Journal of Photochemistry and Photobiology A: Chemistry 214 (2010) 135–144

Contents lists available at ScienceDirect

Journal of Photochemistry and Photobiology A: Chemistry

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

The synthesis, X-ray crystal structure and optical properties of novel 5-aryl-1-arylthiazolyl-3-ferrocenyl-pyrazoline derivatives

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ARTICLE INFO

Article history:
Received 22 February 2010
Received in revised form 11 June 2010
Accepted 16 June 2010
Available online 23 June 2010

Keywords:
Pyrazoline
Ferrocene
Thiazole
X-ray
UV absorption
Fluorescence

ABSTRACT

A series of novel 5-aryl-1-arylthiazolyl-3-ferrocenyl-pyrazoline derivatives has been synthesized by the reaction of ferrocenyl chalcone and thiosemicarbazide followed by the reaction with 2-bromo-1-arylethanone in 48–90% yields. The compounds were characterized using IR, ^{1}H NMR and HRMS and X-ray diffraction analysis. The absorption and fluorescence characteristics of the compounds were investigated in dichloromethane, chloroform and tetrahydrofuran. The results showed that the absorption maxima of the compounds vary from 316 to 347 nm depending on the group bonded to phenylthiazole rings. The electron-donating methoxyl group in phenylthiazole moiety caused red shifts in dichloromethane solution, and the electron-withdrawing chloro group resulted in blue shifts. The absorption maxima of these compounds in tetrahydrofuran were red shift compared with that in dichloromethane and chloroform. The maximum emission spectra of compounds in tetrahydrofuran were also red shift compared with that in dichloromethane.

1. Introduction

Pyrazolines are important nitrogen containing 5-membered heterocyclic compounds and numerous pyrazoline derivatives have been found to possess considerable biological activities [1], such as antimicrobial [2–5], antiamoebic [6,7], antinociceptive [8], anticancer [9], antidepressant [10,11] and anti-inflammatory [12–17], which stimulated the research activity in this field. On the other hand, pyrazoline derivatives are also widely used in electroluminescence fields, for example, organic light-emitting diodes [18–20], due to their blue light emission with high fluorescence quantum yield [21,22]. Attempts have been made to synthesize and elucidate the effects of substituent on the absorption and fluorescence properties of this class of compounds [23–33].

The design and synthesis of fluorescent small molecules with desirable properties is of considerable current interest in biology research. Recently, it is reported that pyrazoline derivatives can be used as DNA probe [34]. To date there have been relatively few studies on the cellular localization of agents in which small molecule linked to a fluorophore, such as coumarin [35,36]. Thus, in continuation of our efforts in synthesizing various bioactive molecules [37–42], we attempt to synthesize novel small molecules with both potential bioactivity and fluorescent property. In our previous paper, we reported that the synthesis and optical properties of 1,3,5-triaryl pyrazoline derivatives [43]. In light of few report concerning ferrocenyl pyrazoline [44–47], herein, we would like to report the synthesis, X-ray crystal structure and optical properties of novel 5-aryl- 1-arylthiazolyl-3-ferrocenyl-pyrazoline derivatives.

2. Materials and methods

2.1. General

Thin-layer chromatography (TLC) was conducted on silica gel 60 F_{254} plates (Merck KGaA). ^{1}H NMR spectra were recorded on a Bruker Avance 400 (400 MHz) spectrometer, using $CDCl_3$ as solvent and tetramethylsilane (TMS) as internal standard. Melting points were determined on an XD-4 digital micro melting point apparatus. IR spectra were recorded with an IR spectrophotometer VERTEX 70 FT-IR (Bruker Optics). HRMS spectra were recorded on a Q-TOF6510 spectrograph (Agilent). UV–vis spectra were recorded on a U-4100 (Hitachi). Fluorescent measurements were recorded on a PerkinElmer LS-55 luminescence spectrophotometer.

2.2. General procedure for the synthesis of ferrocenyl chalcone derivatives

Acetylferrocene **1** (1.14 g, 5 mmol) and aryl aldehyde **2** (5 mmol) were added to a mortar, and grinded up with a pestle. Then KOH

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doi:10.1016/j.jphotochem.2010.06.017

(powder, 0.68 g, 10 mmol) was added to the mixture. After grinded for 0.5 h the mixture was layed aside for 1 h, and then water (10 mL) was added. The solution was neutralized with dilute hydrochloric acid, filtrated under the reduced pressure. The solid was washed with water, subsequently, recrystallized with 95% ethanol to give the products **3a–c**.

*2.2.1. (E)-1-Ferrocenyl-3-phenylprop-2-en-1-one (**3a**)*

Dark red solid, yield 87%; mp 137–138 °C (lit. mp 137–139 °C [48]).

*2.2.2. (E)-1-Ferrocenyl-3-(benzo[d][1,3]dioxol-5-yl)-2-en-1-one (**3b**)*

Brown solid, yield 86%; mp 187–188 °C (lit. mp 169–170 °C [49]).

*2.2.3. (E)-1-Ferrocenyl-3-(2-(benzyloxy)phenyl)-2-en-1-one (**3c**)*

Brown solid, yield 88%; mp 112–113 °C [50].

*2.3. Preparation of 3-ferrocenyl-5-aryl-4,5-dihydro-1H-pyrazole-1-carbothioamide **4a–c***

*2.3.1. 3-Ferrocenyl-5-phenyl-4,5-dihydro-1H-pyrazole-1-carbothioamide (**4a**)*

The mixture of (*E*)-1-ferrocenyl-3-phenylprop-2-en-1-one (**3a**) (2.0 g, 6.3 mmol), thiosemicarbazide (1.15 g, 12.6 mmol) and NaOH (0.63 g, 15.8 mmol) in ethanol (30 mL) was stirred and heated at reflux under nitrogen for 4 h, then cooled to room temperature. Water (15 mL) was added to the reaction mixture, subsequently, filtrated under the reduced pressure. The solid was dried to give intermediate **4a** (1.34 g), yield 55%; mp 128–132 °C; IR (KBr, cm^{-1}): 3580, 3436, 3279, 1585, 1501, 1457, 1360, 825, 477; ^1H NMR ($CDCl_3$, 400 MHz), δ: 7.25–7.36 (s, 5H, Ph), 6.96 (s, 1H, NH), 6.01 (s, 2H, NH, pyrazoline 5-H), 4.66 (s, 1H, Cp), 4.53 (s, 1H, Cp), 4.44 (s, 2H, Cp), 4.07 (s, 5H, Cp), 3.72 (s, 1H, pyrazoline 4-H), 3.01 (d, 1H, J = 14.8 Hz, pyrazoline 4-H). HRESIMS calcd for $[M+H]^+$ $C_{20}H_{20}FeN_3S^+$: 390.0722, found: 390.0726.

*2.3.2. 3-Ferrocenyl-5-(benzo[d][1,3]dioxol-5-yl)-4,5-dihydro-1H-pyrazole-1-carbothioamide (**4b**)*

Compound **4b** was prepared from (*E*)-1-ferrocenyl-3-(benzo[d][1,3]dioxol-5-yl)-2-en-1-one (1.80 g, 5 mmol) using the same procedure as described for **4a**. Purification of the solid resulted in **4b** (1.81 g) as a brown solid, yield 83%; mp 230–236 °C; IR (KBr, cm^{-1}): 3479, 3364, 2893, 1579, 1500, 1452, 1353, 1233, 1033, 826, 489; ^1H NMR ($CDCl_3$, 400 MHz), δ: 6.94 (s, 1H, NH), 6.78 (d, 1H, J = 7.2 Hz, Ar–H), 6.68–6.72 (m, 2H, Ar–H), 5.92 (s, 4H, NH, pyrazoline 5-H, OCH_2O), 4.65 (s, 1H, Cp), 4.53 (s, 1H, Cp), 4.44 (s, 2H, Cp), 4.10 (s, 5H, Cp), 3.68 (dd, 1H, J = 16.8, 11.2 Hz, pyrazoline 4-H), 2.97 (d, 1H, J = 16.8 Hz, pyrazoline 4-H). HRESIMS calcd for $[M+H]^+$ $C_{21}H_{20}FeN_3O_2S^+$: 434.0620, found: 434.0616.

