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DOI: https://doi.org/10.1080/17415993.2018.1427749

First synthesis of ferrocenyl-substituted thiochalcones and their [4+2]-cycloadditions with acetylenic dienophiles

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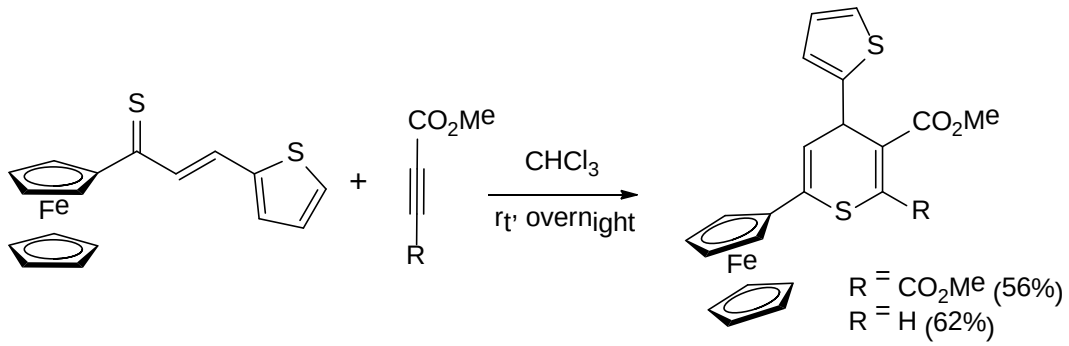
Abstract

Ferrocenyl methyl ketone reacts with aromatic aldehydes yielding 1-ferrocenyl-3-aryl-propenones (chalcones), which upon treatment with Lawesson′s reagent (LR) are converted to the corresponding thiochalcones. The latter enter the thia-Diels-Alder reaction with acetylenic dienophiles (DMAD and methyl propiolate) to give ferrocenyl-substituted 4*H*-thiopyrans. In the case of methyl propiolate, the formation of the six-membered ring occurs with complete regioselectivity.

Graphical abstract



Keywords

Ferrocenyl derivatives, chalcones, thiochalcones, hetero-Diels-Alder reactions, 4*H*-thiopyrans

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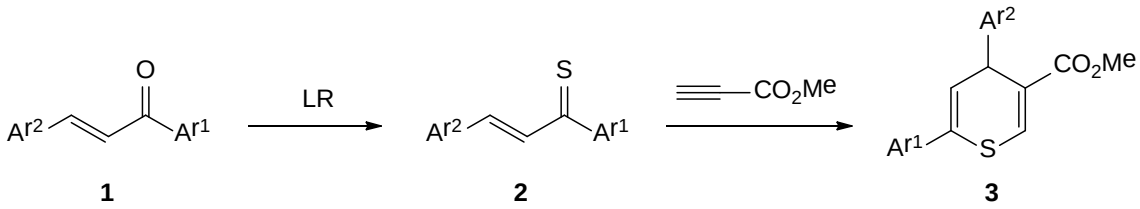
1. Introduction

Thiochalcones **2** are easily available via the typical thionation by treatment of α,β-unsaturated arylketones (chalcones) **1** with Lawesson′s reagent [1]. Spectroscopic studies showed that in solution they exist as an equilibrium mixture of the monomeric and two dimeric forms [2,3]. In contrast to the parent chalcones, they are rarely explored as starting materials for the preparation of more complex organic compounds. The most significant application of thiochalcones comprises the [4+2]-cycloaddition reactions, in which they play the role of active heterodienes. Thus, the thia-Diels-Alder reactions with activated ethenes afford 2,3-dihydrothiopyrans, and an asymmetric version of this reaction is also known [4]. In a very recent publication, asymmetric [4+2]-cycloadditions of thiochalcones acting as heterodienes with in situ generated enantiopure dienamines derived from the (*S*)-prolinol derivatives leading to 2,3-dihydrothiopyrans were reported [5].

In a recent publication we reported that acetylenic dipolarophiles react with thiochalcones **2** (Ar = Aryl or Hetaryl) yielding 4*H*-thiopyrans **3** in good to excellent yields, and in the case of methyl propiolate the reaction occurred with complete regioselectivity [6] (Scheme 1).



1 **2** **3**

Scheme 1. Preparation of thiochalcones **2** and their regioselective hetero-Diels-Alder reactions with methyl propiolate [6].

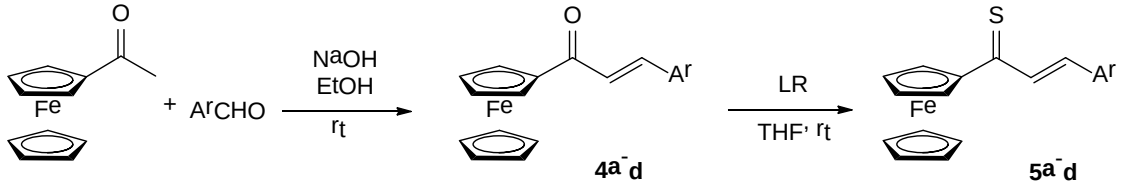
Our recent studies showed that thiochalcones can also act as reactive C=S dipolarophiles towards electron-deficient fluorinated nitrile imines, and the corresponding 1,3,4-thiadiazoles, substituted with a styryl group, are obtained regioselectively in high yields [1].

