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Electrosynthesis of Quinoxalines via Intermolecular Cyclization/Dehydrogenation of Ketones with o-Phenylenediamines

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Abstract:
In this study, we proposed a novel electrochemical dehydrogenative synthetic method for preparing 2-substituted quinoxaline via intermolecular cyclization of aryl alkyl ketones and o-phenylenediamines. This method yielded various quinoxalines, with yields ranging from 35%–71%. This novel protocol employed mild reaction conditions, offering moderate to excellent yields, a wide substrate scope, and high functional group compatibility. Furthermore, the late-stage functionalization and wide substrate scope demonstrated the synthetic utility of this protocol.

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Electrosynthesis of Quinoxalines via Intermolecular Cyclization/Dehydrogenation of Ketones with *o*-Phenylenediamines

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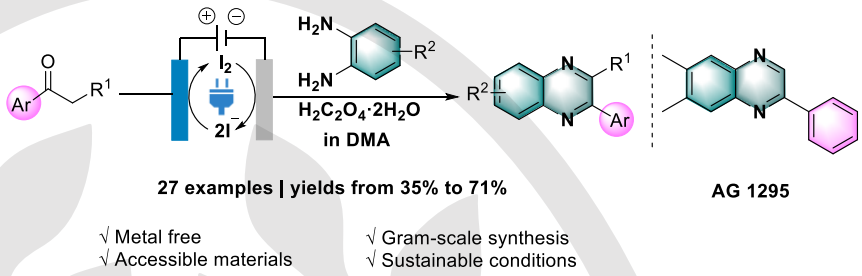

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Abstract In this study, we proposed a novel electrochemical dehydrogenative synthetic method for preparing 2-substituted quinoxaline via intermolecular cyclization of aryl alkyl ketones and o-phenylenediamines. This method yielded various quinoxalines, with yields ranging from 35%–71%. This novel protocol employed mild reaction conditions, offering moderate to excellent yields, a wide substrate scope, and high functional group compatibility. Furthermore, the late-stage functionalization and wide substrate scope demonstrated the synthetic utility of this protocol.

Key words quinoxalines, electrochemical, intermolecular cyclization, green chemistry, dehydrogenation

Quinoxaline structures are a key structural component of many natural products, exhibiting privileged pharmacological and biological activities.[1] For instance, AG1295 is a PDGF receptor tyrosine kinase inhibitor.[2] Chloroquinoxaline sulfonamide is a halogenated heterocyclic sulfanilamide identified as an active agent in various human solid tumors through the *in-vitro* human tumor colony-forming assay.[3] Moreover, riboflavin or vitamin B_2 possesses a ribose-derived quinoxaline core fused with a uracil.[4] Concurrently, several recent studies have demonstrated that incorporating quinoxalines into luminescent materials would provide unique characteristics.[5]

Various methods have been developed to exploit their unique biological activities, employing general, efficient, and sustainable strategies with readily available building blocks. Despite these advancements, challenges persist in synthesizing quinoxaline derivatives, including severe reaction conditions, limited raw material availability, expensive reagents, multistep synthetic processes, and stoichiometric waste.[6] Zhang (2017) employed a catalyst to facilitate the oxidative synthesis of quinoxalines from primary amines under mild conditions, with an *ortho*-quinone catalyst as the terminal oxidant (Scheme 1a).[7] In 2022, Guo presented a method for the annulation of terminal alkynes and *o*-phenylenediamines, employing oxygen as the terminal oxidant and a cobalt catalyst (Scheme 1b).[8] Chaubey developed an iridium-catalyzed [4+2] annulation of β-ketosulfoxonium Ylides and *o*-phenylenediamines to synthesize quinoxaline derivatives (Scheme 1c).[9] Besides, Ngo Nguyen conducted an oxidative condensation of *o*-phenylenediamines with aryl alkyl ketones in the presence of sulfur to synthesize quinoxaline derivatives (Scheme 1d).[10] However, there is a high demand for strategies that enable the high-efficiency synthesis of the quinoxaline skeleton using mild conditions and readily available starting materials.

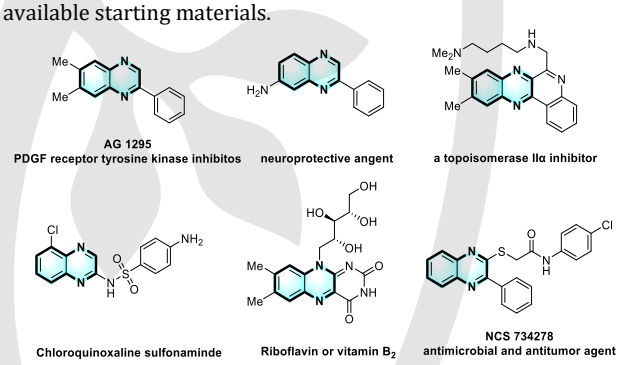


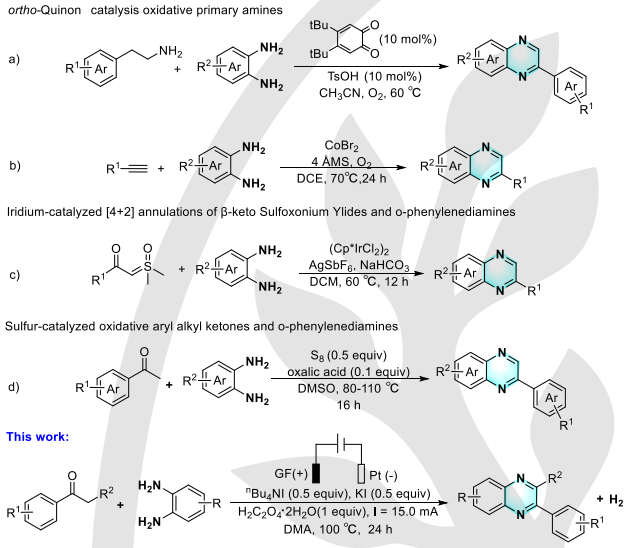
Figure 1. Important Quinoxaline Derivatives

Developing novel, metal-free, and versatile synthetic strategies for synthesizing quinoxaline derivatives is crucial in academia and the pharmaceutical sector to discover bioactive compounds.(11) Electrochemical synthesis has recently emerged as a "green" and "sustainable strategy" for preparing non-traditional and innovative molecules, with the advantage of using electrons as traceless reagents instead of dangerous and toxic redox reagents.[12] The cyclization of aryl alkyl ketones and *o*-phenylenediamines is a direct and convenient method for preparing quinoxalines, considering the availability of chemicals and high atom economy.

In 2016, Zeng's team reported an electrochemical protocol for the synthesis of α-amino ketones through the oxidative cross-dehydrogenative coupling of ketones and secondary amines.[13] The electrochemistry occurs in a simple undivided cell utilizing NH_4I as a redox catalyst and cheap graphite plates as electrodes under constant current conditions. The reaction is proposed to

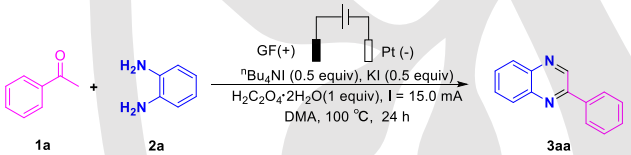
proceed through an initial α-iodination of the ketone, followed by a nucleophilic substitution of amines. Inspired by these works and our program on electrochemical transformation, we herein report a highly selective intermolecular cyclization and dehydrogenation of o-phenylenediamines with aryl alkyl ketones, facilitating the versatile synthesis of quinoxalines.[14]

Scheme 1. Synthetic strategy and routes of 2-substituted benzoxazoles



Result And Discussion

Table 1. Optimization of the Reaction Conditions

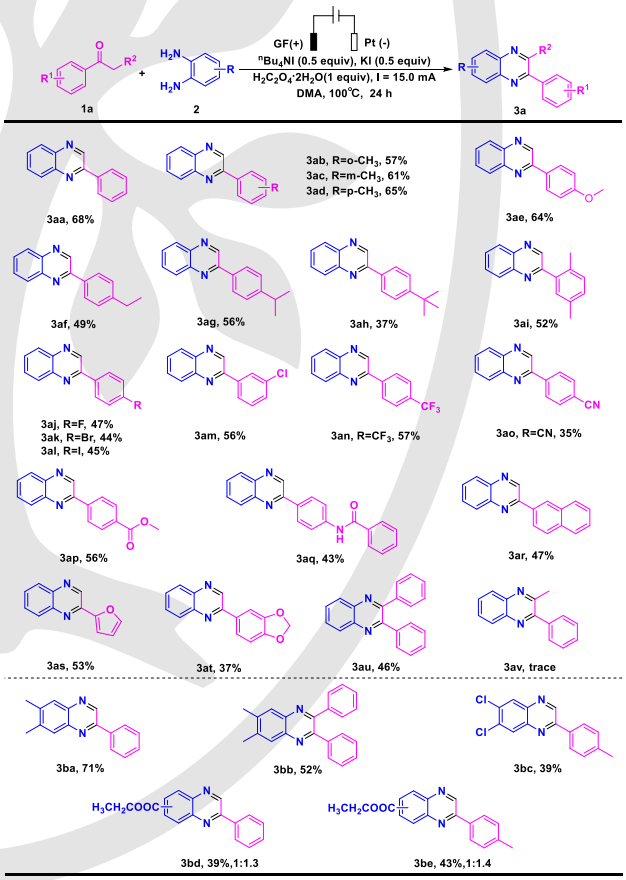


1a 2a 3aa

Entry	variation from titled conditions	Yield[b]
1	none	68
2	HCOOH instead of $H_2C_2O_4·2H_2O$	64
3	CH_3COOH instead of $H_2C_2O_4·2H_2O$	53
4	CF_3COOH instead of $H_2C_2O_4·2H_2O$	50
5	TsOH instead of $H_2C_2O_4·2H_2O$	43
6	0.5 equiv. $H_2C_2O_4·2H_2O$	46
7	1.5 equiv. $H_2C_2O_4·2H_2O$	57
8	No KI	32
9	1.0 equiv. KI	45
10	NaI, NH_4I instead of KI	35,54
11	50°C, 120°C	0, 60
12	10 mA, 18 mA	43, 65
13	DMSO instead of DMA	60
14	$^nBu_4NBF_4$ instead of $^nBu_4NI$	32
15	$^nBu_4NClO_4$ instead of $^nBu_4NI$	26
16	KPF_6 instead of $^nBu_4NI$	trace
17	no $^nBu_4NI$	46
18	1.0 equiv. $^nBu_4NI$	56
19	Ni as cathode	trace
20	Pt as anode	trace
21	no electric current	0

To validate our assumption, we screened the intermolecular cyclization of acetophenone (**1a**) with 1,2-phenylenediamine (**2a**). The results are presented in Table 1. The reaction was performed using graphite felt (GF) anode and Pt cathode as the supporting electrodes, with 0.5 equivalents of each $^nBu_4NI$ and KI in an undivided cell (a Schlenk tube). Treatment **1a** and **2a** in DMA (6 mL) in the presence of $H_2C_2O_4·2H_2O$ (1 equivalent) at 100 °C for 24 h yielded 2-phenylquinoxaline (**3aa**) with a 68% isolated yield (Table 1; entry 1). Substituting $H_2C_2O_4·2H_2O$ with HCOOH, CH_3COOH, TFA, and TsOH decreased the yield to 64%, 53%, 50%, and 43%, respectively (Table 1; entries 2–5). Changing the concentration of $H_2C_2O_4·2H_2O$ did not increase the yield (Table 1, entries 6 and 7). Similarly, adjusting the KI dosage did not improve the production yield (Table 1; entries 8 and 9). However, iodide salts, such as NaI and NH_4I, resulted in lower yields (Table 1; entry 10). The best yield was achieved at 100 °C, while the reaction at different temperatures led to lower yields of **3aa** (Table 1; entry 11). Additionally, decreasing or increasing the constant current negatively influenced the reaction outcomes (Table 1; entry 12). When DMSO was employed as the solvent, the yield decreased to 60% (Table 1; entry 13). Changing the electrolyte to $^nBu_4NBF_4$, $^nBu_4NClO_4$, or KPF_6 resulted in the formation of the desired products with isolated yields of 32%, 26%, trace, and 35%, respectively (Table 1; entries 14–16). Notably, the yield declined when $^nBu_4NI$ was not added or when the dosage of $^nBu_4NI$ was decreased (Table 1; entries 17 and 18). Conversely, the Ni and Pt as anodes proved unsuitable for this electrochemical reaction (Table 1; entries 19 and 20). As anticipated, the reaction failed to give any product without an electric current (Table 1; entry 21).

Table 2. Investigation of the Scope of Benzoxazole-2-carboxylatea

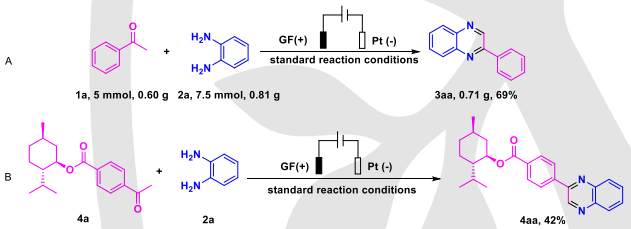


[a] Reaction conditions: 1a (0.5 mmol), 2a (0.75 mmol), $^nBu_4NI$ (0.25 mmol), KI (0.25 mmol), $H_2C_2O_4·H_2O$(0.5 mmol), DMA (6 mL), constant current = 15 mA, undivided cell, GF anode (1.5 cm × 1.0 cm) and Pt cathode (1.5 cm × 1.0 cm), 100 °C, 24 h. [b]Isolated yield.

The scope of quinoxaline synthesis was then examined. As depicted in Table 2, 2-aryl quinoxalines (**3aa**) with a substituent of varying electronic natures were accessible. It was revealed that **1a** bears either electron-rich groups, such as methyl **(3ab**,

3ac, **3ad**, **3ai**), methoxy (**3ae**), ethyl (**3af**), isopropyl (**3ag**), and ter-butyl (**3ah**), or electron-deficient substituents like halogen (**3aj-am**), trifluoromethyl (**3an**), and cyano (**3ao**) groups at different positions. Substrates containing ester groups and amides could react to synthesize the corresponding compounds with moderate yields (**3ap**, **3aq**). Furthermore, naphthalenyl (**3ar**), furyl (**3as**), and benzo[d][1,3]dioxolyl (**3at**) containing substrates were compatible with the reaction conditions. Subsequently, 1,2-diphenylethanone could react with **2a** to produce the corresponding 2,3-diphenylquinoxaline (**3au**). Unfortunately, phenylacetone substrates were incompatible with the standard reaction conditions (**3av**).

Next, 4,5-dimethylbenzene-1,2-diamine and acetophenone derivatives were investigated under optimized conditions that produced moderate to high yields of the corresponding products (Table 2; **3ba**, **3bb**). Remarkably, AG 1295 (**3ba**), anti-PDGF receptor reagent, was synthesized under optimized conditions that produced a high yield of the product. Notably, significant electrical effects were observed in disubstituted 1,2-diaminoarenes, which possessed electron-donating substituents. Substrates (**3ba**) exhibited higher compatibility than those with electron-withdrawing substituents, such as halogens (**3bc**). Furthermore, asymmetrical 1,2-diaminoarenes as substrates resulted in two isomers in the corresponding product quinoxalines (Table 2; **3bd**, **3be**), respectively. These isomers could not be isolated on flash silica gel column chromatography for the reason for similarity in polarity.



Scheme 2. Gram Scale Experiment and Derivatization

In addition, to further explore the applications of this method in constructing quinoxalines, this electro-redox process was evaluated through a 10 mM scale reaction. Gram-scale synthesis of **3aa** was achieved using **1a** (0.6 g, 5.0 mM) and **2a** (0.81 g, 7.5 mM) with a yield of 69% (0.71 g) (Scheme 2, A). Next, the acetophenone substrate of menthol esters **4a** (0.151 g, 0.5 mM) could be dehydrogenated with **2a** (0.081 g, 0.75 mM) for intermolecular cyclization, resulting in the formation of a more complex molecule, **4aa** in a 42% yield (0.081 g) (Scheme 2, B).

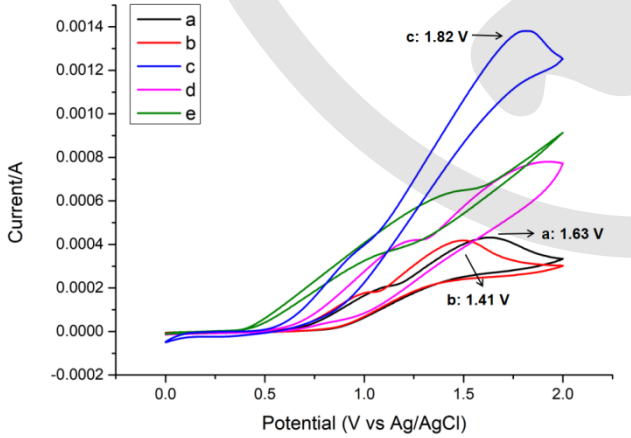
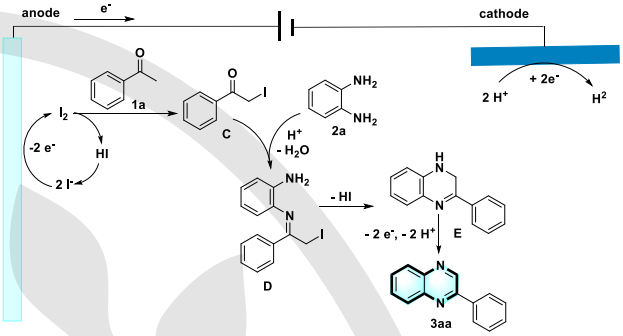


Figure 2. Cyclic voltammograms of substrates.

Cyclic voltammograms of substrates in 0.1 M $^{n}Bu_4NI$/DMA, using a Pt wire working electrode and glassy carbon and Ag/AgCl (0.1 M in DMA) as counter and reference electrodes at 100 mV s^{-1} scan rate: a) blank (0.1 M $^{n}Bu_4NI$ in DMA), b) blank+KI (20mM), c) blank+ 1a (20 mM) + 2a (20 mM)+KI (20 mM) + $H_2C_2O_4•2H_2O$ (20 mM), d) blank+ 1a (20 mM), e) blank+ 2a (20 mM).



Scheme 3. Proposed Mechanism

The cyclic voltammetry (CV) experiments were conducted to further elucidate the electrochemical oxidation processes for this reaction. As depicted in Figure 2, CV measurements of $^{n}Bu_4NI$ revealed an oxidative wave at 1.63 V (**curve a**), and KI revealed an oxidative wave at 1.41 V, indicating that KI was oxidized first (**curve b**). Moreover, when all raw materials were mixed with KI and a blank, the redox response value was significantly increased. The concentration of proton(addition of acid) might play a role here since it reduces the nucleophilicity of amine thus slower the first substitution. However, as a tradeoff, it probably helps accelerate the cathodic reaction rate thus lower the overall resistance of the cell. (**curve c**). Additionally, no obvious redox change was observed when the blank was mixed with the two raw materials. The blanks with **1a** and **2a** exhibited oxidation waves at 1.02 and 1.49 V, respectively (**curves d, e**). These results indicated that substrate **1a** was initially more susceptible to oxidation.

Based on the experimental results and previous reports, a plausible reaction mechanism between **1a** and **2a** is displayed in Scheme 3.[14] Initially, iodide was oxidized into the iodine radical, which then reacted with **1a** to form 2-iodo-1-(4-methylphenyl)ethanone (C). The presence of acid facilitated the condensation between diamines and iodinated intermediates to form imines. Subsequently, an intramolecular nucleophilic attack of an amino group on the C–I bond generated a cyclic intermediate, and anodic oxidation potentially yielded the desired aromatization product. Simultaneously, the reduction of protons at the cathode resulted in the release of hydrogen.

Conclusion

In summary, a practical and atom-economical electrocatalysis strategy was developed for the intramolecular dehydrogenative cyclization of quinoxaline derivatives. This strategy resulted in the production of various 2-substituted quinoxalines in moderate to good yields.[16] The electrocatalytic approach modulated the reactivity of starting materials to facilitate complex transformations in a single step. Oxidative dehydrogenation cyclization was performed to achieve this transformation without using transition metals and stoichiometric chemical oxidants under mild conditions. Notably, the reaction that releases H_2 as a theoretical by-product demonstrates a high atom economy. Furthermore, the broad substrate scope and late-stage functionalization features of this

method extended its adaptability. We anticipate that this novel approach will be used to construct complex quinoxaline derivatives as active ingredients.

Funding Information

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Supporting Information

YES (this text will be updated with links prior to publication)

Conflict of Interest

The authors declare no conflict of interest.

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(16) **Quinoxalines 3aa-3be; General Procedure**

A tube was charged with **1a** (0.5 mmol, 1.0 equiv.), **2a** (0.75 mmol, 1.5 equiv.), KI (0.25 mmol, 0.5 equiv.), $H_2C_2O_4$•$2H_2O$ (0.5 mmol, 1.0 equiv.), $^nBu_4NI$ (0.25 mmol, 0.5 equiv.) and DMA 6 mL. The tube was equipped with a graphite felt anode and Pt foam cathode. The constant current (15.0 mA) electrolysis was carried out at 100 °C for 24 h. After complete consumption of the starting material, the mixture was extracted with EtOAc, and the organic layer was dried (Na_2SO_4), filtered, and concentrated. The residue was purified by column chromatography (silica gel, EtOAc–hexane).

2-phenylquinoxaline (3aa)[17a]

Yellow solid, 68% yield, 70 mg. ^{1}H NMR(600 MHz, Chloroform-d) δ 9.33 (s, 1H), 8.22 – 8.19 (m, 2H), 8.15 (ddd, J = 22.2, 8.4, 1.8 Hz, 2H), 7.77 (dddd, J = 23.4, 8.4, 7.2, 1.2 Hz, 2H), 7.59 – 7.52 (m, 3H). ^{13}C NMR(150 MHz, Chloroform-d) δ 152.2, 143.7, 142.7, 141.8, 137.1, 130.7, 130.6, 130.0, 129.9, 129.5, 129.4, 127.9.

