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Electrochemistry and *in-situ* spectroelectrochemistry properties of *N*-, *S*-substituted-1,4-naphthoquinone compounds (NQ's)

Zeynep Ozyildiz [a], Celal Erkan [a], Nahide Gulsah Deniz [a,*], Zeliha Gokmen [a,*], Özlem Uğuz Neli [b], Atıf Koca [b,*]

[a] Istanbul University-Cerrahpasa, Engineering Faculty, Department of Chemistry, Division of Organic Chemistry, Avcilar 34320, Istanbul, Turkey
[b] Marmara University, Engineering Faculty, Department of Chemical Engineering, 34722 Goztepe, Istanbul, Turkey

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ABSTRACT

Quinones are ubiquitous in nature and form one of the largest classes of antitumor agents approved for clinical use. Naphthoquinones and their derivatives are important in many fields such as pharmaceutical, medical, and environmental applications. It is also known that such compounds show strong biological activity against various bacteria, viruses, fungi, and cancer cells. They are known to be efficient in inhibiting cancer cell growth. Under physiological conditions, they can undergo non-enzymatic one-electron reduction to give the moderately toxic species of semiquinone radical-anion. Thus, the electrochemical study of quinones might provide a basic knowledge of semi-quinone radical formation in both in vivo and in vitro under different media. In this study, firstly, novel *N*-, *S*- and/or halo(Br/Cl)-substituted-1,4-naphthoquinone derivatives (**2a-d**, **3e**, **4**, **6a-f**, **7**, **8** and **9**) were synthesized. The structures of all compounds were elucidated by using spectroscopic methods [FT-IR, NMR ($^{1}H/^{13}C$), MS, and microanalysis]. Electrochemical characterization indicated that all compounds underwent two well-resolved reduction reactions assigned to $NQ/NQ^{\cdot-}$ and $NQ^{\cdot-}/NQ^{2-}$ processes respectively. Additionally, an all-defined irreversible oxidation wave was also recorded for all compounds. The substituents on the NQ ring altered the peak position and reversibility of the electron transfer reactions. Redox processes considerably influenced the spectra of the compounds which showed different colors and spectra for different electrogenerated anionic and cationic forms of the compounds.

1. Introduction

The quinone-based compounds can exist in many structures, both naturally or synthetically obtained. The quinone derivatives have been widely studied by the scientist all around the world because of their diverse pharmacological properties of quinone pharmacophore. Quinone derivatives (e.g. benzo-, anthra-, and naphthoquinone (NQ) have important functions in various electrochemical and biological processes due to their rich electron transfer reactions. These molecules take part in two-electron reduction reactions in aprotic solvents and two-electron reduction and two-proton reactions in aqueous media. The character of these redox reactions provides them rich functionality in various applications such as enzyme catalysis, storage and transfer of genetic information, and the bioenergetics of the respiration [1,2]. For example, in many biological processes, the mechanism involves the reduction of the quinones as the first activating step. Thus, the electrochemical characterization of newly synthesized quinones issues is an important step to imitating the mechanism of the biological system [3]. Naphthoquinones (NQs) were intensively studied among quinones due to their applications in various bio-electrochemical applications such as redox acceptors, inhibitors, antimicrobials, and sensors [4–7]. To manipulate the redox responses of NQ compounds numerous electron-withdrawing and/or electron-releasing groups were substituted on the NQ ring and their functionality in different bio-electrochemical applications [2,8–11]. For example, Prince R.C. et.al. published electrochemical responses of many benzo-, anthra- and naphthoquinone derivatives and put forth their redox mechanism. They proposed that all quinone derivatives illustrated $NQ/NQ^{\cdot-}$ and $NQ^{\cdot-}/NQ^{2-}$ processes in aprotic solvents, and redox inactive substituents influenced their peak positions [12]. In our previous studies, we have reported electrochemical responses of different NQ derivatives and we illustrated the influence of the electron-withdrawing and/or releasing nature of the different substituents on their redox mechanisms [13,14]. As a continuation of our previous work, we have studied the synthesis, spectral,

* Corresponding authors.
E-mail addresses: yurdakul@iuc.edu.tr (N.G. Deniz), gokm@iuc.edu.tr (Z. Gokmen), akoca@marmara.edu.tr (A. Koca).

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electrochemical, and spectroelectrochemical analyses of novel NQ derivatives to manipulate the worth redox feature of NQ derivatives.

2. Material and methods

2.1. Apparatus

All the chemicals used in the present work were of reagent grade and procured from Sigma Aldrich and Alfa-Aesar. IR spectra were done on Shimadzu IR Prestige 21 model Diamond by ATR method. NMR spectra were performed on a Varian Unity Inova 125 MHz and 500 MHz instruments using solvents $CDCl_3$. Tetramethylsilane (TMS) was used as an internal standard. Chemical shift and coupling constant are provided in Hertz (Hz) and parts per million (ppm), respectively. QTRAP-4000 (hybrid triple quadrupole linear ion trap, ABSciex) using electron spray ionization method was used for recording the mass spectra and provided in *m/z*. Melting points were recorded by using the Büchi B-540 apparatus. Elemental analyses were performed on a Thermo Finnigan Flash EA 1112 elemental analyzer.

2.2. Electrochemistry and in situ spectroelectrochemistry

Electrochemical characterizations were performed with cyclic voltammetry (CV), square wave voltammetry (SWV), and controlled potential coulometry (CPC) by using a Gamry Reference 600 Potentiostat/Galvanostat. All measurements were carried out in a three-electrode configuration following the procedure conducted in our previous paper [14]. The three-electrode system consists of GCE, Pt wire, and Ag/AgCl electrodes as the working, counter, and reference electrodes respectively. 0.10 $moldm^{-3}$ tetrabutylammonium perchlorate (TBAP) dissolved in dimethyl sulfoxide (DMSO) was used as the electrolyte of the electrochemical cell. For spectroelectrochemical measurements, a thin-layer quartz spectroelectrochemical cell with a Pt mesh working electrode was used and an OceanOptics QE65000 diode array spectrophotometer was used as the light source.

3. Synthesis procedures

3.1. Procedure 1: Preparation of mono- and bis(thio)-substituted naphthoquinones (2a-d, 3e and 4)

In a 250 mL round bottom flask, one molar equivalent of starting compounds 2,3-dibromo-1,4-naphthoquinone (**1a)** or 2,3-dichloro-1,4-naphthoquinone (**1b**) and one molar equivalent of thiols were dissolved in dry ethanol (60 mL) and anhydrous potassium carbonate (0.934 g, 8.81 mmol) and stirred for 24 h at room temperature. Then dichloromethane (100 mL) was added to the reaction mixture. The organic layer was separated, washed with water (4 × 30 mL), and dried with anhydrous sodium sulfate. The solvent was evaporated, and the residue was purified by column chromatography on silica gel with solvents. The compounds **2a**, **2b** [23], **2c**, **2d** [24], **3e**, and **4** [25] were isolated by chromatography.

3.2. Procedure 2: Preparation of amino(substituted) and dimeric naphthoquinones (6a-f, 7 and 8)

In a 250 mL round bottom flask, one molar equivalent of compounds **1a** or **1b** and one molar equivalent of amines were stirred in chloroform (50 mL) for 8 h. The progress of the reaction was monitored by TLC. Chloroform (4 × 30 mL) was added to the reaction mixture. The organic layer was washed with water (100 mL), and dried with anhydrous sodium sulphate. After the solvent was evaporated the residue was purified by column chromatography with solvents. The new compounds **6a-f**, **7,** and **8** were isolated by chromatography.

3.3. Procedure 3: Preparation of dimeric naphthoquinone (9)

In a 250 mL round bottom flask, one molar equivalent of compound **1b** and one molar equivalent of amines were stirred in triethylamine (1 mL) in chloroform (25 mL) for 8 h. The progress of the reaction was monitored by TLC. Chloroform (4 × 30 mL) was added to the reaction mixture. The organic layer was washed with water (100 mL), and dried with anhydrous sodium sulphate. After the solvent was evaporated the residue was purified by column chromatography with solvents. The new crude compound **9** was isolated by chromatography.

3.4. 2,3-Bis((2-ethylhexylthio)naphthalene-1,4-dione (2a)

Synthesized from 1a: Compound **2a** was synthesized by the reaction of **1a** (0.50 g, 1.58 mmol) with 2-ethylhexanethiol (0.23 g, 1.58 mmol) according to procedure 1.

Yield: 0.55 g, 46 %; red oil; $R_f = 0.55$ in hexane/ethyl acetate (25:1) as a developing solvent; IR (ATR): 2955, 2923, 2859, 1656, 1590 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 0.87–0.91 (m, 12H, $4CH_3$), 1.26–1.32 (m, 16H, $8CH_2$), 1.38–1.56 (m, 2H, 2CH), 3.22–3.30 (m, 4H, $2S\text{-}CH_2$), 7.67–7.71 (m, 2H, $2CH_{naphthyl}$), 8.04–8.08 (m, 2H, $2CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 10.8, 14.0 (CH_3), 23.0, 25.3, 28.7, 29.7, 32.2 (CH_2, CH.), 39.1, 40.4 ($S\text{-}CH_2$), 126.8, 133.1, 133.3 ($C_{naphthyl}$), 148.7 (=C—S), 179.0 (C═O); MS [+ESI]: *m/z* (%): (1 0 0) 469.2 $[M + Na]^+$; Micro An.: $C_{26}H_{38}O_2S_2$ (M, 446.71 g/mol) = Calcd. C, 69.91; H, 8.57; S, 14.36; found C, 69.95; H, 8.58; S, 14.33 %.

