of cyclic and acyclic carbon frameworks in these reactions and the possibility of easily (and often spontaneously) eliminating SO_2 from the reaction products make thiophene dioxides convenient "building" blocks for the creation of various classes of organic compounds. In addition, thiophene dioxides are quite promising as intermediates for the design of up-to-date semiconducting and optical materials; recently, they have been used to create materials with unique optical properties.[6,7]

Although thiophene dioxides[8,9] were first obtained in the beginning of the XX century, there is no route to their derivatives bearing strong electron-withdrawing substituents. However, they are of considerable interest since these compounds constitute a new class of dienes with the extremely low electron density making them highly reactive.

The main approach to the synthesis of thiophene 1,1-dioxides involves oxidation of the corresponding thiophenes with both standard oxidants (*m*-chloroperbenzoic acid[10] hydrogen peroxide in acetic acid[9,10]) and recently discovered strong oxidants such as complex $HOF \cdot CH_3CN$[11] and dimethyldioxirane.[12] However, none of them is capable of oxidizing thiophenes containing electron-withdrawing substituents.

Results and Discussion

The oxidation of thiophenes into thiophene dioxides directly correlates with the electron-donating properties of the starting thiophenes (the higher these properties, the easy the oxidation) and, consequently, with their nucleophilicity. For this reason, we estimated the nucleophilic properties of some substituted thiophenes by quantum-chemical methods. Moreover, the resulting thiophene dioxides should have pronounced electrophilic properties, which can also be easily calculated.

In recent years, the global electrophilicity index ω has been widely used to estimate the reactivity of a chemical compound. This semiempirical parameter reflects the energy effect produced by the transfer of electrons to the LUMO of a molecule under consideration[13] and is calculated by the formula $\omega = \mu^2/2\eta$, where ω is the global electrophilicity, μ is the electronic chemical potential ($\mu = 0.5(E_{\mathrm{HOMO}} + E_{\mathrm{LUMO}})$), and η is the chemical rigidity ($\eta = E_{\mathrm{LUMO}} - E_{\mathrm{HOMO}}$). This parameter considers both the withdrawing and donating properties of the molecule and correlates well with experimental electrophilicity data for various compounds.[14] The parameters and HOMO (for nucleophiles) and LUMO energies (for electrophiles) provide accurate information on the reactivities of the starting thiophenes and the resulting thiophene dioxides. The global electrophilicity parameter was used as a universal estimate of both the electrophilic and nucleophilic properties of various compounds.[14—16]

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Using the DFT method with the PBE 96 functional[17] and the PRIRODA program, we performed a quantum-chemical calculation of the LUMO and HOMO energies and the electrophilicity index (Table 1) for thiophenes and thiophene dioxides, respectively. A variety of substituents in the thiophene ring were investigated; calculations were performed both for already known thiophene dioxides and their precursors and for thiophenes that could not be oxidized earlier. Our calculated data revealed a dependence of the electrophilicity indices on the nature of the substituents in the thiophene ring.

It is easy to see that introduction of any electron-withdrawing substituents makes the starting thiophenes substantially less nucleophilic. The HOMO energy is especially strongly reduced (and, in contrast, the electrophilicity index is increased) for mesomeric acceptors. For instance, replacement of a methyl group in 2,5-dimethylthiophene by a methylsulfonyl one reduces the HOMO energy by 1.01 eV and increases the electrophilicity by 1.03 eV and, consequently, diminishes the nucleophilic properties of the molecule. In turn, introduction of two and more strong acceptor groups makes thiophenes inert toward known oxidants. For instance, the difference between the HOMO energies of tetrachlorothiophene and 2-chloro-5-nitrothiophene is about 0.74 eV, while the electrophilicity index of the starting thiophenes is increased by nearly 2.5 eV. The oxidation reactions of the former were studied extensively and are known to smoothly yield the corresponding dioxide,[18] while the latter has not been oxidized to date. The electrophilicities of the corresponding thiophene dioxides increase as well; introduction of electron-withdrawing substituents makes them, according to the calculated data, very reactive electrophiles. This can be illustrated with 2,5-dimethylthiophene dioxide[10] and tetrachlorothiophene dioxide with the well-known reactivity.[18] For instance, the former reacts only with strong dienophiles such as dimethyl acetylenedicarboxylate under drastic conditions (elevated