2-(4-bromophenyl)quinoxaline(3ak)[17b]

Yellow solid, 44% yield, 63 mg. 1H NMR (600 MHz, Chloroform-d) δ 9.27 (s, 1H), 8.11 (ddd, J = 8.4, 6.4, 2.0 Hz, 2H), 8.08 – 8.04 (m, 2H), 7.80 – 7.72 (m, 2H), 7.70 – 7.65 (m, 2H). 13C NMR (150 MHz, Chloroform-d) δ 150.4, 142.6, 142.0, 141.5, 135.4, 132.1, 130.3, 129.6, 129.4, 129.0, 128.8, 124.8.

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Supplementary Information for:

Electrochemically Induced Synthesis of Quinoxaline from Aryl Alkyl Ketones with o-Phenylenediamines

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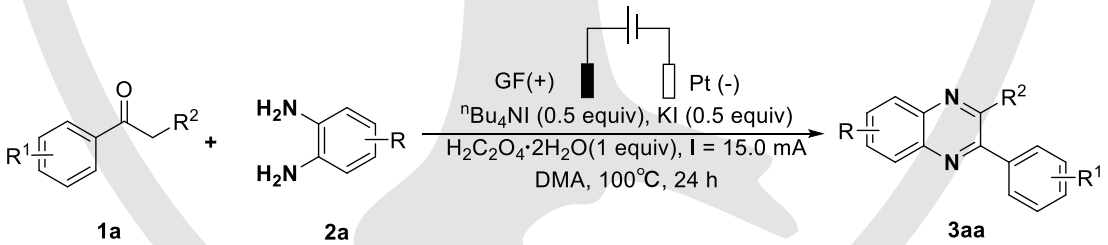
1. General Information

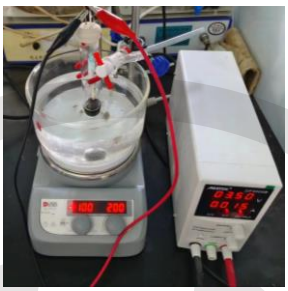
Unless otherwise specified, all reagents and solvents were obtained from commercial suppliers and used without further purification. NMR spectra were recorded with tetramethylsilane (TMS) as the internal standard. ^{1}H NMR spectra were recorded at 600 MHz and 400 MHz, ^{13}C NMR spectra were recorded at 150 MHz and 100 MHz, ^{19}F NMR spectra were recorded at 375 MHz (Bruker Avance). ^{1}H NMR chemical shifts (δ) are reported in ppm relative to tetramethylsilane (TMS) with the solvent signal as the internal standard ($CDCl_3$ at 7.26 ppm). ^{13}C NMR chemical shifts are reported in ppm from tetramethylsilane (TMS) with the solvent resonance as the internal standard ($CDCl_3$ at 77.0 ppm). Data are given as: s (singlet), d (doublet), t (triplet), q (quartet), dd (double of doublet), dt (doublet of triplet), td (triplet of doublet), ddd (doublet of doublet of doublet) or m (multiplets), coupling constants (Hz) and integration. Flash column chromatography was carried out using silica gel eluting with ethyl acetate, petroleum ether. High resolution mass spectra were obtained with the Q-TOF-Premier mass spectrometer. Reactions were monitored by TLC and visualized with ultraviolet light. Cyclic voltammetry experiments were carried out in an equipment of CHI761E. CV curves were recorded using a three-electrode scheme. The working electrode was a glassy carbon electrode, a platinum electrode served as counter electrode. Ag/AgCl (KCl sat'd) was used as the reference electrode (Shanghai Chenhua Instrument Co.,Ltd). The working electrode was polished before recording each CV curve.

2. General procedure of the synthesis of the products

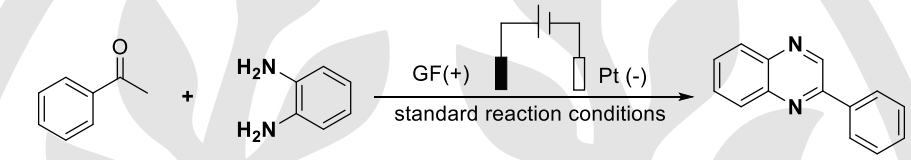


A tube was charged with **1a** (0.5 mmol, 1.0 equiv.), **2a** (0.75 mmol, 1.5 equiv.), KI (0.25 mmol, 0.5 equiv.), $H_2C_2O_4$•$2H_2O$ (0.5 mmol, 1.0 equiv.), $^{n}Bu_4NI$ (0.25 mmol, 0.5 equiv.) and DMA 6 mL. The tube was equipped with a graphite felt anode (1.5 cm × 1 cm × 0.5 cm) and a Pt foam (1.5 cm × 1 cm) cathode. The constant current (15.0 mA) electrolysis was carried out at 100 °C (oil bath temperature) for 24 h. After complete consumption of the starting material, the reaction mixture was treated with H_2O (150 mL) and ethyl acetate (30 mL × 3) was used to extract the product. After evaporation of ethyl acetate, The residue was purified by flash column

chromatography using a mixture of petroleum ether and ethyl acetate (20:1-30:1) as eluent to give the desired product.



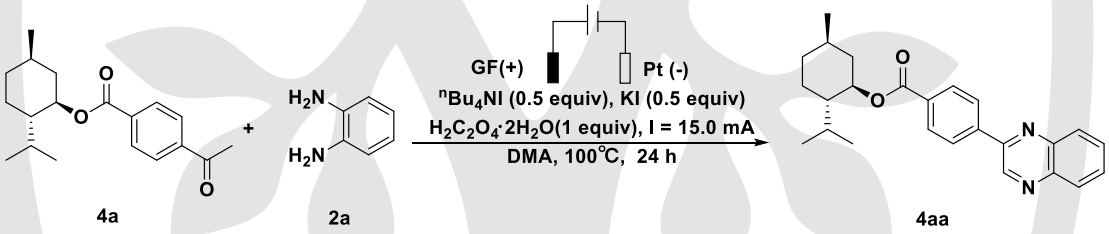
3. Procedure for gram-scale experiment



1a, 5 mmol, 0.60 g **2a**, 7.5 mmol, 0.81 g **3aa**, 0.71 g, 69%

In addition, to further explore the uses of this method for constructing quinoxalines, this anodic oxidation was then evaluated by performing a 10 mmol scale reaction. 3aa was synthesized on a gram scale utilizing **1a** (0.6 g, 5.0 mmol) and **2a** (0.841 g, 7.5 mmol) with a yield of 69% (0.71 g).

4. Further functionalization of product



4a **2a** **4aa**

A tube was charged with **4a** (0.5 mmol, 1.0 equiv.), dihydroisoquinoline **2a** (0.75 mmol, 1.5 equiv.), KI (0.25 mmol, 0.5 equiv.), $H_2C_2O_4$•$2H_2O$ (0.5 mmol, 1.0 equiv.), ^{n}Bu_4NI (0.25 mmol, 0.5 equiv.) and DMA 6 mL. The tube was equipped with a graphite felt anode (1.5 cm × 1 cm × 0.5 cm) and a Pt foam (1.5 cm × 1 cm) cathode. The constant current (15 mA) electrolysis was carried out at 100 °C (oil bath temperature) for 24 h. After complete consumption of the starting material, the reaction mixture was treated with H_2O (150 mL) and ethyl acetate (30 mL × 3) was used to extract the product. The residue was purified by flash column chromatography using a mixture of petroleum ether and ethyl acetate (30:1) as eluent to give the desired yellow solid product **4aa** in 26% yield.

5. Cyclic voltammetry studies.

The cyclic voltammograms were recorded in an electrolyte of ^{n}Bu_4NI (0.5 M) in DMA (6.0

mL) using a glassy carbon disk working electrode (diameter, 3 mm), a Pt wire auxiliary electrode and an Ag/AgCl reference electrode. The scan rate is 100 mV/s.

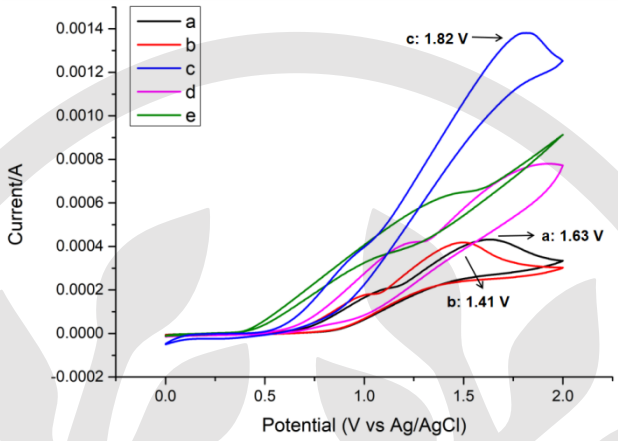
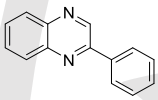


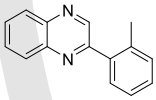
Figure S1. Cyclic voltammograms.

6. Spectra characterization data of products[1,2]



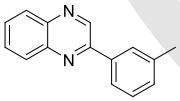
2-phenylquinoxaline (3aa)

Yellow solid, 68% yield, 70 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.33 (s, 1H), 8.22 – 8.19 (m, 2H), 8.15 (ddd, J = 22.2, 8.4, 1.8 Hz, 2H), 7.77 (dddd, J = 23.4, 8.4, 7.2, 1.2 Hz, 2H), 7.59 – 7.52 (m, 3H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 152.2, 143.7, 142.7, 141.8, 137.1, 130.7, 130.6, 130.0, 129.9, 129.5, 129.4, 127.9. **HRMS** (ESI) calcd for $C_{14}H_{10}N_2$ $[M+H]^+$: 207.0917, found: 207.0911.



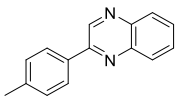
2-(o-tolyl)quinoxaline (3ab)

Yellow solid, 57% yield, 63 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.02 (s, 1H), 8.17 (dd, *J* = 7.8, 2.4 Hz, 2H), 7.83 – 7.79 (m, 2H), 7.57 – 7.54 (m, 1H), 7.43 – 7.40 (m, 1H), 7.37 (dt, *J* = 6.6, 3.6 Hz, 2H), 2.48 (s, 3H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 155.1, 146.0, 142.2, 141.1, 137.2, 136.7, 131.4, 130.5, 130.2, 130.0, 129.7, 129.6, 129.3, 126.5, 20.5. **HRMS** (ESI) calcd for $C_{15}H_{13}N_2$ $[M+H]^+$: 221.1074, found: 221.1073.



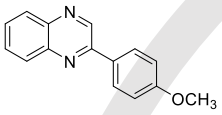
2-(m-tolyl)quinoxaline (3ac)

Yellow solid, 61% yield, 67 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.31 (s, 1H), 8.16 (dd, *J* = 7.8, 1.8 Hz, 1H), 8.12 (dd, *J* = 8.4, 1.8 Hz, 1H), 8.02 (s, 1H), 7.97 (d, *J* = 7.8 Hz, 1H), 7.76 (dddd, *J* = 24.6, 8.4, 6.6, 1.8 Hz, 2H), 7.46 (t, *J* = 7.8 Hz, 1H), 7.34 (d, *J* = 7.8 Hz, 1H), 2.50 (s, 3H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 152.2, 143.6, 142.4, 141.6, 139.1, 136.8, 131.1, 130.4, 129.7, 129.7, 129.6, 129.2, 129.2, 128.3, 124.8, 21.7. **HRMS** (ESI) calcd for $C_{15}H_{13}N_2$ $[M + H]^+$: 221.1074. Found: 221.1071.



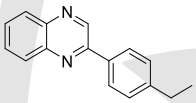
2-(p-tolyl)quinoxaline (3ad)

Yellow solid, 65% yield, 72 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.32 (s, 1H), 8.18 – 8.09 (m, 4H), 7.76 (dddd, J=27.0, 8.4, 6.8, 1.2 Hz, 2H), 7.38 (d, J=7.8 Hz, 2H), 2.46 (s, 3H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 151.8, 143.1, 142.2, 141.2, 140.6, 133.8, 130.3, 129.9, 129.4, 129.4, 128.9, 127.4, 21.4. **HRMS** (ESI) calcd for $C_{15}H_{12}N_2$ $[M+H]^+$: 221.1074, found: 221.1067.



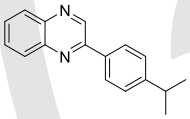
2-(4-methoxyphenyl)quinoxaline(3ae)

Yellow solid, 64% yield, 72 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.28 (t, *J* = 3.2 Hz, 1H), 8.16 (dt, *J* = 9.0, 3.0 Hz, 2H), 8.10 (ddt, *J* = 15.6, 8.4, 1.8 Hz, 2H), 7.77 – 7.66 (m, 2H), 7.06 (dt, *J* = 9.0, 3.6 Hz, 2H), 3.89 (d, *J* = 3.6 Hz, 3H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 161.6, 151.5, 143.1, 142.4, 141.3, 130.3, 130.3, 129.5, 129.3, 129.2, 129.2, 129.1, 114.7, 55.5. **HRMS** (ESI+) calcd for $C_{15}H_{13}N_2O$ $[M+H]^+$: 237.1023, found: 237.1021.



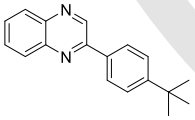
2-(4-ethylphenyl)quinoxaline(3af)

Yellow solid, 49% yield, 57 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.31 (d, *J* = 1.2 Hz, 1H), 8.16 – 8.09 (m, 4H), 7.78 – 7.70 (m, 2H), 7.39 (d, *J* = 7.8 Hz, 2H), 2.74 (q, *J* = 7.8 Hz, 2H), 1.30 (t, *J* = 7.8 Hz, 3H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 152.0, 146.9, 143.4, 142.4, 141.5, 134.3, 130.3, 129.6, 129.4, 129.2, 128.8, 127.7, 28.9, 15.6. **HRMS** (ESI) calcd for $C_{15}H_{14}N_2$ $[M+H]^+$: 235.1230, found: 235.1243.



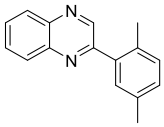
2-(4-isopropylphenyl)quinoxaline(3ag)

Yellow solid, 56% yield, 69 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.31 (s, 1H), 8.17 – 8.09 (m, 4H), 7.78 – 7.69 (m, 2H), 7.45 – 7.39 (m, 2H), 3.04 – 2.97 (m, 1H), 1.31 (dd, *J* = 6.9, 1.5 Hz, 6H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 152.0, 151.5, 143.4, 142.4, 141.5, 134.5, 130.3, 129.7, 129.4, 129.2, 127.7, 127.4, 34.2, 24.0. **HRMS** (ESI) calcd for $C_{17}H_{17}N_2$ $[M+H]^+$: 249.1387, found: 249.1385.



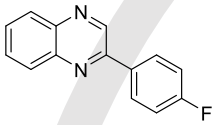
2-(4-(tert-butyl)phenyl)quinoxaline(3ah)

Yellow solid, 37% yield, 48 mg. **^{1}H NMR**(600 MHz, Chloroform-*d*) δ 9.31 (s, 1H), 8.17 – 8.09 (m, 4H), 7.78 – 7.69 (m, 2H), 7.45 – 7.39 (m, 2H), 3.04 – 2.97 (m, 1H), 1.31 (dd, *J* = 6.9, 1.5 Hz, 6H). **^{13}C NMR**(150 MHz, Chloroform-*d*) δ 152.0, 151.5, 143.4, 142.4, 141.5, 134.5, 130.3, 129.7, 129.4, 129.2, 127.7, 127.4, 34.2, 24.0. **HRMS** (ESI) calcd for $C_{15}H_{13}N_2$ $[M+H]^+$: 249.1387, found: 249.1385.



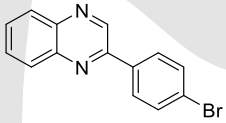
2-(2,5-dimethylphenyl)quinoxaline(3ai)

Yellow solid, 52% yield, 61 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*)δ 8.89 (s, 1H), 8.05 (ddd, *J* = 7.2, 4.8, 2.4 Hz, 2H), 7.69 (tt, *J* = 7.2, 5.4 Hz, 2H), 7.26 (d, *J* = 2.4 Hz, 1H), 7.14 (d, *J* = 7.2 Hz, 1H), 7.10 (dd, *J* = 7.8, 2.4 Hz, 1H), 2.30 (d, *J* = 5.4 Hz, 6H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 155.1, 145.9, 142.0, 140.9, 136.9, 135.8, 133.3, 131.1, 130.5, 130.2, 130.1, 129.6, 129.5, 129.1, 20.9, 19.8. **HRMS** (ESI) calcd for $C_6H_{14}N_2$ [M+H]: 235.1230, found: 235.1227.



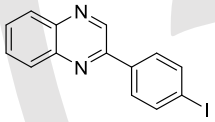
2-(4-fluorophenyl)quinoxaline(3aj)

Yellow solid, 47% yield, 60 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.32 (s, 1H), 8.24 – 8.19 (m, 2H), 8.14 (dd, J = 12.0, 8.4 Hz, 2H), 7.78 (dddd, J = 22.2, 8.4, 6.8, 1.2 Hz, 2H), 7.28 – 7.24 (m, 2H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 164.2 (q, J = 249.0 Hz), 150.8, 141.4, 132.9, 130.4, 129.6, 129.5, 129.4, 129.1, 116.2 (q, J = 21.0 Hz). **^{19}F NMR** (375 MHz, Chloroform-*d*) δ -110.50. **HRMS** (ESI) calcd for $C_{14}H_9FN_2$ $[M+H]^+$: 225.0823, found: 225.0825.



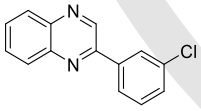
2-(4-bromophenyl)quinoxaline(3ak)

Yellow solid, 44% yield, 63 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.27 (s, 1H), 8.11 (ddd, *J* = 8.4, 6.4, 2.0 Hz, 2H), 8.08 – 8.04 (m, 2H), 7.80 – 7.72 (m, 2H), 7.70 – 7.65 (m, 2H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 150.4, 142.6, 142.0, 141.5, 135.4, 132.1, 130.3, 129.6, 129.4, 129.0, 128.8, 124.8. **HRMS** (ESI) calcd for $C_{14}H_9FN_2$ $[M+H]^+$: 225.0823, found: 225.0825.



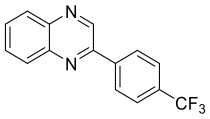
2-(4-iodophenyl)quinoxaline(3al)

Yellow solid, 45% yield, 75 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.29 (s, 1H), 8.17 – 8.10 (m, 2H), 7.96 – 7.93 (m, 2H), 7.92 – 7.88 (m, 2H), 7.78 (dddd, *J* = 19.8, 8.4, 6.6, 1.8 Hz, 2H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 151.1, 143.0, 142.6, 142.0, 138.7, 136.5, 130.9, 130.2, 130.0, 129.5, 129.4, 97.4. **HRMS** (ESI) calcd for $C_{14}H_9FN_2$ $[M+H]^+$: 331.9810, found: 331.9807.



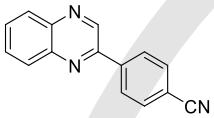
2-(3-chlorophenyl)quinoxaline(3am)

Yellow solid, 56% yield, 67 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.30 (s, 1H), 8.24 (q, *J* = 1.5 Hz, 1H), 8.15 (ddd, *J* = 15.0, 8.4, 1.8 Hz, 2H), 8.07 (ddd, *J* = 6.8, 3.6, 1.8 Hz, 1H), 7.84 – 7.76 (m, 2H), 7.50 (dd, *J* = 3.6, 1.8 Hz, 2H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 150.3, 142.8, 142.2, 141.7, 138.4, 135.3, 130.5, 130.3, 130.2, 130.0, 129.6, 129.1, 127.6, 125.5. **HRMS** (ESI) calcd for $C_{14}H_9ClN_2$ $[M+H]^+$: 241.6975, found: 241.6971.



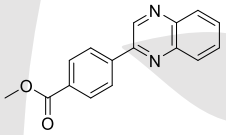
2-(4-(trifluoromethyl)phenyl)quinoxaline(3an)

Yellow solid, 57% yield, 78 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.36 (s, 1H), 8.33 (d, *J* = 8.4 Hz, 2H), 8.17 (ddt, *J* = 14.4, 7.8, 1.2 Hz, 2H), 7.85 – 7.78 (m, 4H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 150.2, 142.9, 142.2, 141.8, 140.0, 131.9 (q, J = 31.5 Hz), 130.6, 130.2, 129.7, 129.1, 127.8, 126.0 (q, J = 3.0 Hz), 123.9 (q, J = 270.0 Hz). **^{19}F NMR** (375 MHz, Chloroform-*d*) δ -62.76. **HRMS** (ESI) calcd for $C_{15}H_9F_3N_2$ $[M+H]^+$: 275.0791, found: 275.0794.



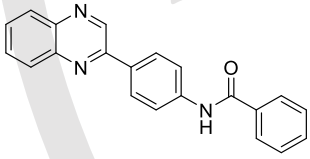
4-(quinoxalin-2-yl)benzonitrile(3ao)

Yellow solid, 35% yield, 40 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.35 (s, 1H), 8.36 – 8.33 (m, 2H), 8.17 (tt, *J* = 8.4, 1.8 Hz, 2H), 7.88 – 7.80 (m, 4H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 149.5, 142.7, 142.1, 141.9, 140.8, 132.8, 130.8, 130.5, 129.7, 129.2, 128.0, 118.4, 113.6. **HRMS** (ESI) calcd for $C_{14}H_9FN_2$ $[M+H]^+$: 232.2870, found: 232.2863.



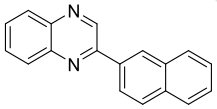
methyl 4-(quinoxalin-2-yl)benzoate(3ap)

Yellow solid, 56% yield, 74 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.37 (s, 1H), 8.31 – 8.28 (m, 2H), 8.25 – 8.22 (m, 2H), 8.20 – 8.14 (m, 2H), 7.81 (dddd, *J* = 18.0, 8.4, 7.2, 1.8 Hz, 2H), 3.98 (s, 3H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 166.8, 150.8, 143.3, 142.4, 142.0, 141.0, 131.6, 130.8, 130.5, 130.3, 129.9, 129.3, 127.6, 52.5. **HRMS** (ESI) calcd for $C_{16}H_{12}N_2O_2$ $[M + H]^+$: 265.0972, found: 265.0978.



