Synthesis of Functionalized Anthraquinones, Phthalates and Quinolines
by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

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DEDICATION

This work is dedicated to............

The dream has just been vanished..................My Mother

............Never forget her
ACKNOWLEDGMENT

In the name of ALLAH, the Beneficent, the Merciful, Ubiquitous, Omniscient. Praise be to Allah; without his blessings this work would never been accomplished.

I want to express my philosophy which I have practiced along my study and found it precious more than my work inside the laboratory or even writing this thesis, at least from my point of view. Chemists especially those who are working in the field of organic synthesis often define their achievement in the terms of numbers; numbers of the chemical compounds that they have made; or numbers of novel reactions that they could developed. Yet, As far as I can see, the greatest achievements along my study journey are the successful and deep relationships that I have developed. This is my well-practiced philosophy and therefore I am writing this acknowledgment to admit my sincere gratitude to those people who helped me throughout past years and without their support I could not finish this work.

I would like to express my grateful and appreciation to my advisor Prof. Peter Langer (PL) for his constant advice, guidance, insight, and for sharing his extensive knowledge of chemistry. PL’s scientific integrity has been both inspiring and motivating over the years. Also I thank the entire PL group for their friendship and support.

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I would like to take the opportunity to especially thank the DAAD Foundation for providing me a scholarship over three and a half past years, deep gratitude for the contact person of Iraqi section Frau. Steuernagel for her kindness.

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Finally, I would like to thank all members of my family who have provided me patience, heartiest feelings and eternity support over past years. My deep respect and appreciation goes to my father. He has been always an inspiration for me, and my grateful to you for his special emotions towards me along the past years. My elder brother Ehab: my best friend, my mentor and my pillar of encouragement. I know him as far as I know myself, and on most days I felt he knows me better than I know myself. I could not imagine living a single day of my life without his support and guidance. To my younger sis Redhab, younger bro Nifal and the youngest sis Rehab; all thanks to you for your enormous encouragement, your goodwill, love and support. In addition, I would like to thank my family, which means to me not only my relatives but also my friends. Without you, this thesis would never see the light.

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Ahmed Mahal
SUMMARY

Suzuki coupling reactions of the bis(triflate) of alizarin afforded 1,2-diarylanthraquinones. The reaction of the bis(triflate) with 1 equivalent of arylboronic acids proceeded with very good site-selectivity. The first attack occurred at carbon atom C-1 at the electronically more deficient position. Unsymmetrical 1,2-diarylanthraquinones were obtained by one-pot Suzuki coupling reactions with different arylboronic acids. The reactions were carried out by using Pd(PPh$_3$)$_4$ as a catalyst and K$_3$PO$_4$ as a base.

The reaction of the tris(triflate) of purpurin and 4 equivalents of arylboronic acids afforded 1,2,4-triarylanthraquinones. The reactions with 2 equivalents of arylboronic acids resulted in very good yields and proceeded with very good site-selectivity. The first attack occurred at carbon atom C-4 and the second one occurred at carbon atom C-1.
I also studied the synthesis of dimethyl 3,5-dihydroxypythalate starting from the reaction of 1-methoxy-1,3-bis(trimethylsilyloxy)-1,3-diene with dimethyl acetylenedicarboxylate. The reaction of the bis(triflate) of the product with arylboronic acids gave arylated phthalates with very good site-selectivity in favour of carbon atom C-5.
The reaction of 5,7-dibromo-8-hydroxyquinoline and triflic acid anhydride afforded the triflate in good yield. The reaction of the latter with 2 equivalents of arylboronic acids occurred at carbon atoms C-5 and C-7. The reaction with one equivalent of arylboronic acid occurred at carbon atom C-5.
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</tr>
<tr>
<td>1.54</td>
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<tr>
<td>1.55</td>
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LIST OF ABBREVIATIONS