Synthesized from 1b: Compound **2a** was synthesized by the reaction of **1b** (1.00 g, 4.40 mmol) with 2-ethylhexanethiol (0.65 g, 4.40 mmol) according to procedure 1.

Yield: 0.42 g, 36 %; red oil; $R_f = 0.37$ in petroleum ether/ethyl acetate (1:1) as a developing solvent; IR (ATR): 2963, 2919, 1657, 1590, 1589 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 0.87–0.91 (m, 12H, $4CH_3$), 1.26–1.60 (m, 18H, $8CH_2$, 2CH), 3.18–3.24 (m, 4H, $2S\text{-}CH_2$), 7.67–7.75 (m, 2H, $2CH_{naphthyl}$), 7.98–8.02 (m, 2H, $2CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 9.7, 13.8 (CH_3), 21.9, 24.3, 28.6, 31.2, 33.1 (CH_2, CH), 38.0, 39.3 ($S\text{-}CH_2$), 125.8, 132.3, 133.8 ($C_{naphthyl}$), 147.7 (=C—S), 177.9 (C═O); MS [+ESI]: *m/z* (%): (1 0 0) 447.1 $[M + H]^+$; Micro An.: $C_{26}H_{38}O_2S_2$ (M, 446.71 g/mol) = Calcd. C, 69.91; H, 8.57; S, 14.36; found C, 70.02; H, 8.52; S, 14.40 %.

3.5. 2,3-Bis(phenylethylthio)naphthalene-1,4-dione (2b) [23]

Compound **2b** [23] was synthesized by the reaction of **1a** (1.00 g, 3.17 mmol) with 2-phenyl ethanethiol (0.33 g, 3.17 mmol) according to procedure **1**.

Compound **2b** is synthesized by a different method from the literature [23]: 2,3-Dichloro-1,4-naphthoquinone was dissolved in ethanol (68.75 mL) and then into the resulting solution, thiol was added in small portions. The mixture was refluxed at 60℃ until completion of the reaction (TLC)).

Yield: 0.57 g, 49 %, (Lit. [23]: Yield 0.90 g (47 %); red oil; $R_f = 0.79$ in $CHCl_3$ as a developing solvent; IR (ATR): 3060, 3026, 2926, 2846, 1655, 1588 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 2.88–2.90 (m, 4H, SCH_2), 3.36–3.48 (m, 4H, CH_2), 7.11–7.14 (m, 10*H*, $CH_{arom.}$), 7.59–7.62 (m, 2H, $CH_{arom.}$), 7.90–7.98 (m, 2H, $CH_{arom.}$); ^{13}C NMR (125 MHz,): *δ* 34.8, 36.2, 38.9,125.5, 127.4, 127.8, 132.6, 138.8, 146.3, 158.2, 177.8 (C═O); MS [+ESI]: *m/z* (%): (85) 453.1 $[M + Na]^+$; Micro An.: $C_{26}H_{22}O_2S_2$ (M, 430.58 g/mol) = Calcd. C, 72.52; H, 5.15; S, 14.89; found C, 72.63; H, 5.12; S, 14.83 %.

3.6. 2,3-Bis(2-chlorobenzylthio)naphthalene-1,4-dione (2c):

Compound **2c** was synthesized by the reaction of **1a** (1.00 g, 3.17 mmol) with 2-chlorobenzene methanethiol (0.50 g, 3.17 mmol) according to procedure 1.

Yield: 0.60 g, 90 %; orange solid; mp: 124.9–125.0 °C; $R_f = 0.62$ in

$CHCl_3$ as a developing solvent; IR (ATR): 2978, 2904, 1656, 1587 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 4.59 (s, 4H, 2S-CH_2), 7.13–7.20 (m, 4H, 4CH_{benzyl}), 7.29–7.30 (d, 2H, CH_{benzyl}), 7.33–7.35 (d, 2H, CH_{benzyl}), 7.70–7.74 (m, 2H, 2$CH_{naphthyl}$), 8.06–8.10 (m, 2H, 2$CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 37.1 (S-CH_2), 126.9, 127.0, 129.0, 129.8, 131.1, 132.9, 133.6, 133.8, 134.4, 135.0 ($C_{naphthyl}$, C_{benzyl}), 148.0 (=C—S), 179.1 (C=O); MS [+ESI]: *m/z* (%): (100) 493.0 $[M + Na]^+$; Micro An.: $C_{24}H_{16}Cl_2O_2S_2$ (M, 471.42 g/mol) = Calcd. C, 61.15; H, 3.42; S, 13.60; found C, 61.18; H, 3.45; S, 13.62 %.

3.7. 2,3-Bis((4-metoxybenzyl)thio)naphthalene-1,4-dione (2d) [24]

Compound **2d** [24] was synthesized by the reaction of **1a** (1.00 g, 3.17 mmol) with 4-metoxytoluenethiol (0.49 g, 3.17 mmol) according to procedure 1.

Yield: 0.41 g, 35 %; red solid; mp: 194.6–194.9 °C (lit. [24]: Yield, 0.65 g (38.69 %). 194.0–195.0 °C); R_f = 0.62 in hexane/ethylacetate (2:1) as a developing solvent; IR (ATR): 3005, 2938, 2834,1644,1584 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 3.77 (s, 6H, O–CH_3), 4.44 (s, 4H, S–CH_2), 6.70–6.72 (m, 4H, H_{arom}), 7.14–7.18 (d, 4H, H_{arom}). 7.58–7.64 (m, 2H, $H_{naphthtyl}$) 7.92–7.98 (m, 2H, $H_{naphthtyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 37.8 (S–CH_2), 54.2 (O–CH_3), 112.9, 125.7, 128.1,129.4, 132.4,146.6,157.8,178.1 (C=O); MS [+ESI]: *m/z* (%): (100) 485.2 $[M + Na]^+$. Micro An.: $C_{26}H_{22}O_4S_2$ (M, 462.58 g/mol) = Calcd. C, 61.15; H, 3.42; S, 13.60; found C, 61.19; H, 3.48; S, 13.61 %.

3.8. 2-[1-(4-tert.-Butylbenzylthio]-3-chloro-naphthalene-1,4-dione (3e)

Compound **3e** was synthesized by the reaction of **1b** (2.00 g, 8.81 mmol) with 4-*tert*-butylbenzene-thiol (1.59 g, 8.81 mmol) according to procedure 1.

Yield: 0.62 g, 38 %; red solid; mp: 69.9–70.0 °C; R_f = 0.76 in petroleum ether/ethylacetate (1:2) as a developing solvent; IR (ATR): 3064, 2950, 2861, 1645, 1585, 1525 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 1.16–1.19 (s, 9H, CH_3), 4.38 (s, 2H, CH_2), 7.60–7.80 (m, 6H, 2$CH_{naphthyl.}$, 4CH_{phenyl}), 8.00–8.10 (d, 1H, $CH_{nafthtyl}$), 8.12–8.15 (d, 1H, $CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 30.3 (CH_3), 33.6 ($C_{tertbuthyl}$), 35.8 (S-CH_2), 124.5, 124.7, 125.6, 126.4, 127.7, 127.9, 128.5, 128.8, 132.3, 132.4, 133.3, 133.9, 149.5, 154.1 (C_{phenyl}, $C_{naphthyl.}$), 177.8, 181.0 (C=O); MS [-ESI]: *m/z* (%): (100) 351.6 $[M-H_2O]^+$; Micro An.: $C_{21}H_{19}ClO_2S$ (M, 370.89 g/mol) = Calcd. C, 68.00; H, 5.16; S, 8.65; found. C, 68.06; H, 5.17; S, 8.61 %.

3.9. 2,3,5,6,8,9-Hexahydronaphtho([2,3H][1,4]dioxo[7,10] dithiacyclododecyin)-11,16-dione (4) [25]:

Compound **4** [25] was synthesized by the reaction of **1a** (1.00 g, 3.17 mmol) with 2,2′-ethylenedioxyethanethiol (0.570 g, 3.17 mmol) according to procedure 1.

Compound **4** is synthesized by a different method from the literature [25]: A mixture of 2,2′-ethylenedioxyethanethiol (1.1 mmol) and Ce_2CO_3 (1.2 mmol) in DMF (15 mL) was cooled to 5–10 °C under nitrogen, and 1,4-naphthoquinone (1.0 mmol) in DMF (15 mL) was added to the mixture dropwise. The mixture was allowed to warm to room temperature. After 24 h, the mixture was poured into cold water (100 mL) and acidified with 5 % HCl (30 mL). The aqueous solution was extracted with CH_2Cl_2 (50 mLx4). The combined extracts were dried with $MgSO_4$ and concentrated under reduced pressure to provide a crude product. The crude product was purified by silica gel chromatography).

Yield: 0.35 g, 33 %; orange solid; mp: 174.8–175.2 °C (Lit. [25]: Yield, 72 %, mp: 175–176 °C). R_f = 0.45 in hexane:$CHCl_3$:CH_2Cl_2 (1:1:1) as a developing solvent; IR (ATR): 2979, 2901, 1665, 1507 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 3.30–3.36 (m, 8H, 4 CH_2), 3.62–3.66 (dd, *J* = 11.5, 5.7 Hz, 2 CH_2), 7.63–7.68 (dd, 2H, *J* = 5.7 Hz, 3.2 Hz, 2CH), 8.02–8.06 (dd, 2H, *J* = 5.7 Hz, 3.2 Hz, 2CH); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 34.2, 66.9, 69.8, 126.1, 132.5, 133.4, 148.5, 178.4 (C=O); MS [+ESI]: *m/z* (%): (100) 337.1 $[M + H]^+$; Micro An.: $C_{16}H_{16}O_4S_2$ (M, 336.43 g/mol) = Calcd. C, 57.12; H, 4.79; S, 8.65; found C, 57.18; H, 4.75; S, 8.68 %.