Table 1. Calculated HOMO and LUMO energies (eV) and global electrophilicity indices ω (eV) for thiophenes and thiophene dioxides

Substituent	Thiophene			Thiophene dioxide		
	E_{HOMO}	E_{LUMO}	ω	E_{HOMO}	E_{LUMO}	ω
2,5-Ph$_2$	−5.26	−2.15	2.20	−5.75	−3.44	4.58
2,5-Me$_2$	−5.24	−1.20	1.28	−6.02	−2.94	3.26
H	−5.87	−1.39	0.68	−6.62	−3.51	4.12
2,5-Cl$_2$	−5.72	−1.97	1.97	−6.37	−3.66	4.64
2,5-Br$_2$	−5.69	−2.00	2.00	−6.29	−3.66	4.71
2,4-Br$_2$	−5.88	−2.01	2.01	−6.55	−3.75	4.73
2,3,5-Br$_3$	−5.80	−2.28	2.32	−6.34	−3.76	4.94
3-Br-2,5-Cl$_2$	−5.83	−2.18	2.19	−6.41	−3.77	4.91
2-SO$_2$Me-5-Me	−6.25	−2.30	2.31	−6.82	−3.82	4.73
2,3,4,5-Cl$_4$	−5.93	−2.31	2.35	−6.45	−3.85	5.10
2-COOEt-5-Me	−5.86	−2.32	2.36	−6.48	−3.68	4.61
2-CN-5-Me	−6.16	−2.57	2.65	−6.81	−4.10	5.49
2-Cl-5-SO$_2$Me	−6.40	−2.63	2.70	−6.95	−4.14	5.48
2-Br-5-SO$_2$Me	−6.35	−2.64	2.72	−6.88	−4.13	5.52
2,3,4,5-Br$_4$	−5.87	−2.60	2.74	−6.32	−3.82	5.15
2-Cl-5-COOMe	−6.08	−2.68	2.82	−6.68	−4.03	5.42
2-Br-5-COOMe	−6.05	−2.69	2.84	−6.62	−4.03	5.47
2,5-Cl$_2$-3-COOH	−6.07	−2.76	2.94	−6.64	−4.15	5.84
2,4-(SO$_2$Me)$_2$	−7.05	−2.95	3.05	−7.48	−4.55	6.16
2,5-(COOEt)$_2$	−6.37	−3.04	3.33	−6.85	−4.26	5.97
2,5-(SO$_2$Me)$_2$	−7.06	−3.16	3.35	−7.44	−4.56	6.24
2-SO$_2$Me-5-COOEt	−6.74	−3.13	3.38	−7.12	−4.42	6.16
3,4-Cl$_2$-2,5-(SO$_2$Me)$_2$	−6.95	−3.29	3.58	−7.40	−4.63	6.54
2,4-(CN)$_2$	−7.08	−3.43	3.78	−7.67	−5.08	7.85
2,5-(COOH)$_2$	−6.75	−3.41	3.86	−7.23	−4.63	6.75
2-NO$_2$-5-Me	−6.50	−3.52	4.22	−7.11	−4.50	6.45
2,5-(CN)$_2$	−7.01	−3.74	4.43	−7.55	−5.14	8.33
2,5-Cl$_2$-3-NO$_2$	−6.46	−3.72	4.71	−7.02	−4.72	7.48
2-Cl-5-NO$_2$	−6.67	−3.82	4.82	−7.24	−4.77	7.28
2,4-(NO$_2$)$_2$	−7.41	−4.31	5.53	−7.85	−5.47	9.31
2,5-(NO$_2$)$_2$	−7.49	−4.74	6.79	−7.82	−5.62	10.29

temperature and pressure). The latter is known to enter into the Diels—Alder reaction with many dienophiles. The calculated data agree fully with the observed reactivity: the LUMO energies of these thiophene dioxides differ by *ca.* 0.91 eV, while the difference between their electrophilicity indices reaches 1.84 eV. On the whole, our calculated data (see Table 1) predict a dramatic change in the nucleophilic properties of the starting thiophenes (HOMO energy difference is 0.69 eV and the electrophilicity index difference is nearly 1.07 eV) and a jump in the electrophilic properties of thiophene dioxides (LUMO energy difference is 0.91 eV and the electrophilicity index difference is nearly 1.84 eV).