Å  Angstrom
Ac  Acetate
aq.  Aqueous
Ar  Aryl
9-BBN  9-Borabicyclo[3.3.1]nonane
Boc  N-tert-butoxycarbonyl
calcd  Calculated
Cp  Cyclopentadiene
Cy  Cyclohexyl
dba  Dibenzylideneacetone
DEM  Diethoxymethane
DEPT  Distortion-less Enhancement by Polarization Transfer
DME  Dimethyl Ether
DMF  N,N-Dimethylformamide
DMSO  Dimethylsulfoxide
dppb  Bis-1,4-(diphenylphosphino)butane
dppf  1,1'- Bis(diphenylphosphanyl)ferrocene
dt  Doublet of triplet
EtOBpin  2-Ethoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane
g  Gram(s)
HB(lpc)₂  Disiamylborane
Hz  Hertz
η₄  Tetrahapto
η₅  Pentahapto
KHB(OPr')  Potassium Trisopropoxyborohydride
LDA  Lithium Diisopropylamide
MOM  Methoxyethane
mp  Melting Point
NMR  Nuclear Magnetic Resonance
NOE  Nuclear Overhauser Effect
<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>Nu</td>
<td>Nucleophile</td>
</tr>
<tr>
<td>OAc</td>
<td>Acetate</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>OTf</td>
<td>Triflate</td>
</tr>
<tr>
<td>PCy₃</td>
<td>Tricyclohexylphosphine</td>
</tr>
<tr>
<td>Ph</td>
<td>Phenyl</td>
</tr>
<tr>
<td>piv</td>
<td>N-pivaloyl</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per Million</td>
</tr>
<tr>
<td>Sia</td>
<td>3-methyl-2-butyl</td>
</tr>
<tr>
<td>TBAF</td>
<td>Tetra-n-Butylammonium Fluoride</td>
</tr>
<tr>
<td>TBDMS</td>
<td>tert-butyldimethylsilyl</td>
</tr>
<tr>
<td>TBDPS</td>
<td>tert-Butyldiphenylsilane</td>
</tr>
<tr>
<td>TBS</td>
<td>tert-butyldimethylsilyl</td>
</tr>
<tr>
<td>TES</td>
<td>Triethylsilane</td>
</tr>
<tr>
<td>Tf₂O</td>
<td>Trifluoromethanesulfonic anhydride</td>
</tr>
<tr>
<td>TFA</td>
<td>Trifluoroacetic Acid</td>
</tr>
<tr>
<td>THF</td>
<td>Tetrahydrofuran</td>
</tr>
<tr>
<td>TLC</td>
<td>Thin Layer Chromatography</td>
</tr>
<tr>
<td>TMB</td>
<td>Trimethylboroxine</td>
</tr>
<tr>
<td>TMS</td>
<td>Trimethylsilane</td>
</tr>
<tr>
<td>TMSOK</td>
<td>Potassium Trimethylsilanolate</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet Spectroscopy</td>
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BACKGROUND AND INTRODUCTION

CHAPTER ONE
1.1 Palladium Catalyzed Cross-Coupling Reactions

In organic chemistry, cross-coupling reactions of unsaturated (aryl, alkynyl, or alkenyl) carbon centers, catalyzed by transition metals, play a very important role. These types of reactions are becoming very important through their wide applications in organic synthesis, therefore organic chemists attach great importance particularly to study the organometallic mechanisms of these reactions.¹ For example, the Wacker Process is an oxidation of ethylene to acetaldehyde using oxygen and palladium tetrachloride as catalyst;² this process is concerned as an important example for the use of palladium catalysts in the industry. In the last 30 years, palladium catalyzed cross-coupling reactions have been widely used to form carbon-carbon bond in organic synthesis.

The reaction of organic halides (usually aryl/alkenyl halides) with olefins were developed by Heck and co-workers and is also called "Mizoroki-Heck reaction".³ Tsuji and Trost first reported the reaction of π-allyl-\(\eta^3\)-allyl)palladium cations with nucleophiles, it is also often referred to as "Trost Allylation or Tsuji-Trost Reaction".⁴ The cross-coupling reactions of organometallic reagents (such as organotin, organoboron and organozinc reagents) with organic halides were particularly developed by Kumada,⁵ Stille,⁶ Suzuki.⁷ In 2010, the nobel prize was awarded jointly to Richard F. Heck, Ei-ichi Negishi and Akira Suzuki for the development of methods for palladium-catalyzed cross-couplings in organic synthesis.
1.2 Types of Palladium Catalyzed Cross-Coupling Reactions

There are many types including palladium catalyzed cross-coupling reactions. Some of them are mentioned here, but not exhaustively.