*2.3.3. 3-Ferrocenyl-5-(2-(benzyloxy)phenyl)-4,5-dihydro-1H-pyrazole-1-carbothioamide (**4c**)*

Compound **4c** was prepared from (*E*)-1-ferrocenyl-3-(2-(benzyloxy)phenyl)-2-en-1-one (1.00 g, 2.37 mmol) using the same procedure as described for **4a**. Purification of the solid resulted in **4c** (0.90 g) as a dark brown solid, yield 77%; mp 167–169 °C; IR (KBr, cm^{-1}): 3422, 3255, 1583, 1499, 1452, 1358, 1248, 1109, 1004, 830, 754, 476; ^1H NMR ($CDCl_3$, 400 MHz), δ: 7.50 (d, 2H, J = 7.2 Hz, Ar–H), 7.41 (t, 2H, J = 7.2 Hz, Ar–H), 7.35 (t, 1H, J = 7.2 Hz, Ar–H), 7.23 (d, 1H, J = 7.2 Hz, Ar–H), 6.99–7.04 (m, 3H, NH, Ar-2H), 6.95 (t, 1H, J = 7.2 Hz, Ar–H), 6.33 (d, 1H, pyrazoline 5-H), 5.99 (s, 1H, NH), 5.19 (s, 2H, $PhCH_2O$) 4.62 (s, 1H, Cp), 4.49 (s, 1H, Cp), 4.40 (s, 2H, Cp), 4.00 (s, 5H, Cp), 3.67 (dd, 1H, J = 17.6, 11.2 Hz, pyrazoline 4-H), 2.97 (d, 1H, J = 17.6 Hz, pyrazoline 4-H). HRESIMS calcd for $[M+H]^+$ $C_{27}H_{26}FeN_3OS^+$: 496.1141, found: 496.1129.

*2.4. The synthesis of 2-(3-ferrocenyl-5-aryl-4,5-dihydro-1H-pyrazol-1-yl)-4-(4-substituted- phenyl)thiazole **6a–i***

*2.4.1. 2-(3-Ferrocenyl-5-phenyl-4,5-dihydro-1H-pyrazol-1-yl)-4-phenylthiazole (**6a**)*

3-Ferrocenyl-5-phenyl-4,5-dihydro-1*H*-pyrazole-1-carbothioamide (**4a**) (400 mg, 1.03 mmol), 2-bromo-1-phenylethanone (203 mg, 1.03 mmol) and dichloromethane (8 mL) were added to a round-bottomed flask. The mixture was stirred and heated at reflux under nitrogen for 2 h. The solvent was removed on a rotary evaporator. The residue was purified by column chromatography (silica gel; 3:1 petroleum ether–EtOAc) to afford **6a** as a brown solid (450 mg), yield 89%; mp 214–216 °C; IR (KBr, cm^{-1}): 3103, 3057, 3023, 2917, 2849, 1585, 1556, 1479, 1443, 1335, 1301, 1232, 1119, 1051, 1026, 823, 703, 481; ^1H NMR ($CDCl_3$, 400 MHz), δ: 7.66 (d, 2H, J = 7.6 Hz, Ph), 7.43 (d, 2H, J = 7.5 Hz, Ph), 7.38 (t, 2H, J = 7.5 Hz, Ph), 7.30 (t, 3H, J = 7.5, Ph), 7.21 (t, 1H, J = 7.3 Hz, Ph), 6.79 (s, 1H, thiazole), 5.60 (dd, 1H, J = 11.7, 6.3 Hz, pyrazoline), 4.72 (s, 1H, Cp), 4.59 (s, 1H, Cp), 4.40 (s, 2H, Cp), 4.16 (s, 5H, Cp), 3.79 (dd, 1H, J = 17.1, 11.8 Hz, pyrazoline), 3.19 (dd, 1H, J = 17.1, 6.3 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{28}H_{24}FeN_3S^+$: 490.1035, found: 490.1029.

*2.4.2. 2-(3-Ferrocenyl-5-(benzo[d][1,3]dioxol-5-yl)-4,5-dihydro-1H-pyrazol-1-yl)-4-phenylthiazole (**6b**)*

Compound **6b** was prepared from 3-ferrocenyl-5-(benzo[d][1,3]dioxol-5-yl)-4,5-dihydro-1*H*-pyrazole-1-carbothioamide (**4b**) (400 mg, 0.92 mmol), 2-bromo-1-phenylethanone (182 mg, 0.92 mmol) and dichloromethane (8 mL) by the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 2:1 petroleum ether–EtOAc) resulted in **6b** (352 mg) as a dark brown solid, yield 71%; mp 187–189 °C; IR (KBr, cm^{-1}): 3101, 3058, 3028, 2977, 2884, 2775, 1591, 1545, 1517, 1481, 1434, 1310, 1233, 1106, 1084, 1039, 935, 841, 820, 719, 537, 473; ^1H NMR ($CDCl_3$, 400 MHz), δ: 7.71 (dd, 2H, J = 7.6, 1.1 Hz, Ph), 7.32 (t, 2H, J = 7.9 Hz, Ph), 7.23 (t, 1H, J = 7.3 Hz, Ph), 6.93 (dd, 1H, J = 8.0, 1.5 Hz, benzo[d][1,3]dioxole), 6.88 (d, 1H, J = 1.5 Hz, benzo[d][1,3]dioxole), 6.81 (d, 1H, J = 8.0 Hz, benzo[d][1,3]dioxole), 6.80 (s, 1H, thiazole), 5.93 (dd, 2H, J = 4.1, 1.1 Hz, OCH_2O), 5.52 (dd, 1H, J = 11.6, 6.0 Hz, pyrazoline), 4.71 (d, 1H, J = 1.4 Hz, Cp), 4.59 (d, 1H, J = 1.4 Hz, Cp), 4.40 (m, 2H, Cp), 4.17 (s, 5H, Cp), 3.76 (dd, 1H, J = 17.0, 11.7 Hz, pyrazoline), 3.14 (dd, 1H, J = 17.2, 6.1 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{29}H_{24}FeN_3O_2S^+$: 534.0933, found: 534.0924.

*2.4.3. 2-(3-Ferrocenyl-5-(2-(benzyloxy)phenyl)-4,5-dihydro-1H-pyrazol-1-yl)-4-phenylthiazole (**6c**)*

Compound **6c** was prepared from 3-ferrocenyl-5-(2-(benzyloxy)phenyl)-4,5-dihydro-1*H*-pyrazole-1-carbothioamide (**4c**) (250 mg, 0.51 mmol), 2-bromo-1-phenylethanone (100 mg, 0.51 mmol) and dichloromethane (4 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 8:1 dichloromethane–EtOAc) resulted in **6c** (270 mg) as a dark brown solid, yield 90%; mp 191–193 °C; IR (KBr, cm^{-1}): 3110, 2923, 2878, 2852, 1592, 1552, 1494, 1444, 1382, 1296, 1245, 1104, 1042, 1025, 1000, 853, 817, 752, 702, 490, 474; ^1H NMR ($CDCl_3$, 400 MHz), δ: 7.68 (d, 2H, J = 7.2 Hz, ArCl), 7.51 (d, 2H, J = 7.2 Hz benzyl), 7.40 (t, 2H, J = 7.3 Hz, benzyl), 7.34 (t, 1H, J = 7.3 Hz, benzyl), 7.18–7.29 (5H, ArH), 7.01 (d, 1H, J = 8.2 Hz, ArO), 6.93 (t, 1H, J = 7.4 Hz, ArO), 6.77 (s, 1H, thiazole), 5.99 (dd, 1H, J = 11.5, 6.0 Hz, pyrazoline), 5.23 (s, 2H, $PhCH_2O$), 4.65 (d, 1H, J = 1.7 Hz, Cp), 4.55 (d, 1H, J = 1.2 Hz, Cp), 4.35 (d, 2H, J = 1.7 Hz, Cp), 4.07 (s, 5H, Cp), 3.77 (dd, 1H, J = 17.2, 11.7 Hz, pyrazoline), 3.05

(dd, 1H, J = 17.2, 6.1 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{35}H_{30}FeN_3OS^+$: 596.1454, found: 596.1462.