3.10. 2-(1-(3-Hidroxyphenyl)piperazinyl)-3-chloronaphthalene-1,4-dione (6a)

Compound **6a** was synthesized by the reaction of **1b** (0.80 g, 3.53 mmol) with 1-(3-hydroxyphenyl)piperazine (0.63 g, 3.53 mmol) according to procedure 2.

Yield: 0.51 g, 40 %; black solid; mp: 162.0–162.4 °C; R_f = 0.33 in ethylacetate/petroleum ether 1:2) as a developing solvent; IR (ATR): 3666, 2979, 2903, 1672, 1587, 1542 cm^{-1}; ^1H NMR (500 MHz, DMSO), δ (ppm): = 3.38–3.40 (m, 4H, 2$CH_{2piperazine}$), 3.78–3.80 (dd, *J* = 25.2, 20.4 Hz, 4H, 2$CH_{2piperazine}$), 4.95 (s, 1H, OH), 6.38–6.40 (d, *J* = 7.8 Hz, 1H, CH_{phenyl}), 6.51 (s, 1H, CH_{phenyl}), 6.52–6.58 (d, *J* = 8.2H, 1H, CH_{phenyl}), 7.10–7.17 (t, *J* = 8.1 Hz, 1H, CH_{phenyl}), 7.65–7.70 (dd, *J* = 7.4 Hz, 6.1 Hz, 1H, $CH_{naphthyl}$), 7.73–7.77 (m, 1H, $CH_{naphthyl}$), 8.00–8.05 (m, 1H, $CH_{naphthyl}$), 8.13–8.16 (m, 1H, $CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm): 50.2, 51.1 ($CH_{piperazine}$), 109.0, 126.6, 126.7, 127.0, 131.4, 131.6, 131.6, 133.1 133.2, 134.0, 134.2, 149.8, 156.6 ($C_{phenyl-OH}$), 178.1, 181.8 (C=O); MS[+ESI] *m/z* (%): (100) 368.7 $[M + H]^+$; Micro An.: $C_{20}H_{17}ClN_2O_3$ (M, 368.81 g/mol) = Calcd. C, 65.13; H, 4.65; N, 7.60; found C, 65.18; H, 4.61; N, 7.61 %.

3.11. 2-Bromo-3-(4-(pyridine-2-yl)piperazin-1-yl)naphthalene-1,4-dione (6b):

Compound **6b** was synthesized by the reaction of **1a** (1.00 g, 3.17 mmol) with 2-pyridinylpiperazine (0.52 g, 3.17 mmol) according to procedure 2.

Yield: 0.57 g, 27 %; red solid; mp: 100.9–101.1 °C; R_f = 0.46 in hexane/ethylacetate (3:1) as a developing solvent; IR (ATR): 2979, 2899, 1669, 1588, 1542 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 3.17–3.39 (m, 4H, $CH_{2piperazine}$), 3.80–3.84 (d, *J* = 13.2 Hz, 4H, $CH_{2piperazine}$), 7.08–7.18 (m, 2H, 2$CH_{pyridinyl}$), 7.22–7.25 (m, 2H, 2$CH_{pyridinyl}$), 7.70–7.73 (m, 2H, 2$CH_{naphthyl}$), 8.11–8.13 (m, 2H, 2$CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 43.2, 52.6 ($C_{piperazine}$), 110.0, 126.9, 128.3, 128.6, 129.5, 130.8, 131.4, 132.9, 133.9, 134.5, 140.1, 142.6 ($C_{naphthyl}$, $C_{pyridinyl}$), 155.9 (=C-Br), 175.8 (C=O); MS [+ESI]: *m/z* (%): (100) 398.1 $[M + H]^+$; Micro An.

$C_{19}H_{16}BrN_3O_2$ (M, 398.25 g/mol): Calcd. C, 57.30; H, 4.05; N, 10.55; found C, 57.35; H, 4.07; N, 10.52 %.

3.12. 3,3′-[(Etan-1,2-diylbis(azanediiyl)bis(etan-2,1-diyl))bis (azanediyl)]bis(2-bromo-naphthalene-1,4-dione) (7)

Compound **7** was synthesized by the reaction of **1a** (1.00 g, 3.17 mmol) with triethylenetetramine (0.46 g, 3.17 mmol) according to procedure 2.

Yield: 0.15 g, 30 %; purple oil; R_f = 0.80 in $CHCl_3$/ethyl acetate (2:1) as a developing solvent; IR (ATR): 3260, 2966, 2918, 1675, 1645, 1589, 1550 cm^{-1}; ^1H NMR (500 MHz, DMSO-d_6), δ (ppm): 1.86–2.00 (m, 2H, 2$NH_{aliphatic}$), 2.12–2.54 (m, 4H, CH_2-NH-$\underline{CH_2}$-$\underline{CH_2}$-NH), 3.60–3.73 (m, 4H, Naphtyl-NH-CH_2-$\underline{CH_2}$), 4.12–4.30 (m, 4H, Naphtyl-NH-$\underline{CH_2}$-CH_2), 5.36 (s, 2H, 2$\underline{NH}$-Naphthyl), 7.67–7.85 (m, 4H, $CH_{naphthyl}$), 8.09–8.10 (d, 2H, 2$CH_{naphthyl}$), 8.15–8.20 (q, 2H, 2$CH_{naphthyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 47.5, 50.2, 51.1 (NH-CH_2-CH_2-NH), 126.6, 126.7, 127.0, 131.4, 131.6, 131.6, 133.1 133.2, 134.0, 134.2, 149.8, ($C_{naphthyl}$), 109 (=C-Br), 156.6, 157.10 (=C—N), 178.1, 181.8 (C=O). MS [+ESI]: *m/z* (%): (100) 619.0 $[M + 3H]^+$; Micro An. $C_{26}H_{24}Br_2N_4O_4$ (M, 616.31 g/mol): Calcd. C, 50.67; H, 3.93; N, 9.09; found C, 50.70; H, 4.00; N, 9.05 %.

3.13. 2-(4-(4–2-Chloro-1,4-dihydro-1,4-dioxonaphthalene-3-ylamino) phenylpiperazin-1-yl)-3-chloronaphthalene-1,4-dione (8)

Compound **8** was synthesized by the reaction of **1b** (0.64 g, 2.81 mmol) with 1-(4-aminophenyl)piperazine (0.50 g, 2.81 mmol) according to procedure 2.

Yield: 0.62 g, 39 %; Brown solid; mp: 215.4–215.9 °C; R_f = 0.86 in petroleum ether/ethyl acetate (3:1) as a developing solvent; IR (ATR): 3292, 2956, 2916, 2812, 1673, 1637, 1591, 1556 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 3.17–3.40 (s, 4H, 2 N-$\underline{CH_{2piperazine}}$), 3.72–4.13 (m, 4H, $2CH_2$-*N*-$\underline{CH_{phenyl}}$), 7.58–7.72 (m, 4H, C_{phenyl}), 7.96–8.00 (d, 2H, $2CH_{naphtyl}$), 8.02–8.08 (t, 4H, $4CH_{naphtyl}$), 8.10–8.16 (d, 2H, $2CH_{naphtyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 48.7, 50.0 ($C_{piperazine}$), 123.9, 125.3, 128.2, 129.9, 130.6, 131.6, 139.1, 147.9 (C_{phenyl}, $C_{naphthyl}$), 175.8, 176.4, 178.9, 180.2 (C═O); MS [+ESI]: *m/z* (%): (100) 556.1 $[M-H]^+$; Micro An. $C_{30}H_{21}Cl_2N_3O_4$ (M, 558.41 g/mol): Calcd. C, 64.53; H, 3.79; N, 7.52; found C, 64.51; H, 3.74; N, 7.59 %.

3.14. 2,2′-[4-(4-([4-(4-Aminophenoxy)phenyl]sulfonyl)phenoxy) benzenaminyl]-3,3′-dichloronaphthalene-1,4-dione (9)

Compound **9** was synthesized by the reaction of **1b** (2.00 g, 8.81 mmol) with 4-(4-([4-(4-aminophenoxy)phenyl]sulfonyl)phenoxy) benzylamine (3.81 g, 8.81 mmol) according to procedure 3.