1.2.1 Buchwald-Hartwig Reaction

The Buchwald-Hartwig reaction is a palladium catalyzed cross-coupling reaction of aryl halides or pseudohalides (for example triflates) with primary or secondary amines as shown below in Scheme 1.1.8

![Scheme 1.1 Buchwald-Hartwig reaction]

1.2.2 Fukuyama Reaction

The Fukuyama reaction is a palladium catalyzed reaction of organozinc compounds with thioesters to give ketones (Scheme 1.2).9

![Scheme 1.2 Fukuyama reaction]

1.2.3 Heck Reaction

The Heck reaction (also called the Mizoroki-Heck reaction) is a reaction of aryl halides or vinyl halide with activated alkenes in the presence of base as well as using the palladium as catalyst (Scheme 1.3).10

![Scheme 1.3 Heck reaction]
1.2.4 Hiyama Coupling

The Hiyama coupling is a palladium catalyzed coupling reaction between aryl, alkenyl, alkyl halides or pseudohalides and organosilanes. This reaction is similar to the Suzuki coupling reaction which needs the base or fluoride ion as an activating reagent (Scheme 1.4).\textsuperscript{11,12}

\textbf{Scheme 1.4} Hiyama coupling

\[
\begin{array}{c}
R^1\text{-Si}(R^3)_3 + R^2\text{-X} \xrightarrow{\text{Pd-Cat}} R^1\text{-}R^2 \\
\text{or base} \\
F
\end{array}
\]

1.2.5 Kumada Reaction

The Kumada reaction is a cross-coupling reaction in organic chemistry between an alkyl or aryl Grignard reagent and an aryl or vinyl halocarbon catalyzed by nickel or palladium (Scheme 1.5).\textsuperscript{13}

\textbf{Scheme 1.5} Kumada reaction

\[
\begin{array}{c}
R^1\text{-X} + R^3\text{MgX} \xrightarrow{\text{Pd-Cat or Ni-Cat}} R^1\text{-}R^2
\end{array}
\]

1.2.6 Negishi Reaction

The Negishi reaction is a reaction of various halides (aryl, vinyl, benzyl, or allyl) with organozinc compounds involving the nickel- or palladium catalyst. This reaction is used to synthesize unsymmetrical biaryls (Scheme 1.6).\textsuperscript{14,15}

\textbf{Scheme 1.6} Negishi reaction

\[
\begin{array}{c}
R^1\text{-X} + R^2\text{ZnX} \xrightarrow{\text{PdCl}_2(\text{PPh}_3)_2} 2(i\text{-Bu})_2\text{AlH} \xrightarrow{} R^1\text{-}R^2
\end{array}
\]

1.2.7 Sonogashira Coupling

The Sonogashira coupling is a reaction between terminal alkynes with aryl or vinyl halides. This reaction is performed with palladium catalysts, copper(I) as cocatalyst and an amine base (Scheme 1.7).\textsuperscript{16}
**Background and Introduction**

**Scheme 1.7** Sonogashira coupling

![Sonogashira coupling](image)

### 1.2.8 Stille Coupling

The Stille coupling is a reaction of organotin compounds with organic halide including sp²-hybridized catalyzed by palladium (Scheme 1.8).

**Scheme 1.8** Stille coupling

![Stille coupling](image)

### 1.2.9 Tsuji-Trost Reaction

The Tsuji-Trost reaction is a palladium-catalyzed allylation of nucleophiles such as active methylenes, enolates, amines and phenols, with allylic compounds such as allyl acetates and allyl bromides (Scheme 1.9).

**Scheme 1.9** Tsuji-Trost reaction

![Tsuji-Trost reaction](image)

### 1.3 Suzuki-Miyaura Cross-Coupling Reaction; A Brief History

The Suzuki-Miyaura cross-coupling reaction is an extremely versatile methodology for generation of carboncarbon bonds. This is a reaction of an aryl- or vinyl-boronic acid with an aryl-, vinyl- or an alkyl-halide catalyzed by palladium. It is widely used to synthesize polyolefins, styrenes and substituted biphenyls. The first published reaction was reported in 1979 by Akira Suzuki and co-workers. The reaction of alkyne 1 with borate 2 in benzene using 5 mol% of tetrakis(triphenylphosphine)palladium Pd(PPh₃)₄ gave (E)-1,2-diphenylethene (4) in reasonable yields (Scheme 1.10). This reaction was done in presence of base, such as sodium ethoxide in ethanol or sodium hydroxide in ethanol.
**Background and Introduction**