N-(4-(quinoxalin-2-yl)phenyl)benzamide(3aq)

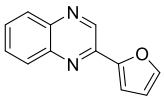
Yellow solid, 43% yield, 70 mg. **^{1}H NMR** (400 MHz, Chloroform-*d*) δ 9.34 (s, 1H), 8.25 (d, *J* = 8.4 Hz, 2H), 8.14 (t, *J* = 8.4 Hz, 2H), 8.07 (s, 1H), 7.98 – 7.84 (m, 4H), 7.82 – 7.71 (m, 2H), 7.52 (d, *J* = 7.2 Hz, 3H). **^{13}C NMR** (100 MHz, Chloroform-*d*) δ 165.9, 151.2, 143.1, 142.5, 141.4, 140.1, 134.8, 133.7, 132.8, 132.3, 130.5, 130.3, 129.6, 129.0, 128.6, 127.2, 120.5. **HRMS** (ESI) calcd for $C_{21}H_{15}N_3O$ $[M+H]^+$: 325.1215, found: 325.1213.



2-(naphthalen-2-yl)quinoxaline(3ar)

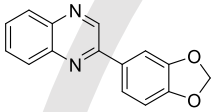
Yellow solid, 47% yield, 60 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.48 (s, 1H), 8.66 (d, J = 1.8 Hz, 1H), 8.36 (dd, J = 8.4, 1.8 Hz, 1H), 8.21 (dd, J = 8.4, 1.8 Hz, 1H), 8.15 (dd, J = 8.4, 1.8 Hz, 1H), 8.04 – 8.01 (m, 2H), 7.92 – 7.89 (m, 1H), 7.81 (ddd, J = 8.4, 6.8, 1.8 Hz, 1H), 7.76 (ddd, J = 8.4, 6.8, 1.8 Hz, 1H), 7.59 – 7.55 (m, 2H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 157.1, 148.4,

141.2, 140.8, 140.1, 134.6, 129.7, 129.6, 129.3, 129.3, 128.6, 128.6, 128.6, 128.4, 127.4, 126.7, 124.8, 120.8. **HRMS** (ESI+) calcd for $C_{18}H_{16}N_2O_2$ $[M+H]^+$: 257.1074, found: 257.1085.



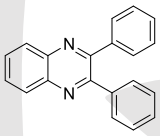
2-(furan-2-yl)quinoxaline(3as)

Yellow solid, 53% yield, 52 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.24 (d, *J* = 2.4 Hz, 1H), 8.08 (ddd, *J* = 19.8, 8.4, 1.8 Hz, 2H), 7.75 (ddq, *J* = 8.4, 6.6, 1.2 Hz, 1H), 7.72 – 7.67 (m, 2H), 7.32 (t, *J* = 3.0 Hz, 1H), 6.63 (dt, *J* = 3.0, 1.8 Hz, 1H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 151.5, 145.1, 143.8, 142.0, 142.0, 141.2, 130.4, 129.3, 129.1, 112.4, 111.8. **HRMS** (ESI+) calcd for $C_{12}H_9N_2O$ $[M+H]^+$: 197.2165, found: 197.2162.



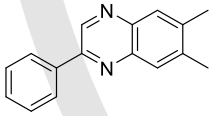
2,3-diphenylquinoxaline(3at)

Yellow solid, 37% yield, 46 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.25 (s, 1H), 8.10 (td, J = 8.4, 1.8 Hz, 2H), 7.78 – 7.74 (m, 2H), 7.74 – 7.69 (m, 2H), 6.98 (d, J = 8.4 Hz, 1H), 6.07 (s, 2H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 151.4, 149.8, 148.9, 143.1, 142.3, 141.3, 131.2, 130.5, 129.5, 129.4, 129.1, 122.2, 108.9, 107.8, 101.8. **HRMS** (ESI) calcd for $C_{12}H_8N_2O$ $[M+H]^+$: 197.0710, found: 197.0699.



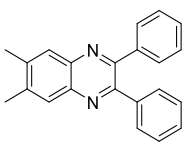
2,3-diphenylquinoxaline (3au)

Yellow solid, 46% yield, 65 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 8.22 (dd, *J* = 6.6, 3.6 Hz, 2H), 7.79 (dd, *J* = 6.6, 3.6 Hz, 2H), 7.54 – 7.52 (m, 4H), 7.38 – 7.32 (m, 6H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 153.8, 141.4, 139.1, 135.3, 130.5, 130.2, 129.4, 128.7. **HRMS** (ESI) calcd for $C_{20}H_{14}N_2$ $[M+H]^+$: 283.1230, found: 283.1228.



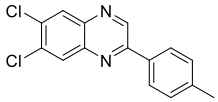
6,7-dimethyl-2-phenylquinoxaline(3ba)

Yellow solid, 71% yield, 115 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.21 (s, 1H), 8.17 – 8.15 (m, 2H), 7.90 (s, 1H), 7.85 (s, 1H), 7.55 (dd, J = 8.4, 6.6 Hz, 2H), 7.51 – 7.48 (m, 1H), 2.50 (s, 6H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 151.1, 142.4, 141.4, 140.9, 140.6, 140.3, 137.2, 130.0, 129.2, 128.8, 128.2, 127.5, 20.5, 20.5 **HRMS** (ESI) calcd for $C_6H_{14}N_2$ $[M+H]^+$: 235.1230, found: 235.1229.



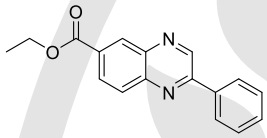
6,7-dimethyl-2,3-diphenylquinoxaline(3bb)

Yellow solid, 52% yield, 81 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 7.95 (s, 2H), 7.50 (dd, *J* = 7.8, 1.2 Hz, 4H), 7.36 – 7.31 (m, 6H), 2.52 (s, 6H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 151.0, 142.6, 141.5, 141.1, 140.5, 140.5, 134.5, 134.1, 133.6, 129.1, 129.0, 128.8, 128.2, 127.9, 127.3, 127.3, 126.8, 124.6, 20.6, 20.5. **HRMS** (ESI) calcd for $C_{22}H_{18}N_2$ $[M+H]^+$: 311.1543, found: 311.1541.



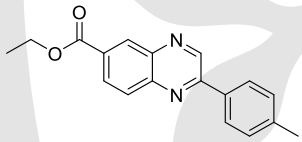
6,7-dichloro-2-(p-tolyl)quinoxaline(3bc)

Yellow solid, 39% yield, 56 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.28 (s, 1H), 8.23 (d, *J* = 1.8 Hz, 1H), 8.19 (s, 1H), 8.09 – 8.05 (m, 2H), 7.37 (d, *J* = 7.8 Hz, 2H), 2.46 (s, 3H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 152.7, 144.3, 141.4, 141.2, 140.2, 134.9, 133.8, 133.3, 130.2, 130.1, 129.9, 127.6, 21.6. **HRMS** (ESI) calcd for $C_{15}H_{11}Cl_2N_2$ $[M+H]^+$: 289.0294, found: 289.0292.



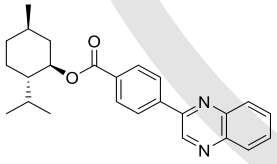
ethyl 2-phenylquinoxaline-6-carboxylate(3bd)

Yellow solid, 39% yield, 54 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.38 (td, *J* = 4.2, 2.4 Hz, 1H), 8.84 (dq, *J* = 25.8, 1.8 Hz, 1H), 8.35 (ddq, *J* = 22.2, 8.4, 1.8 Hz, 1H), 8.24 – 8.19 (m, 2H), 8.18 – 8.11 (m, 1H), 7.61 – 7.51 (m, 3H), 4.47 (qd, *J* = 7.2, 1.8 Hz, 2H), 1.46 (td, *J* = 7.2, 1.2 Hz, 3H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 165.9, 152.7, 145.1, 144.4, 144.4, 143.6, 141.7, 136.3, 132.3, 132.1, 131.8, 130.9, 130.7, 130.0, 129.9, 129.4, 129.4, 129.2, 127.9, 127.7, 61.7, 61.7, 14.5. **HRMS** (ESI) calcd for$C_{17}H_{14}N_2O_2$ $[M+H]^+$: 279.1129, found: 279.1131.



ethyl 2-(p-tolyl)quinoxaline-6-carboxylate(3be)

Yellow solid, 43% yield, 63 mg. **^{1}H NMR** (600 MHz, Chloroform-*d*) δ 9.42 – 9.35 (m, 1H), 8.93 – 8.79 (m, 1H), 8.39 – 8.30 (m, 1H), 8.19 – 8.11 (m, 3H), 7.39 (d, *J* = 7.8 Hz, 2H), 4.48 (qd, *J* = 7.2, 0.6 Hz, 2H), 2.46 (s, 3H), 1.47 (t, *J* = 7.2 Hz, 3H). **^{13}C NMR** (150 MHz, Chloroform-*d*) δ 165.8, 153.1, 152.5, 144.8, 144.3, 144.1, 143.2, 141.2, 141.0, 140.5, 133.3, 132.0, 131.9, 131.6, 130.8, 130.0, 129.9, 129.8, 129.6, 129.2, 128.8, 127.6, 127.4, 61.5, 61.5, 21.4, 21.4, 14.3. **HRMS** (ESI) calcd for $C_{18}H_{16}N_2O_2$ $[M+H]^+$: 293.1285, found: 293.1287.



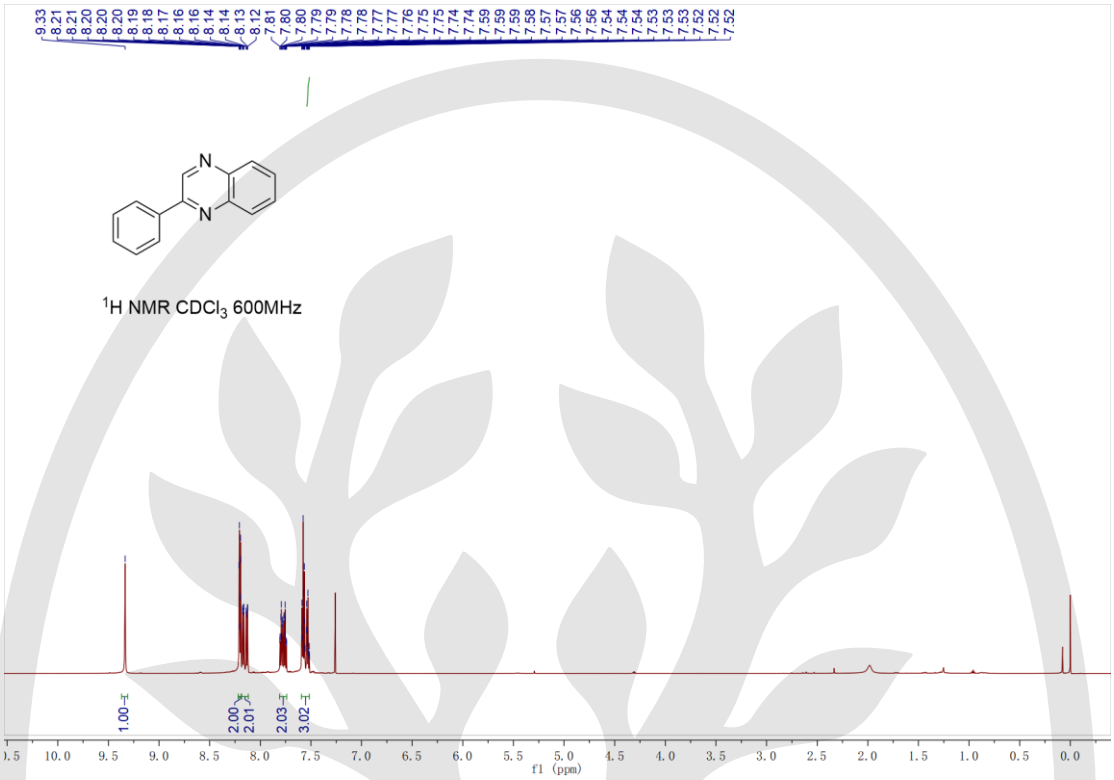
(1R,2S,5R)-2-isopropyl-5-methylcyclohexyl 4-(quinoxalin-2-yl)benzoate(4aa)

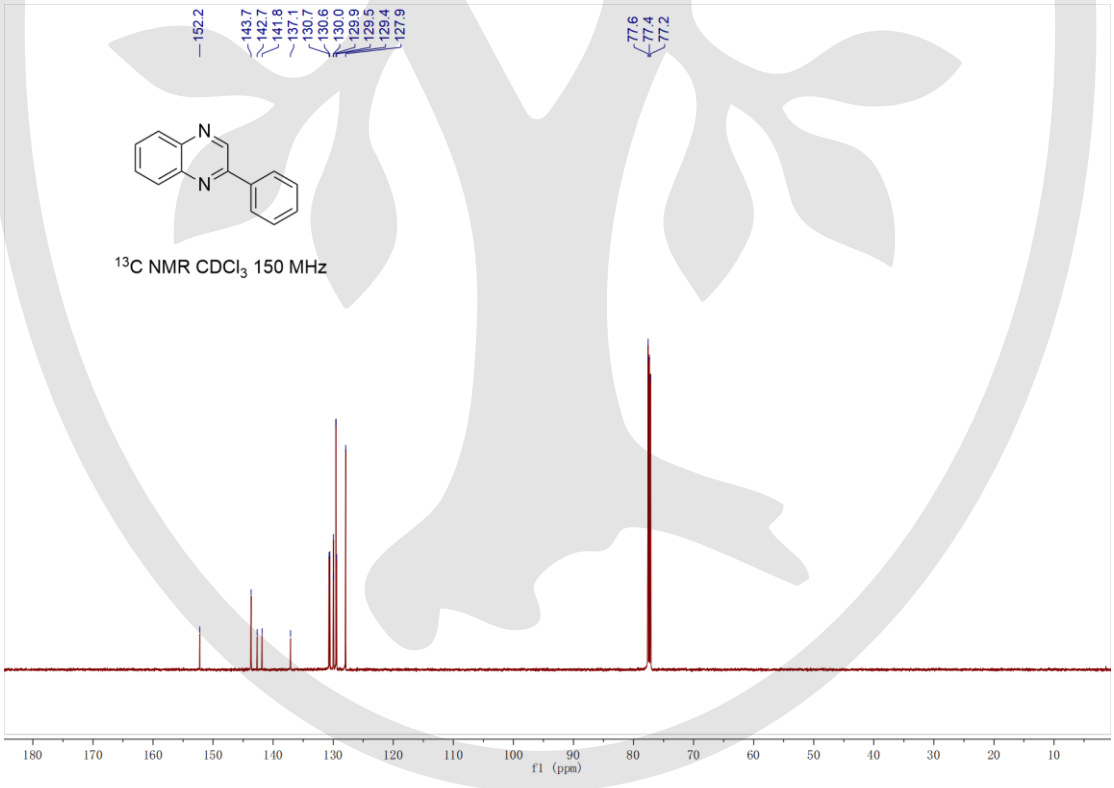
Yellow solid, 42% yield, 81 mg. **^{1}H NMR** (400 MHz, Chloroform-d) δ 8.19 (d, J = 8.4 Hz, 2H), 8.10 (d, J = 8.4 Hz, 2H), 7.65 (dd, J = 6.0, 3.2 Hz, 2H), 7.30 – 7.26 (m, 2H), 4.95 (td, J = 10.8, 4.4 Hz, 1H), 2.15 – 2.08 (m, 1H), 1.94 (td, J = 7.2, 2.8 Hz, 1H), 1.76 – 1.69 (m, 2H), 1.59 – 1.47 (m, 2H), 1.26 (d, J = 3.6 Hz, 1H), 1.11 (d, J = 11.2 Hz, 2H), 0.91 (dd, J = 6.8, 2.0 Hz, 6H), 0.79 (d, J = 6.8 Hz, 3H). **^{13}C NMR** (100 MHz, Chloroform-*d*) δ 165.6, 150.6, 133.5, 132.3, 130.5, 126.7, 123.7,

75.5, 71.8, 50.3, 47.3, 45.2, 41.1, 34.7, 34.4, 31.8, 31.6, 26.6, 26.0, 23.7, 23.3, 22.4, 22.2, 21.2, 20.9, 16.6, 16.2. **HRMS** (ESI) calcd for $C_{25}H_{29}N_2O_2$ $[M+H]^+$: 389.2224, found: 389.2219.

7. ^{1}H and ^{13}C NMR spectra

3aa





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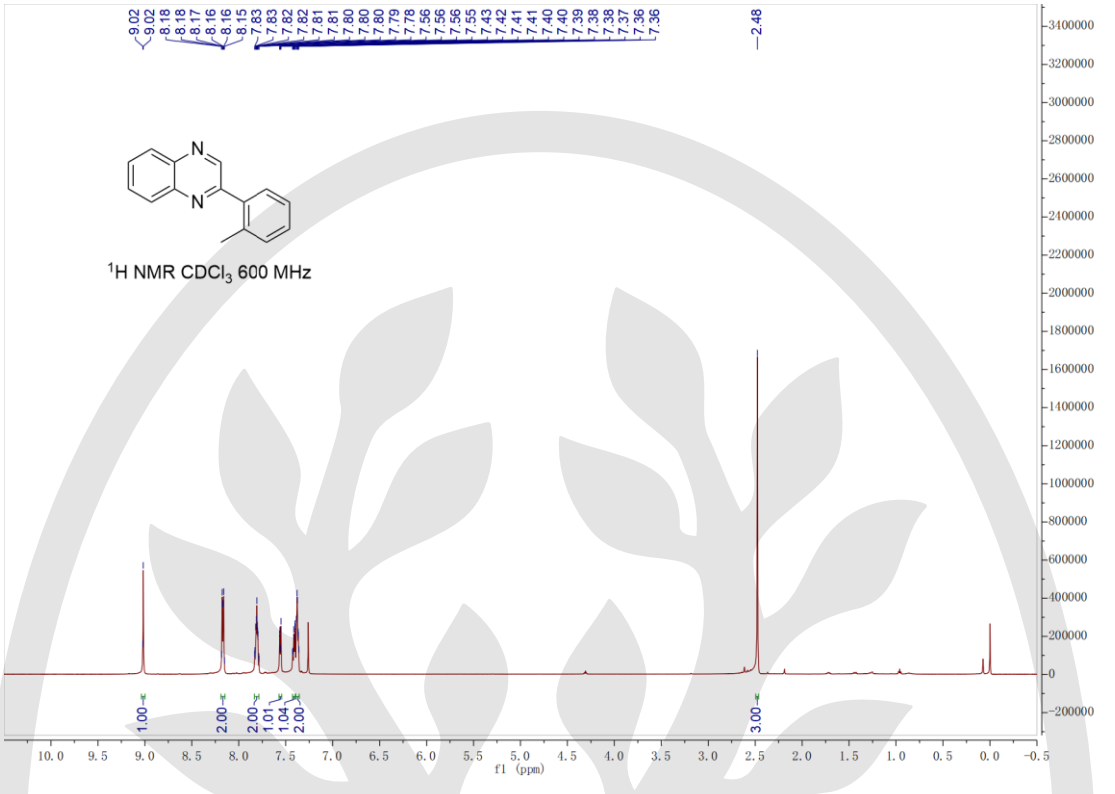