These reports demonstrated that thiochalcones are very attractive building blocks for the synthesis of diverse sulfur heterocycles. On the other hand, there is a growing interest in ferrocenyl-substituted six-membered sulfur heterocycles [7,8], and in recent decades, the chemistry of ferrocenyl-functionalized compounds has been a research focus [9]. In a very recent review, ferrocene was referred to an exceptional molecule [10]. Diverse functionalizations of ferrocene are summarized in a very recent review [11], and chalcones containing a ferrocenyl moiety at both C(1) or C(3) positions are well known [12,13]. However, their thio-analogues, i.e. the corresponding thiochalcones, have not been reported yet.

The goal of the present study was the first preparation of ferrocenyl-functionalized thiochalcones **5** (Ar = Fc, Ph or Hetar) and their reactions with acetylenic dienophiles aimed at the preparation of the corresponding 4*H*-thiopyrans **6**.

2. Results and Discussion

1-Ferrocenyl-substituted chalcones **4** were prepared from ferrocenyl methyl ketone and the corresponding aldehydes according to the general procedure applied for chalcone synthesis [14]. The obtained products were converted into thiochalcones **5** by treatment with Lawesson′s reagent (LR) in THF at room temperature for 7 min only, and pure compounds **5** were isolated after flash-chromatography. The spectroscopic characterization is limited to IR spectroscopy as the attempted collection of NMR spectra (^{1}H and ^{13}C) was unsuccessful. Unexpectedly, in both cases the spectra of analytically pure samples of thiochalcones **5** showed a strong broadening of the signals with no defined chemical shifts. Along with ferrocenyl/phenyl and ferrocenyl/hetaryl thiochalcones **5a**–**c**, the bisferrocenyl representative **5d** was also obtained in 47% yield as a dark blue colored solid (Scheme 2).

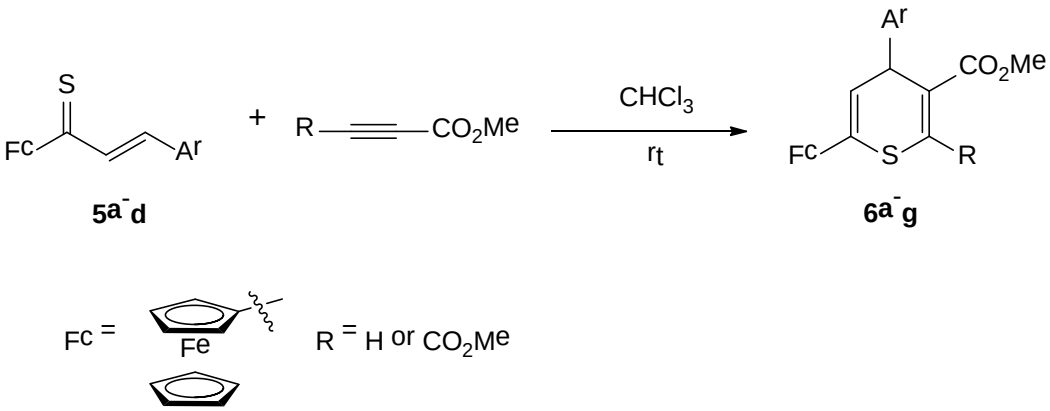


a Ar = Ph, **b** Ar = Furan-2-yl, **c** Ar = Thiophen-2-yl, **d** Ar = Ferrocenyl (Fc)

Scheme 2. Synthesis of 1-ferrocenyl-substituted thiochalcones **5**.

However, it is worth mentioning that the attempted synthesis of isomeric thiochalcones with exchanged location of the Ar (at C(1)) and Fc (at C(3)) groups was unsuccessful, and after treatment of the corresponding chalcones, isomeric with **4,** with LR, only mixtures of non-identified decomposition products were formed.

The freshly prepared thiochalcones **5** were used for thia-Diels-Alder reactions with dimethyl acetylenedicarboxylate (DMAD) and methyl propiolate, respectively. In the test experiment, **5a** was reacted with excess of DMAD in $CHCl_3$ solution at room temperature, and TLC monitoring showed completion of the reaction after 15 h. The pure product was isolated by flash chromatography as a yellow solid in 54% yield. The spectroscopic data confirmed the expected structure of 4*H*-thiopyran-2,3-dicarboxylate **6a**, bearing the ferrocene unit at C(6) (Scheme 3). In the ^{1}H NMR spectrum, the signals of the ferrocenyl group appeared at 4.19 (singlet, 5H) and two multiplets at 4.28 and 4.47 ppm (2H each). The signals of HC(4) and HC(5) appeared as doublets at 4.74 and 5.99 ppm with J = 6.0 Hz. The ^{13}C NMR spectrum revealed two signals for ester carbonyl groups at 164.0 and 166.0 ppm. The molecular formula $C_{25}H_{22}FeO_4S$ was confirmed by the mass spectrum (m/z = 475.36, $[M+1]^+$) and by elemental analysis.