*2.4.4. 2-(3-Ferrocenyl-5-phenyl-4,5-dihydro-1H-pyrazol-1-yl)-4-(4-methoxyphenyl)thiazole (**6d**)*

Compound **6d** was prepared from **4a** (450 mg, 1.16 mmol), 2-bromo-1-(4-methoxyphenyl)ethanone (263 mg, 1.16 mmol) and dichloromethane (9 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 2:1 petroleum ether–EtOAc) resulted in **6d** (495 mg) as a brown solid, yield 82%; mp 189–190 °C; IR (KBr, cm^{-1}): 3077, 3004, 2932, 2892, 2833, 2639, 1607, 1511, 1299, 1257, 1185, 1106, 1012, 840, 815, 739, 701, 477; ^{1}H NMR ($CDCl_3$, 400 MHz), δ: 7.61 (d, 2H, J = 8.7 Hz, ArOMe), 7.44 (d, 2H, J = 7.5 Hz, Ph), 7.37 (t, 2H, J = 7.6 Hz, Ph), 7.28 (d, 1H, J = 7.2 Hz, Ph), 6.84 (d, 2H, J = 8.7 Hz, ArOMe), 6.63 (s, 1H, thiazole), 5.61 (dd, 1H, J = 11.7, 6.0 Hz, pyrazoline), 4.72 (s, 1H, Cp), 4.60 (s, 1H, Cp), 4.40 (s, 2H, Cp), 4.16 (s, 5H, Cp), 3.86 (dd, 1H, J = 17.2, 11.7 Hz, pyrazoline), 3.19 (dd, 1H, J = 17.2, 6.0 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{29}H_{26}FeN_3OS^+$: 520.1141, found: 520.1173.

*2.4.5. 2-(3-Ferrocenyl-5-(benzo[d][1,3]dioxol-5-yl)-4,5-dihydro-1H-pyrazol-1-yl)-4-(4-methoxyphenyl)thiazole (**6e**)*

Compound **6e** was prepared from **4b** (390 mg, 0.89 mmol), 2-bromo-1-(4-methoxyphenyl)ethanone (204 mg, 0.89 mmol) and dichloromethane (8 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 2:1 petroleum ether–EtOAc) resulted in **6e** (321 mg) as a dark brown solid, yield 63%; mp 203–205 °C; IR (KBr, cm^{-1}): 3098, 2996, 2954, 2910, 2831, 2796, 1586, 1538, 1519, 1485, 1444, 1245, 1173, 1100, 1030, 813, 737, 474; ^{1}H NMR ($CDCl_3$, 400 MHz), δ: 7.64 (d, 2H, J = 8.7 Hz, ArOMe), 6.92 (dd, 1H, J = 8.0, 1.1 Hz, benzo[d][1,3]dioxole), 6.88 (d, 1H, J = 1.5 Hz, benzo[d][1,3]dioxole), 6.84, 6.87 (d, 2H, J = 8.7 Hz, ArOMe), 6.80 (d, 1H, J = 8.0 Hz, benzo[d][1,3]dioxole), 6.66 (s, 1H, thiazole), 5.93 (dd, 2H, J = 4.9, 1.5 Hz, OCH_2O), 5.51 (dd, 1H, J = 11.7, 6.2 Hz, pyrazoline), 4.70 (d, 1H, J = 1.4 Hz, Cp), 4.59 (d, 1H, J = 1.4 Hz, Cp), 4.40 (m, 2H, Cp), 4.17 (s, 5H, Cp), 3.81 (s, 3H, CH_3O), 3.75 (dd, 1H, J = 17.3, 11.7 Hz, pyrazoline), 3.13 (dd, 1H, J = 17.2, 6.2 Hz, pyrazoline). HRESIMS calcd for $[M+H]^+$ $C_{30}H_{26}FeN_3O_3S^+$: 564.1039, found: 564.1052.

*2.4.6. 2-(3-Ferrocenyl-5-(2-(benzyloxy)phenyl)-4,5-dihydro-1H-pyrazol-1-yl)-4-(4-methoxyphenyl)thiazole (**6f**)*

Compound **6f** was prepared from **4c** (250 mg, 0.51 mmol), 2-bromo-1-(4-methoxyphenyl)ethanone (115 mg, 0.51 mmol) and dichloromethane (8 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 2:1 petroleum ether–EtOAc) resulted in **6f** (152 mg) as a dark brown solid, yield 48%; mp 187–190 °C; IR (KBr, cm^{-1}): 3111, 3088, 3066, 3034, 2922, 2896, 2854, 2834, 1592, 1556, 1487, 1448, 1286, 1245, 1171, 1106, 1027, 816, 760, 732, 686, 580, 492; ^{1}H NMR ($CDCl_3$, 300 MHz), δ: 7.62 (d, 2H, J = 8.7 Hz, ArOMe), 7.51 (d, 2H, J = 7.2 Hz benzyl), 7.40 (t, 2H, J = 7.1 Hz, benzyl), 7.35 (t, 1H, J = 6.9 Hz, benzyl), 7.20–7.30 (2H, ArH), 7.01 (d, 1H, J = 7.8 Hz, ArO), 6.93 (t, 1H, J = 7.5 Hz, ArO), 6.81 (d, 2H, J = 8.7 Hz, ArOMe), 6.66 (s, 1H, thiazole), 5.99 (dd, 1H, J = 11.7, 6.3 Hz, pyrazoline), 5.23 (s, 2H, $PhCH_2O$), 4.65 (s, 1H, Cp), 4.55 (s, 1H, Cp), 4.35 (s, 2H, Cp), 4.06 (s, 5H, Cp), 3.76 (dd, 1H, J = 17.1, 11.7 Hz, pyrazoline), 3.79 (s, 3H, CH_3O), 3.04 (dd, 1H, J = 17.1, 6.0 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{36}H_{32}FeN_3O_2S^+$: 626.1559, found: 626.1556.

*2.4.7. 4-(4-Chlorophenyl)-2-(3-ferrocenyl-5-phenyl-4,5-dihydro-1H-pyrazol-1-yl)thiazole (**6g**)*

Compound **6g** was prepared from **4a** (400 mg, 1.03 mmol), 2-bromo-1-(4-chlorophenyl)ethanone (238 mg, 1.03 mmol) and dichloromethane (8 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 3:1 petroleum ether–EtOAc) resulted in **6g** (470 mg) as a dark brown solid, yield 87%; decomposition at 233 °C; IR (KBr, cm^{-1}): 3103, 3057, 3023, 2922, 2852, 1586, 1554, 1473, 1401, 1084, 1047, 1008, 895, 840, 821, 727, 694, 487; ^{1}H NMR ($CDCl_3$, 400 MHz), δ: 7.66 (d, 2H, J = 8.6 Hz, Ph), 7.24–7.42 (m, 7H, Ar), 6.76 (s, 1H, thiazole), 5.57 (dd, 1H, J = 11.7, 6.4 Hz, pyrazoline), 4.72 (s, 1H, Cp), 4.59 (s, 1H, Cp), 4.40 (s, 2H, Cp), 4.16 (s, 5H, Cp), 3.79 (dd, 1H, J = 17.1, 11.7 Hz, pyrazoline), 3.19 (dd, 1H, J = 17.2, 6.4 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{28}H_{23}ClFeN_3S^+$: 524.0645, found: 524.0636.