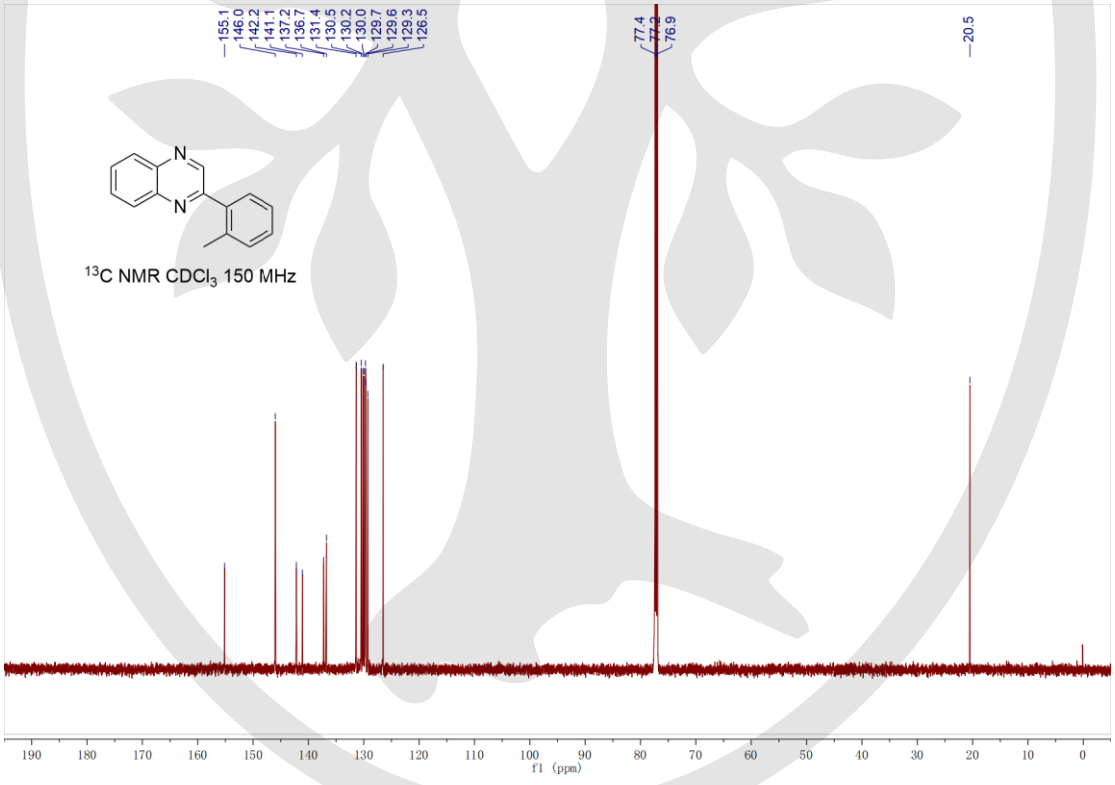

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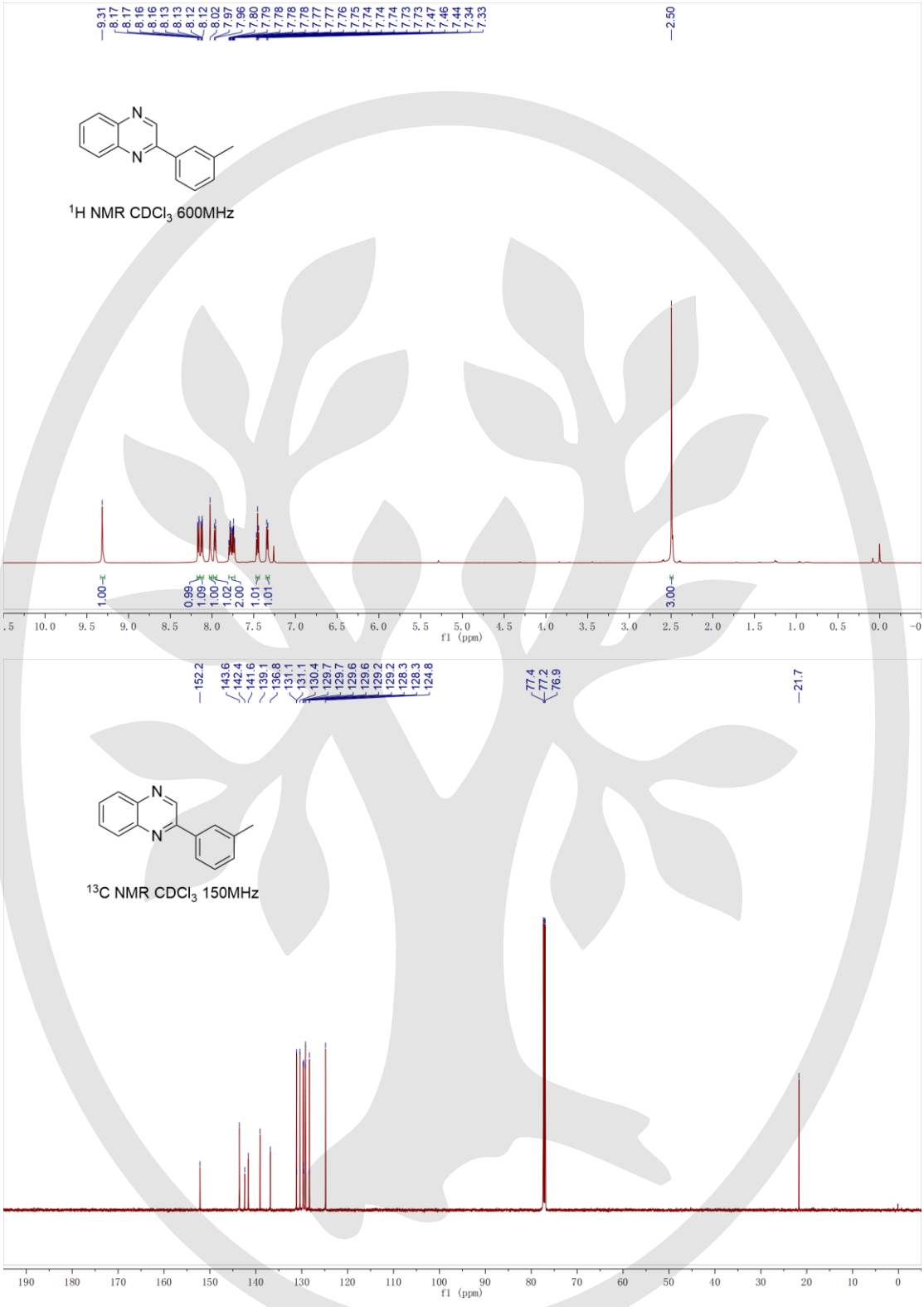

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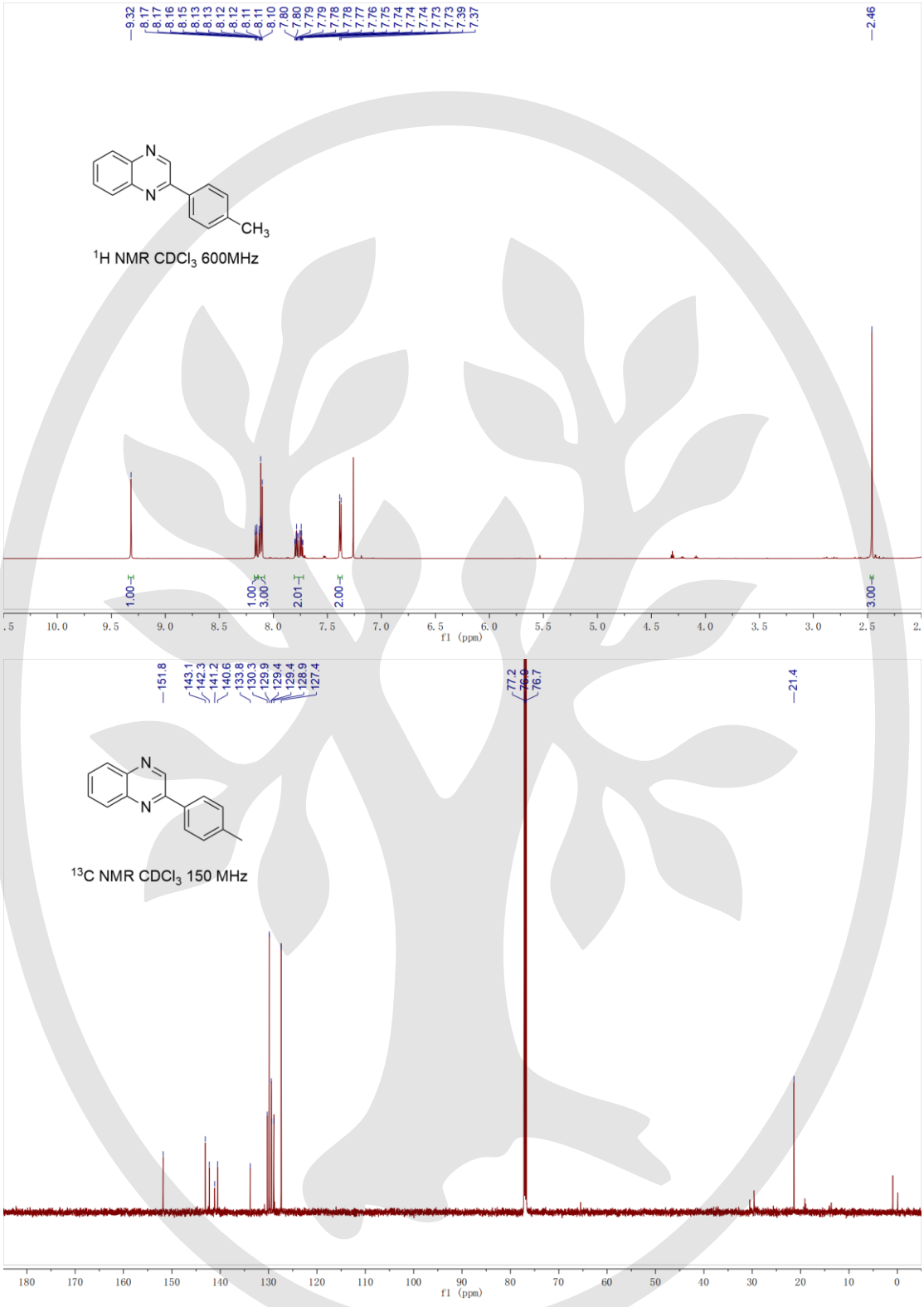

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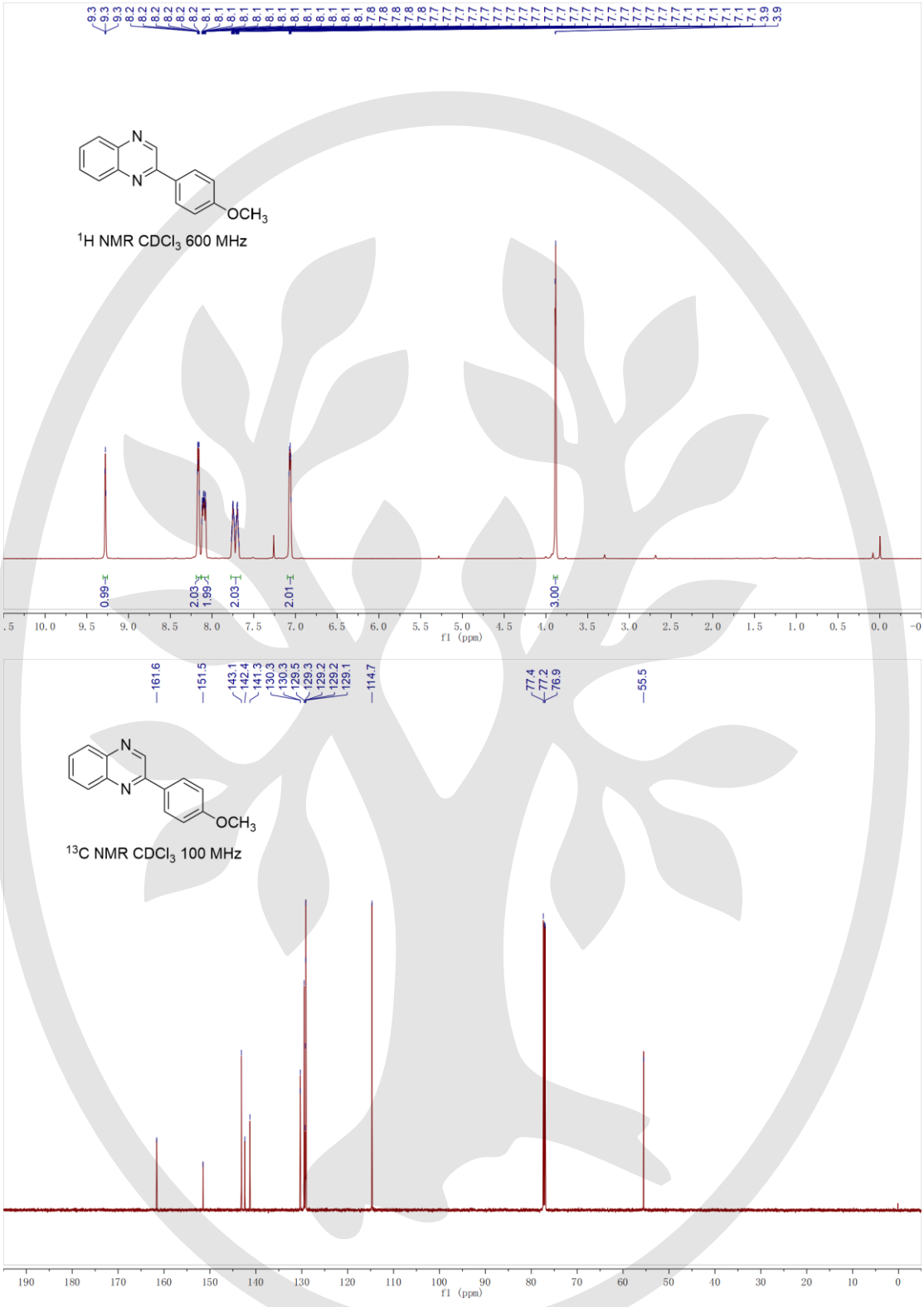

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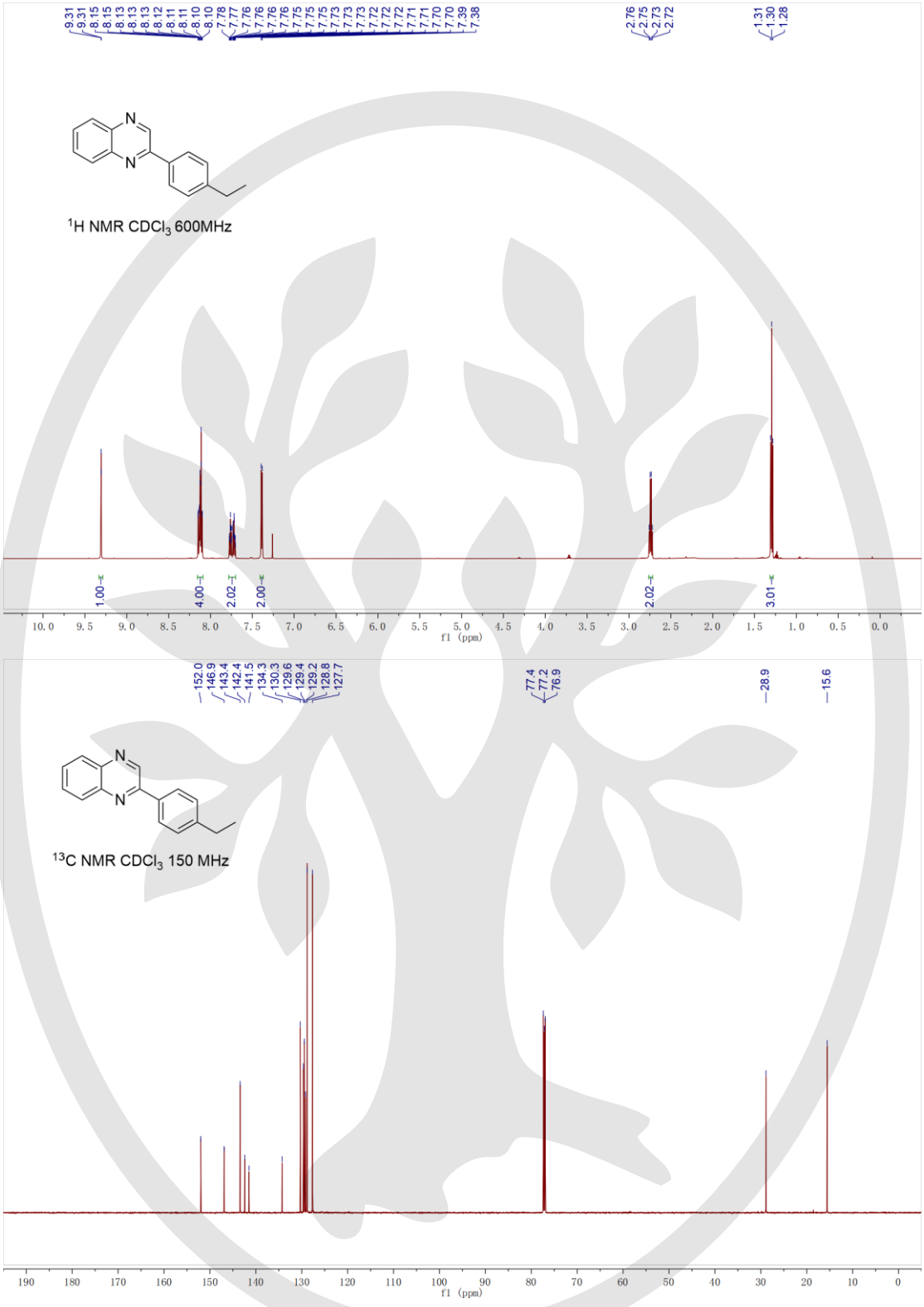

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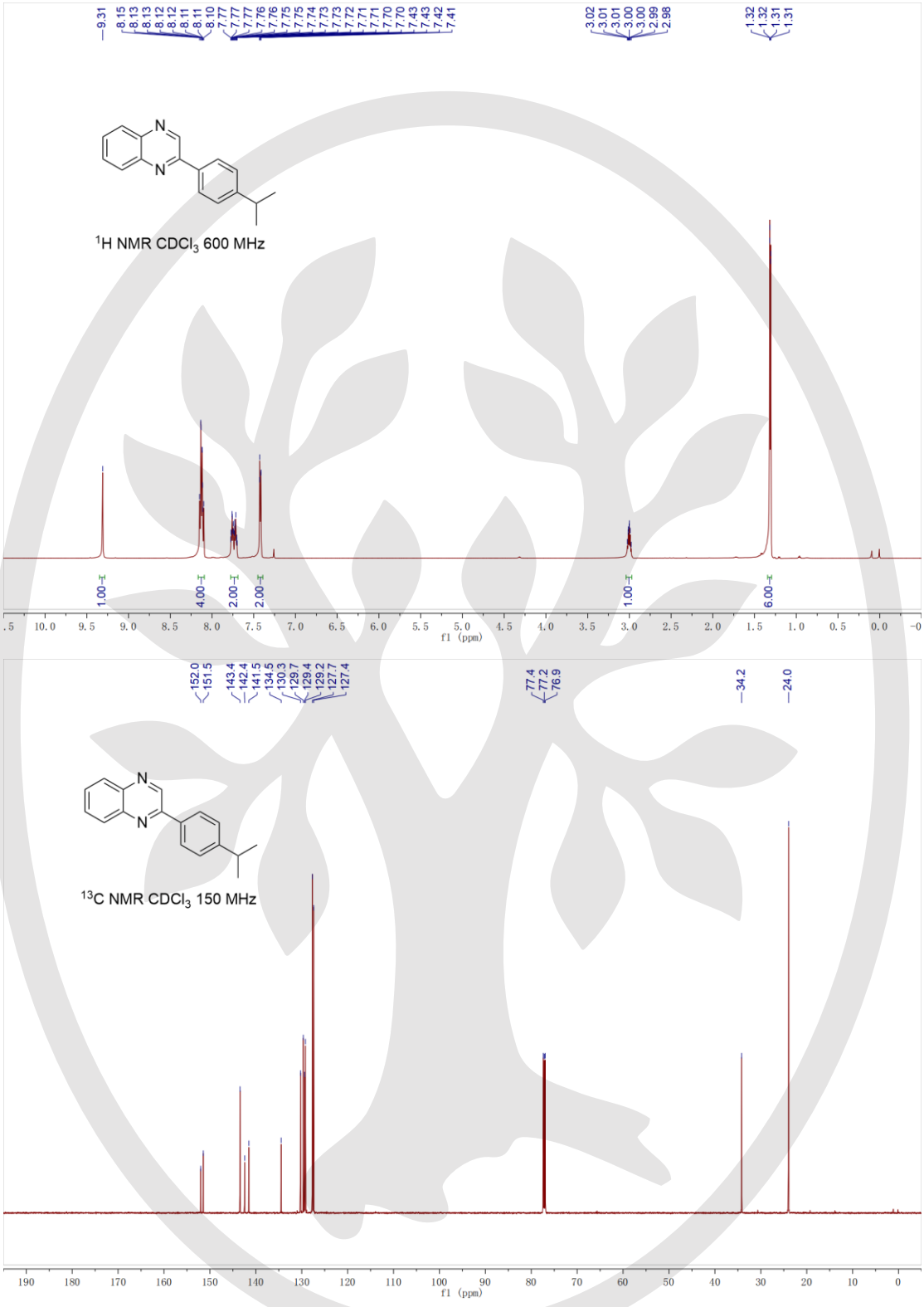