Scheme 3. Reaction of ferrocenyl-substituted thiochalcones **5** with acetylenic esters leading to 6-ferrocenyl substituted 4*H*-thiopyrans **6**.

Table 1. Synthesis of 6-ferrocenyl-4*H*-thiopyran derivatives **6** via thia-Diels-Alder reaction.

6	R	Ar	Yield (%)[a)]
a	CO_2Me	Ph	54
b	CO_2Me	Furan-2-yl	63
c	CO_2Me	Thiophen-2-yl	56
d	CO_2Me	Ferrocenyl	34
e	H	Furan-2-yl	66
f	H	Thiophen-2-yl	62
g	H	Ferrocenyl	42

a) Yields of isolated products.

Analogous reactions performed with thiochalcones **5b**–**d** afforded the expected 4*H*-thiopyran derivatives **6b**–**d** in 63–34% yield (Table 1). The lowest yield was obtained in the case of the bisferrocenyl derivative **6d**. The spectroscopic data confirmed its structure and the purity of the sample. The presence of two different ferrocenyl units was evidenced by two sets of the typical signals in the ^{1}H NMR spectrum. Interestingly, in comparison with **6a**, the HC(4) doublet appeared at higher field (4.46 ppm). This finding demonstrates that the ferrocenyl substituent acts as a strongly shielding group.

The same series of thiochalcones **5** was used for analogous reactions with methyl propiolate, and the corresponding products **6e**–**g** were isolated in 66–42% yield (Table 1). The ^{1}H NMR analyses of the crude mixtures pointed out that in each case only one [4+2]-cycloadduct was formed. For example, the product obtained with **5c** showed the same pattern for HC(4) and HC(5) as observed for **6a**. In addition, the signal found at 7.68 ppm (singlet, 1H) confirmed the fragment HC(2). Therefore, the structures **6e**–**g** were established as 4*H*-thiopyran-3-carboxylates (Scheme 3, Table 1). These structures evidence that the [2+4]-cycloaddition occurred regioselectively, and the S-atom of the heterodiene attacks the more electrophilic center of propiolate exclusively. In analogy to **6d**, the signal attributed to HC(4) of **6g** appeared at 4.50 ppm due to the shielding effect of the ferrocenyl group located at C(4).

3. Conclusions

The study presented shows that ferrocenyl-substituted thiochalcones of type **5** can be prepared according to typical procedures known for the synthesis of thiochalcones. However, they are rather unstable compounds and should be used for further conversions immediately after their preparation. The reactivity of ferrocenyl thiochalcones **5**, including the bisferrocenyl representative **5d**, towards acetylenic dienophiles is comparable with that of aryl and hetaryl analogues **2**. The availability of ferrocenyl thiochalcones opens new opportunities for a simple access to sulfur heterocycles, and 4*H*-thiopyrans are accessible via thia-Diels-Alder reaction with acetylenic dienophiles.

4. Experimental design

4.1. General

All solvents were dried over appropriate drying agents and distilled before use. The ^{1}H and ^{13}C NMR spectra were measured on a Bruker Avance III instrument (600 and 150 MHz, respectively), using the solvent ($CDCl_3$/residual $CHCl_3$) signal as reference. The IR spectra (KBr pellets) were recorded on a Nexus FT-IR spectrophotometer. The elemental analyses were recorded on a Vario Micro Cube. Flash column chromatography (FCC) was carried out using Silica gel 60 (Sigma-Aldrich, 230–400 mesh). Melting points were determined in a capillary using a Stewart® SMP30. The notation Fc in this study represents ferrocenyl. Ferrocenyl methyl ketone applied in the study was obtained by a known method according to the literature protocol [15,16]. Other reagents used were commercially available chemicals.

4.2. Preparation of ferrocenyl substituted chalcones 4a–d [14]

The solution of sodium hydroxide (0.05 g) in H_2O (2 mL) and ethanol (1 mL) was cooled to 0^{o}C (ice bath), and at this temperature ferrocenyl methyl ketone (228 mg, 1 mmol) dissolved in ethanol (2 mL) was added drop-wise. The obtained solution was allowed to warm slowly to rt, and then the solution of an aromatic aldehyde (1 mmol) in ethanol (1 mL) was added. The mixture was stirred overnight at rt. After that time, the obtained precipitate was filtered off and dried in the air. The crude products were used for further reactions without additional purification.