Yield: 2.54 g, 35 %; Red solid; mp: 158.5–159.2 °C; R_f = 0.30 in $CHCl_3$ as a developing solvent; IR (ATR): 3284, 3022, 1668, 1644, 1566 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$), δ (ppm): 5.30 (s, 2H, 2NH), 6.66 (s, 2H, $2CH_{phenyl}$), 6.80–6.89 (q, 4H, $4CH_{phenyl}$), 6.96–7.00 (d, 4H, $4CH_{phenyl}$), 7.26–7.31 (t, 2H, $2CH_{phenyl}$), 7.61–7.72 (t, 4H, $4CH_{phenyl}$), 7.79–7.84 (d, 4H, $4CH_{naphthyl}$), 8.02–8.05 (d, 2H, $2CH_{naphtyl}$), 8.09–8.12 (d, 2H, $2CH_{naphtyl}$); ^{13}C NMR (125 MHz, $CDCl_3$), δ (ppm); 115.97, 116.14, 117.23, 118.08, 120.44, 127.01, 127.25, 129.92, 132.41, 133.21, 135.16, 135.86, 139.30, 141.25, 155.14, 161.40 (C_{phenyl}, $C_{naphthyl}$), 177.40, 180.34 (C═O); MS [-ESI]: *m/z* (%): (100) 811.4 $[M-H]^+$; Micro An. $C_{44}H_{26}Cl_2N_2O_8S$ (M, 813.66 g/mol): Calcd. C, 64.95; H, 3.22; N, 3.44; S, 3.94; found C, 65.92; H, 3.26; N, 3.57; S, 3.98 %.

Methods and materials of all the synthesized compounds, their spectroscopic data, copies of NMR (^1H, ^{13}C), and MS spectra have been included in the supplementary data. Supplementary data associated with this article can be found via the supplementary content section of this article's web page.

4. Results and discussion

4.1. Chemistry

The quinone-based compounds can exist in many structures, both naturally or synthetically obtained. Several reports also contain the redox behaviors of quinone derivatives in electron transfer reactions. [15,19–22]. The synthesis of new synthetic heterocyclic compounds with quinone moieties has gained considerable importance in recent years. In the present study, as a continuation of our attempts to synthesize substituted quinone derivatives, we synthesized some of the novel thio-, bis(thio)-, and amino(substituted) naphthoquinone derivatives and characterized them with spectroscopic methods.

The mechanism for the reactions involves a Michael addition of a nucleophile to the reacting naphthoquinone compounds under an atmosphere of oxygen. Thio- and bis(thio)substituted compounds (**2a**, **2b** [23], **2c**, **2d**[24], **3e** and **4** [25]) were synthesized from the reactions of DHNQs (2,3-dibromonaphthoquinone (**1a**) and 2,3-dichloronaphthoquinone (**1b**) with Na_2CO_3 in the ethanolic medium at room temperature with some thiols (2-ethylhexanethiol, 2-phenyl-ethanethiol, 2-chlorobenzenemethanethiol, 4-metoxytoluenethiol, 4-*tert.*-butylbenzenethiol and 2,2′-ethylenedi-oxyethanethiol) as shown in Fig. 1.

Compound **2a** is the new compound synthesized from two different starting materials, DHNQs (**1a** and **1b)**. In the mass spectrum of the compound **2a**, the molecular ion peaks were observed at *m/z* (%) 469.2 (100) $[M + Na]^+$ and 447.1 (100) $[M + H]^+$ (Fig. S4a and S4b in Supplementary file**)**. Compound **2c** is a new compound synthesized from the reaction of compound **1a** with 2-chlorobenzene methanethiol at room temperature in ethanol with Na_2CO_3. In the mass spectrum of the compound **2c**, the molecular ion peak was observed at *m/z* (%) 493.0 (100) $[M + Na]^+$ (Fig. S12). The IR spectrum of compounds **2a** and **2c** showed characteristic carbonyl group's band at 1653 cm^{-1} (Figs. S1b and S9). The carbon atom signals of carbonyl groups of compounds **2a** and **2c** were observed at 179.0 and 179.1 ppm as one peak only in the ^{13}C NMR spectrum, respectively (Figs. S3a and S11). In addition, compound **3e** is a new thio(substituted) naphthoquinone compound synthesized from compound **1b.** In the ^{13}C NMR spectrum of compound **3e**, the carbon atoms of the carbonyl groups were given two signals at 177.8 and 181.0 ppm (Fig. S19). The molecular ion peak of compound **3e** was

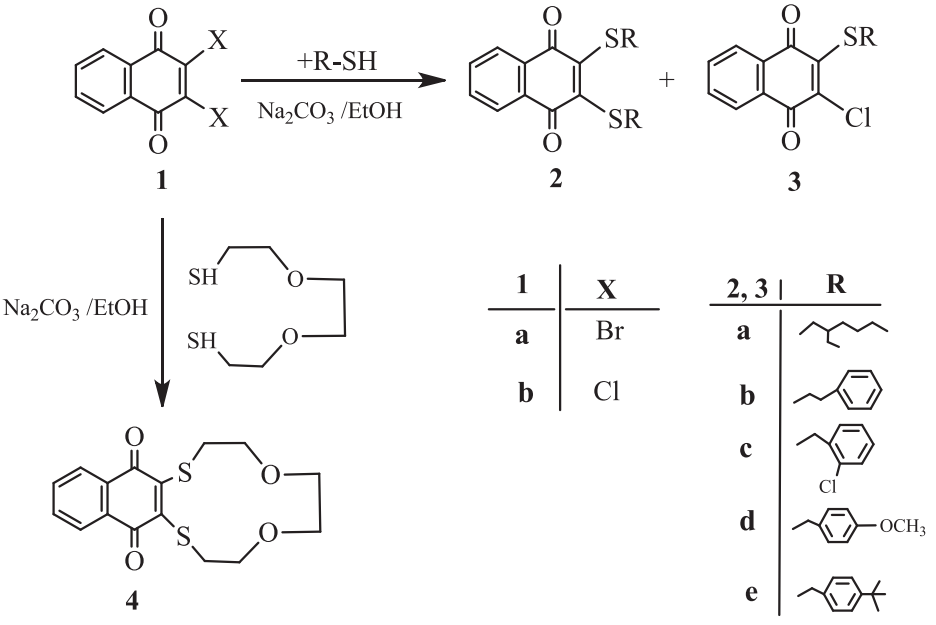

Fig. 1. The synthesis of *S*- and *S,S*-substituted-1,4-naphthoquinones **(2a-d**, **3e** and **4)**.

identified at *m/z* (%) 351.6 (100) $[M-H_2O]^+$ in the negative ion mode for the ESI technique (Fig. S20). Compounds **2b** [23], **2d** [24] and **4** [25] are known compounds synthesized from the starting compound **1b**. However, in this study, we synthesized the same compounds with good yields from compound **1a**, which is a different starting material. Compounds **2b** and **4** are synthesized by a different method from the literature [23,25]. In addition, R_f value, MS spectra, and microanalysis data of compound **2b** were included in this study for the first time, respectively.

The synthesis of a series of new piperazine(substituted) derivatives of 1,4-naphthoquinone focused on the replacement of one chlorine or bromine atom in quinone pharmacophore. The preparation of amino (substituted) naphthoquinone products is illustrated in Fig. 2. Amino (substituted) compounds **6a-6f** were obtained from the reactions of starting compounds **1a** and **1b** with piperazines in chloroform solution (Fig. 2).

Compounds **6a** and **6b** are new piperazine (substituted) naphthoquinone compounds. The IR spectrum the compound **6a** showed a band at 3666 cm^{-1} for the hydroxyl (–OH) stretching. (Fig. S25) and the proton of the hydroxyl group at 1H NMR of compound **6a** was observed at 4.95 ppm as singlet (Fig. S27). The protons of the piperazine at 1H NMR of the compounds **6a** and **6b** containing the piperazine ring were observed between 3.17 and 3.80 ppm. The molecular ion peaks of compounds **6a** and **6b** were identified at *m/z* 368.7 and 398.1 $[M+H]^+$ in the positive ion mode for the ESI technique, respectively (Figs. S28 and S32).

4.2. High-temperature nuclear magnetic resonance spectroscopy (NMR) analyses

In this study, the methylene protons of the piperazine ring of the 2-bromo-3-(4-(pyridin-2-yl)piperazin-1-yl)naphthalene-1,4-dione (**6b**) in ^1H NMR taken at 25 °C (in DMSO-d_6) and at 45 °C (in DMSO-d_6) were shown in Fig. 3. The peaks of piperazine methylene groups were determined as single broad and triplet between δ = 3.00-0.3.80 ppm (Fig. S30c). The piperazine protons are changing from axial to equatorial. This movement slows down at lower temperatures and picks up at higher temperatures. We saw that the peaks of piperazine ($-CH_2$) groups were singlet and triplet bands at room temperature and when the temperature of the NMR system increased from 25℃ to 45℃, the piperazine ring signals of compound **6b** were getting sharpened and changed. In this case, it was shown that the peaks of protons were not split but got sharpened at higher temperatures. It is thought that the non-split peaks corresponding to ($-CH_2$) protons of the piperazine ring may result from the effects of neighbor groups and ring isomerism.

The compounds **(6c-f)** were synthesized and reported before [3]. For this study, these compounds were synthesized again for investigation of their electrochemical studies. The Electro- and *in-situ* spectroelectrochemical analyses of these known compounds were first determined in this study.

Reactions of compounds **1a** and **1b** with triethylenetetramine, 1-(4-amino-phenyl)piperazine, and 4-(4-[4-(4-aminophenoxy)phenyl]sulfonyl)phenoxy)benzenamine resulted in the dimeric quinone compounds **7**, **8** and **9**. (Fig. 4) Aliphatic methylene protons attached to the naphthalene group of compound **7** gave multiplet peaks at 3.60–3.73 and 4.12–4.30 ppm in the ^1H NMR. The IR spectrum of compounds **8** and **9** showed a band at 3292 and 3284 cm^{-1} for the aromatic amine group (–NH) stretching, respectively (Figs. S37 and S41).