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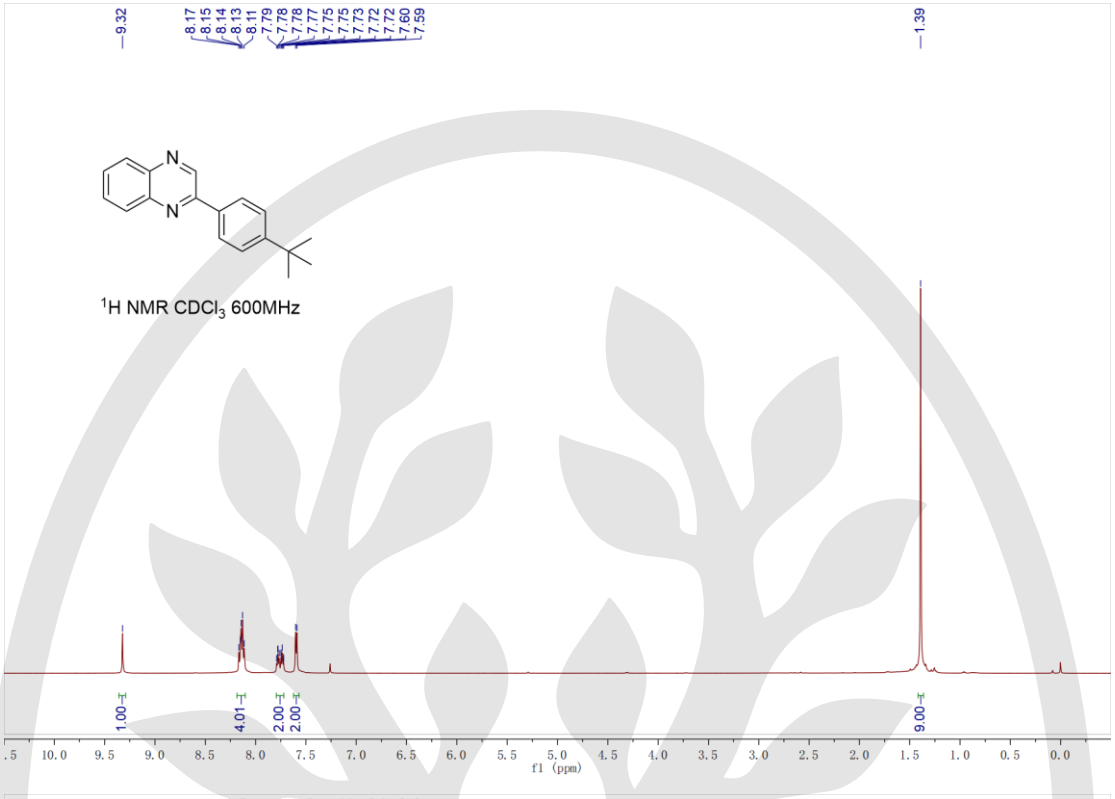
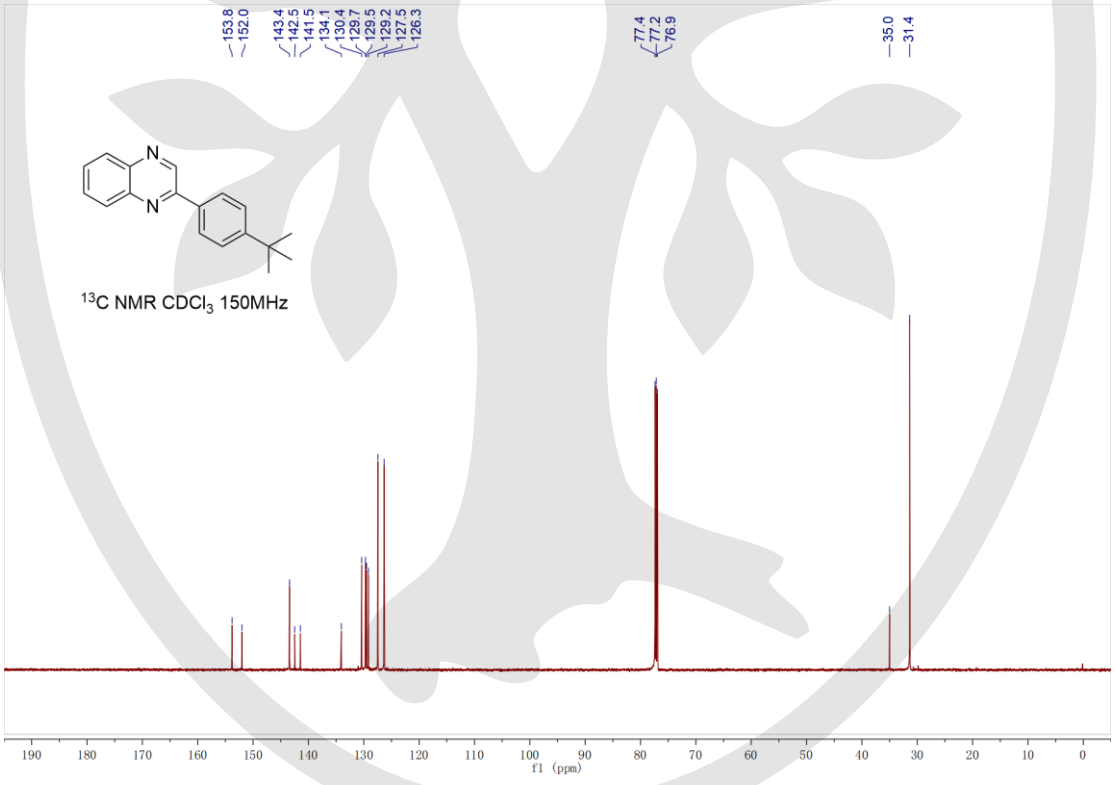
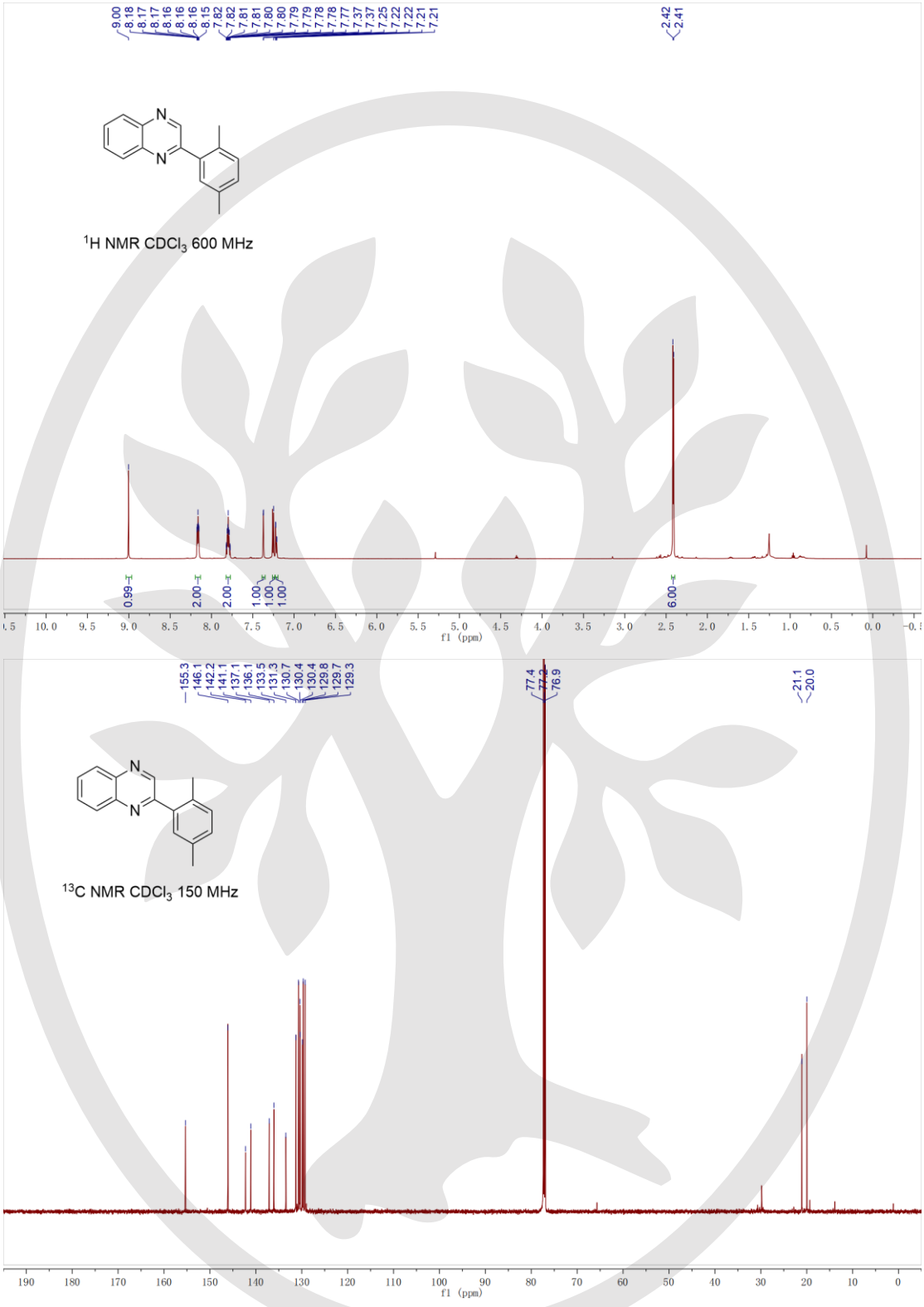


^{1}H NMR $CDCl_3$ 600MHz



^{13}C NMR $CDCl_3$ 150MHz

3ai



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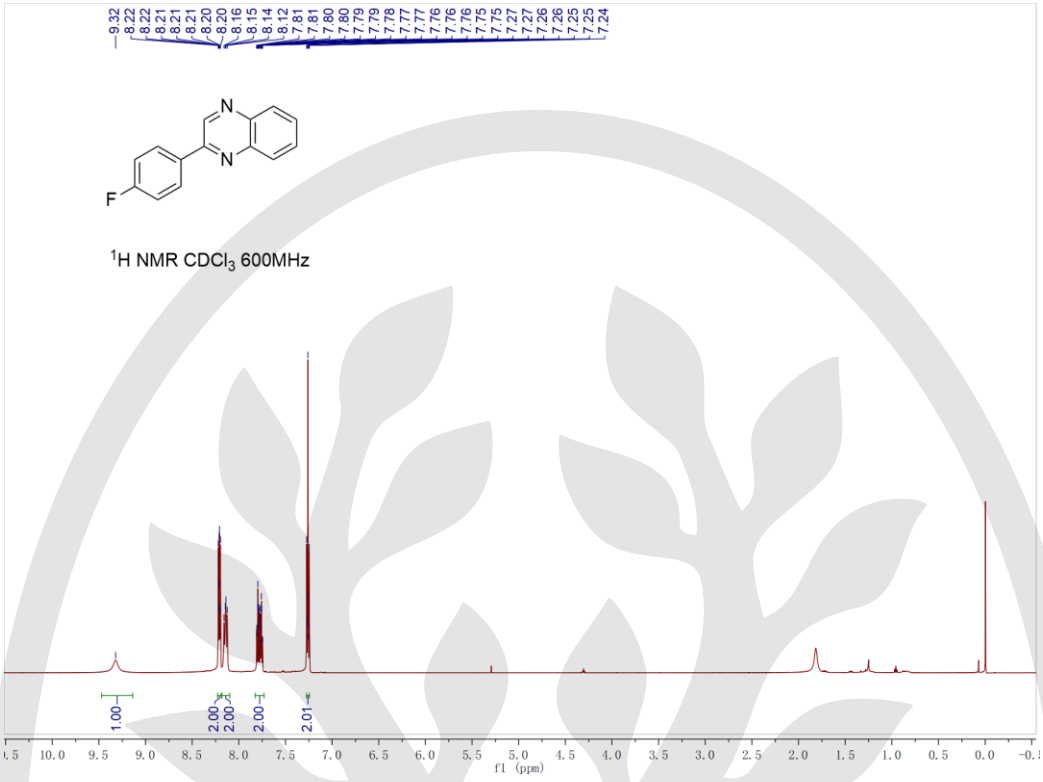

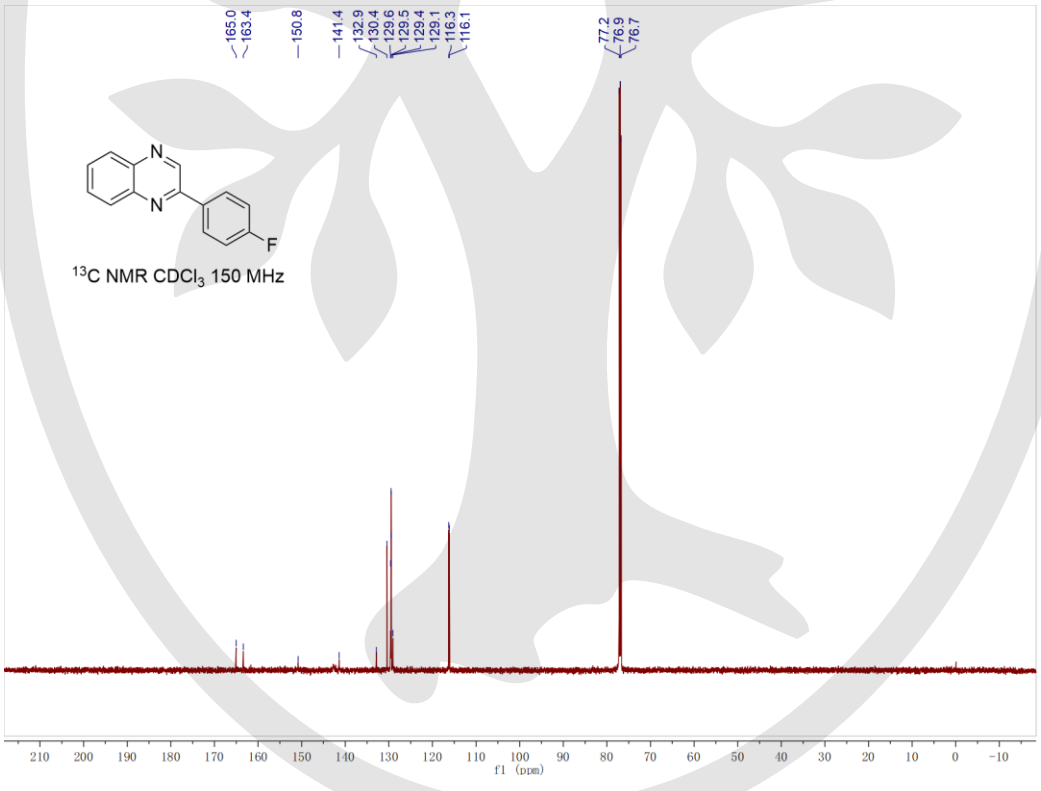

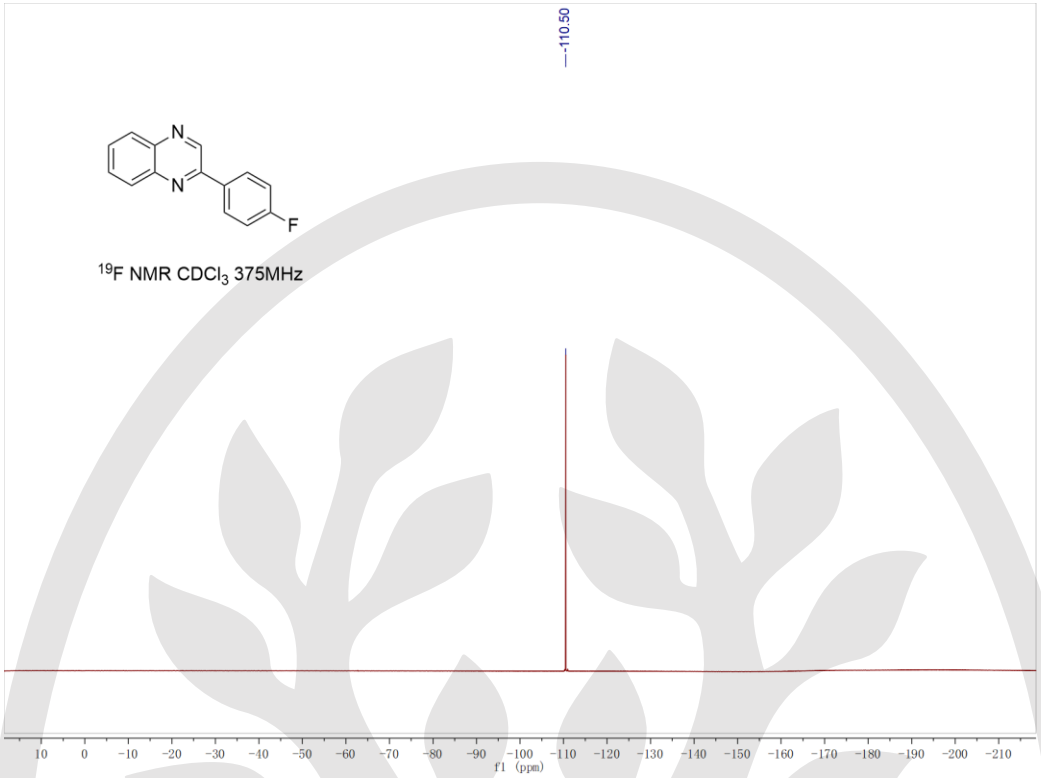

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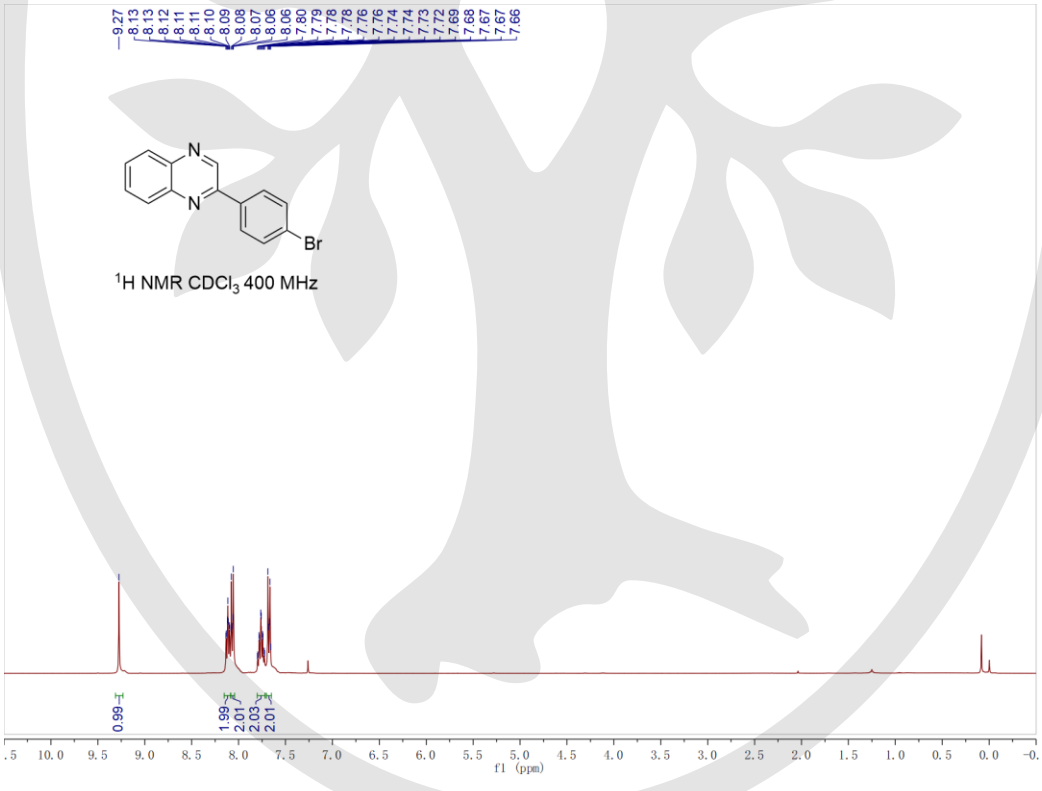

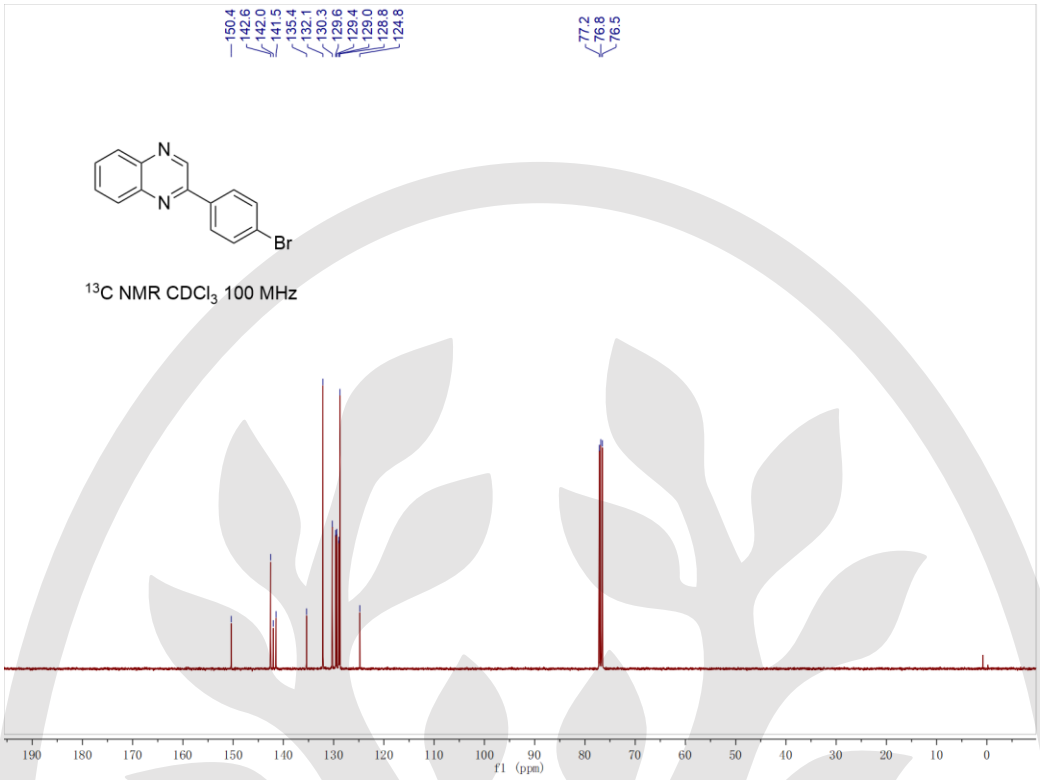

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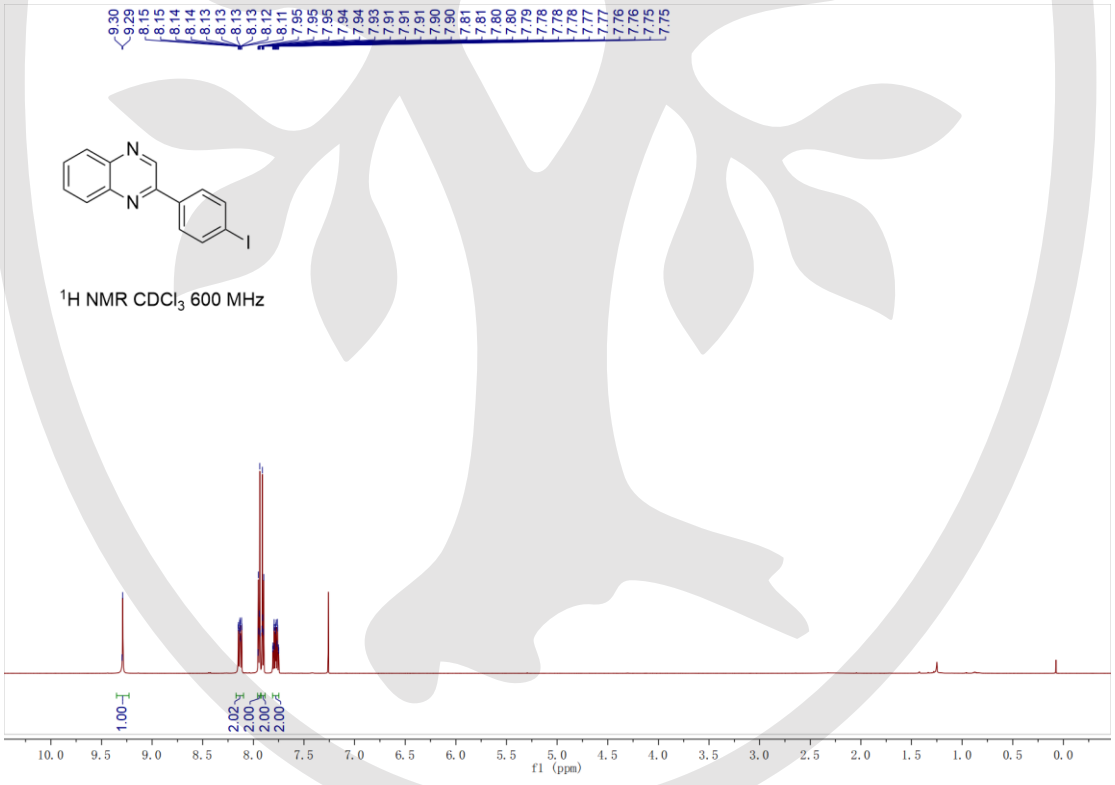