**Scheme 1.10** The first example of a Suzuki coupling reaction

\[
\begin{align*}
1 & \quad \text{HC≡CPh} & \quad \rightarrow & \quad 2 & \quad \text{OB-O} & \quad \rightarrow & \quad 3 & \quad \text{Ph} & \quad H & \quad \text{B} & \quad \text{O} & \quad \text{Ph} & \quad \text{ArBr} & \quad \text{Pd(PPh}_{3}\text{)}_{4} (5 \text{ mol\%}) & \quad \rightarrow & \quad 4 (50\%) \\
\end{align*}
\]

They also applied the same reaction in order to prepare \((E,Z)\)-dienes. Although the reactions proceeded smoothly, the results were unsatisfactory because the initially formed \((E,Z)\) isomer 7 was isomerized to the more stable \((E,E)\) isomer 8 (Scheme 1.11).

**Scheme 1.11** Synthesis of 7, 8

\[
\begin{align*}
5 & \quad \text{C}_{6}\text{H}_{13} & \quad \text{OB-O} & \quad \text{EtO}^- & \quad \text{Br} & \quad \text{C}_{6}\text{H}_{13} & \quad \text{Pd(PPh}_{3}\text{)}_{4} (1 \text{ mol\%}) & \quad \rightarrow & \quad 7 & \quad (\text{E,Z}) & \quad (41\%) & \quad 8 & \quad (\text{E,E}) & \quad (47\%)
\end{align*}
\]

A novel route for the synthesis of \((E)\)-enyne 11 was also reported in the same paper (Scheme 1.12).

**Scheme 1.12** A novel route for the synthesis of 11

\[
\begin{align*}
9 & \quad \text{Bu} & \quad \text{H} & \quad \text{B(Sia)}_{2} & \quad \text{Pd(PPh}_{3}\text{)}_{4} (1 \text{ mol\%}) & \quad \rightarrow & \quad 10 & \quad \text{Ph} & \quad \text{Br} & \quad \text{NaOMe, Benzene} & \quad \text{Reflux} & \quad 11 & \quad (72\%)
\end{align*}
\]

The reaction appears in almost all publications as the name of Suzuki-Miyaura cross- coupling reaction, but it is also often referred to as "Suzuki Coupling".

1.4 Reaction Mechanism

To identify more clearly how a Suzuki coupling reaction occurs, we should keep the following statement (Scheme 1.13) as an example\(^{10}\) of the coupling and follow the mechanism to understand the coupling how to occur.
Scheme 1.13 Suzuki coupling reaction of boronic ester and bromobenzene

1.4.1 Catalytic Cycle

The mechanism of the Suzuki coupling reaction is best viewed from the perspective of the palladium catalyst. The catalytic cycle of Suzuki coupling reaction involves three basic steps: Oxidative addition, Transmetallation and Reductive elimination.\textsuperscript{19,21,22} The catalytic cycle for the Suzuki coupling reaction is shown to be that depicted in Figure 1.1. The first step is the oxidative addition of palladium to the halide forming intermediate. Reaction with base gives intermediate 14, which via transmetalation with the boronate complex 12 forms the organopalladium species 16. Reductive elimination of the desired product 17 restores the original palladium catalyst.\textsuperscript{23}

Figure 1.1 Catalytic cycle of Suzuki coupling reaction
The efficiency of palladium originates from its ability, when it is zerovalent, to activate C-X bonds (X=I, Cl, Br, O) by an oxidative addition which provides an organopalladium (II) complex prone to react with nucleophiles.\textsuperscript{24,25} A large variety of palladium(0) catalysts or precursors can be used for this reaction. Palladium(II) complexes along with a reducing agent are also used.\textsuperscript{26}

### 1.4.2 Oxidative Addition

The first step in Suzuki cross-coupling reaction is oxidative addition of palladium to the halide. Oxidative addition of 1-alkenyl, 1-alkynyl, allyl, benzyl and aryl halides to a Pd(0) complex gives a stable trans-6-palladium (II) complex (Scheme 1.14).\textsuperscript{2} The reaction proceeds with complete retention of stereochemistry for alkenyl halide and with inversion for allylic and benzylic halides. Oxidative addition is often the rate limiting step in the catalytic cycle. The relative reactivity decreases in the order of I > OTf > Br >> Cl. Aryl and 1-alkenyl halides, activated by the proximity of electron-withdrawing groups, are more reactive to the oxidative addition than those containing donating groups, thus allowing the use of chlorides, such as 3-chloroenones, for the cross-coupling reaction.