The specific single peak of the NH group was observed in the ^1H NMR spectrum at 5.36 and 5.30 ppm for compounds **7** and **9** (Figs. S34 and S42). Also, In the ^{13}C NMR spectrum, the carbonyl peaks were seen as four separate peaks at 175.8, 176.4, 178.9, and 180.2 ppm, confirming the structure of compound **8**. (**Fig. S39**). In the positive ion mode of electrospray ionization (ESI) mass spectra for compounds **7**, **8,** and **9** the respective molecular ion peak was observed at *m/z* (%) 619.0 $[M+3H]^+$, 556.1 $[M-H]^+$ and 811.4 $[M-H]^+$respectively. (**Figs. S36, S40 and S44**).

4.3. Electro- and in-situ spectroelectrochemical analyses

Electrochemical behaviors of fourteen NQ derivatives bearing different substituent environments are investigated on GCE working electrode with CV, SWV, and CV with various vertex potentials (CVvP) techniques in DMSO/TBAP vs. Ag/AgCl reference electrode, and the recorded voltammograms are compared with each other to predict the influence of the feature of the substituents. Voltammetric results tabulated in Table 1 and illustrated in Figs. 5–10 indicate that all NQ derivatives illustrated two well-resolved one-electron reduction couples between −0.21 and −0.49 V during the cathodic potential scans. Altering the substituents influences the peak position and chemical and electrochemical reversibility of the redox couples. In addition to the reduction processes, all derivatives illustrate one irreversible ill-defined oxidation process. While the reduction processes are observed with CV, SWV, and CV with different vertex potentials (CVvP) techniques, the oxidation processes have very low peak currents and ill-defined appearance even though these processes also have one electron

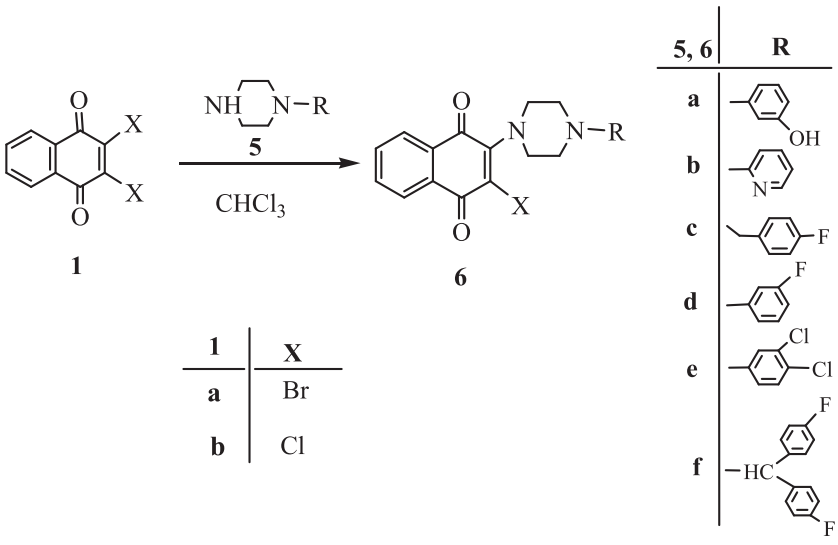

Fig. 2. The synthesis of *N*-substituted-1,4-naphthoquinones **(6a-f)**.

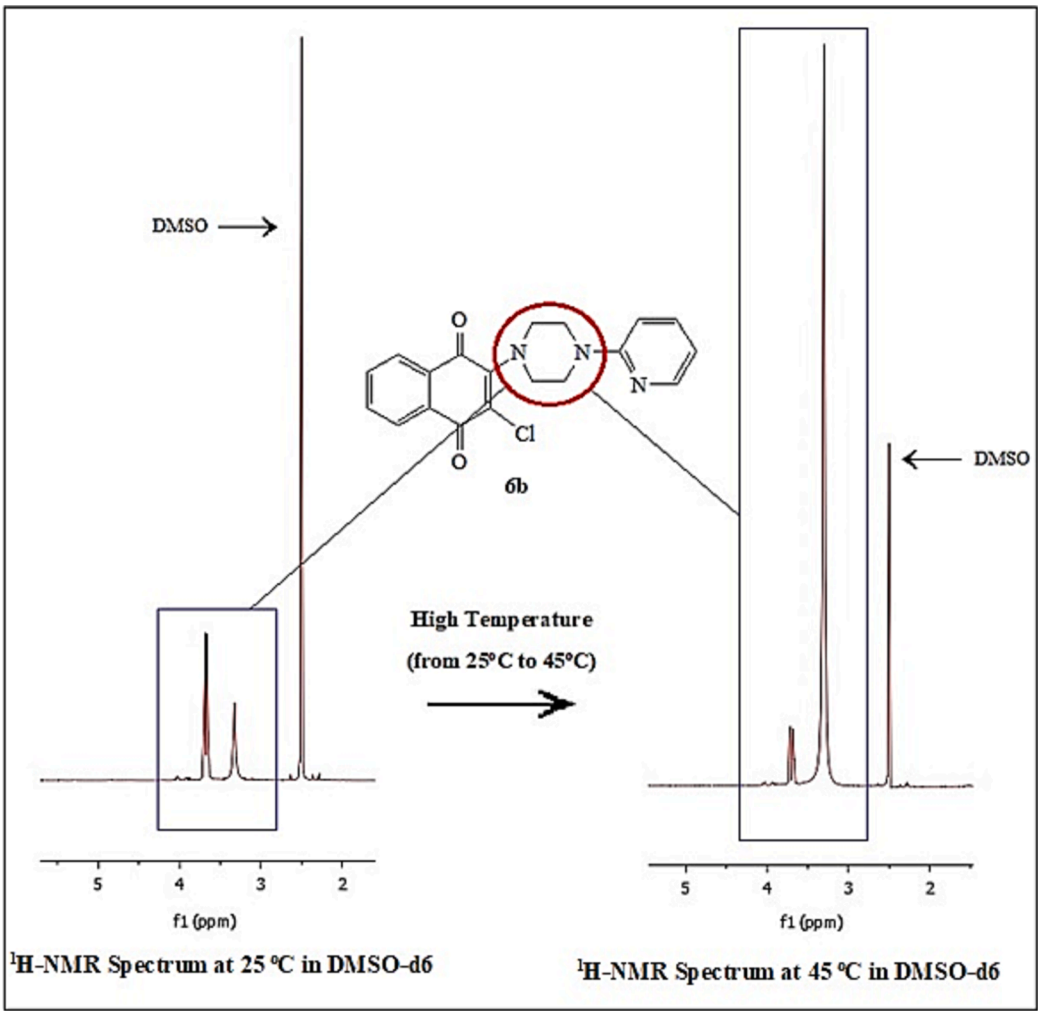

Fig. 3. ^{1}H NMR signals of the methylene protons of piperazine ring in **6b** at room temperature (25°C) and high temperature (45°C) in DMSO-d_6.

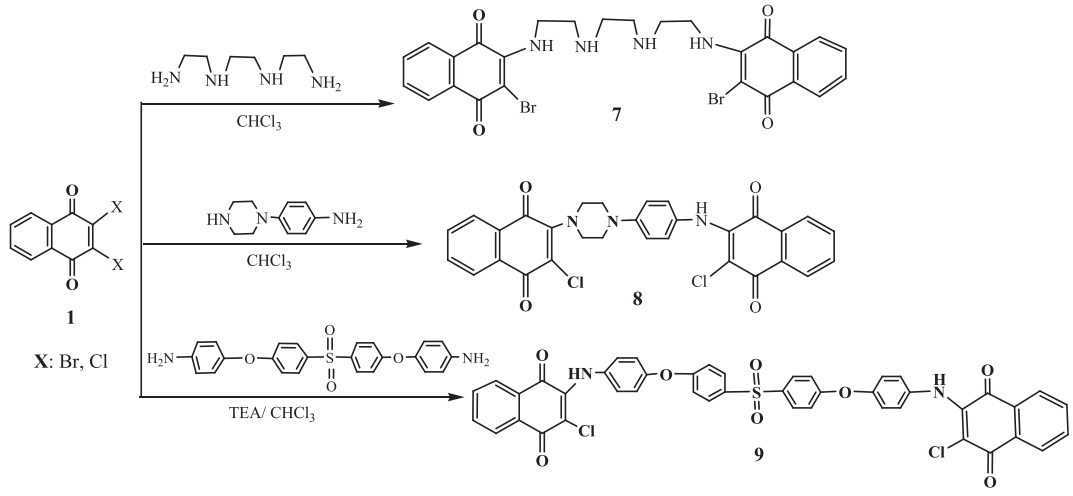

Fig. 4. The synthesis of *N*-substituted-1,4-naphthoquinones (**7**, **8** and **9**).

transfer character like the reduction counterparts. It is well known that the NQ ring can illustrate two successive 1e^{-} reduction processes for the reduction of NQ to NQ$^{\cdot -}$ radical anion and then to NQ^{2-} dianion [15–18]. The voltammograms recorded here are in harmony with these assignments. Additionally, the type, number, and positions of the substituents on the NQ ring significantly affect the redox responses of the NQs [15–18]. Here the influences of the type, number, and positions of the substituents are observed when the voltammograms are compared with each other.

Among the NQ derivatives, **7**–**9** illustrate remarkably different

Table 1
Voltammetric data of NQ derivatives.