*4.2.1. (***E***)-1-Ferrocenyl-3-phenylprop-2-en-1-one (4a)* [17]

Red solid; yield: 284 mg (90%); m.p. 130.1–132.3°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 4.23 (bs, 5H, 5CH(Fc)), 4.60 (bs, 2H, 2CH(Fc)), 4.93 (bs, 2H, 2CH(Fc)), 7.15 (d, 1H, $J_{H,H}$ = 15.6 Hz, =CH), 7.40–7.47 (m, 3H, $3CH_{arom.}$), 7.64–7.69 (m, 2H, $2CH_{arom.}$), 7.81 (d, 1H, $J_{H,H}$ = 15.6 Hz, =CH) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 69.7, 72.7 (2 signals for 4CH(Fc)), 70.1 (1 signal for 5CH(Fc)), 80.6 (C(Fc)), 123.0, 128.2, 128.9, 130.0, 140.8 (3 signals for $5CH_{arom.}$, 2C=), 135.2 ($C_{arom.}$), 192.8 (C=O) ppm. IR (KBr): υ 3085*m*, 3025*w*, 1742*w*, 1647*vs*, 1597*vs*, 1572*m*, 1458*s*, 1445*m*, 1378*m*, 1321*m*, 1283*m*, 1236*m*, 1078*s*, 989*m*, 824*m*, 764*s*, 688*s*, 546*m* cm^{-1}. Anal. calcd. for $C_{19}H_{16}FeO$ (316.17): C 72.18, H 5.10; found: C 72.26, H 5.13.

*4.2.2. (***E***)-1-Ferrocenyl-3-(furan-2-yl)prop-2-en-1-one (4b)*

Red solid; yield: 208 mg (68%); m.p. 145.0–147.0°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 4.23 (bs, 5H, 5CH(Fc)), 4.59 (bs, 2H, 2CH(Fc)), 4.92 (bs, 2H, 2CH(Fc)), 6.52 (bs, 1H, $CH_{arom.}$), 6.69 (d, 1H, $J_{H,H}$ = 3.0 Hz, $CH_{arom.}$), 7.03 (d, 1H, $J_{H,H}$ = 15.6 Hz, =CH), 7.52–7.57 (m, 2H, =CH, 1 $CH_{arom.}$) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 69.7, 72.7 (2 signals for 4CH(Fc)), 70.1 (1 signal for 5CH(Fc)), 80.8 (C(Fc)), 112.5, 115.3, 120.8, 127.1, 144.3 (3 $CH_{arom.}$, 2C=), 151.9 ($C_{arom.}$), 192.7 (C=O) ppm. IR (KBr): υ 3082*w*, 1647*s*, 1594*vs*, 1546*m*, 1451*m*, 1372*m*, 1280*m*, 1241*m*, 1087*m*, 973*m*, 821*m*, 758*m*, 688*m*, 549*m* cm^{-1}. Anal. calcd. for $C_{17}H_{14}FeO_2$ (306.14): C 66.70, H 4.61; found: C 66.78, H 4.70.

*4.2.3. (***E***)-1-Ferrocenyl-3-(thiophen-2-yl)prop-2-en-1-one (4c)*

Red solid; yield: 187 mg (58%); m.p. 134.2–136.1°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 4.23 (bs, 5H, 5CH(Fc)), 4.59 (bs, 2H, 2CH(Fc)), 4.91 (bs, 2H, 2CH(Fc)), 6.93 (d, 1H, $J_{H,H}$ = 15.6 Hz, =CH), 7.10 (dd, 1H, $^{3}J_{H,H}$ = 4.8 Hz, $^{3}J_{H,H}$ = 3.0 Hz, $CH_{arom.}$), 7.36 (d, 1H, $^{3}J_{H,H}$ = 3.0 Hz, $CH_{arom.}$), 7.41 (d, 1H, $^{3}J_{H,H}$ = 4.8 Hz, $CH_{arom.}$), 7.91 (d, 1H, $J_{H,H}$ = 15.6 Hz, =CH) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 69.7, 72.7 (2 signals for 4CH(Fc)), 70.1 (1 signal for 5CH(Fc)), 80.6 (C(Fc)), 122.1, 127.8, 128.3, 131.3, 133.3 (3 $CH_{arom.}$, 2C=), 140.7 ($C_{arom.}$), 192.5 (C=O) ppm. IR (KBr): υ 3083*m*, 1646*vs*, 1582*vs*, 1458*s*, 1426*m*, 1380*s*, 1281*m*, 1242*m*, 1083*s*, 1076*m*, 1001*m*, 977*s*, 856*m*, 828*s*, 704*vs*, 545*m*, 503*s*, 478*s* cm^{-1}. Anal. calcd. for $C_{17}H_{14}FeOS$ (322.20): C 63.37, H 4.38, S 9.95; found: C 63.45, H 4.40, S 10.00.

*4.2.4. (***E***)-1,3-Diferrocenylprop-2-en-1-one (4d)* [17,18]

Red solid; yield: 128 mg (30%); m.p. > 175°C (decomposition). ^{1}H NMR (600 MHz, $CDCl_3$): δ 4.21 (bs, 10H, 10CH(Fc)), 4.41–4.68 (m, 6H, 6CH(Fc)), 4.88 (bs, 2H, 2CH(Fc)), 6.75 (br d, 1H, $J_{H,H} \approx 12.5$ Hz, =CH), 7.72 (br d, 1H, $J_{H,H} \approx 12.5$ Hz, =CH) ppm. ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ 68.7, 69.6, 70.9, 72.4 (4 signals for 8CH(Fc)), 69.7, 70.0 (2 signals for 10CH(Fc)), 79.6, 80.8 (2C(Fc)), 120.4, 142.0 (2C=), 192.2 (C=O) ppm. IR (KBr): υ 1641*vs*, 1578*s*, 1448*m*, 1378*m*, 1287*m*, 1249*m*, 1106*m*, 1078*m*, 998*m*, 824*m*, 514*m*, 479*m* cm^{-1}. Anal. calcd. for $C_{23}H_{20}Fe_2O$ (424.09): C 65.14, H 4.75; found: C 65.22, H 5.02.