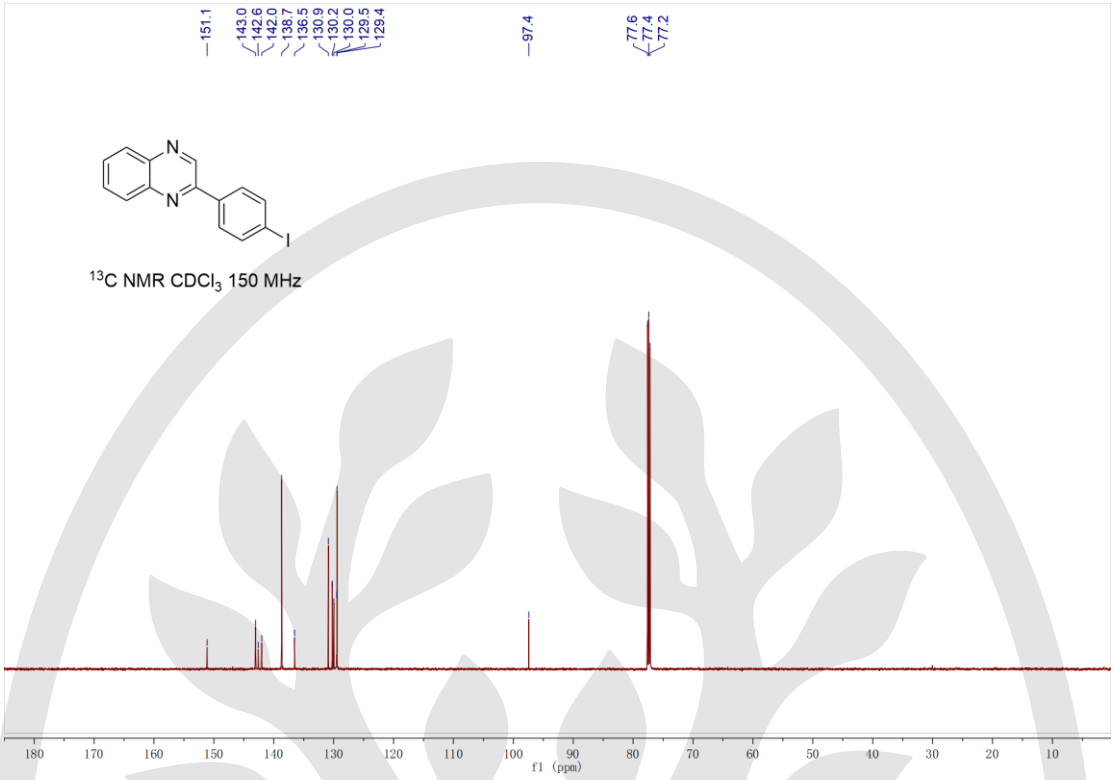

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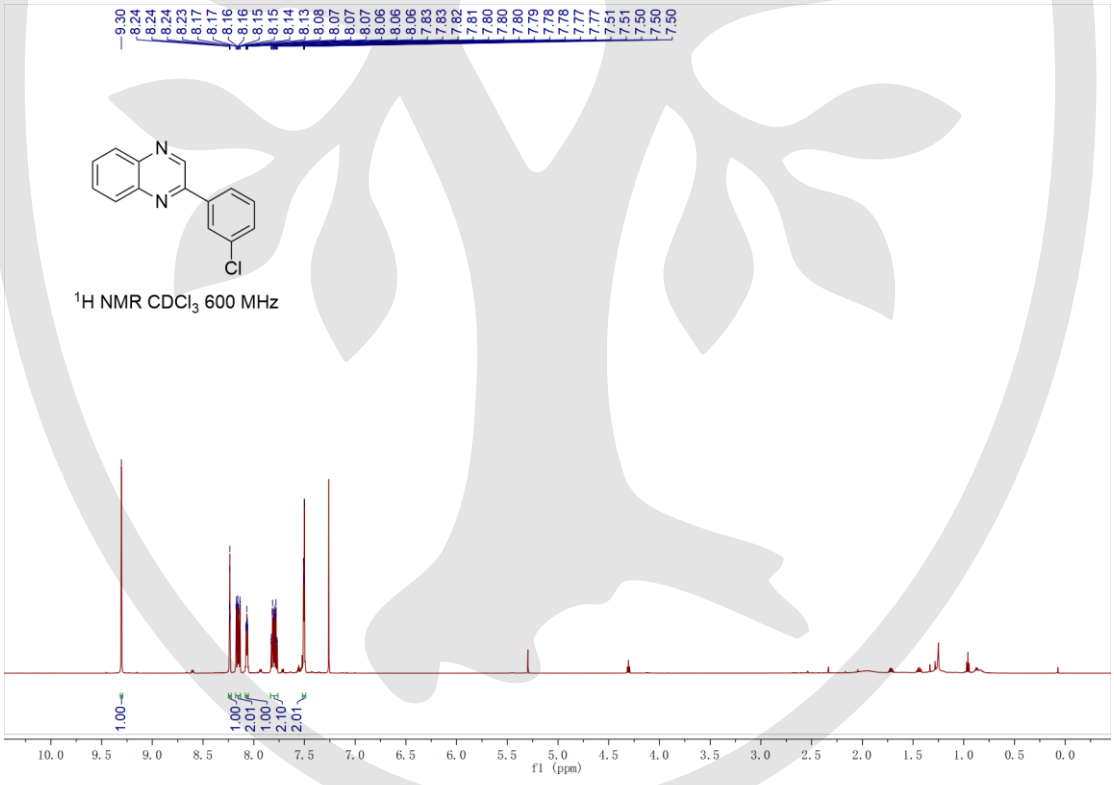

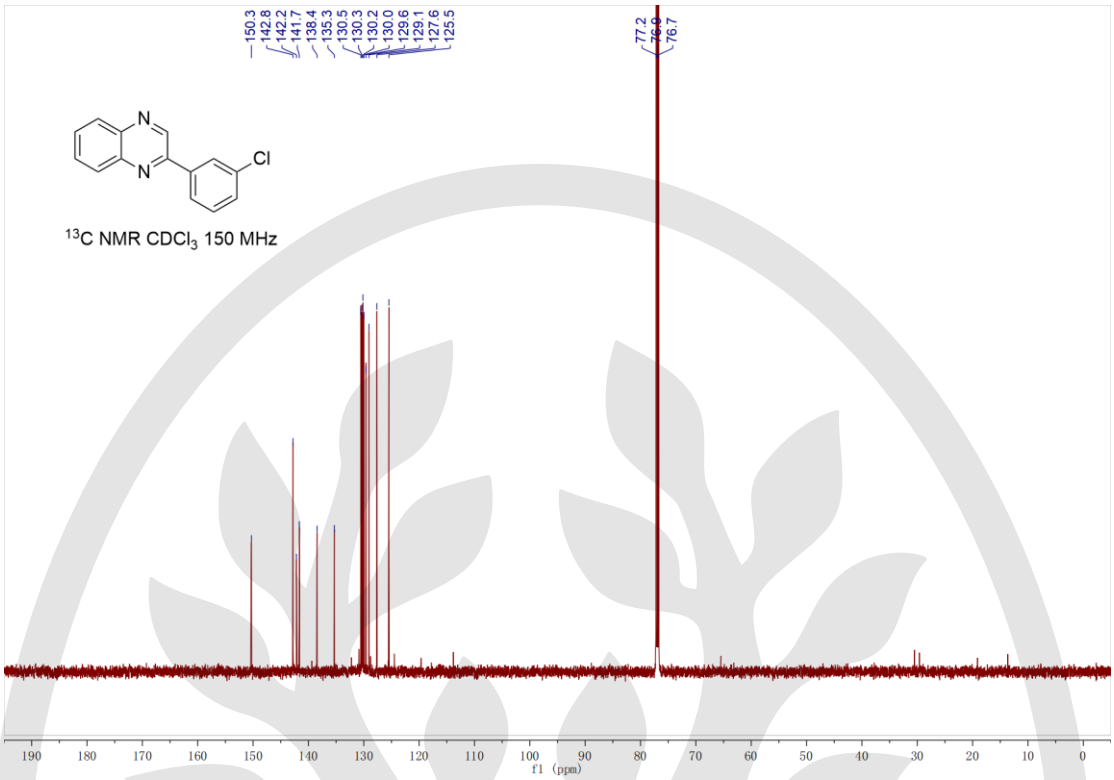

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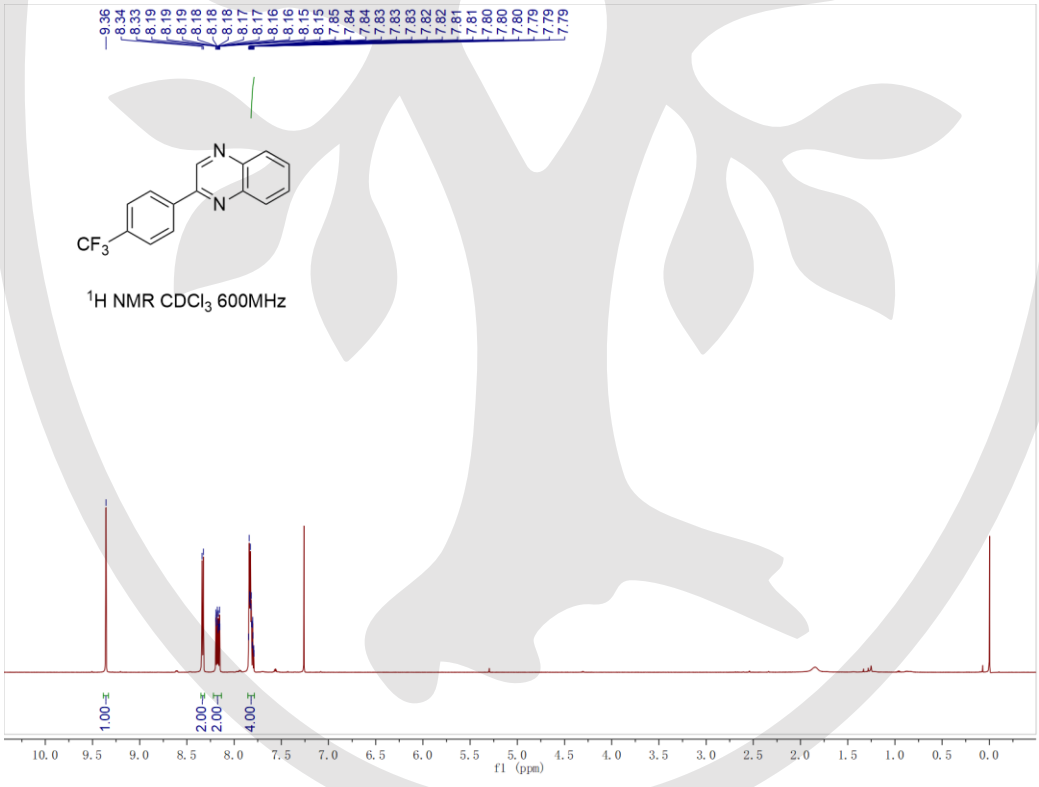

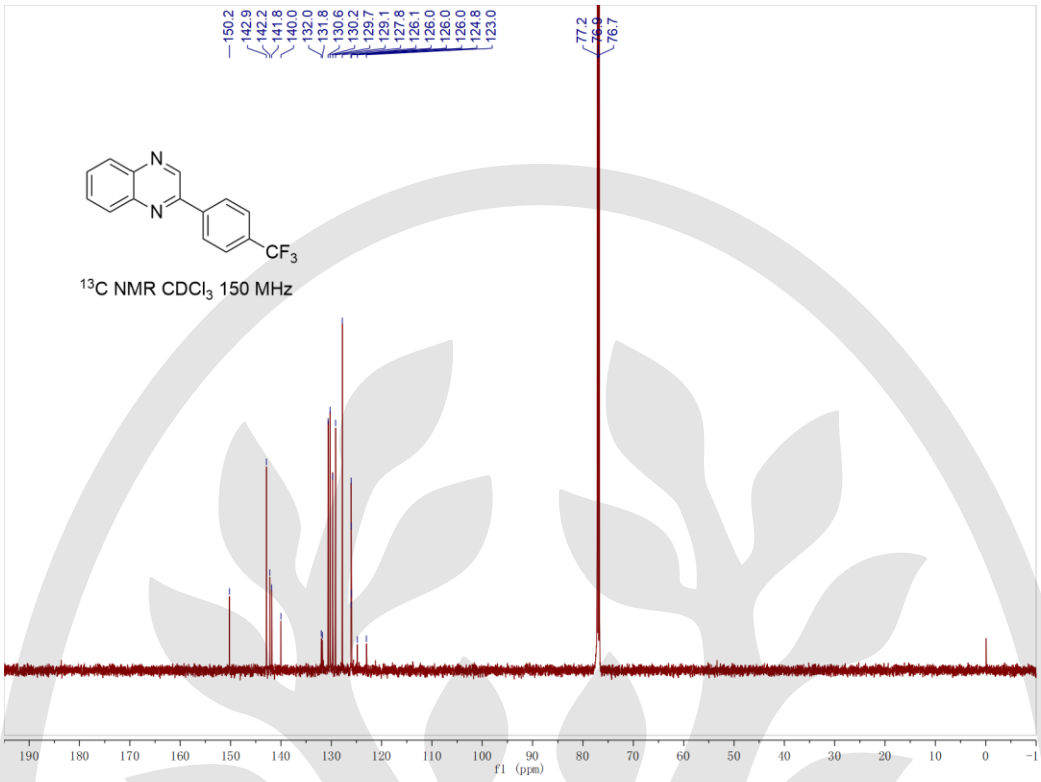

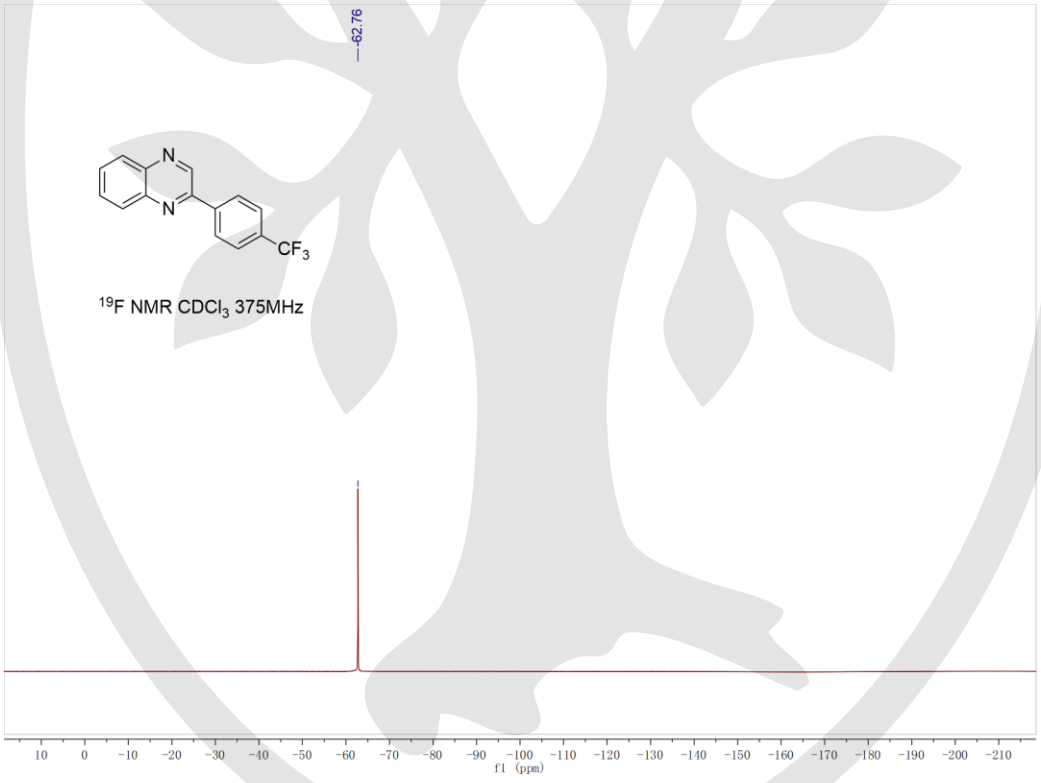

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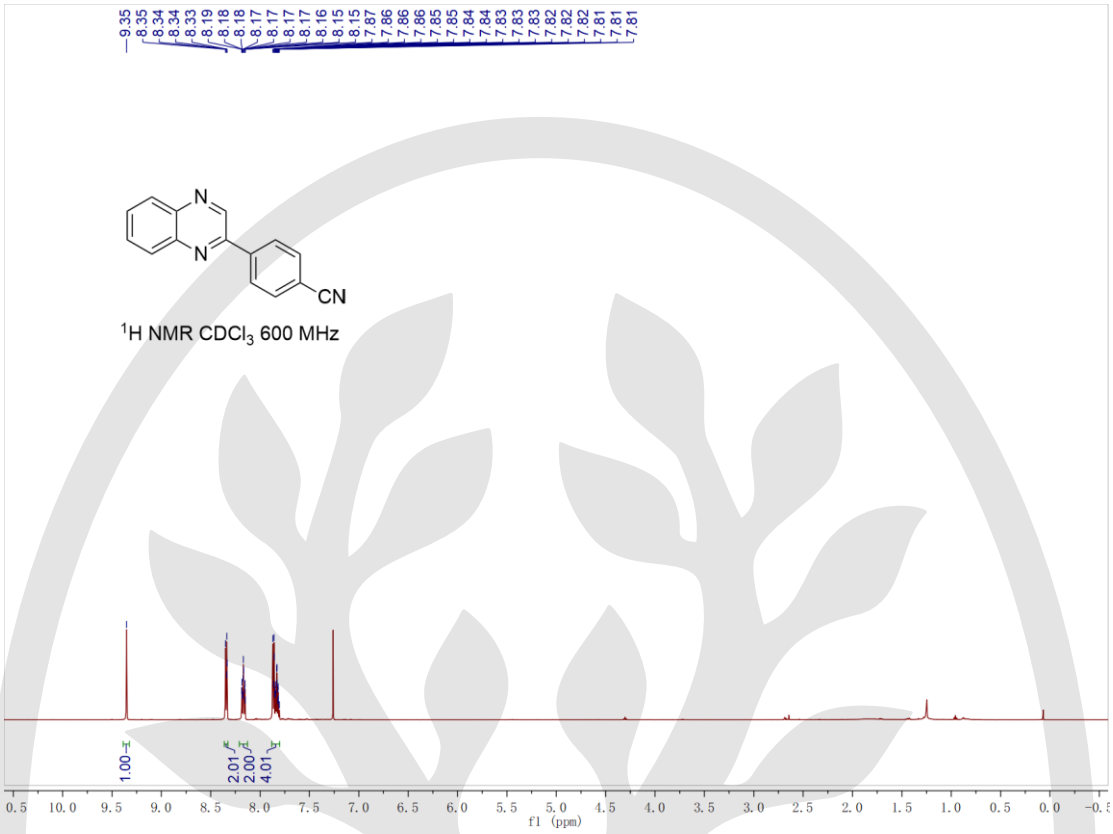