Comp.	[a]NQ/NQ$^{\cdot-}$ reduction couple			[a]NQ$^{\cdot-}$/NQ^{2-} reduction couple			[a]NQ/NQ$^{\cdot+}$		
	$E_{1/2}$(V)	[b]Δ E_p(mV)	I_{pa}/I_{pc}	$E_{1/2}$(V)	[b]Δ E_p(mV)	I_{pa}/I_{pc}	[a]$E_{1/2}$(V)	[b]Δ E_p(mV)	I_{pa}/I_{pc}
2a	−0.42	115	0.90	−0.98	123	0.92	0.63	–	–
2b	−0.41	112	0.93	−0.97	120	0.90	0.62	–	–
2c	−0.44	110	0.91	−0.96	119	0.89	0.67	–	–
2d	−0.40	112	0.97	−0.97	120	0.95	0.66	–	–
3e	−0.45	61	0.96	−1.00	62	1.05	0.60	–	–
4	−0.44	73	0.97	−0.99	64	0.95	0.59	–	–
6a	−0.46	63	0.93	−1.03	64	1.07	0.58	–	–
6b	−0.44	65	0.94	−1.01	67	1.01	0.62	–	–
6c	−0.49	68	0.90	−1.08	66	1.02	0.55	–	–
6d	−0.46	67	0.92	−0.98	65	1.00	0.59	–	–
6f	−0.47	170	0.97	−1.03	75	0.98	0.60	–	–
7	−0.49	125	1.16	−1.05	110	1.13	0.74	–	–
8	−0.47	53	0.86	−0.95	68	1.26	0.63	–	–
9	−0.21	68	0.96	−0.86	82	0.92	0.76	–	–

([a]) = $E_{1/2}$ values were derived from the CVs recorded between 0.0 and −1.20 V. [b]: $\Delta E_p = |E_{pa} - E_{pc}|$.
All potentials were given vs. Ag/AgCl.

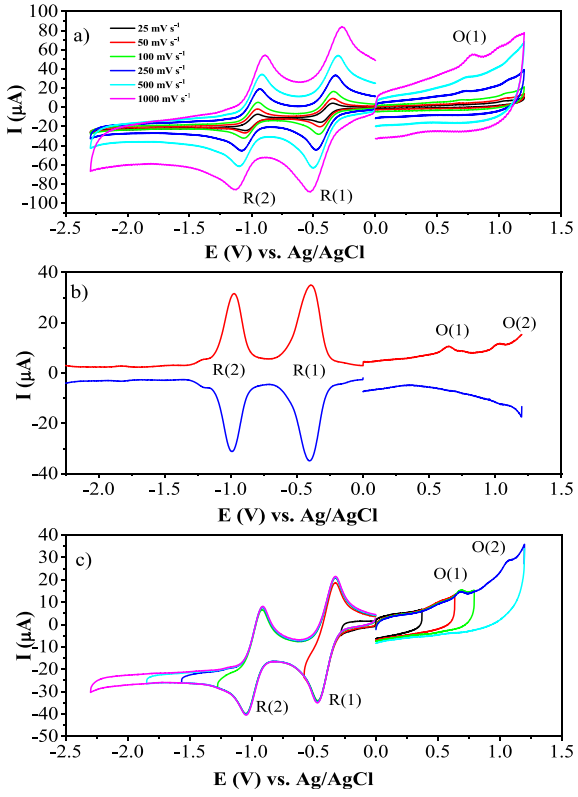

Fig. 5. A) CV, **b)** SWV and **c)** CVvP responses of compound **2d** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

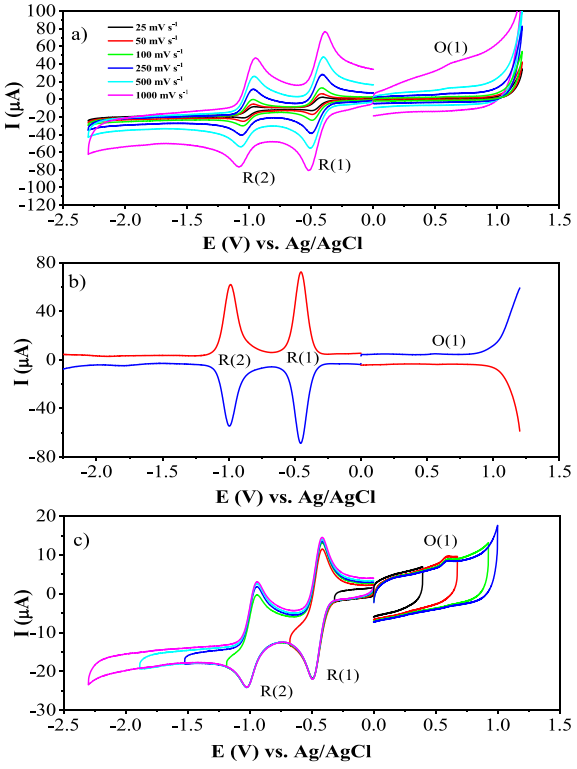

Fig. 6. A) CV, **b)** SWV and **c)** CVvP responses of compound **3e** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

reversibility for the reduction couples than the others due to the presence of two NQ units in these compounds. All other compounds illustrated electrochemically and chemically reversible reduction couples. Additionally, the linearity of the peak currents (I_p) versus the square root of the scan rates ($\nu^{1/2}$) for the redox couples of all compounds indicates diffusion-controlled mass transfer features during the redox processes.

2a-d compounds illustrate very similar voltammetric responses with each other with small potential shifts of the redox processes and the reversibility differences between them. The voltammetric responses of **2d are** illustrated in Fig. 5 as an example. The **2d** compound illustrates two one-electron reduction couples at −0.40 and −0.97 V and an ill-defined oxidation wave at 0.66 V. The anodic to cathodic peak separations (ΔE_p = 112 mV for R(1) and 120 mV for R(2)) of the reduction couples show their electrochemically quasi-reversible characters. However, the closeness of the anodic to cathodic peak current ratio (I_{pa}/I_{pc} = 0.97 for R(1) and 0.95 for R(2)) to unity indicates the chemical reversibility of the couples. Controlled potential coulometric analysis supported the one-electron transfer character of the reduction and oxidation processes. The proposed redox couples and their reversibility were well recorded with the SWV (Fig. 5b) and CVvP (Fig. 5b) measurements. CVvP responses also illustrate the possible influences of sequential redox reactions on each other. As shown in Fig. 5b, scanning the potential until just after the R(1) and R(2) does not influence the peak character of both couples. **2a**, **2b** and **2c** compounds indicates very similar peak characters with the **2d** compound. These responses show that the substituent on the compounds slightly alters the peak potentials and does not affect the reversibility of the NQ ring reduction couples.

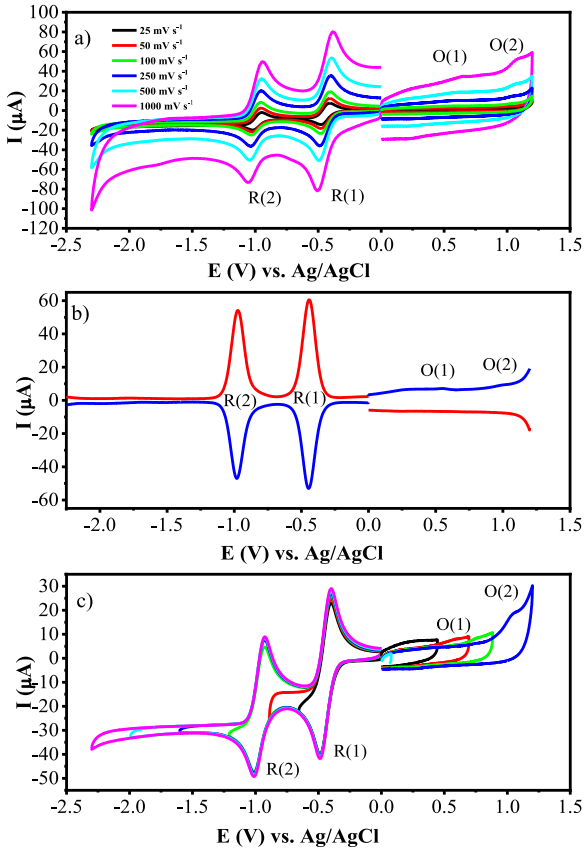

Fig. 7. A) CV, **b)** SWV and **c)** CVvP responses of compound **4** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

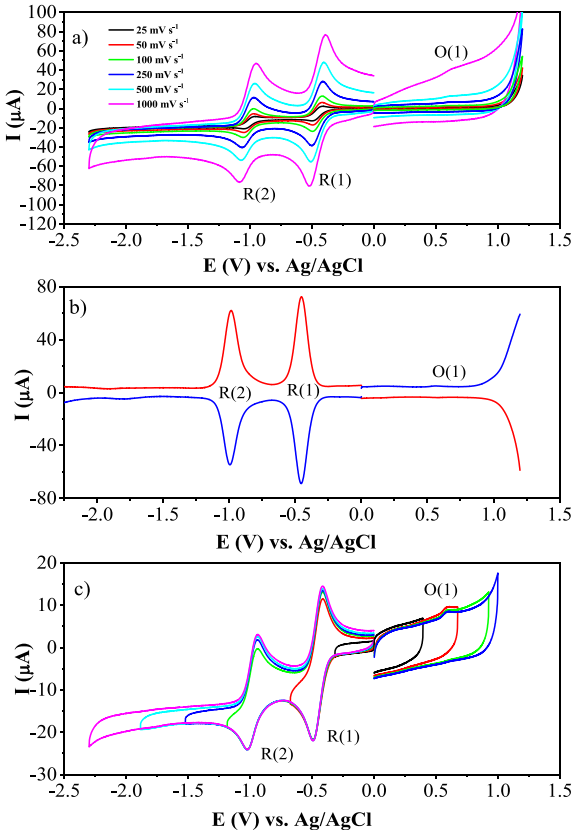

Fig. 8. A) CV, **b)** SWV, and **c)** CVvP responses of compound **6b** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

Among these compounds, **2d** is the easiest reduced one, and **2c** is the most difficult reduced one.