*2.4.8. 4-(4-Chlorophenyl)-2-(3-ferrocenyl-5-(benzo[d][1,3]dioxol-5-yl)-4,5-dihydro-1H-pyrazol-1-yl)thiazole (**6h**)*

Compound **6h** was prepared from **4b** (400 mg, 0.92 mmol), 2-bromo-1-(4-chlorophenyl)ethanone (213 mg, 0.92 mmol) and dichloromethane (8 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 2:1 petroleum ether–EtOAc) resulted in **6h** (270 mg) as a brown solid, yield 52%; mp 202–204 °C; IR (KBr, cm^{-1}): 3110, 2901, 1590, 1552, 1504, 1474, 1440, 1400, 1307, 1236, 1085, 1041, 1007, 936, 820, 728, 489; ^{1}H NMR ($CDCl_3$, 400 MHz), δ: 7.63 (d, 2H, J = 8.3 Hz, ArCl), 7.28 (d, 2H, J = 8.3 Hz, ArCl), 6.91 (dd, 1H, J = 8.0, 1.5 Hz, benzo[d][1,3]dioxole), 6.87 (d, 1H, J = 1.8 Hz, benzo[d][1,3]dioxole), 6.80 (d, 1H, J = 8.0 Hz, benzo[d][1,3]dioxole), 6.78 (s, 1H, thiazole), 5.94 (dd, 2H, J = 4.3, 1.4 Hz, OCH_2O), 5.50 (dd, 1H, J = 11.3, 5.9 Hz, pyrazoline), 4.70 (d, 1H, J = 1.5 Hz, Cp), 4.59 (d, 1H, J = 1.5 Hz, Cp), 4.39–4.41 (m, 2H, Cp), 4.17 (s, 5H, Cp), 3.76 (dd, 1H, J = 17.2, 11.7 Hz, pyrazoline), 3.14 (dd, 1H, J = 17.3, 6.0 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{29}H_{23}ClFeN_3O_2S^+$: 568.0543, found: 568.0534.

*2.4.9. 4-(4-Chlorophenyl)-2-(3-ferrocenyl-5-(2-(benzyloxy)phenyl)-4,5-dihydro-1H-pyrazol-1-yl)thiazole (**6i**)*

Compound **6i** was prepared from **4c** (247 mg, 0.50 mmol), 2-bromo-1-(4-chlorophenyl)ethanone (116 mg, 0.50 mmol) and dichloromethane (4 mL) using the same procedure as described for **6a**. Purification of the solid by column chromatography (silica gel; 4:1 petroleum ether–EtOAc) resulted in **6i** (230 mg) as a brown solid, yield 73%; mp 211–214 °C; IR (KBr, cm^{-1}): 3108, 3089, 3063, 3032, 2891, 2858, 1592, 1555, 1494, 1475, 1447, 1242, 1105, 1088, 1042, 817, 755, 727, 687, 490; ^{1}H NMR ($CDCl_3$, 400 MHz), δ: 7.60 (d, 2H, J = 8.4 Hz, ArCl), 7.49 (d, 2H, J = 7.4 Hz, benzyl), 7.40 (t, 2H, J = 7.2 Hz, benzyl), 7.34 (t, 1H, J = 7.2 Hz, benzyl), 7.22–7.28 (4H, ArH), 7.02 (d, 1H, J = 8.1 Hz, ArO), 6.93 (t, 1H, J = 7.5 Hz, ArO), 6.77 (s, 1H, thiazole), 5.97 (dd, 1H, J = 11.3, 6.1 Hz, pyrazoline), 5.23 (s, 2H, $PhCH_2O$), 4.65 (s, 1H, Cp), 4.55 (s, 1H, Cp), 4.36 (d, 2H, J = 1.4 Hz, Cp), 4.07 (s, 5H, Cp), 3.77 (dd, 1H, J = 17.1, 11.7 Hz, pyrazoline), 3.06 (dd, 1H, J = 17.1, 6.2 Hz, pyrazoline); HRESIMS calcd for $[M+H]^+$ $C_{35}H_{29}ClFeN_3OS^+$: 630.1064, found: 630.1077.

2.5. X-ray crystallography

Suitable single crystals of **6e** and **6g** for X-ray structural analysis were obtained by slow evaporation of a solution of the solid in dichloromethane at room temperature for 3 days. The crystals with approximate dimensions of 0.15 mm × 0.15 mm × 0.10 mm for **6e** and 0.20 mm × 0.15 mm × 0.10 mm for **6g** were mounted on a Bruker Smart Apex II CCD equipped with a graphite monochromated MoKα radiation (λ = 0.71073 Å) by using φ and ω scan modes and the data were collected at 293(2) K. The structures of the two crystals were solved by direct methods and refined by full-matrix least-squares techniques implemented in the SHELXTL-97 crystallographic software. The non-hydrogen atoms were refined anisotropically. The hydrogen atoms bound to carbon were located by geometrical calculations, with their position and thermal parameters being fixed during the structure refinement. The final

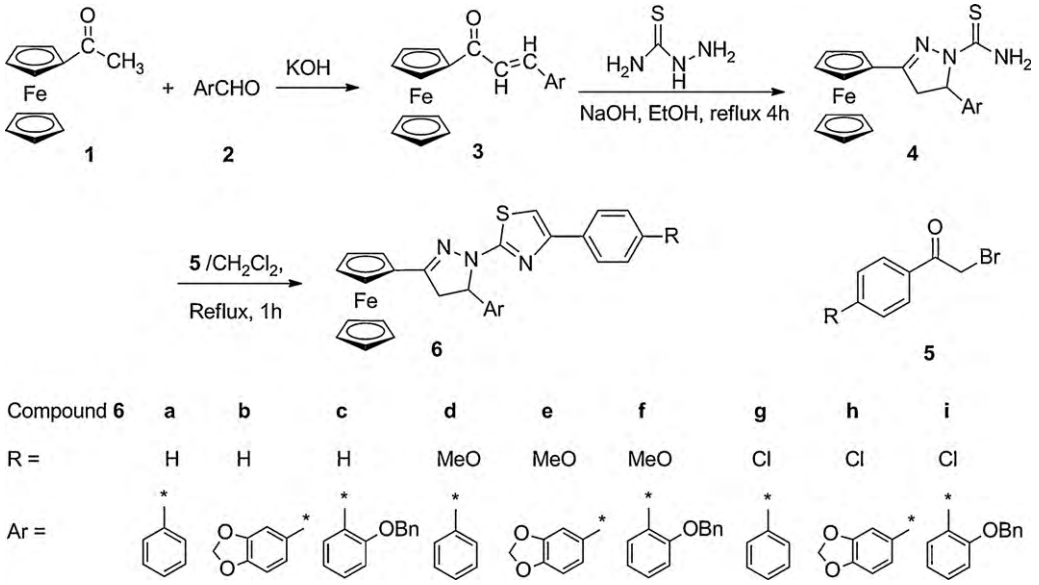

Fig. 1. Synthesis of 5-aryl-1-arylthiazolyl-3-ferrocenyl-pyrazoline derivatives.

refinement converged at $R_1 = 0.0327$, w$R_2 = 0.0847$ for **6e** and $R_1 = 0.0345$, w$R_2 = 0.0943$ for **6g**.

3. Results and discussion

3.1. Synthesis of compounds *6*

The synthetic route of compounds is outlined in Fig. 1. The three ferrocenyl chalcones (**3a–c)** were prepared by base-catalyzed solvent-free aldol condensation in 87%, 86% and 88% yields, respectively, in accordance with the method described in the literature [46]. The 5-aryl-3-ferrocenyl-4,5-dihydro-1*H*-pyrazole-1-carbothioamide (**4a–c**) were prepared by the reaction of ferrocenyl chalcones (**3a–c)** with thiosemicarbazide in 55%, 83% and 77% yield, respectively. The condensation of **4a–c** with appropriate phenacyl bromide (**5a–c**) resulted in the formation of 5-aryl-1-arylthiazolyl-3-ferrocenyl-pyrazoline derivatives (**6a–i**) in 48–90% yields.