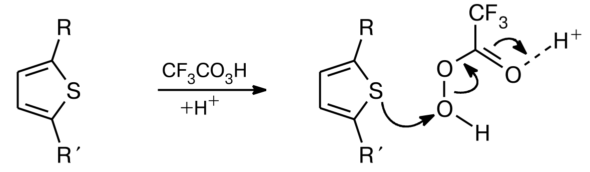
These data explain why it is difficult or impossible to oxidize the known thiophenes containing electron-withdrawing substituents.

Previously,[19] we developed a method for high-yielding oxidation of a sulfur atom in electron-deficient molecules. In the study of sulfur-containing alkenes with strong electron-withdrawing groups, we found that the electron-deficient sulfur atom can be oxidized with trifluoroperacetic acid in anhydrous media. In further investigations, this oxidative system was successfully used to obtain various thiophene dioxides. For instance, thiophenes containing halogen atoms and a methylsulfonyl or ethoxycarbonyl group can be oxidized with trifluoroperacetic acid in acetonitrile in high yields.[20] A solution of trifluoroperacetic acid in acetonitrile was prepared by dropwise addition of trifluoroacetic anhydride to a solution of highly concentrated (95—98%) H_2O_2 in acetonitrile; then, a solution of a substituted thiophene in acetonitrile was added. The molar ratio between the reagents was determined experimentally: thiophene : H_2O_2 : trifluoroacetic anhydride = 1 : 3 : 3.

To study the oxidation of thiophenes containing various substituents and determine the limits of application of the proposed method, we oxidized 2,5-dimethyl- and 2,4-diphenylthiophenes (previously, they were converted into dioxides by oxidation of the corresponding thiophenes with MCPBA[10] and dimethyldioxirane[12]). It turned out that the yields of the target dioxides in acetonitrile at −20 to 0 °C do not exceed 15%, the reaction being accompanied by strong resinification. A decrease in the temperature and the use of an equimolar reagent ratio were ineffective. However, the reaction in dichloromethane at −20 °C with a reagent ratio of 1 : 1 : 1 afforded 2,5-dimethylthiophene 1,1-dioxide in 51% yield and 2,4-diphenylthiophene 1,1-dioxide in a nearly stoichiometric yield. The reactions were completed in 5 to 10 min. Hence, this oxidative system is highly reactive for thiophenes containing no acceptor groups (especially in acetonitrile, in which highly dissociated trifluoroacetic acid are involved in a number of side reactions such as overoxidation and resinification).

Oxidation of halothiophenes was carried out in several solvents. The reactions in methylene chloride, chloroform, and dichloroethane proceeded very slowly (2—3 days) to give the target thiophene 1,1-dioxides in low yields. No positive effect was reached by using trifluoroacetic acid as a solvent. The reaction was very vigorous and accompanied by strong resinification. Acetonitrile proved to be the most convenient solvent; the oxidation (reagent ratio 1 : 3 : 3) was completed in a few hours to give dioxides in good yields. The exceptions are 2,5- and 2,4-dibromothiophene 1,1-dioxides (52 and 32% yields, respectively); apparently, they partially decompose when isolated and are prone to oligomerization during the oxidation. The same low yields were obtained in the oxidation of these substrates with other known oxidants.[12,20]

Thiophenes containing at least one methylsulfonyl, carboxy, or methoxycarbonyl group were oxidized in acetonitrile very slowly, while thiophenes bearing two and more strong electron-withdrawing groups were not oxidized at all. Better results were obtained in trifluoroacetic acid.