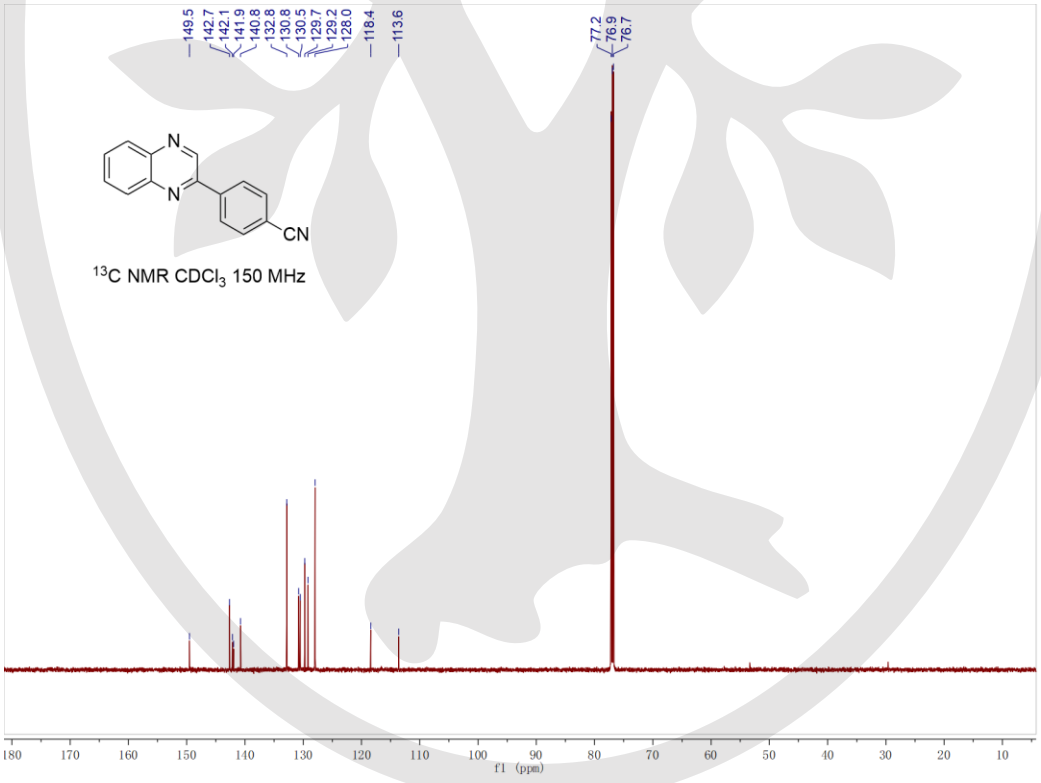

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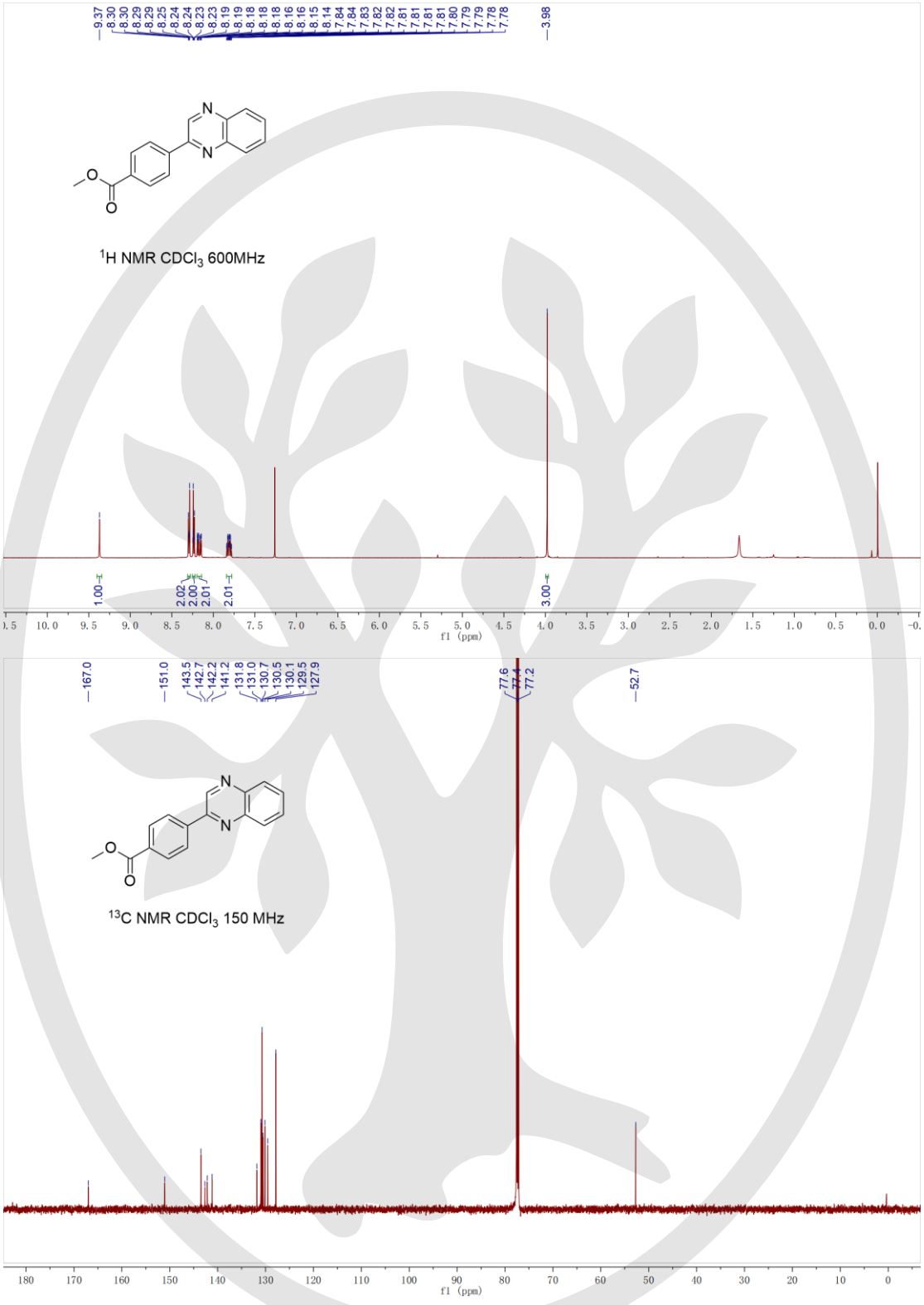

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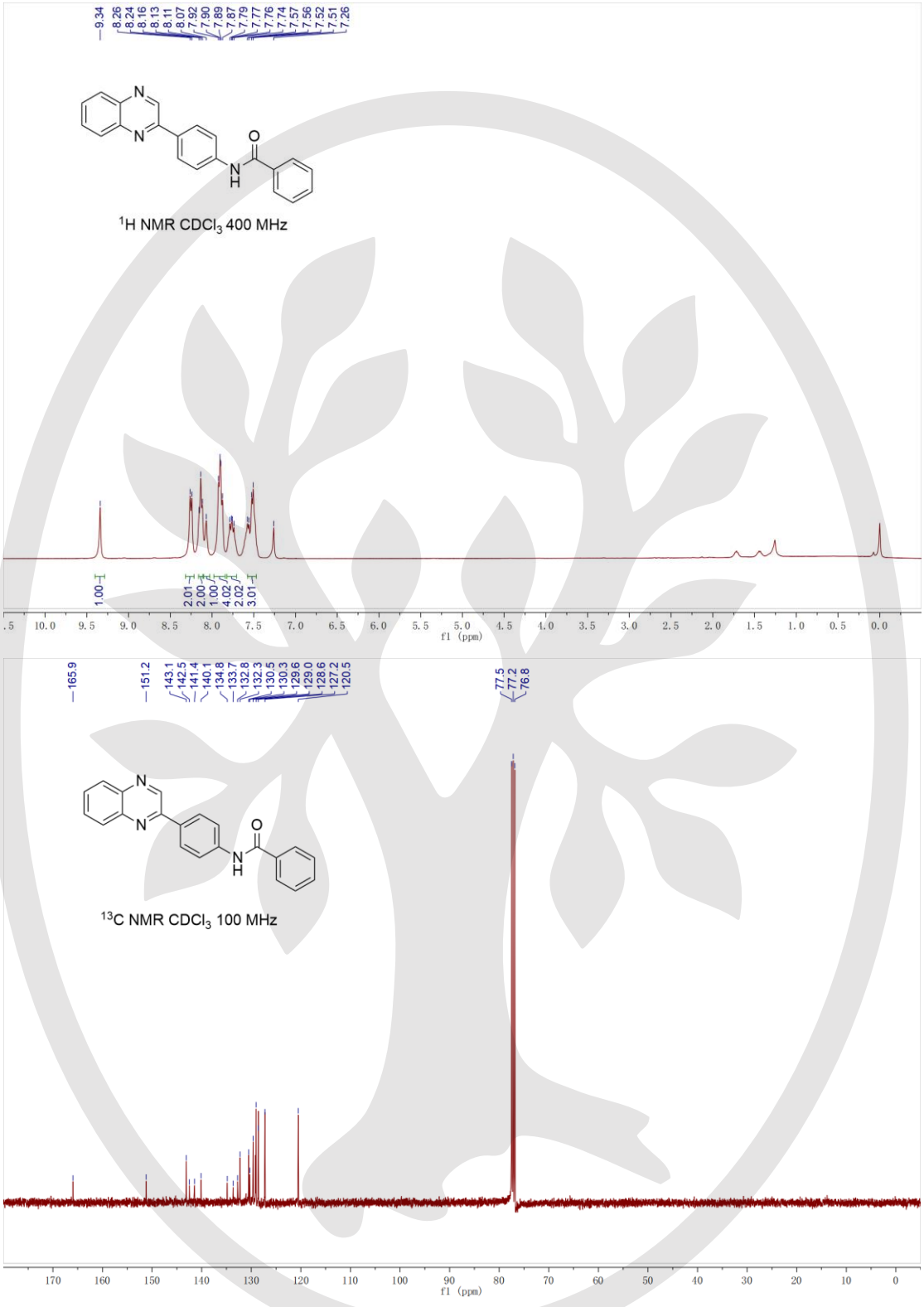

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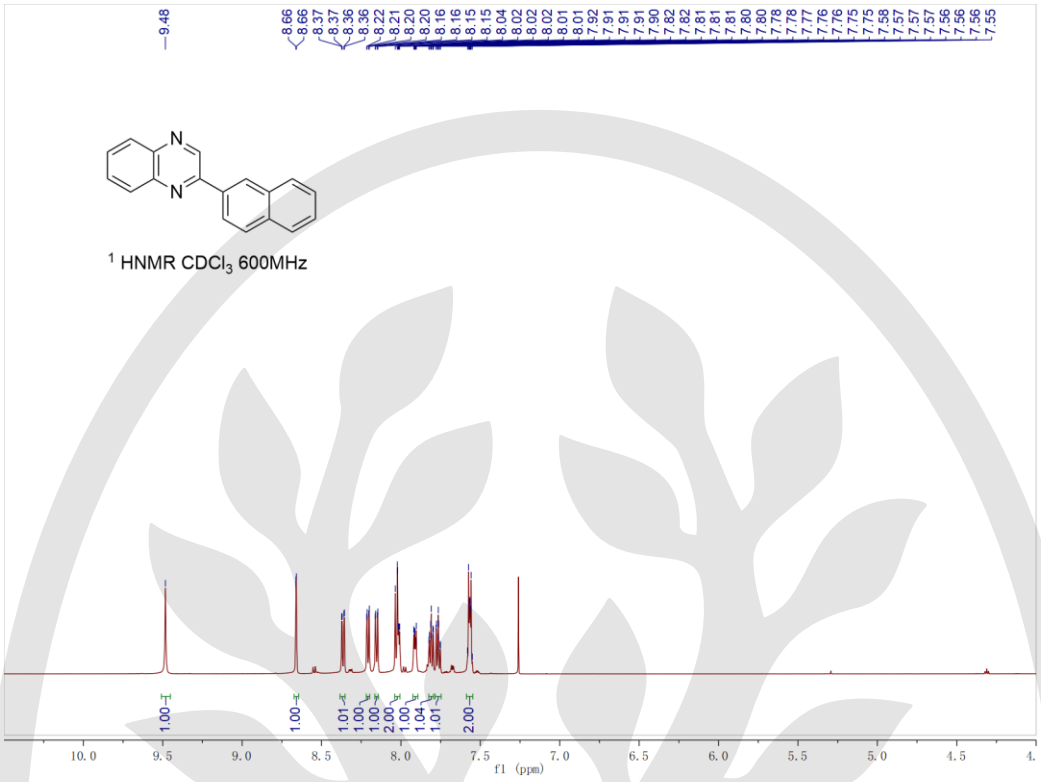

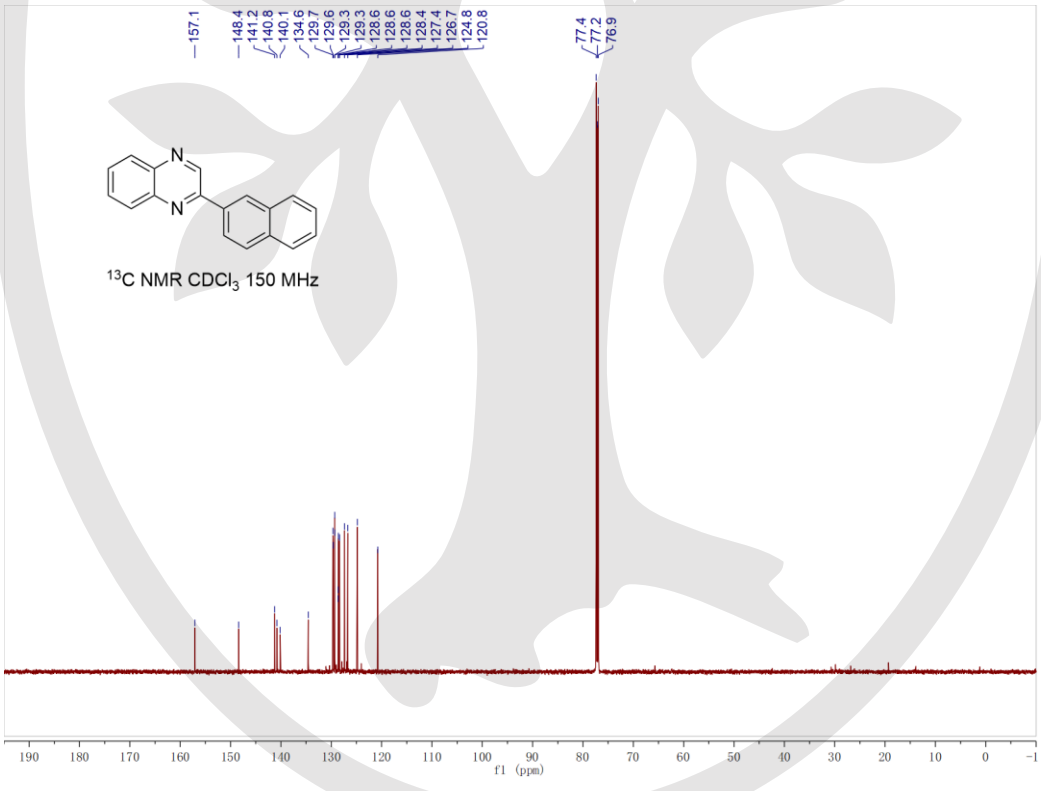

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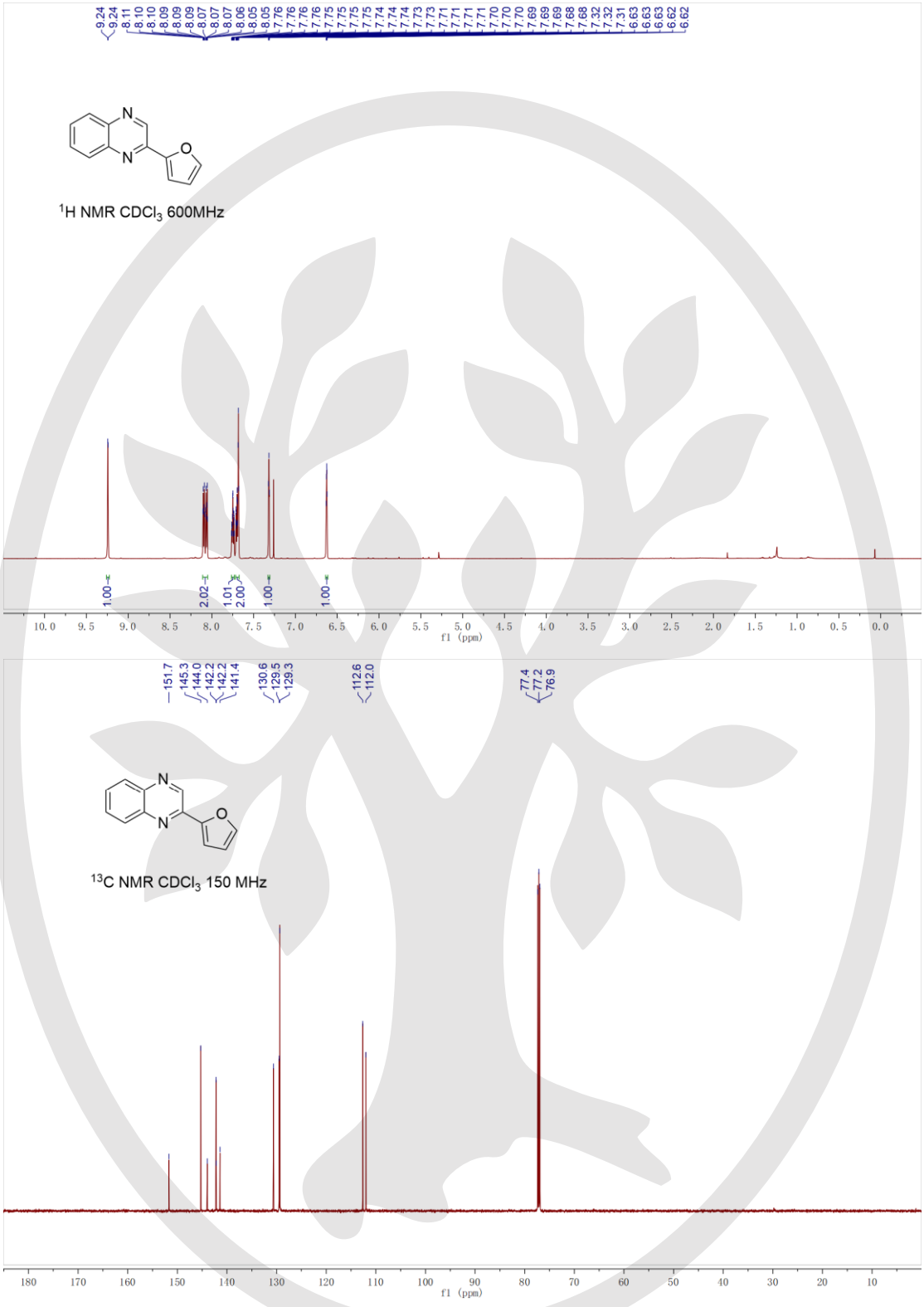

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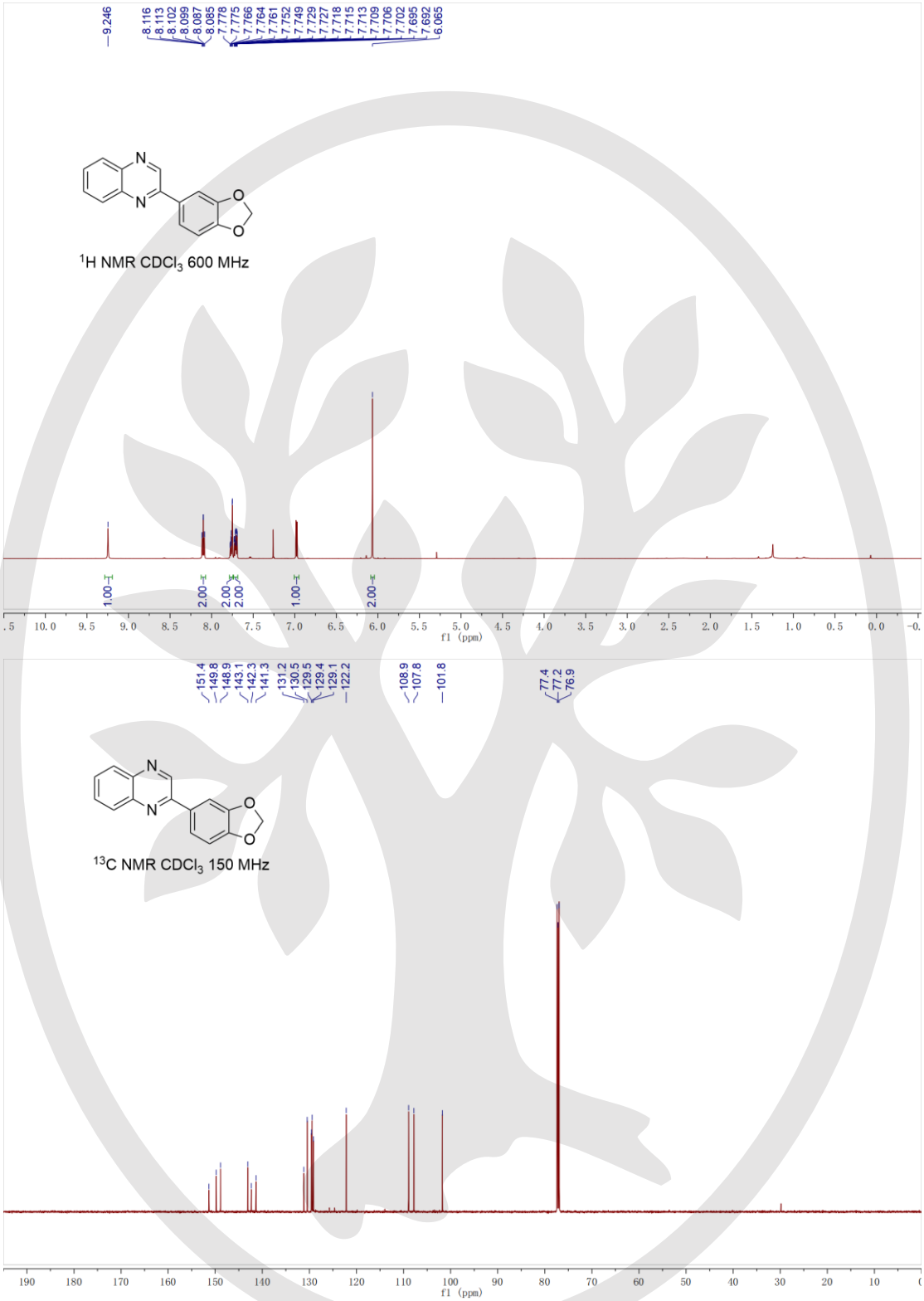

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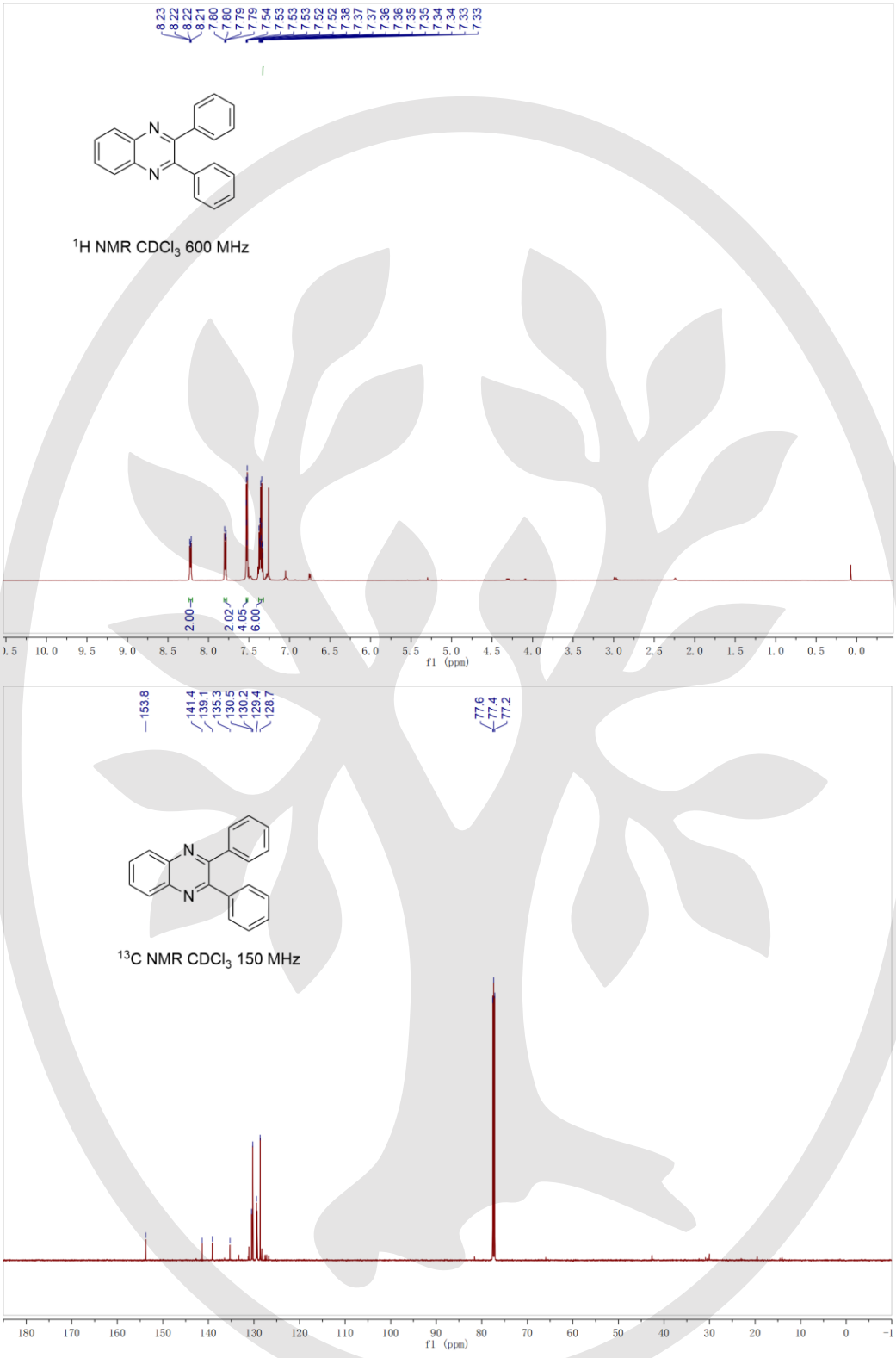