![Scheme 1.14 Oxidative addition](image)

**Scheme 1.14 Oxidative addition**

1.4.3 Transmetallation Processes

Transmetallation step (Scheme 1.15) between organopalladium(II) complex and organoboron compound does not usually proceed in absence of base, due to low nucleophilicity of the organic group located at the boron atom.\textsuperscript{21} However the nucleophilicity can be enhanced by quarternization of the boron with negatively charged bases giving the corresponding “ate” complex.\textsuperscript{27} It is reported that such “ate” complexes undergo clean coupling reaction with organic halides.\textsuperscript{28}
Background and Introduction

Scheme 1.15 Transmetallation processes

![Scheme 1.15](image)

1.4.4 Reductive Elimination

Reductive elimination takes place directly from the cis-complex 16, and trans-complex 16 reacts after its isomerization to the corresponding cis-complex (Scheme 1.16). Relative rates of reductive elimination from palladium(II) complexes are diaryl- > (alkyl)aryl- > diethyl- > dimethylpalladium(II).

Scheme 1.16 Reductive elimination

![Scheme 1.16](image)

1.5 Organoboron Compounds

For many decades, organic compounds containing boron have been attracted an increased attention. Ever since, their chemical properties and their reactivity aspects had been studied. The discovery of hydroboration opened the door to organoboranes, which are represented among the most widely used reagents and intermediates in organic synthesis including asymmetric reactions. In addition, the previous studies on the chemistry of boron hydrides and carboranes conduce to new classes of compounds with unique structure and reactivity. In spite of this, the stability of organoboron compounds was not discovered until recently. In fact, the lists of organoboron compounds are increased nowadays. In addition to organoboranes, now it includes organoboronic acids and boronates, and more recently
organotrifluoroborates. As a result, these compounds mentioned hereinabove, have found their way to new and wide applications. For example: molecular receptors, molecular sensors, novel materials, as well as biological probes and pharmaceuticals (Figure 1.2).

**Figure 1.2** Uses of organoboron compounds. The picture was taken from *Aust. J. Chem.* 2007, 60, 795-798.

1.5.1 Synthesis of Organoboron Reagents

1.5.1.1 From Organolithium or Magnesium Reagents

Aryl- and 1-alkenylboronic acids or their esters can be prepared by reaction of Grignard reagents or lithium reagents with trialethyl (Scheme 1.17).

**Scheme 1.17** Synthesis of organoboronic acids from Grignard reagents

\[
\text{ArMgX} \xrightarrow{\text{B(OEt)}_3} \text{ArB(OE)}_2 \quad \text{18} \rightarrow \text{19}
\]

\[
\text{H} \xrightarrow{\text{MgBr}} \text{B(OEt)}_3 \rightarrow \text{H} \xrightarrow{\text{B(OEt)}_3} \text{H} \quad \text{20} \rightarrow \text{21}
\]
In addition to that, a stereocontrolled synthesis of alkenylboronic acids and esters involves the reaction of a \((Z)\)- or \((E)\)-2-buten-2-ylmagnesium bromide with trimethylborate (Scheme 1.18).\(^{35}\)

**Scheme 1.18 Synthesis of organoboronic acid from trimethyl borate**

\[
\begin{array}{c}
\text{H}_3\text{C} \quad \text{Br} \quad \text{Mg} \\
\text{H} \quad \text{CH}_3
\end{array} \xrightarrow{1. \text{B(OMe}_3\text{)}_3} \begin{array}{c}
\text{H}_3\text{C} \quad \text{B(OH)}_2 \\
\text{H} \quad \text{CH}_3
\end{array}
\]

The disadvantages of application of these procedures include the contamination of small amount of the opposite stereoisomers, or bis-alkylation leading to the boronic acid derivatives and the formation of trialkylboranes.