In such a fashion, a series of thiophene dioxides (**10**, **13**, **14**) containing a methylsulfonyl group were synthesized. Compound **10** was structurally characterized by X-ray diffraction analysis (Fig. 1).

In the case of thiophenes with strong electron-withdrawing substituents (nitro and cyano groups) and with more than one sulfonyl groups, the standard molar ratio was used (thiophene : H_2O_2 : trifluoroacetic anhydride = 1 : 3 : 3). However, the reactions of these substrates took several days, which inevitably resulted in the decomposition of the unstable reagent. For this reason, one more

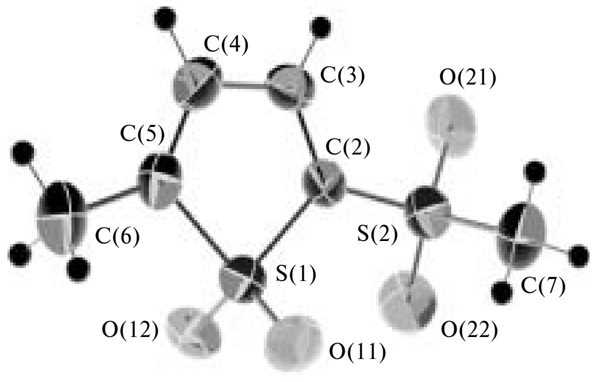
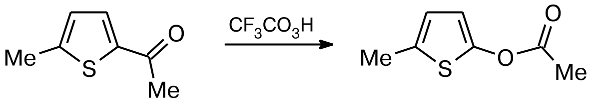


Fig. 1. Crystal structure of compound **10**.

equivalent of the oxidant should be added after 20 to 30 h to ensure the completeness of the conversion. The reagent decomposed at a higher reaction temperature as well. Room temperature was found to be optimum for all oxidation reactions. As a rule, the yields from these reactions are very high. The exceptions are 2,4-bis(methylsulfonyl)thiophene 1,1-dioxide and 5-chloro-2-nitrothiophene 1,1-dioxide. The possible reasons are the low stability of the former (as well as for compound **3**) and the extremely high reactivity for the latter, which reduces its yield upon isolation and purification.

Recrystallization is the sole appropriate technique for the purification of thiophene dioxides. Attempts to isolate any thiophene 1,1-dioxide containing electron-withdrawing substituents by chromatography failed: a single collected fraction contained the unreacted thiophene.

All attempts at oxidizing 2,5-dicyano- and 2,5-dinitrothiophenes were unsuccessful. These thiophenes are the strongest acceptors in the series under study (−3.74 and −4.74 eV for LUMO and 3.78 and 6.79 eV for ω, respectively), remaining virtually unchanged even over 120 h. Nor acetylthiophenes were oxidized. Apparently, the substrates containing an acetyl group in position 2 or 3 undergo the Baeyer—Villiger rearrangement. Further oxidation of the resulting acyloxythiophene with an excess of trifluoroperacetic acid gave destruction products, which is probably due to the high electrophilicity of the reagent.



2,4-Dinitrothiophene was prepared according to a known procedure[21a] and probably contained its 2,5-isomer (see Ref. 21b); therefore, 2,4-dinitrothiophene 1,1-dioxide was isolated as a mixture with 2,5-dinitrothiophene. This mixture could not be separated by recrystallization, while chromatography proved to be destructive for the compound obtained.

In the IR spectra of all the thiophene dioxides obtained, the S=O stretching vibrations appear in the fingerprint range (1350—1310 and 1160—1120 cm^{-1}).

In the ^{1}H NMR spectra of thiophene dioxides, the signals for protons at double bonds are usually shifted downfield by *ca.* 0.1 to 0.3 ppm compared to those for the starting thiophenes. In addition, the chemical shifts and the spin-spin coupling constants for the protons in thiophene dioxides are sometimes analogous to the corresponding data for the starting thiophenes. However, it should be noted that the ^{1}H NMR spectrum of compound **21** contains only one singlet at δ_H 8.33 (Table 2), while the starting thiophene shows two doublets at δ_H 6.94 and 7.74 (J = 4.5 Hz). The ^{13}C NMR spectra of thiophenes and thiophene dioxides usually differ significantly only in the chemical shifts for the C atoms bearing electron-withdrawing groups but remain virtually identical for the hydrogen-bound C atoms. The signals for the SO_2-bound carbon atoms of thiophene dioxide are shifted downfield by 5 to 10 ppm compared to the signals for the corresponding thiophenes.