3.2. Structure characterization

The structure of compounds (**6a–i**) was confirmed by IR, ^{1}H NMR and HRMS spectral data. The IR spectra of all the compounds **6a**–**i** showed ν (C=N) stretch at 1585–1607 cm^{-1} consisting with pyrazoline and thiazole moiety. In the 400 MHz ^{1}H NMR spectra of the compounds, the CH_2 protons of the pyrazoline ring resonated as a pair of doublets of doublets at d 3.05–3.19 ppm (Ha), 3.75–3.86 ppm (Hb). The CH (Hx) proton appeared as a doublet of doublets at d 5.50–5.99 ppm due to vicinal coupling with the two magnetically non-equivalent protons of the methylene

Table 1
Summary of crystallographic data and structure refinement details for **6e** and **6g**.

	6e	**6g**
Empirical formula	$C_{30}H_{25}FeN_3O_3S$	$C_{28}H_{22}ClFeN_3S$
Formula weight	563.44	523.85
Temperature	293(2)	293(2)
Wavelength	0.71073 Å	0.71073 Å
Crystal system	Tetragonal	Monoclinic
Space group	P4(2)/n	P2(1)/c
Unit cell dimensions	$a = 19.8938(7)$ Å, $\alpha = 90.00°$	$a = 11.5240(11)$ Å, $\alpha = 90.00°$
	$b = 19.8938(7)$ Å, $\beta = 90.00°$	$b = 10.2542(10)$ Å, $\beta = 96.226(2)°$
	$c = 12.7785(8)$ Å, $\gamma = 90.00°$	$c = 20.0417(18)$ Å, $\gamma = 90.00°$
Volume	5057.3(4) Å^3	2354.3(4) Å
Z	8	4
Calculated density	1.480 Mg/m^3	1.478 Mg/m^3
Absorption coefficient	0.718 mm^{-1}	0.866 mm^{-1}
F(000)	2336	1080
Crystal size	0.15 mm × 0.15 mm × 0.10 mm	0.20 mm × 0.15 mm × 0.10 mm
θ range for data collection	1.89–27.48°	2.23–26.66
Limiting indices	$-25 \le h \le 22$, $-25 \le k \le 24$, $-14 \le l \le 16$	$-14 \le h \le 14$, $-13 \le k \le 13$, $-25 \le l \le 15$
Reflections collected/unique	29169/5788 [R(int) = 0.0265]	13550/5298 [R(int) = 0.0225]
Completeness to $\theta = 27.5°$	99.6%	98.1%
Absorption correction	None	None
Max. and min. transmission	0.9317 and 0.8999	0.9184 and 0.8459
Refinement method	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2
Data/restraints/parameters	5788/0/443	5298/0/351
Goodness-of-fit on F^2	1.022	0.947
Final R indices [$I > 2\sigma(I)$]	$R_1 = 0.0327$, w$R_2 = 0.0847$	$R_1 = 0.0345$, w$R_2 = 0.0943$
R indices (all data)	$R_1 = 0.0460$, w$R_2 = 0.0933$	$R_1 = 0.0480$, w$R_2 = 0.1086$
Largest diff. peak and hole	0.284 and −0.318 e. Å^{-3}	0.297 and −0.225 e. Å^{-3}

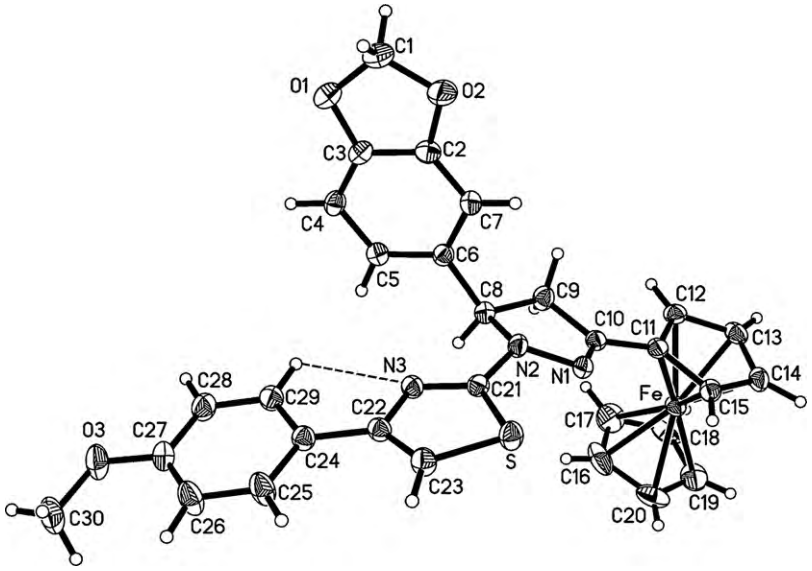

Fig. 2. The molecular structure of compound **6e**, with displacement ellipsoids drawn at the 30% probability level.

group at position 4 of the pyrazoline ring (J_{AB} = 17.1–17.3 Hz, J_{AX} = 6.0–6.3 Hz, J_{BX} = 11.7–11.8 Hz). It was noted that the chemical shift of CH proton in pyrazoline ring was downfield when the benzene ring was substituted by *o*-benzyloxyl benzene such as **6c**, **6f** and **6i**. The H_5-proton of thiazole was observed as a singlet between 6.66 and 6.80 ppm. All the other aromatic and aliphatic protons were observed at expected regions. In the ^{1}H NMR spectra of ferrocene moiety of compounds **6a**–**i**, four protons in mono-substituted Cp of Fc moiety appeared in the region of 4.35–4.41, 4.55–4.60 and 4.65–4.72 ppm as three singlet peaks and five protons of unsubstituted Cp appeared in the region of 4.06–4.17 ppm as singlet peak. HRMS showed that found [M+H]-ion peak accorded with calculated value. Moreover, typically, the structures of compound **6e** and **6g** were confirmed by X-ray diffraction analysis.

3.3. X-ray crystallography

The spatial structures of compounds **6e** and **6g** were determined by using X-ray diffraction analysis. A summary of crystallographic data collection parameters and refinement parameters for **6e** and **6g** are compiled in Table 1.

The single crystal structure and atomic numbering chosen for **6e** are shown in Fig. 2. One phenylthiazole moiety, one benzene ring and a ferrocence moiety are bonded to the pyrazoline ring which adopts a flat-envelope conformation with atom C8 deviating by −0.278 Å from the mean plane of the remaining atoms. In the asymmetry unit, the thiazole ring, two benzene rings and two cyclopentadienyl (Cp) rings are coplanar. And the thiazole ring makes dihedral angles with the benzene (C2–C7) and the substituted Cp ring of 85.4(1)° and 25.9(1)°, respectively, while the dihedral angle between thiazole and the conjoint benzene (C24–C29) is 9.4(1)°. The torsion angle (8.5°) defined as C(11)–C(centroid)–C(centroid)–C(16) indicates almost the eclipsed orientation of two Cp rings. Regarding the crystal structure of **6e**, there is a significant intramolecular C29–H29···N3 hydrogen bonds forming corresponding pseudo five-membered ring. In the crystal structure, four related molecules are linked into tetramer by intermolecular C—H···π hydrogen bonds (C23···Cg1 3.717(2) Å; C26···Cg2 3.545(3) Å) and further connected by weak C—H···π interactions (C13···Cg2 3.809(2) Å) (Fig. 3 and Table 2). Crystal packing diagram of **6e** is shown in Fig. 4.