Brown and co-workers reported the first synthesis of organolithium reagents \(^{24}\) and triisopropyl borate, followed by acidification with HCl to give directly alkyl-, aryl-, 1-alkynyl-, and 1-alkenylboronic esters \(^{25}\) in high yields, over 90\% (Scheme 1.19).\(^{36}\) Triisopropyl borate is shown to be the best of available alkyl borates to avoid such multiple alkylations of the borates.

**Scheme 1.19 Synthesis of organoboronates from organolithium compounds**

\[
\begin{array}{c}
\text{RLi} \quad \text{B(OPr}^\text{i}\text{)}_3 \\
24
\end{array} \xrightarrow{\text{HCl}} \begin{array}{c}
\text{R-B(OPr}^\text{i}\text{)}_3 \\
24a
\end{array} \xrightarrow{\text{HCl}} \begin{array}{c}
\text{R-B(OPr}^\text{i}\text{)}_2 \\
25
\end{array}
\]

R= Alkyl, Aryl

1.5.1.2 Hydroboration of Alkenes and Alkynes\(^{21}\)

Suzuki and co-workers reported that the hydroboration of propargyl chloride and ethyl propiolate resulted terminal boron derivatives \(^{27}\) with excellent regiochemistry, whereas the hydroboration with catecholborane or disiamylborane gives an inseparable mixture of internal and terminal boron adducts (Scheme 1.20).\(^{37}\)
Scheme 1.20 Hydroboration of alkynes with disiamylborane

\[
\begin{align*}
\text{R} & \equiv \text{H} \\
1. & \text{HB(lpc)}_2 \\
2. & \text{CH}_3\text{CHO} \\
\text{26} & \rightarrow \text{H} \quad \text{B(OEt)}_2 \\
\text{27} & \quad \text{R} \quad \text{H}
\end{align*}
\]

The reaction of 2-(haloalkeny1)boronic esters 28 with KHB(ORi) or organolithium compounds proceeded with complete inversion of configuration at the sp\(^2\) carbon (Scheme 1.21). The reaction is almost quantitative and highly selective (inversion >99\%). Thus, the boron derivatives 29, 30 synthesized can be directly used for the following cross-coupling reaction without further purification.\(^{38-42}\)

Scheme 1.21 Hydroboration of alkenes with KHB(ORi) or with organolithium compounds

\[
\begin{align*}
\text{n-Bu} & \quad \text{Br} \\
\text{H} & \quad \text{B(ORi)}_2 \\
\text{28} & \rightarrow \text{1. KHB(ORi)}_3/\text{Ether} \\
& \quad \text{2. H}_2\text{O} \\
& \quad \text{3. HO(\text{CH}_2)}_3\text{OH} \\
\text{n-Bu} & \quad \text{H} \\
\text{29 (87\%)} & \quad \text{B(ORi)}_2 \\
\text{n-Hex} & \quad \text{Br} \\
\text{H} & \quad \text{B(ORi)}_2 \\
\text{28} & \rightarrow \text{n-BuLi/\text{Ether}} \\
& \quad -78 \degree \text{C} \\
\text{n-Hex} & \quad \text{H} \\
\text{30 (87\%)} & \quad \text{B(ORi)}_2 \\
& \quad \text{n-Bu}
\end{align*}
\]

The other method is to prepare the stereospecifically (E)-1-alkenylboronates by alkylation of 31 with organozinc reagents in the presence of a palladium catalyst (Scheme 1.22).\(^{43}\)

Scheme 1.22 Alkylation of alkenes with organozinc reagents

\[
\begin{align*}
\text{C}_4\text{H}_9 & \equiv \text{l} \\
\text{H} & \quad \text{B(ORi)}_2 \\
\text{31} & \rightarrow \text{1. PhZnX, Pd(PPh_3)_4} \\
& \quad \text{THF, 25 \degree \text{C}, 2h} \\
\text{C}_4\text{H}_9 & \equiv \text{Ph} \\
\text{32 (87\%)} & \quad \text{H} \\
& \quad \text{B(ORi)}_2
\end{align*}
\]

1.5.1.3 Haloboration of Terminal Alkynes\(^{21}\)

The bromoboration of a terminal alkyne 33 gives β-bromo-1-alkenylboronic esters 34, followed by palladium-catalyzed displacement of the β-halogen with organozinc reagents which
proceeds strictly with retention of configuration.\textsuperscript{44,45} This reaction proceeds via a Markovnikov addition which provides 2,2-diorgano-1-alkenylboronate 35 (Scheme 1.23).