The bond lengths in thiophene dioxides change by *ca.* 0.04 Å compared to those in the starting thiophenes. For instance, the C=C bond length in compound **10** is 1.33 Å (X-ray diffraction data), which agrees well with the bond lengths in 1,3-dienes.

Thus, we opened a new route to thiophene dioxides containing various (including strong electron-withdrawing) substituents. The corresponding thiophenes are oxidized with trifluoroperacetic acid under mild conditions to give target products in high yields. The course of the reaction significantly depends on the solvent nature. Dichloromethane is the optimum solvent for the synthesis of thiophenes bearing no acceptor groups; thiophenes with electron-withdrawing substituents can be easily oxidized in acetonitrile or trifluoroacetic acid.

Experimental

^{1}H and ^{13}C NMR spectra were recorded on a Varian VXR-400 spectrometer (400 and 100 MHz, respectively) in $CDCl_3$, CD_3CN, and CD_3COCD_3 with $SiMe_4$ as the internal standard. TLC was carried out on Merck 60F_{254} plates; Merck silica gel (63—200 mesh) was used for column chromatography.

Highly concentrated H_2O_2 was prepared from its 50% solution by removal of water *in vacuo*.[22] For the sake of more convenient use and storage, 5 *M* H_2O_2 in acetonitrile and 20% H_2O_2 in trifluoroacetic acid were prepared. All the starting substituted thiophenes were commercially accessible or synthesized according to known procedures, namely, 2,3,5-tribromo-,[23] 2,3,4,5-tetrachloro-,[18] 2,3,4,5-tetrabromo-,[23] 2-methyl-5-methylsulfonyl,-[24] 2-chloro-5-methoxycarbonyl-,[25] 2-bromo-5-methoxycarbonyl-,[26] 2-chloro-5-methylsulfonyl-,[27] 2-bromo-5-methylsulfonyl-,[28] 3-carboxy-2,5-dichloro-,[29] 2,5-bis(methylsulfonyl)-,[30] 2,4-bis(methylsulfonyl)-,[30] 2-ethoxycarbonyl-5-methylsulfonyl-,[31] 2-methylsulfonyl-5-phenylsulfonyl-,[32] 5-chloro-2-nitro-,[21] 2,4-dinitro-,[21a] and 2,4-dicyanothiophenes.[33]

Single crystals of compound **10** were obtained by recrystallization from chloroform. X-ray diffraction analysis was carried out on an Enraf-Nonius CAD4 diffractometer (beta filter, Mo*K*α radiation, λ = 0.71073 Å, 293 K, θ/2θ scan mode). Selected crystallographic parameters and a summary of data collection for compound **10** are given in Table 3. The structure was solved by a combination of the direct method with the Fourier transform. The positions of non-hydrogen atoms were refined by the full-matrix least-squares method in the anisotropic approximation; the positions of hydrogen atoms were calculated in the isotropic approximation. All calculations were performed with the SHELX-97 program package.

Synthesis of thiophene dioxides 1 and 2 (general procedure). Trifluoroacetic anhydride (6.3 g, 30 mmol) was added dropwise to a stirred 5 *M* solution of 95—98% H_2O_2 (6 mL, 30 mmol) in