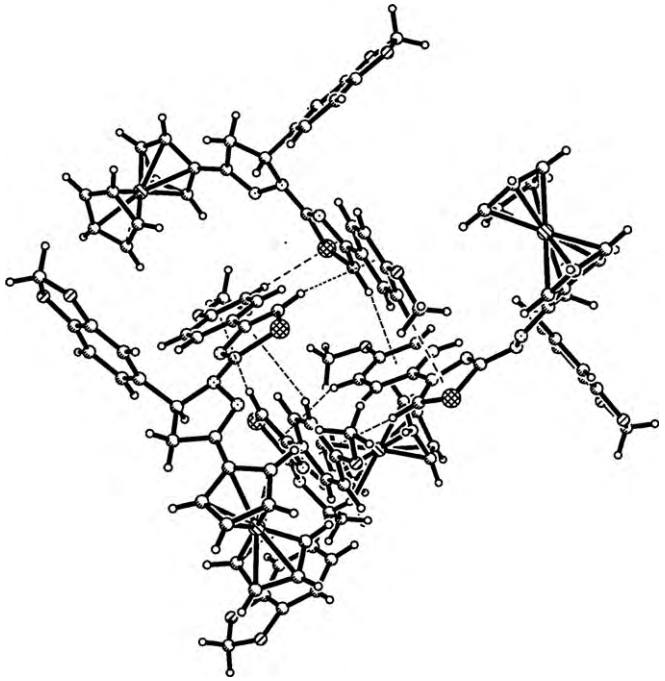

Fig. 3. Hydrogen bond in compound **6e**.

The single crystal structure and atomic numbering chosen for **6g** are shown in Fig. 5. In the ferrocenyl moiety, the cyclopentadienyl rings are perfectly planar but deviate slightly from parallel being 3.4(2)°, twisted from the eclipsed conformation by 1.3–2.7°.

Table 2
Hydrogen-bonding geometry of compound **6e**.

D–H···A[a]	D–H (Å)	H···A (Å)	D···A (Å)	D–H···A (°)
C29—H29···N3	0.94(2)	2.44(2)	2.776(2)	101(2)
C23—H23···Cg1^{i}	0.99(2)	2.75(2)	3.717(2)	167(2)
C13—H13···Cg2^{ii}	0.96(2)	2.98(2)	3.809(2)	146(2)
C26—H26···Cg2^{i}	0.93(3)	2.78(3)	3.545(3)	141(2)

Cg1 and Cg2 are the centroids of benzene (C24–C29) and thiazole ring, respectively.
[a] Symmetry code: (i) y, $3/2-x$, $3/2-z$; (ii) $-1/2+y$, $1-x$, $-1/2+z$.

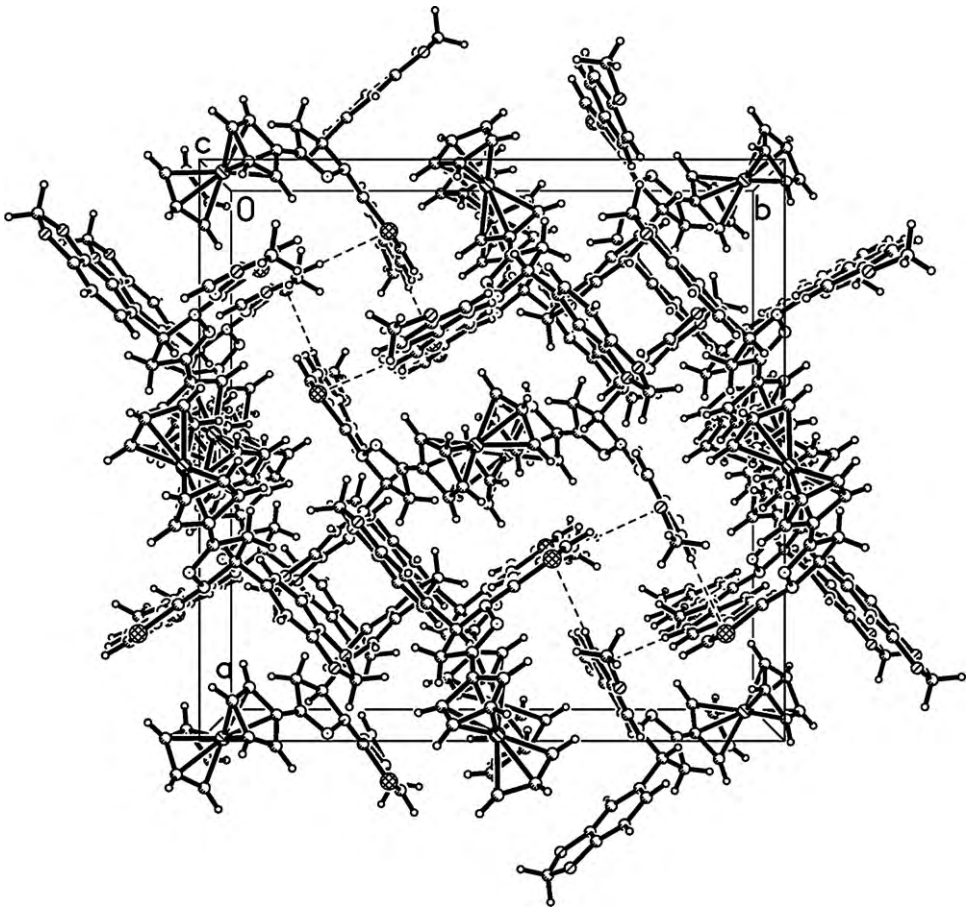

Fig. 4. Crystal packing diagram of **6e** along the *c*-axis.

The pyrazoline ring adopts a flat-envelope conformation with atom C12 (at the flat) deviating by −0.461 Å from the mean plane of the remaining atoms. The thiazole ring makes dihedral angles with the benzene (C13–C18) and the substituted Cp ring of 87.6(2)° and 32.1(2)°, respectively, while the dihedral angle between thiazole and the conjoint benzene (C1–C6) is 16.6(2)°. The molecular conformation is stabilized by intramolecular C5—H5···N1, C14—H14···N2 and C—H···π (C28···Cg3 3.853(3) Å) hydrogen bonds. In the crystal structure, centrosymmetric related molecules are linked into dimers by intermolecular C—H···π (C11···Cg4 3.789(2) Å) hydrogen bonds (Fig. 6 and Table 3). Furthermore, the molecules are connected by Cl(Cl (3.296 Å) interactions and intermolecular C—H···π (C22···Cg5 3.665(3) Å) interactions.

3.4. Absorption and fluorescence spectra

3.4.1. Absorption spectral characteristics of the compounds ***6a–i***

The absorption spectra of compounds **6a**–**i** shown in Fig. 7 have been recorded in dichloromethane solution with the concentration of 10^{-5} M. Several absorption peaks could be observed in the linear

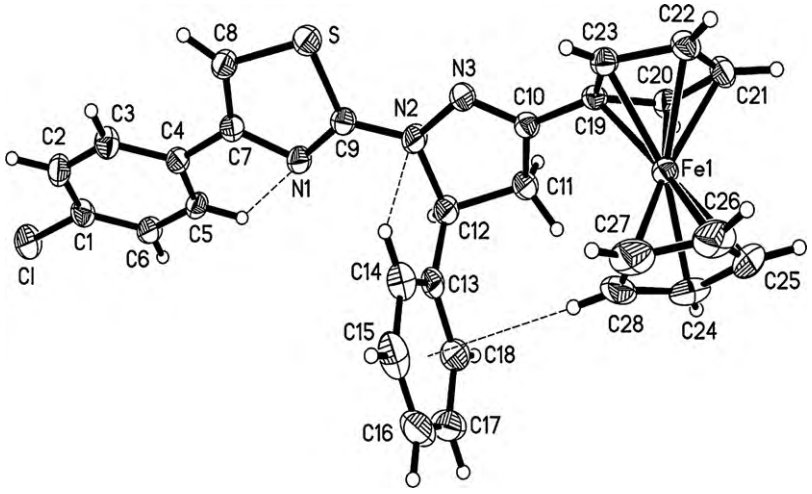

Fig. 5. The molecular structure of compound **6g**, with displacement ellipsoids drawn at the 30% probability level.