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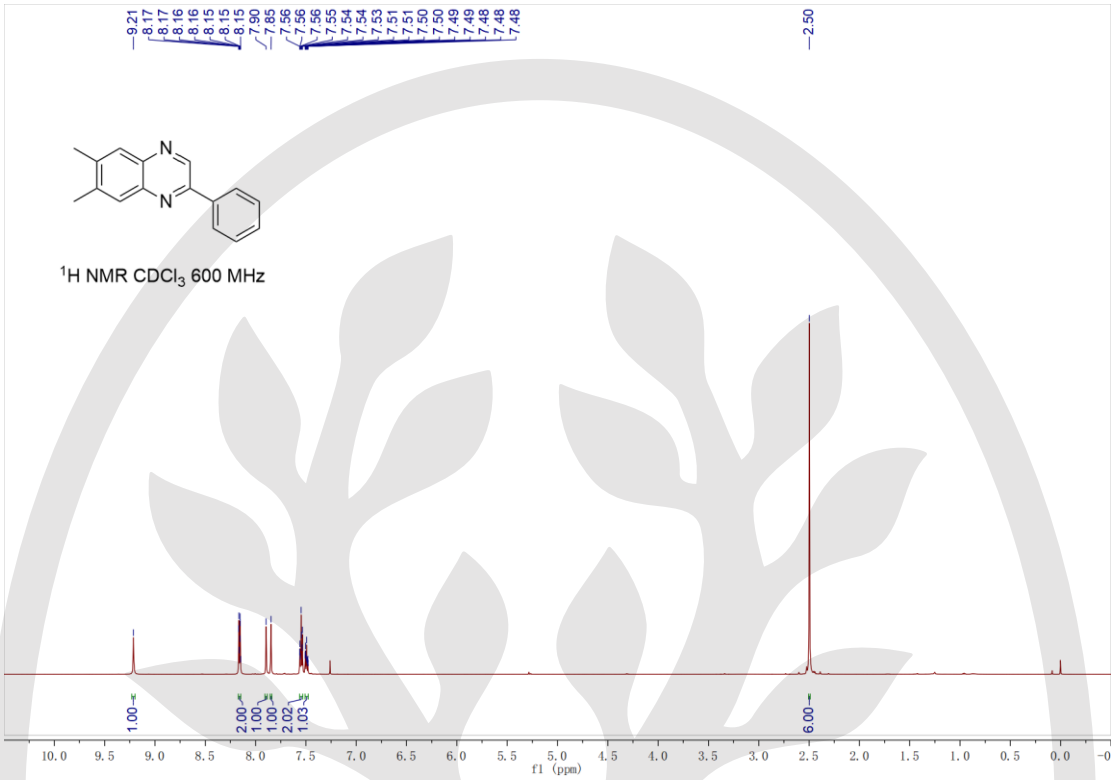

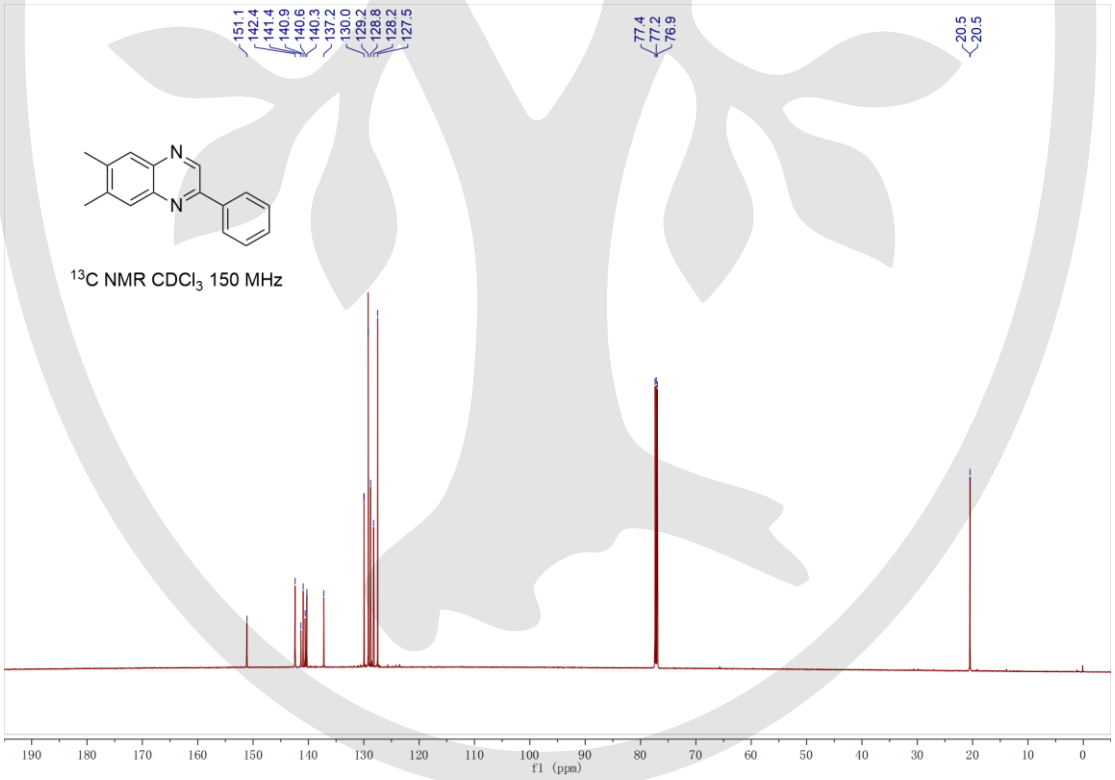

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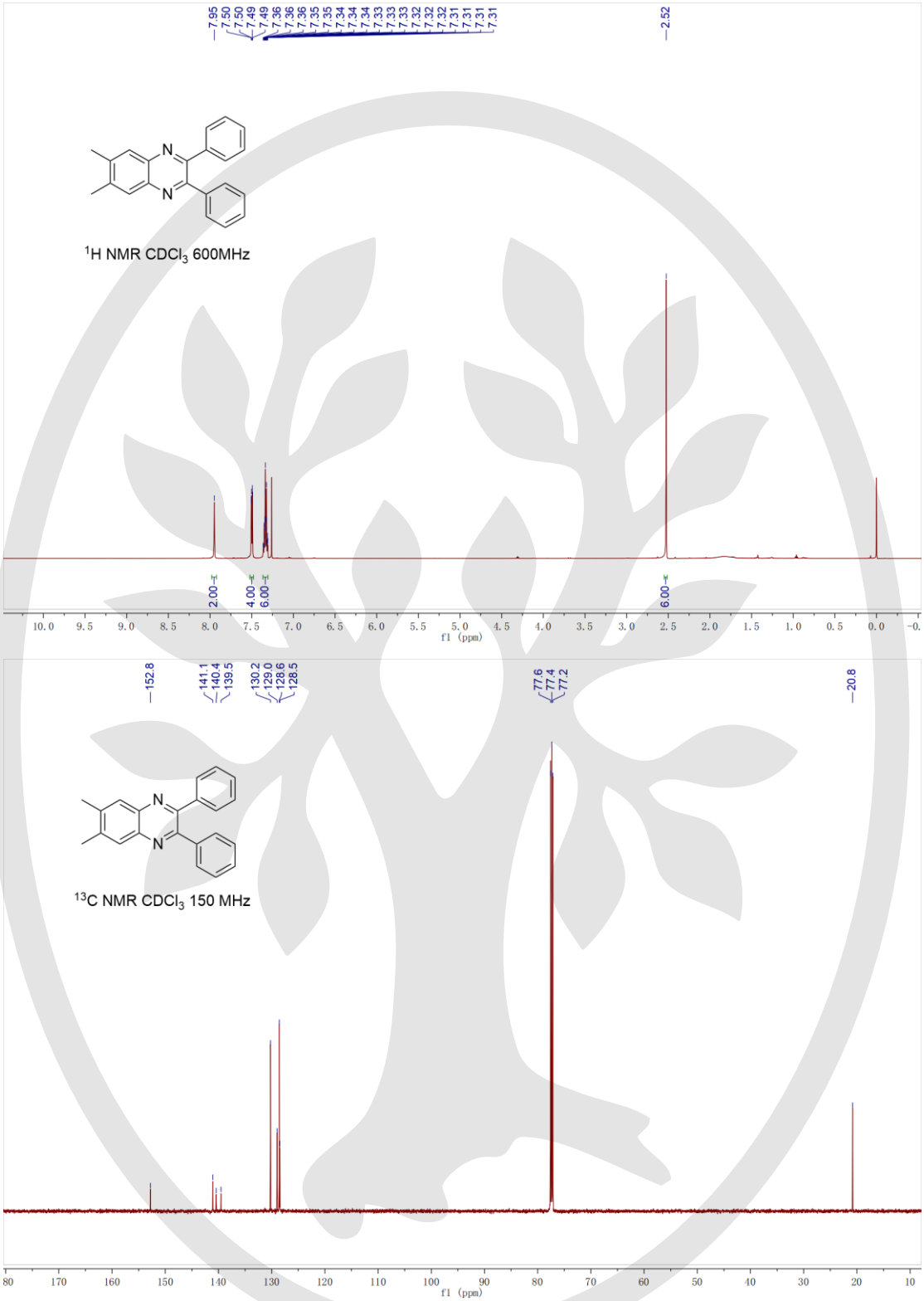

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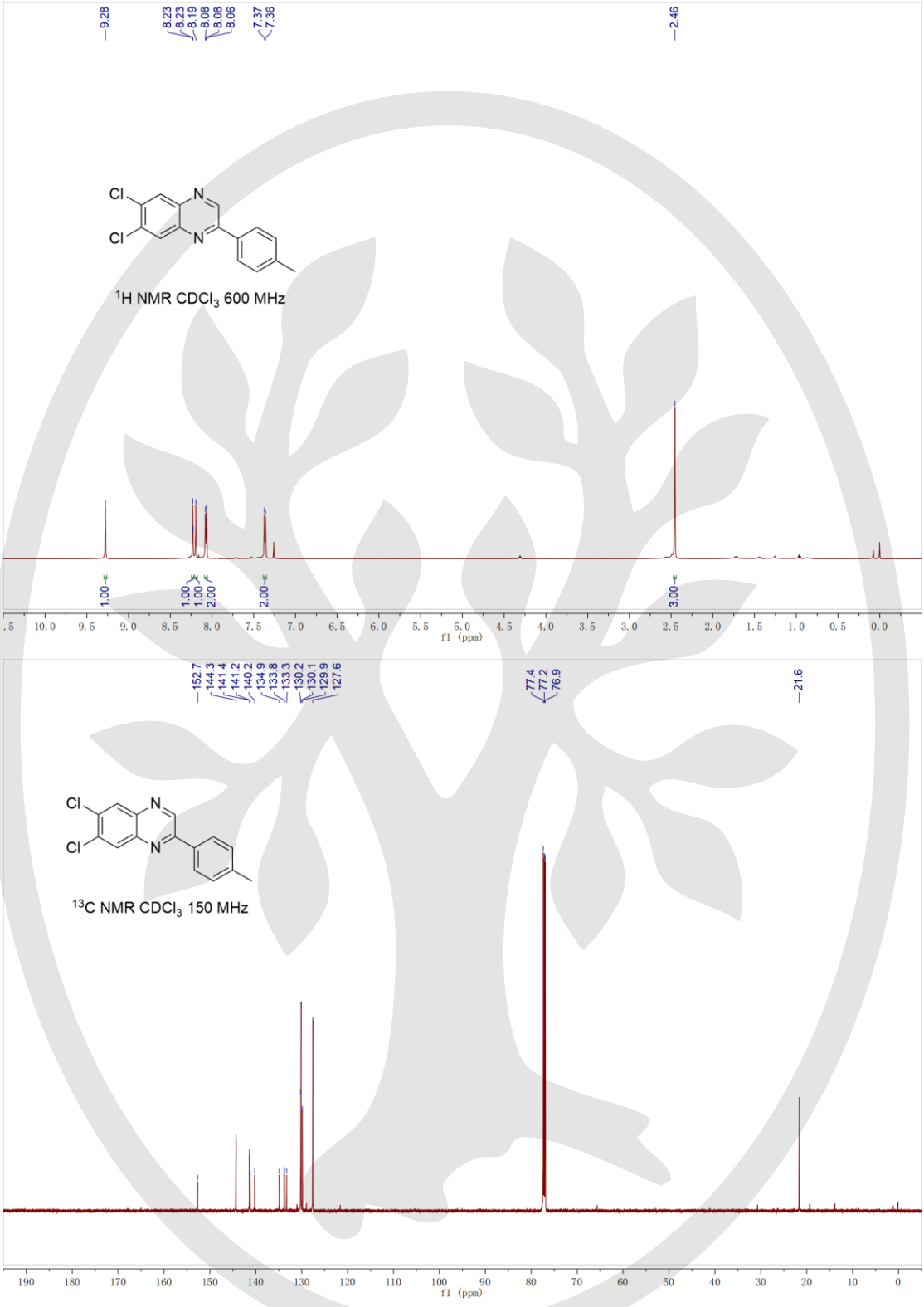

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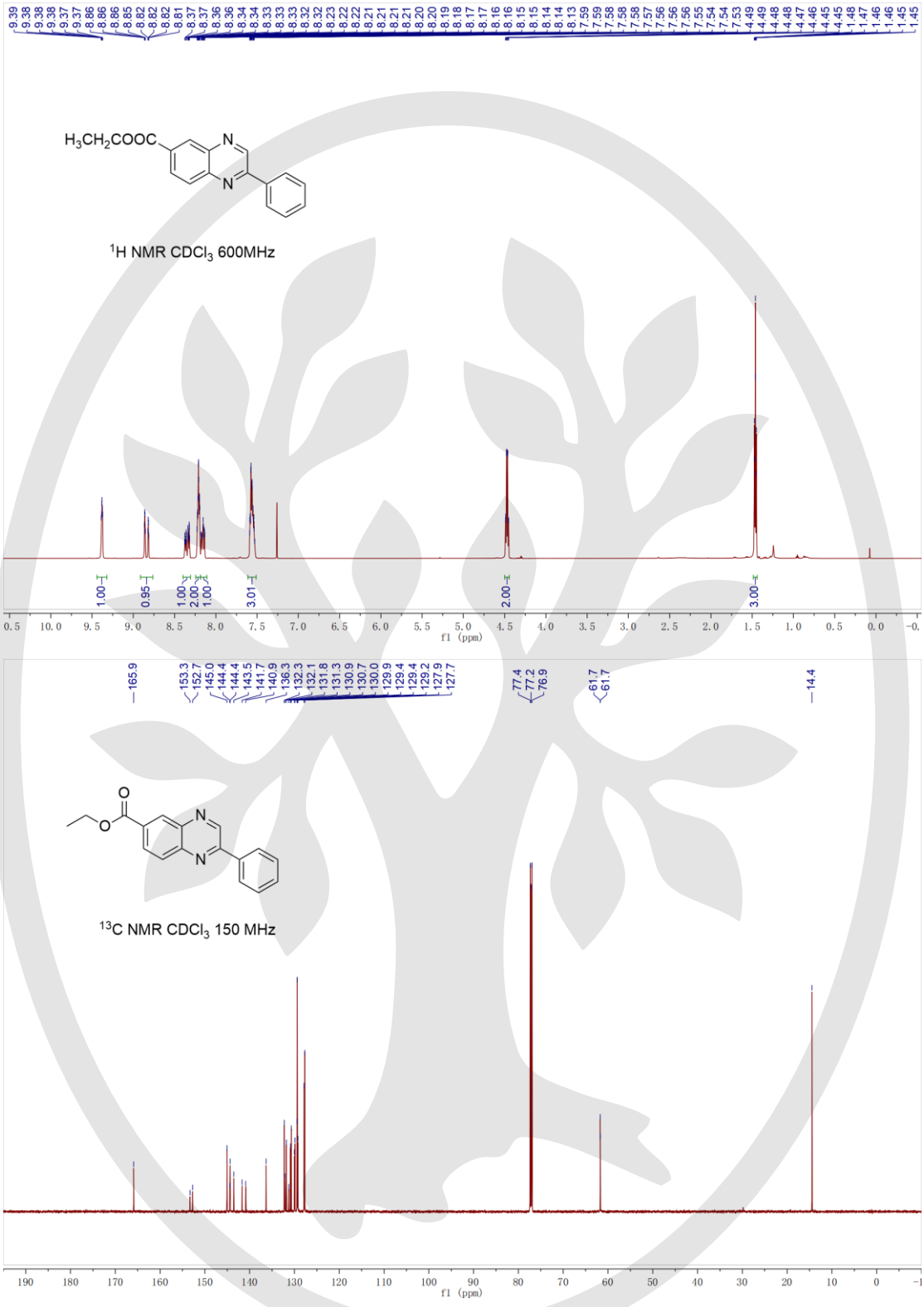

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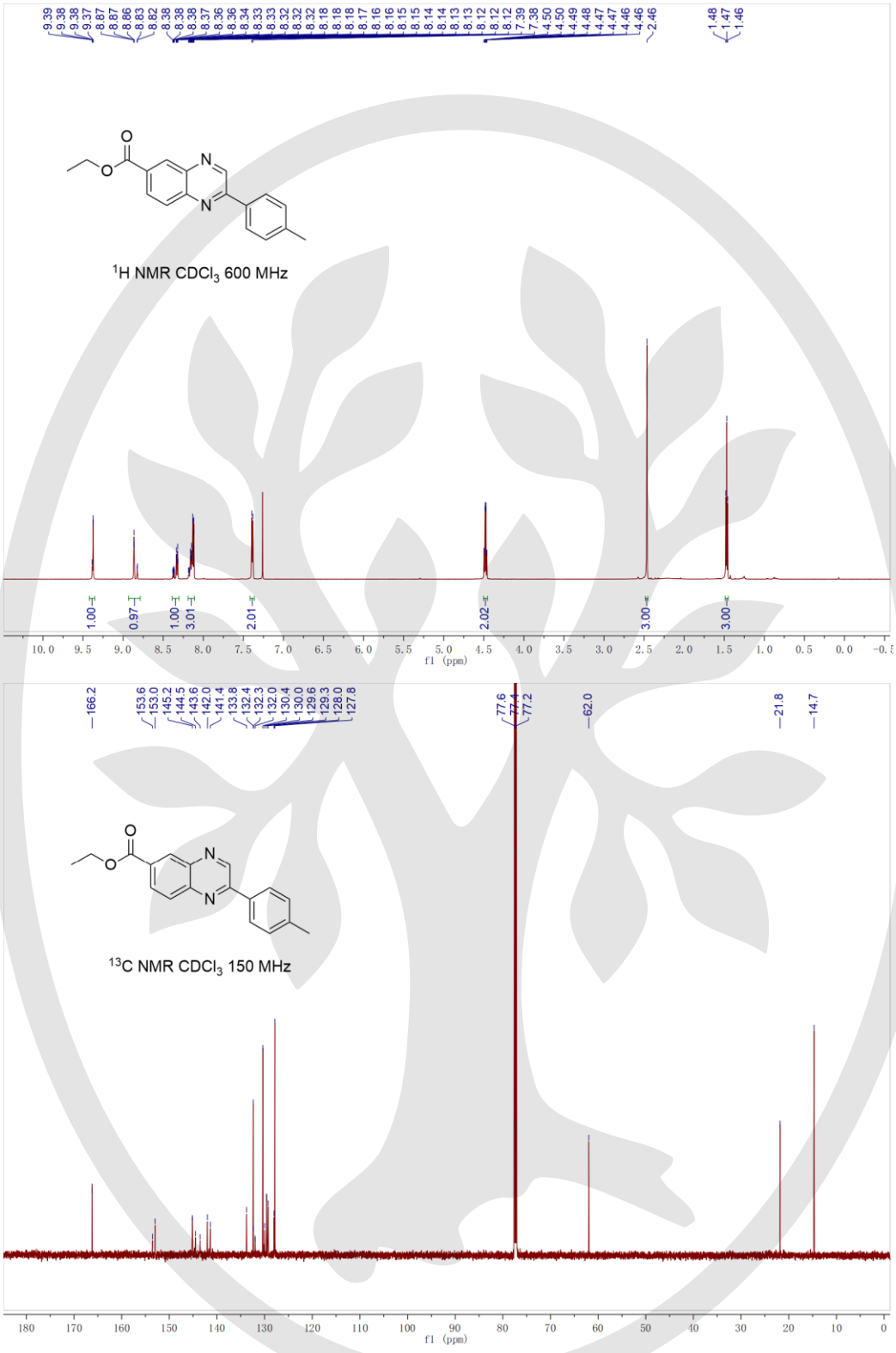

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