Table 2. Elemental analysis and spectroscopic data for the compounds obtained

Compound	Found/Calculated (%)		Molecular formula	NMR (δ, *J*/Hz)*	
	C	H		^{1}H	^{13}C
1[10]	—	—	$C_6H_8O_2S$	2.10 (s, 6 H, CH_3); 6.27 (s, 2 H, CH)	—
2[12]	—	—	$C_{16}H_{12}O_2S$	7.25 (s, 1 H, CH); 7.28 (d, 2 H, Ph); 7.29 (s, 1 H, CH); 7.39 (t, 4 H, Ph); 7.63 (d, 4 H, Ph)	—
3	$\underline{17.39}$ 17.54	$\underline{0.77}$ 0.74	$C_4H_2Br_2O_2S$	6.91, 7.08 (both d, 1 H each, CH)	—
4**	$\underline{13.45}$ 13.62	$\underline{0.51}$ 0.39	$C_4HBr_3O_2S$	—	—
5**	$\underline{18.92}$ 18.92	—	$C_4Cl_4O_2S$	—	—
6**	$\underline{11.34}$ 11.13	—	$C_4Br_4O_2S$	—	—
7	$\underline{18.25}$ 18.20	$\underline{0.35}$ 0.38	$C_4HBrCl_2O_2S$	7.11 (s, 2 H)	118.2; 121.5; 128.8; 131.2
8	$\underline{25.95}$ 25.97	$\underline{1.09}$ 1.09	$C_4H_2Cl_2O_2S$	6.72 (s, 2 H)	123.1; 130.8
9	$\underline{17.82}$ 17.54	$\underline{0.43}$ 0.74	$C_4H_2Br_2O_2S$	6.82 (s, 1 H)	128.3; 130.4
10	$\underline{34.80}$ 34.60	$\underline{3.87}$ 3.87	$C_6H_8O_4S_2$	2.25 (s, 3 H, CH_3); 3.25 (c 3 H, SO_2CH_3); 6.52 (m, 1 H, H(3)); 7.50 (d, 1 H, H(4), *J* = 4.6)	10.1 ($\underline{C}H_3$); 44.5 ($SO_2\underline{C}H_3$); 119.6; 138.2; 140.2; 147.1
11	$\underline{30.86}$ 30.84	$\underline{1.55}$ 1.39	$C_6H_5ClO_4S$	3.88 (s, 3 H); 6.98, 7.71 (both d, 1 H each, H(3), H(4), *J* = 8.0)	53.7 ($\underline{C}H_3$) 123.5; 133.8; 137.7; 139.4, 158.2 ($\underline{C}O_2$)
12	$\underline{28.48}$ 28.34	$\underline{2.00}$ 1.99	$C_6H_5BrO_4S$	3.88 (s, 3 H, CH_3); 6.87, 7.61 (both d, 1 H each, H(3), H(4), *J* = 8.0)	54.8 ($\underline{C}H_3$); 124.7; 127.3; 137.8; 140.6; 157.4 ($\underline{C}O_2$)
13	$\underline{26.21}$ 26.26	$\underline{2.27}$ 2.20	$C_5H_5ClO_4S_2$	3.25 (s, 3 H, CH_3); 7.08, 7.70 (both d, 1 H each, H(3), H(4), *J* = 5.0)	45.3 ($\underline{C}H_3$); 123.4; 138.2; 138.9; 140.8
14	$\underline{22.06}$ 21.99	$\underline{1.89}$ 1.85	$C_5H_5BrO_4S_2$	3.25 (s, 3 H, CH_3); 7.25, 7.65 (both d, 1 H each, H(3), H(4), *J* = 5.0)	45.23 ($\underline{C}H_3$); 123.8 ($\underline{C}H$), 127.5; 141.4; 147.0
15	$\underline{30.56}$ 30.48	$\underline{1.17}$ 1.02	$C_5H_2Cl_2O_4S$	7.26 (s, 1 H)	126.6 ($\underline{C}H$); 127.5; 137.0; 136.6; 165.7 ($\underline{C}O_2$)
16	$\underline{26.51}$ 26.46	$\underline{2.87}$ 2.96	$C_6H_8O_6S_3$	3.29 (s, 6 H, CH_3); 7.71 (s, 2 H, H(3), H(4))	45.4 ($\underline{C}H_3$); 134.3; 143.9
17	$\underline{26.48}$ 26.46	$\underline{2.93}$ 2.96	$C_6H_8O_6S_3$	3.14, 3.25 (both s, 3 H each, CH_3); 8.00, 8.47 (both d, 1 H each, H(3), H(5), *J* = 4.0)	44.9; 45.6; 132.3; 138.9; 143.3; 146.1
18	$\underline{35.80}$ 36.08	$\underline{3.87}$ 3.79	$C_8H_{10}O_6S_2$	1.34 (t, 3 H, $C\underline{H_3}CH_2$, *J* = 7.5, 6.8); 3.34 (s, 3 H, $SO_2\underline{C}H_3$); 4.38 (q, 2 H, OCH_2, *J* = 7.5, 6.8); 7.82, 7.90 (both d, 1 H each, H(3), H(4), *J* = 4.5)	14.8 ($\underline{C}H_3CH_2$,); 45.5 ($SO_2\underline{C}H_3$); 64.0 ($O\underline{C}H_2$); 136.0; 137.4; 138.7; 144.6; 158.2 ($\underline{C}$=O)
19	$\underline{39.02}$ 39.51	$\underline{2.95}$ 3.01	$C_{11}H_{10}O_6S_3$	3.32 (s, 3 H, CH_3); 7.73—7.89 m (4 H, Ph,); 8.01, 8.06 (both d, 1 H each, *J* = 4.6, 1.3); 8.08 (m, 1 H, Ph)	45.1 ($\underline{C}H_3$); 129.4; 130.8; 136.0; 136.3; 136.4; 139.8; 144.0; 145.2
20	$\underline{34.22}$ 34.28	$\underline{2.80}$ 2.88	$C_5H_5NO_4S$	2.88 (s, 3 H, CH_3); 8.34 (s, 2 H, CH)	16.3 ($\underline{C}H_3$); 107.6; 124.4; 149.3 ($\underline{C}NO_2$)
21	$\underline{24.41}$ 24.56	$\underline{0.72}$ 1.03	$C_4H_2ClNO_4S$	8.33 (s, 2 H)	137.3; 138.1; 142.1; 146.9
22	$\underline{43.21}$ 43.37	$\underline{1.18}$ 1.21	$C_6H_2N_2O_2S$	7.81, 8.16 (both s, 1 H each, (CH))	111.8; 112.6; 112.8; 136.6; 138.1(C$\underline{C}$N); 140.4 (C$\underline{C}$N)
23	—	—	—	8.40, 8.43 (both s, 1 H each, CH))	—