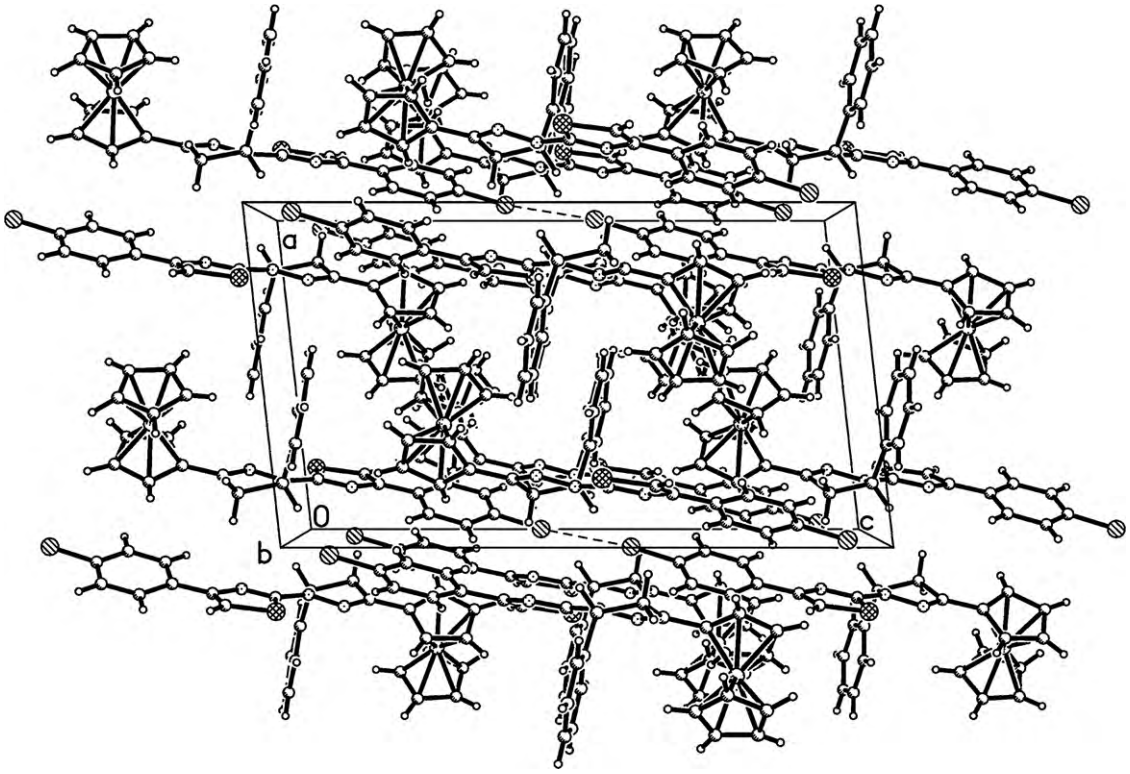

Fig. 6. Crystal packing diagram of **6g** along the *c*-axis.

Table 3
Hydrogen-bonding geometry of compound **6g**.

D–H···*A*[a]	D–H (Å)	H···A (Å)	D···A (Å)	D–H···*A* (°)
C5—H5···N1	0.93	2.52	2.847(3)	101
C14—H14···N2	0.93	2.50	2.846(3)	102
C28—H28···Cg3^{iii}	0.87(3)	2.98(3)	3.853(3)	177(2)
C11—H11B···Cg4^{iv}	0.97	2.89	3.789(2)	154
C22—H22···Cg5^{v}	0.92(2)	2.91(2)	3.665(3)	140(2)

Cg3, Cg4 and Cg5 are the centroids of benzene (C13–C18), thiazole and Cp (C24–C28) ring, respectively.

[a] Symmetry code: (iii) *x*, *y*, *z*; (iv) 2 − *x*, 1 − *y*, −*z*; (iv) 1 − *x*, 1/2 + *y*, 1/2 − *z*.

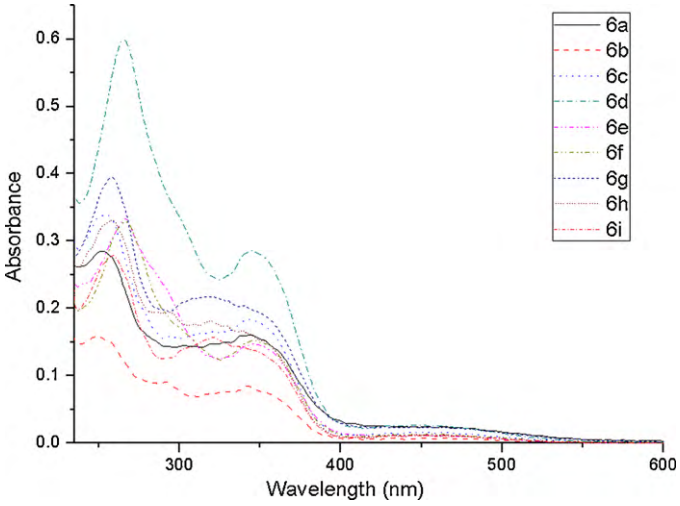

Fig. 7. UV–vis absorption spectra of compounds **6a–i** taken in dichloromethane at the concentration of 1×10^{-5} mol L^{-1}.

absorption spectra of all molecules in the wavelength range from 240 to 600 nm, while almost no linear absorption was observed beyond 600 nm. It can be seen that the spectral shapes are very similar due to these compounds possess a similar structure. The maximum absorptions ranging from 316 to 347 nm are attributed to the π–π* transition of the conjugated backbone. The maximum absorptions between 445 and 464 nm, although the absorbance is very less, are attributed to metal to ligand charge transfer (MLCT) transition from Fe to either the non-bonding or the antibonding orbitals of the cyclopentadienyl rings.

3.4.2. Substituent effects on UV–vis spectra

It can be found from Fig. 7 and Table 4 that the maximum absorption of compounds **6d–f** with electron-donating methoxyl group in 1-position thiazole moiety cause red shifts in dichloromethane solution compared with compounds **6a–c**. The maximum absorption of compounds **6g–i** with electron-withdrawing chloro group result in blue shifts compared with compounds **6a–c**. However, the substituent in 5-position have almost no influence on the maximum absorption, because aromatic (Ar) in C5 cannot extend to the π-conjugation system.

3.4.3. Solvent effects on UV–vis spectra

The absorption spectra of representative compounds **6c**, **6f** and **6i** which possess different substituent (H, OMe Cl) in phenylthiazole moiety and same substituent (BnOPh) in 5-position of pyrazoline moiety as well as compounds **6g–i** which possess same substituent (Cl) in phenylthiazole moiety and different substituent in 5-position of pyrazoline moiety in different solvents with the concentration of 1×10^{-5} M were studied. It was observed that the absorption spectra of these compounds in tetrahydrofuran were red shift compared with that in dichloromethane and chloroform, furthermore, the effect of solvent was more obvious in the case of compounds **6g–i** (Figs. 8 and 9 and Table 5).

Table 4
Optical characteristics of compounds **6a–i** in dichloromethane.

Compounds	6a	6b	6c	6d	6e	6f	6g	6h	6i
λ_{max} (nm)	252	251	254	266	266	266	258	258	259
	343	344	344	345	347	347	318	316	319
	464	453	449	445	446	445	452	452	446
ε_{max} ($L\,mol^{-1}\,cm^{-1}$)	27,315	14,827	30,790	57,227	31,729	32,141	35,779	31,909	27,136
	15,816	7831	17,094	27,530	14,278	14,708	21,573	17,518	14,835
	2479	635	1262	2605	1262	1185	2477	1210	1051

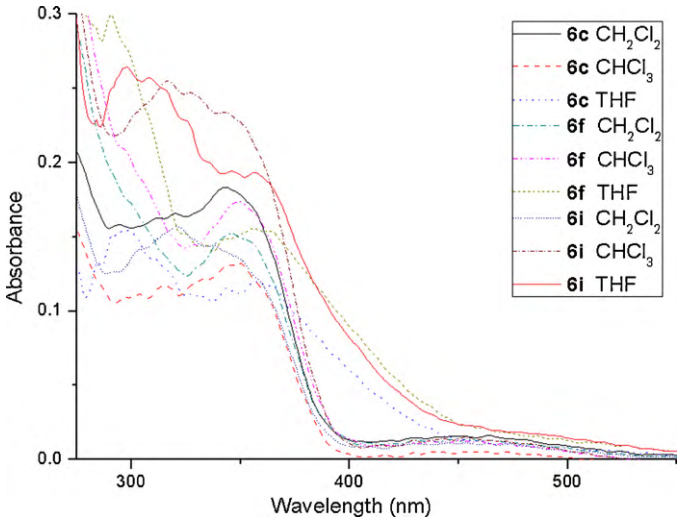

Fig. 8. UV–vis absorption spectra of compounds **6c**, **6f** and **6i** taken in different solvents at the concentration of 1×10^{-5} mol L^{-1}.