The compounds **3e** and **4** show very similar voltammetric responses although they have considerably different substituents, which shows that the substituents on these compound does not considerably influence the reversibility, but slightly influence the ease of electron transfer tendencies of them. Fig. 6 represents the CV, SWV, and CVvP responses of **3e**. As shown in the figure, both reduction couples at −0.45 and −1.00 V are electrochemically and chemically reversible concerning ΔE_p (61 mV for R(1) and 62 mV for R(2)) and I_{pa}/I_{pc} (=1.00 for R(1) and 1.05 for R(2)) responses. SWV (Fig. 6b), and CVvP (Fig. 6c) results support the reversibility of these couples. These voltammetric responses indicate that altering the S bridge alkyls or phenyl substituents with Cl makes the reductions of the NQ ring more reversible. Compound **4** (Fig. 7) shows similar redox waves with slightly less reversibility than those of compound **3**. The ΔE_p (73 mV for R(1) and 63 mV for R(2)) responses of the peaks at −0.44 and −0.99 V are slightly higher than the theoretical reversible ΔE_p of 59 mV. Additionally, reduction couples of **4** slightly shift toward the positive potentials concerning compound **3**.

All **6a**, **6b**, **6c**, and **6d** compounds illustrate similar reduction couples having similar reversibility with those of **3** and **4**. Voltammetric responses of **6b** are represented in Fig. 8 as an example. The reduction couples of **6b** are observed at −0.44 and −1.01 V and ΔE_p (65 mV for R(1) and 67 mV for R(2)) and I_{pa}/I_{pc} (1.01 for R(1) and 1.01 for R(2)) analyses show electrochemical and chemical reversibility of these processes. Additionally, an irreversible small oxidation wave is recorded at 0.62 V during the anodic potential scans. All **6a**, **6c**, and **6d** also illustrated similar redox responses with small potential shifts and different reversibility as shown in Table 1.

Even though compounds **7**–**9** have two NQ units in the structure, these compounds illustrated similar voltammetric responses with the

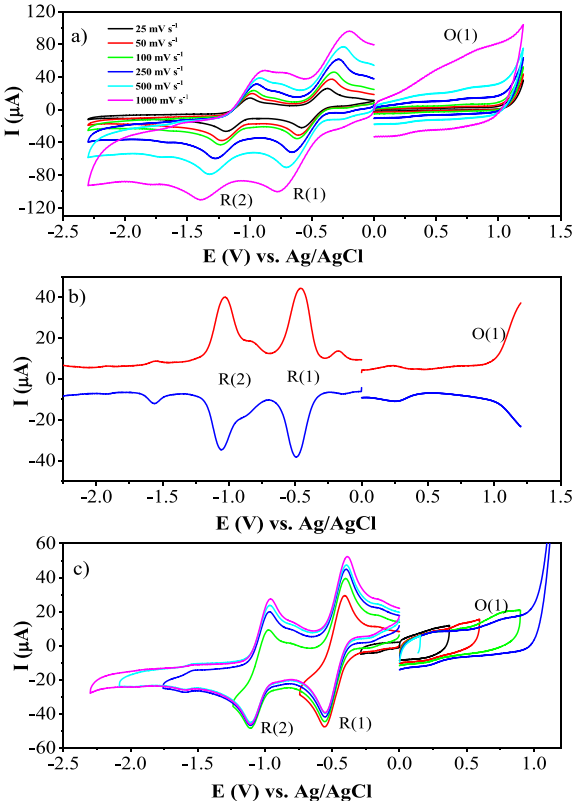

Fig. 9. A) CV, **b)** SWV, and **c)** CVvP responses of compound **7** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

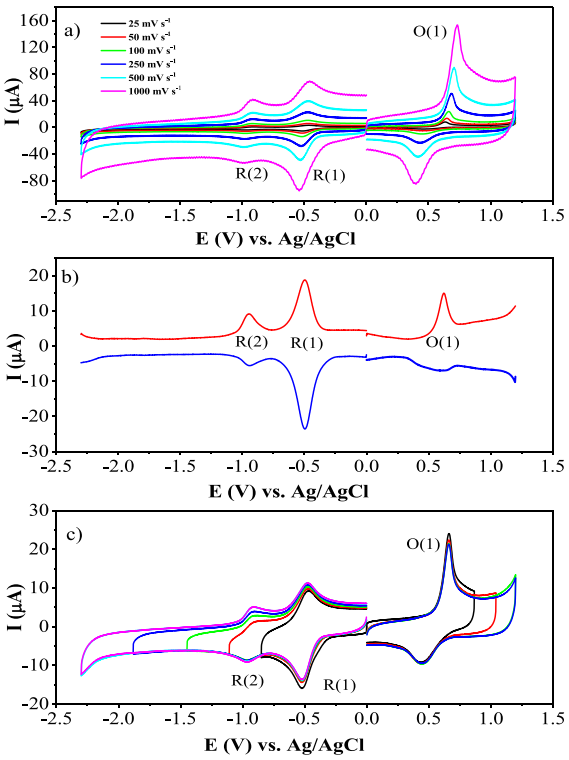

Fig. 10. A) CV, **b)** SWV and **c)** CVvP responses of compound **8** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

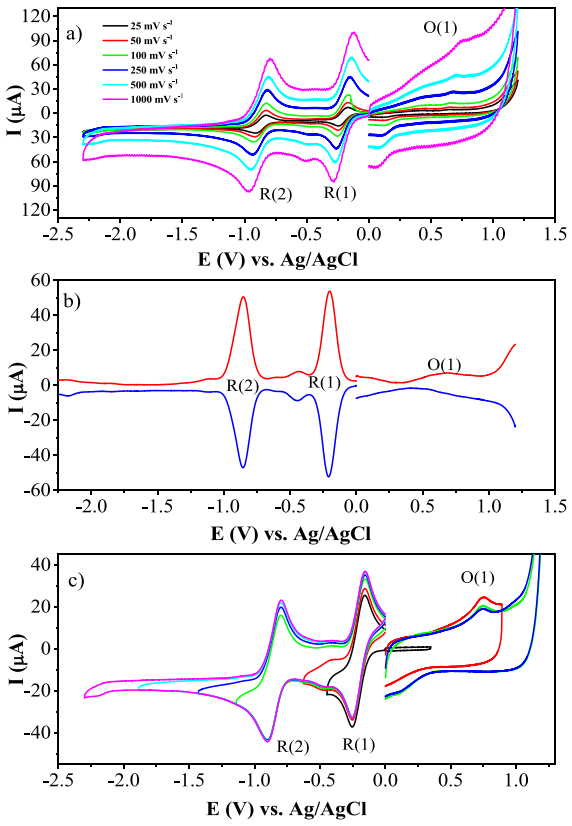

Fig. 11. A) CV, **b)** SWV, and **c)** CVvP responses of compound **9** (5.0 10^{-5} mol dm^{-3}) at various scan rates on GCE in DMSO/TBAP.

others (2–6) having only one NQ unit. Although these compounds are expected to give two reduction couples having two-electron transfer characters, voltammetric studies show that these complexes give very similar redox responses with the compounds 2–6 having one main NQ unit. These behaviors might be because both NQ units are reduced at the same potential due to the very similar electron density on the NQ units since the linker structure and its electron releasing and/or withdrawing tendency to each NQ unit should be identical. Due to the similar voltammetric responses with the others, the redox peak characters of the compounds **7**–**9** could be assigned to sequential reduction of one of the NQ units to monoanionic during the first reduction reaction and then to dianionic during the second reduction reaction. We have performed controlled potential electrolysis analyses which indicated the one-electron character of all couples. The presence of two NQ units and the type of the linkers between these units also influence the reversibility of the redox couples of compounds 7–9. As shown in Fig. 9, The alkyl amine linkers between the two NQ units of compound **7** considerably decrease the electrochemical reversibility of the reduction couples. ΔE_p values of R(1) (at −0.49 V) and R(2) (at −1.05 V) increase to 125 mV and 119 mV respectively which deviates their behaviors towards irreversibility. The redox couples of compound **8** have different characters than those of compound **7.** As shown in Fig. 10, while the R (1) couple of compound **8** has similar characters with that of other compounds, the R(2) couples has very small anodic and cathodic peaks concerning R(1), even though both R(1) and R(2) couples are found as one-electron transfer processes with controlled potential coulometric analysis. This different current response may result from the presence of a fast chemical reaction succeeding R(1). The chemical reaction most probably could be the decomposition of the monoanionic NQ species at a more negative potential application. Additionally, while all compounds have oxidation waves with very small peak currents concerning reduction waves, this is not the case for compound **8**. The O(1) couple has a peak current as high as that of the R(1) couple.

As shown in Fig. 11, compound **9** illustrates similar voltammetric responses with those of **6a**, **6b**, **6c**, and **6d**, even though this compound has different substituents. Two reversible one-electron reductions are observed at −0.21 V (R(1)) and −0.86 V (R(2)) are observed for compound **9**. Due to the different electron-withdrawing nature of the substituents, different redox couples of **9** shift towards positive potentials considerably. Thus compound **9** is found as the easiest reduced one among all compounds.