* The spectra were recorded in $CDCl_3$ (**1—15**, **21—23**), CD_3CN (**16—18**), and acetone-d_6 (**19**, **20**).

** The ^{1}H and ^{13}C NMR spectra are not informative.

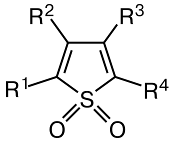
Table 3. Selected crystallographic parameters and a summary of data collection for compound **10**

Parameter	Value
Molecular formula	$C_6H_8O_4S_2$
Molecular mass	208.24
Crystal system	Monoclinic
Space group	$P2_1/n$
a/Å	9.190(2)
b/Å	10.068(2)
c/Å	10.442(3)
β/deg	113.68(2)
V/Å^3	884.8(3)
Z	4
d/g cm^{-3}	1.563
μ/mm^{-1}	0.573
θ_{max}/deg	27.96
Scan range	$2.50° \le \theta \le 27.96°$
Number of independent reflections	1930
Number of reflections with $I \ge 2\sigma(I)$	2027
Number of refined parameters	142
R_1 ($I \ge 2\sigma(I)$)	0.0341
wR_2 (for all reflections)	0.0784

acetonitrile, while maintaining the reaction temperature at −10 °C. The reaction mixture was stirred at ~20 °C for 15 min. The resulting transparent solution was cooled to −20 °C and a solution of a corresponding thiophene (30 mmol) in 10 mL of dichloromethane was carefully added dropwise so that the temperature of the reaction mixture did not exceed −15 °C. The mixture was stirred at this temperature for 10 to 15 min. The course of the reaction was monitored by TLC. Then the mixture was neutralized with sodium bicarbonate and diluted with water. The product was extracted with dichloromethane. The organic layer was separated, dried with sodium sulfate, and evaporated *in vacuo*. The residue was recrystallized from hexane—chloroform (1 : 1).