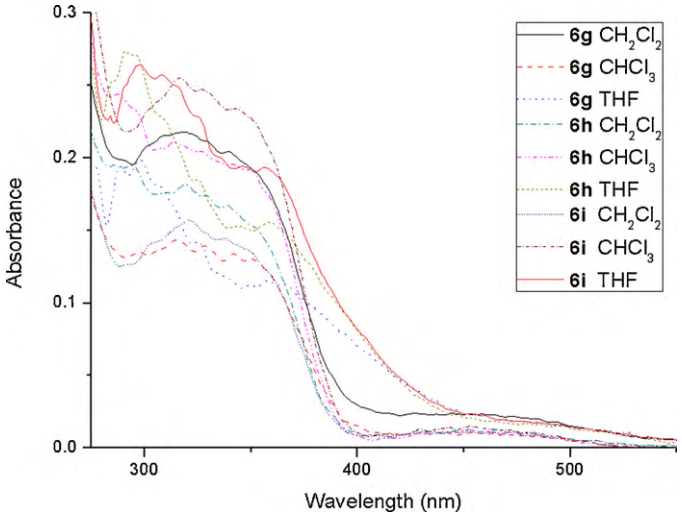

Fig. 9. UV–vis absorption spectra of compounds **6g**, **6h** and **6i** taken in different solvents at the concentration of 1×10^{-5} mol L^{-1}.

Table 5
Maximum absorption (λ_{max} (nm) of compounds **6c** and **6f-i** in dichloromethane, chloroform and tetrahydrofuran (1×10^{-5} mo L^{-1}).

Compounds	6c	6f	6g	6h	6i
CH_2Cl_2	344	347	318	316	319
$CHCl_3$	346	350	316	317	319
THF	361	358	359	359	358

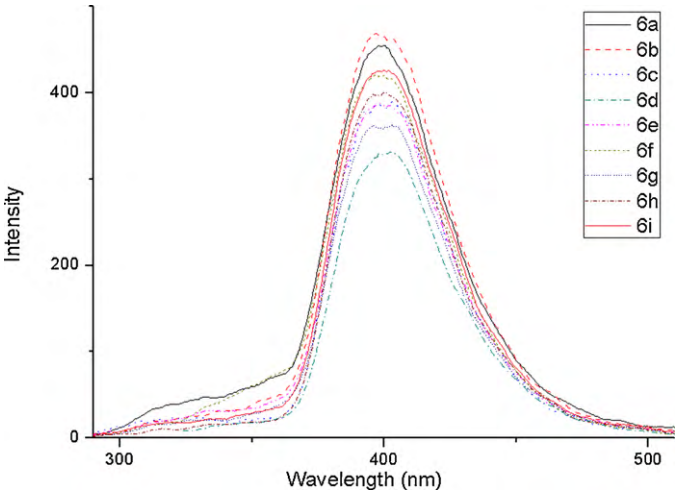

Fig. 10. Emission spectra of **6a–i** at 5×10^{-6} mol L^{-1} in dichloromethane (excitation slit width 10 nm, emission slit width 5 nm).

3.4.4. Fluorescence spectral characteristics

The emission spectra of compounds **6a–i** in dichloromethane solution (5×10^{-6} M) are shown in Fig. 10. Their excitation wavelengths are shown in Table 6. It can be found that their maximum emission wavelength and intensity of fluorescence differ from each other. Compounds **6a**, **6d** and **6g** which possess substituent phenyl group in 5-posision of pyrazoline ring have red-shift phenomenon compared with **6b**, **6e** and **6h** which possess substituent 3,4-dioxymethylenephenyl group in 5-posision of pyrazoline ring.

The effect of solvent on the emission spectra of representative compounds **6c** and **6f–i** was also investigated. It can be found that these compounds have red-shift phenomenon in tetrahydrofuran compared with in dichloromethane as shown in Fig. 11 and Table 6. The red shift effect might attribute to the polar solvent by which molecule is solvated significantly in the S1 excited state.

Table 6
Maximum excitation and emission wavelength of compounds **6a–i** in dichloromethane and THF solution (5×10^{-6} mol L^{-1}).

Compounds	CH_2Cl_2		THF	
	λ_{ex}	λ_{em}	λ_{ex}	λ_{em}
6a	273	400	nd[a]	nd
6b	269	397	nd	nd
6c	273	403	385	474
6d	309	403	nd	nd
6e	269	399	nd	nd
6f	272	400	386	483
6g	269	403	384	469
6h	272	400	389	480
6i	270	400	384	480

[a] nd: not determined.

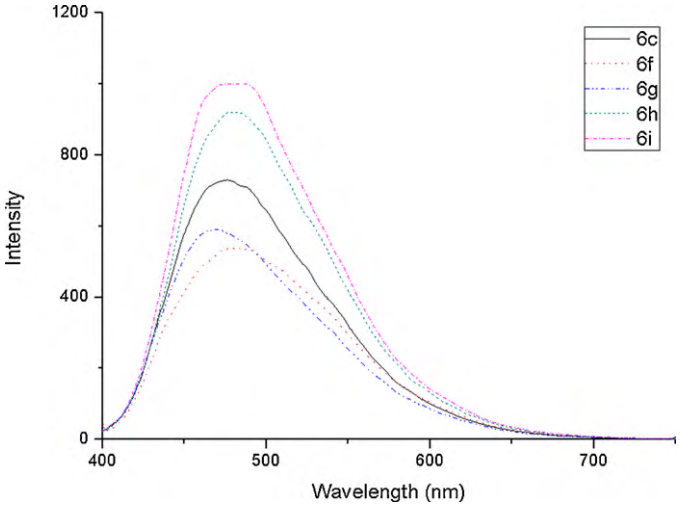

Fig. 11. Emission spectra of **6c** and **6f–i** at 5×10^{-6} mol L^{-1} in THF (excitation slit width 10 nm, emission slit width 5 nm).

4. Conclusion

A series of novel 5-aryl-1-arylthiazolyl-3-ferrocenyl-pyrazoline derivatives has been synthesized and characterized by IR, ^{1}H NMR and HRMS and X-ray diffraction analysis. The absorption and fluorescence characteristics of the compounds were investigated in dichloromethane, chloroform and tetrahydrofuran. The results showed that the absorption maxima of the compounds vary from 316 to 347 nm depending on the group bonded to phenylthiazole rings. The electron-donating methoxyl group in phenylthiazole moiety caused red shifts in dichloromethane solution, and the electron-withdrawing chloro group resulted in blue shifts. The absorption maxima of these compounds in tetrahydrofuran were red shift compared with that in dichloromethane and chloroform. The maximum emission spectra of compounds in tetrahydrofuran were also red shift compared with that in dichloromethane.

Supplementary materials

CCDC 763384 and 763385 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, by emailing data_request@ccdc.cam.ac.uk or by contacting The Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB21EZ, UK; fax: +44 1223 336033.

Acknowledgements

This study was supported by 973 Program (2010CB933504) and the National Natural Science Foundation of China (20972088).

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