4.3. Preparation of ferrocenyl substituted thiochalcone derivatives 5a–d.

To the solution of a corresponding chalcone **4** (1 mmol) in freshly distilled THF (5 mL) was treated with Lawesson's reagent (250 mg, 0.6 mmol). The reaction was carried out at rt under inert gas atmosphere. The progress of the reaction was monitored by TLC. After only few min, the reactions were complete. The solvent was evaporated and the crude products were purified by FCC (petroleum ether/CH_2Cl_2 4:1). Collected spectroscopic data confirmed the expected structures of thiochalcones **5**.

*4.3.1. (***E***)-1-Ferrocenyl-3-phenylprop-2-en-1-thione (5a)*

Dark violet solid; yield: 236 mg (71%). IR (KBr): υ 3088*w*, 3025*w*, 2917*m*, 2847*m*, 1600*w*, 1496*m*, 1451*m*, 1378*m*, 1252*m*, 1106*m*, 1024*m*, 998*m*, 960*w*, 818*s*, 758*m*, 739*m*, 694*s*, 479*s* cm^{-1}. Anal. calcd. for $C_{19}H_{16}FeS$ (332.24): C 68.69, H 4.85, S 9.65; found: C 68.53, H 5.02, S 9.70. MS (ESI): *m/z* 332 (100, $[M]^+$).

*4.3.2. (***E***)-1-Ferrocenyl-3-(furan-2-yl)prop-2-en-1-thione (5b)*

Dark violet solid; yield: 277 mg (86%). IR (KBr): υ 3093*m*, 2923*m*, 2851*m*, 1667*m*, 1595*m*, 1498*m*, 1438*m*, 1377*m*, 1259*m*, 1149*m*, 1106*s*, 1010*s*, 926*m*, 884*m*, 818*vs*, 731*vs*, 597*m*, 482*vs* cm^{-1}. Anal. calcd. for $C_{17}H_{14}FeOS$ (322.20): C 63.37, H 4.38, S 9.95; found: C 63.37, H 4.44, S 9.75. MS (ESI): *m/z* 323 (100, $[M+1]^+$), 322 (85, $[M]^+$).

*4.3.3. (***E***)-1-Ferrocenyl-3-(thiophen-2-yl)prop-2-en-1-thione (5c)*

Dark violet solid; yield: 199 mg (59%). IR (KBr): υ 3082*m*, 2927*w*, 2857*w*, 1591*w*, 1426*m*, 1410*m*, 1261*m*, 1214*m*, 1109*s*, 1046*m*, 1021*s*, 998*m*, 954*m*, 818*vs*, 691*vs*, 482*vs* cm^{-1}. Anal. calcd. for $C_{17}H_{14}FeS_2$ (338.27): C 60.36, H 4.17, S 18.95; found: C 60.18, H 4.39, S 18.77. MS (ESI): *m/z* 338 (100, $[M]^+$).

4.3.4. (E)-1,3-Diferrocenylprop-2-en-1-thione (5d)

Dark violet solid; yield: 207 mg (47%). IR (KBr): *υ* 3091*m*, 2920*m*, 2844*m*, 1432*m*, 1410*m*, 1255*m*, 1103*s*, 1030*m*, 1002*s*, 812*vs*, 482*vs* cm^{-1}. Anal. calcd. for $C_{23}H_{20}Fe_2S$ (440.16): C 62.76, H 4.58, S 7.28; found: C 62.89, H 4.38 S 7.08 MS (ESI): *m/z* 440 (100, $[M]^+$).

4.4. Reaction of thiochalcones 5 with acetylenic dienophiles 6a–g

The mixture of an acetylenic dienophile (1.1 mmol) [methyl propiolate (92.0 mg, 0.1 mL) or dimethyl acetylenedicarboxylate (156 mg, 0.14 mL)] and the solution of the corresponding thiochalcone **5** (1 mmol) in $CHCl_3$ (2 mL) was stirred under inert gas atmosphere at rt overnight. Next, the solvent was evaporated and the crude products were purified by FCC (petroleum ether/ethyl acetate 9:1). Analytically pure samples were obtained by additional PTLC (SiO_2) or by precipitation of the solid material from petroleum ether with cooling in dry ice.