Synthesis of thiophene dioxides 3—15 in acetonitrile (general procedure). Trifluoroacetic anhydride (6.3 g, 30 mmol) was added dropwise to a stirred 5 *M* solution of 95—98% H_2O_2 (6 mL, 30 mmol) in acetonitrile, while maintaining the reaction temperature at −10 °C. The reaction mixture was stirred at ~20 °C for 15 min and a solution of a corresponding substituted thiophene (10 mmol) in 10 mL of acetonitrile was added. The course of the reaction was monitored by TLC. All highly volatile products were removed in water aspirator vacuum. The residue was separated from traces of trifluoroacetic acid *in vacuo* (oil pump, 1—2 Torr) and recrystallized from hexane—chloroform.

Table 4. Characteristics of the thiophene 1,1-dioxides obtained



Compound	Thiophene 1,1-dioxide				Solvent	Reaction time/h	M.p. /°C	Yield (%)
	R^1	R^2	R^3	R^4				
1	Me	H	H	Me	CH_2Cl_2/MeCN	0.15	88	51
2	Ph	H	Ph	H	CH_2Cl_2/MeCN	0.2	147	98
3	Br	H	Br	H	MeCN	2	96	42
4	Br	H	Br	Br	MeCN	3	118	85
5	Cl	Cl	Cl	Cl	MeCN	2.5	92	92
6	Br	Br	Br	Br	MeCN	2.5	200	84
7	Cl	H	Br	Cl	MeCN	3	62	81
8	Cl	H	H	Cl	MeCN	4	106	76
9	Br	H	H	Br	MeCN	4	126	82
10	Me	H	H	SO_2Me	CF_3COOH	4	145	85
11	Cl	H	H	CO_2Me	CF_3COOH	5	115	77
12	Br	H	H	CO_2Me	CF_3COOH	5	189	80
13	Cl	H	H	SO_2Me	CF_3COOH	6	147	66
14	Br	H	H	SO_2Me	CF_3COOH	6	124	77
15	Cl	H	CO_2H	Cl	CF_3COOH	4	163	80
16	SO_2Me	H	H	SO_2Me	CF_3COOH	48	226227	85
17	H	SO_2Me	H	SO_2Me	CF_3COOH	48	183184	28
18	CO_2Et	H	H	SO_2Me	CF_3COOH	24	143144	51
19	SO_2Ph	H	H	SO_2Me	CF_3COOH	48	176179	88
20	Me	H	H	NO_2	CF_3COOH	48	9396	41
21	Cl	H	H	NO_2	CF_3COOH	72	118 (decomp.)	28
22	H	CN	H	CN	CF_3COOH	120	256	45
23	H	NO_2	H	NO_2	CF_3COOH	120		30*

* Compound **23** was obtained as a mixture with 2,5-dinitrothiophene. The yield of **23** was determined from the integral intensity ratio in the ^{1}H NMR spectrum.

Synthesis of thiophene dioxides 16—23 in trifluoroacetic acid (general procedure). Trifluoroacetic anhydride (10.5 g, 50 mmol) and one to two drops of trifluoroacetic acid as a catalyst were added at −10 °C to a vigorously stirred 95—98% H_2O_2 (1.02 g, 30 mmol). The reaction mixture was stirred for 10 min in an ice bath until it became transparent and homogeneous and then a solution or suspension of a corresponding thiophene (10 mmol) in 10 mL of trifluoroacetic acid was added. The reaction mixture was vigorously stirred in the dark at ~20 °C for 48 to 120 h, depending on the substituent in the thiophene ring (Table 4). The course of the reaction was monitored by TLC. All highly volatile products were removed in water aspirator vacuum. The residue was separated from traces of trifluoroacetic acid *in vacuo* (oil pump, 1—2 Torr) and recrystallized from $CHCl_3$, CH_3CN, or their mixture.

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