When we compare the voltammetric results studied here with those of published NQ derivatives, the two reduction reactions are in agreement with each other. In our previous study, we investigated electrochemical responses of the N-,O-substituted-5-Nitro-1,4-naphthoquinones (NQ) and we observed a reduction of NQ to the $NQ^{\cdot-}$ radicalic anion and then reduction of $NQ^{\cdot-}$ radicalic anion to the NQ^{2-} dianion between −0.10 and −1.10 V in addition to the reduction of dimeric species (NO_2/NO_2^{1-}) after −1.60 V [13]. Here we have observed NQ / $NQ^{\cdot-}$ and $NQ^{\cdot-}/NQ^{2-}$ processes however, the reduction of dimeric species (NO_2/NO_2^{1-}) is not differently observed. Additionally, the reduction reactions are observed at more negative potentials concerning the N- and O-substituted-5-Nitro-1,4-naphthoquinones (NQ) published. In a review paper, Prince R.C. et.al. summarized the electrochemical responses of many naphthoquinones in dry dimethylformamide containing 50 mM tetrabutylammonium-fluoroborate versus a saturated calomel electrode and they reported that the reported $E_{1/2}$ value of NQ / $NQ^{\cdot-}$ couple deviated from −0.167 V to −1.016 V by altering the substituents on the NQ ring. Similarly, $NQ^{\cdot-}/NQ^{2-}$ processes were reported between −094 and −1.60 V [12].

Although electrochemical characterizations of NQ derivatives were intensely studied in the literature, there are few studies on the *in situ* UV–Vis spectroelectrochemical characterization of them [14,18,19]. For instance, S. Záliš et.al reported the spectra of the neutral, monoanionic, and dianionic NQ species [19]. For example, Hui Y. et.al. reported the investigation of the degree of hydrogen bonding in the monoanionic

radical and dianion of vitamin Vitamin K1 which is a kind of phylloquinone with the *in situ* UV–Vis spectroelectrochemical measurements and they correlated the stability of the reduced species with the spectroelectrochemical responses [18]. In another study, Záliš S. and coworkers reported the spectral changes recorded under potential control and investigated the bands of neutral and reduced species of naphthoquinones containing aniline moiety [19]. Our previous study also reported the *in situ* UV–Vis spectroelectrochemical responses of different NQ derivatives to support the redox mechanism proposed from the voltammetric measurements [13]. Here, we have performed the *in situ* UV–Vis spectroelectrochemical characterizations of NQs to determine the optoelectronic responses of neutral monoanionic radical and dianionic and monocationic radical forms of the compounds. *in situ* UV–Vis spectroelectrochemical results of all compounds show approximately similar spectral changes thus *in situ* UV–Vis spectral changes of compound **8** are represented as an example in Fig. 12.

When there is no applied potential on the working electrode, four bands are observed at 300, 470, 510, and 541 nm for the neutral NQ **8** (Fig. 12a). When −0.60 V is applied to the working electrode for the R (1) process, while the bands at 510 and 541 nm diminish in intensity, four new bands are enhanced at 396, 436, 472, and 582 nm (Fig. 12a). Clear well-resolved isosbestic points at 497 and 563 nm show the chemical reversibility of the reduction of NQ to $NQ^{\cdot -}$ species. After the first reduction reaction, when the reverse potential was applied the initial spectrum of the neutral NQ **8** was obtained again which supported the chemical reversibility of this reduction. During R(1) process the pink color of the neutral NQ (point; x = 0.351 and y = 0.289) changes to light orange (point; x = 0.344 and y = 0.349) for the $NQ^{\cdot -}$ species (Fig. 12d). Under −1.20 V application (Red(2) process), while the band at 392 nm continues to increase, the band at 442 nm shifts to 430 nm with increasing. At the same time, other bands decrease in intensity (Fig. 12d). Like R(1), two isosbestic points at 354 and 444 nm are observed during the R(2) process due to the chemical reversibility of the $NQ^{\cdot -}/NQ^{2-}$ process of the compound **8** (Fig. 12b). During this process, the light purple color of the $NQ^{\cdot -}$ species turns to deep yellow (point; x = 0.481 and y = 0.396) as shown in the chromaticity diagram (Fig. 12d). Although compound **8** illustrates an ill-defined oxidation wave in CV and SWV, it illustrates clear spectral changes as shown in Fig. 12c. Observation of new bands at 346, 390, 438, and 471 nm and decreasing the band at 541 nm causes a color change from light purple to red color (point; x = 0.408 and y = 0.326) for the cationic NQ species. The isosbestic point at 525 nm and returning the spectra to the original one after the reduction of the oxidized species indicate chemical reversibility of the oxidation of NQ to $NQ^{\cdot +}$ species, although voltammetric analyses indicate only anodic wave for the compound **8** which behaves as an electrochemically irreversible wave. The profound spectral changes and well-resolved color differences of the electrogenerated species indicate their possible usage in various electrooptical applications, such as electrochromism and data storage.

5. Conclusions

The quinone-based compounds can exist in many structures, both naturally or synthetically obtained. Synthesis of new synthetic heterocyclic compounds with quinone moiety has gained considerable importance in recent years. The quinone derivatives have been widely studied by the scientist all around the world because of their diverse pharmacological properties of quinone pharmacophore. Derivatization

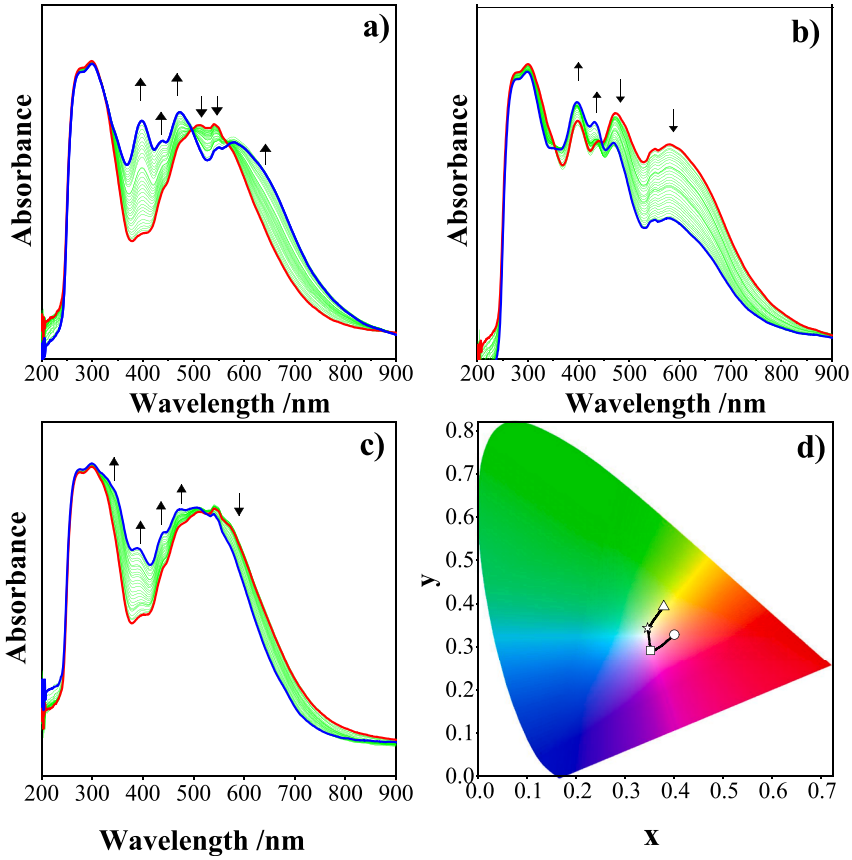

Fig. 12. UV–Vis spectral changes of compound **8** (1.0 10^{-5} mol dm^{-3}) recorded during *in-situ* spectroelectrochemical measurements at applied potentials of **a**) E_{app} = -0.60 V, **b**) E_{app} = -1.25 V, **c**) E_{app} = 0.80 V in DMSO/TBAP electrolyte system (changing of the spectrum during the redox reactions were represented with the arrow directions) and **d**) color of the species (Neutral:; Red(1):; Red(2):; O(1):).

of 2,3-dihalo-1,4-naphthoquinone compounds (DHNQs) focuses on amino, thio, and alkoxy substituted compounds as they contain biological activity properties. The main reason for the incorporation of heteroatoms with quinone moiety is increased activity properties such as antibacterials, antimalarials, antitumor agents, antioxidants, herbicides, and fungicides. In this paper, firstly, we have described the synthesis and characterization of some N(H)-, S- and S,S-substituted-1,4-naphthoquinones. All new compounds were characterized based on nuclear magnetic resonance spectroscopy (^{1}H- and ^{13}C NMR), MS, FT-IR, and elemental analysis.

Electrochemical measurements illustrate that all compounds represent characteristic NQ/NQ$^{\cdot-}$ and NQ$^{\cdot-}$/NQ^{2-} processes, and substituents on the NQ ring only alter the peak positions and reversibility of the electron transfer processes. The results indicated the possibility of manipulating the redox processes by choosing proper substituents on the NQ ring. In situ spectroelectrochemical measurements showed that anionic and cationic forms of the compounds have different colors and spectra which are the basic requirements for the possible photoelectrochemical application of these compounds.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelechem.2023.117913.

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