4.4.1. Dimethyl 6-ferrocenyl-4-phenyl-4H-thiopyran-2,3-dicarboxylate (6a)

Yellow solid; yield: 256 mg (54%); m.p. 66.0–68.1°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.68 (bs, 3H, $1CH_3O$), 3.89 (bs, 3H, $1CH_3O$), 4.19 (bs, 5H, 5CH(Fc)), 4.28 (bs, 2H, 2CH(Fc)), 4.63 (bs, 1H, 1CH(Fc)), 4.49 (bs, 1H, 1CH(Fc)), 4.75 (d, 1H, $J_{H,H}$ = 6.0 Hz, CH), 6.00 (d, 1H, $J_{H,H}$ = 6.0 Hz, =CH), 7.25–7.29 (m, 1H, $1CH_{arom.}$), 7.32–7.36 (m, 2H, $2CH_{arom.}$), 7.39–7.42 (m, 2H, $2CH_{arom.}$) ppm. ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ 43.8 (1CH), 52.4, 53.1 ($2CH_3O$), 66.1, 66.6, 69.1, 69.2 (4CH(Fc)), 69.6 (1 signal for 5CH(Fc)), 82.3 (C(Fc)), 116.1 (=CH), 127.4, 127.8, 128.8 (3 signals for $5CH_{arom.}$), 129.6, 134.4, 141.8 (3 signals for C(2), C(3), C(6), $C_{arom.}$), 165.4, 166.0 (2C=O) ppm. IR (KBr): *υ* 3098*w*, 3031*w*, 2946*m*, 2841*w*, 1733*vs*, 1711*vs*, 1644*m*, 1600*m*, 1486*m*, 1435*s*, 1264*vs*, 1239*vs*, 1106*m*, 1062*m*, 1024*s*, 1002*m*, 818*m*, 758*m*, 694*m* cm^{-1}. Anal. calcd. for $C_{25}H_{22}FeO_4S$ (474.35): C 63.30, H 4.67, S 6.76; found: C 63.24, H 4.63 S 6.72.

4.4.2. Dimethyl 6-ferrocenyl-4-(furan-2-yl)-4H-thiopyran-2,3-dicarboxylate (6b)

Orange solid; yield: 292 mg (63%); m.p. 51.0–53.0°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (bs, 3H, $1CH_3O$), 3.90 (bs, 3H, $1CH_3O$), 4.18 (bs, 5H, 5CH(Fc)), 4.27–4.29 (m, 1H, 1CH(Fc)), 4.30–4.31 (m, 1H, 1CH(Fc)), 4.50 (bs, 2H, 2CH(Fc)), 4.97 (d, 1H, $J_{H,H}$ = 6.6 Hz, CH), 5.99 (d, 1H, $J_{H,H}$ = 6.6 Hz, =CH), 6.18 (d, 1H, $^3J_{H,H}$ = 3.6 Hz, $CH_{arom.}$),

6.32 (dd, 1H, $^{3}J_{H,H}$ = 3.6 Hz, $^{3}J_{H,H}$ = 1.8 Hz, $CH_{arom.}$), 7.37 (bs, 1H, $CH_{arom.}$) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 37.2 (1CH), 52.5, 53.1 ($2CH_3O$), 66.2, 67.0, 69.3, 69.4 (4CH(Fc)), 69.7 (1 signal for 5CH(Fc)), 81.8 (C(Fc)), 106.4, 110.4, 112.3, 142.2 (=CH, $3CH_{arom.}$), 124.2, 132.4, 136.8, 152.3 (C(2), C(3), C(6), $C_{arom.}$), 165.3, 165.5 (2C=O) ppm. IR (KBr): υ 3094*w*, 2955*m*, 2923*w*, 2841*w*, 1736*vs*, 1698*s*, 1628*m*, 1591*m*, 1496*w*, 1429*m*, 1331*m*, 1268*vs*, 1236*s*, 1185*m*, 1131*m*, 1106*m*, 1024*m*, 1049*m*, 1005*m*, 840*m*, 812*m*, 739*m*, 726*m*, 476*m* cm^{-1}. Anal. calcd. for $C_{23}H_{20}FeO_5S$ (464.31): C 59.50, H 4.34, S 6.91; found: C 59.52, H 4.37, S 6.74.

*4.4.3. Dimethyl 6-ferrocenyl-4-(thiophen-2-yl)-4*H*-thiopyran-2,3-dimethyl dicarboxylate (6c)*

Orange solid; yield: 269 mg (56%); m.p. 60.3–62.4°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (bs, 3H, $1CH_3O$), 3.89 (bs, 3H, $1CH_3O$), 4.24 (bs, 5H, 5CH(Fc)), 4.29–4.30 (m, 1H, 1CH(Fc)), 4.31–4.32 (m, 1H, 1CH(Fc)), 4.52 (t, 2H, $J_{H,H}$ = 1.8 Hz, 2CH(Fc)), 5.13 (d, 1H, $J_{H,H}$ = 6.6 Hz, CH), 6.06 (d, 1H, $J_{H,H}$ = 6.6 Hz, =CH), 6.96 (dd, 1H, $^{3}J_{H,H}$ = 3.6 Hz, $^{3}J_{H,H}$ = 4.8 Hz, $CH_{arom.}$), 6.98–7.00 (m, 1H, $CH_{arom.}$), 7.22 (dd, 1H, $^{4}J_{H,H}$ = 1.2 Hz, $^{3}J_{H,H}$ = 4.8 Hz, $CH_{arom.}$) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 38.1 (1CH), 52.5, 53.1 ($2CH_3O$), 66.2, 67.2, 69.3, 69.4 (4CH(Fc)), 69.7 (1 signal for 5CH(Fc)), 82.0 (C(Fc)), 115.1, 124.4, 124.5, 126.7 (=CH, $3CH_{arom.}$), 125.9, 131.6, 136.0, 144.0 (C(2), C(3), C(6), $C_{arom.}$), 165.3, 165.5 (2C=O) ppm. IR (KBr): υ 2955*w*, 2917*w*, 2847*w*, 1730*vs*, 1704*s*, 1652*m*, 1432*m*, 1264*vs*, 1239*s*, 1106*m*, 1021*m*, 824*m*, 720*m*, 704*m*, 489*m* cm^{-1}. Anal. calcd. for $C_{23}H_{20}FeO_4S_2$ (480.38): C 57.51, H 4.20, S 13.35; found: C 57.60, H 4.35, S 13.38.

*4.4.4. Dimethyl 4,6-diferrocenyl-4*H*-thiopyran-2,3-dicarboxylate (6d)*

Yellow solid; yield: 198 mg (34%); m.p. 168.5–171.7°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.77 (bs, 3H, $1CH_3O$), 3.84 (bs, 3H, $1CH_3O$), 4.15 (bs, 2H, 2CH(Fc)), 4.21 (bs, 2H, 2CH(Fc)), 4.25 (bs, 5H, 5CH(Fc)), 4.27 (bs, 5H, 5CH(Fc)), 4.31–4.33 (m, 1H, 1CH(Fc)), 4.34–4.36 (m, 1H, 1CH(Fc)), 4.47 (d, 1H, $J_{H,H}$ = 6.6 Hz, CH), 4.54 (bs, 1H, 1CH(Fc)), 4.57 (bs, 1H, 1CH(Fc)), 6.15 (d, 1H, $J_{H,H}$ = 6.6 Hz, =CH) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 37.8 (1CH), 52.4, 53.0 ($2CH_3O$), 66.3, 67.0, 67.1, 67.8, 67.9, 68.0, 69.2, 69.3 (8CH(Fc)), 68.5, 69.6 (2 signal for 10CH(Fc)), 82.5, 88.1 (2C(Fc)), 115.6 (=CH), 128.8, 130.7, 133.6 (C(2), C(3), C(6)), 165.4, 166.1 (2C=O) ppm. IR (KBr): υ 3088*w*, 2949*w*, 1711*vs*, 1600*m*, 1442*m*, 1347*w*, 1283*vs*, 1261*vs*,

1103*m*, 1036*m*, 1021*m*, 995*m*, 821*m*, 644*m*, 485*m* cm^{-1}. Anal. calcd. for $C_{29}H_{26}Fe_2O_4S$ (582.27): C 59.82, H 4.50, S 5.51; found: C 59.81, H 4.70, S 5.33.

*4.4.5. Methyl 6-ferrocenyl-4-(furan-2-yl)-4***H***-thiopyran-3-carboxylate (6e)*

Yellow solid; yield: 268 mg (66%); m.p. 103.0–105.0°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (bs, 3H, CH_3O), 4.18 (bs, 5H, 5CH(Fc)), 4.26–4.31 (m, 2H, 2CH(Fc)), 4.47–4.48 (m, 1H, 1CH(Fc)), 4.49–4.50 (m, 1H, 1CH(Fc)), 4.95 (d, 1H, $J_{H,H}$ = 6.6 Hz, CH), 6.02 (d, 1H, $J_{H,H}$ = 6.6 Hz, =CH), 6.12 (d, 1H, $^3J_{H,H}$ = 3.0 Hz, $CH_{arom.}$), 6.31 (dd, 1H, $^3J_{H,H}$ = 1.8 Hz, $^3J_{H,H}$ = 3.0 Hz, $CH_{arom.}$), 7.35 (dd, 1H, $^3J_{H,H}$ = 1.8 Hz, $^4J_{H,H}$ = 0.6 Hz, $CH_{arom.}$), 7.75 (bs, 1H, =CH) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 34.5 (1CH), 52.0 (CH_3O), 66.0, 66.5, 69.0, 69.1 (4CH(Fc)), 69.7 (1 signal for 5CH(Fc)), 82.7 (C(Fc)), 105.6, 110.3, 113.4, 134.2, 141.7 (2=CH, 3$CH_{arom.}$), 121.5, 130.2, 154.6 (C(3), C(6), $C_{arom.}$), 165.0 (C=O) ppm. IR (KBr): υ 3123*w*, 3091*w*, 2993*w*, 2946*m*, 2920*w*, 1701*vs*, 1625*m*, 1594*m*, 1508*m*, 1429*m*, 1350*m*, 1264*m*, 1249*s*, 1226*vs*, 1176*m*, 1106*m*, 1084*m*, 1040*m*, 1005*m*, 922*m*, 834*m*, 802*m*, 748*m*, 710*m*, 533*m*, 476*m* cm^{-1}. Anal. calcd. for $C_{21}H_{18}FeO_3S$ (406.28): C 62.08, H 4.47, S 7.89; found: C 61.98, H 4.44, S 7.90.

*4.4.6. Methyl 6-ferrocenyl-4-(thiophen-2-yl)-4***H***-thiopyran-3-carboxylate (6f)*

Yellow solid; yield: 262 mg (62%); m.p. 100.1–102.1°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (bs, 3H, CH_3O), 4.25 (bs, 5H, 5CH(Fc)), 4.27–4.32 (m, 2H, 2CH(Fc)), 4.48–4.50 (m, 1H, 1CH(Fc)), 4.51–4.53 (m, 1H, 1CH(Fc)), 5.12 (d, 1H, $J_{H,H}$ = 6.6 Hz, CH), 6.10 (d, 1H, $J_{H,H}$ = 6.6 Hz, =CH), 6.96 (dd, 1H, $^3J_{H,H}$ = 4.8 Hz, $^3J_{H,H}$ = 3.6 Hz, $CH_{arom.}$), 7.01 (d, 1H, $^3J_{H,H}$ = 3.6 Hz, $CH_{arom.}$), 7.19 (dd, 1H, $^3J_{H,H}$ = 4.8 Hz, $^4J_{H,H}$ = 0.6 Hz, $CH_{arom.}$), 7.68 (bs, 1H, =CH) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 35.4 (1CH), 51.9 (CH_3O), 66.0, 66.7, 69.0, 69.1 (4CH(Fc)), 69.6 (1 signal for 5CH(Fc)), 82.9 (C(Fc)), 116.1, 124.3, 124.4, 126.7, 132.9 (2=CH, 3$CH_{arom.}$), 123.8, 129.6, 146.5 (C(3), C(6), $C_{arom.}$), 164.9 (C=O) ppm. IR (KBr): υ 3101*w*, 3094*w*, 3066*w*, 2946*m*, 1701*vs*, 1625*m*, 1584*m*, 1429*s*, 1356*m*, 1277*s*, 1252vs, 1109*m*, 1055*m*, 1036*s*, 1027*s*, 1002*m*, 824*s*, 802*s*, 751*s*, 713*s*, 533*m* cm^{-1}. Anal. calcd. for $C_{21}H_{18}FeO_2S_2$ (422.34): C 59.72, H 4.30, S 15.18; found: C 59.63, H 4.33, S 15.08.

*4.4.7. Methyl 4,6-diferrocenyl-4***H***-thiopyran-3-carboxylate (6g)*

Orange solid; yield: 220 mg (42%); m.p. 159.0–161.3°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.77 (bs, 3H, CH_3O), 4.10 (bs, 1H, 1CH(Fc)), 4.14 (bs, 1H, 1CH(Fc)), 4.17 (bs, 1H,

1CH(Fc)), 4.25 (bs, 5H, 5CH(Fc)), 4.27 (bs, 5H, 5CH(Fc)), 4.30–4.33 (m, 2H, 2CH(Fc)), 4.34 (bs, 1H, 1CH(Fc)), 4.50 (d, 1H, $J_{H,H}$ = 6.6 Hz, CH), 4.52 (bs, 1H, 1CH(Fc)), 4.59 (bs, 1H, 1CH(Fc)), 6.22 (d, 1H, $J_{H,H}$ = 6.6 Hz, =CH), 7.53 (bs, 1H, =CH) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 34.1 (1CH), 51.8 (CH_3O), 66.1, 66.6, 66.8, 67.5, 67.7, 68.1, 69.0, 69.1 (8CH(Fc)), 68.5, 69.6 (2 signal for 10CH(Fc)), 83.4, 90.3 (2C(Fc)), 116.5, 132.1 (2=CH), 125.3, 129.0 (C(3), C(6)), 165.3 (C=O) ppm. IR (KBr): υ 3094*w*, 3085*w*, 2942*w*, 2901*w*, 1698*vs*, 1597*m*, 1432*m*, 1356*m*, 1280*m*, 1233*s*, 1084*m*, 1033*m*, 1002*m*, 941*m*, 818*m*, 777*m*, 748*m*, 707*m*, 523*m*, 485*m* cm^{-1}. Anal. calcd. for $C_{27}H_{24}Fe_2O_2S$ (524.23): C 61.86, H 4.61, S 6.12; found: C 61.79, H 4.66, S 6.11.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Authors thank the National Science Center (Cracow, Poland) for generous financial support (Grant Maestro-3; Dec-2012/06/A/ST5/00219). G.M. and R. H.-F. acknowledge also the Alexander von Humboldt-Striftung (Bonn, Germany) for financial support within the ‘Institutspartnerschaft’ project (2018–2020).

Acknowledgement

Skillful performance of elemental analysis of all new compounds by Ms Agnieszka Cieślińska and Ms Hanna Jatczak (University of Łódź) is gratefully acknowledged.

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