Scheme 1.23 Bromoboration of terminal alkynes

\[
\begin{align*}
\text{R}^1\equiv\text{H} & \xrightarrow{1. \text{BBr}_3} \text{R}^1\equiv\text{H} \\
& \xrightarrow{2. \text{tPr}_2\text{O}} \text{R}^1\equiv\text{H}\text{B}((\text{OPr})_2) \\
& \xrightarrow{\text{R}^2\text{ZnX}} \text{R}^1\equiv\text{H}\text{B}((\text{OPr})_2)
\end{align*}
\]

While the addition of borontribromide of acetylene 36 itself results first a \textit{cis} adduct which then isomerizes to the \textit{trans} adduct of (\textit{E})-l-alkenylborates 37 during its isolation (Scheme 1.24).\textsuperscript{46,47}

Scheme 1.24 Bromoboration of acetylenes

\[
\begin{align*}
\text{H}\equiv\text{H} & \xrightarrow{1. \text{BBr}_3} \text{H}\equiv\text{H}\text{B}((\text{OPr})_2) \\
& \xrightarrow{2. \text{tPr}_2\text{O}} \text{H}\equiv\text{H}\text{B}((\text{OPr})_2) \\
& \xrightarrow{\text{R}^1\text{ZnX}} \text{H}\equiv\text{H}\text{B}((\text{OPr})_2)
\end{align*}
\]

1.5.1.4 Cross-Coupling Reactions\textsuperscript{48}

Miyaura and co-workers were reported the first cross-coupling reactions of aryl halides 40, 42 with the pinacol ester of diboronate 39 (Scheme 1.25).\textsuperscript{49} KOAc was selected to be a more suitable base for borylation of aryl iodides,\textsuperscript{50} bromides,\textsuperscript{51} chlorides\textsuperscript{49a} and triflates.\textsuperscript{52,53} PdCl\textsubscript{2}(dppf) is better than Pd(PPh\textsubscript{3})\textsubscript{4} because palladium-triphenylphosphine complexes often resulted in formation of byproducts derived from coupling of the diboron with a phenyl group on triphenylphosphine in the reaction of electron-rich aryl halides.\textsuperscript{49a}
Background and Introduction

Scheme 1.25 Synthesis of organoboronates by cross-coupling reactions

\[
\begin{align*}
\text{PdCl}_2(\text{dpdf})_2 & \quad \text{KOAc, DMSO, 24 h} \\
& \quad 80 \, ^\circ\text{C} \\
\end{align*}
\]

After the first preparation of organoboronic esters, a lot of publications appeared related to synthesis of organoboronic esters by using cross-coupling reactions of aryl halides.\textsuperscript{54-57}

1.5.1.5 Diboration, Silylboration, and Stannylboration\textsuperscript{48}

Addition reaction of various element-element bonds (B-B, B-Si and B-Sn) to alkenes and alkynes provides polymetallic organic compounds (Scheme 1.26).\textsuperscript{58} Suzuki and co-workers published the first addition reaction of the pinacol ester of diborate 39 to alkynes 44 using Pt(PPh\textsubscript{3})\textsubscript{4} as catalyst and DMF as solvent.

Scheme 1.26 Addition of various diboronates bonds to alkynes

They proposed a catalytic cycle for the diboration of alkynes, which involves the oxidative addition of the B-B bond to the platinum(0) complex, the stereospecific insertion of alkyne to the B-Pt bond, and finally the reductive elimination of the bis(boryl)- alkene as outlined in Figure 1.3.
Figure 1.3 Catalytic cycle for the diboration of alkynes

In addition to this reaction, many applications were applied to synthesize boronic acids and esters by using these methods.\textsuperscript{59}

1.5.1.6 Olefin Metathesis\textsuperscript{48}

Renaud and co-workers reported the synthesis of cyclic 1-alkenylboronic esters \textit{47}, \textit{50} from organoboronic esters \textit{46}, \textit{49} at room temperature by using Grubbs’ alkylidene-ruthenium complexes (Scheme 1.27).\textsuperscript{60} Many cyclic alkenylboronic esters have been obtained by using these methods.\textsuperscript{61-63}
Scheme 1.27 Synthesis of organoboronates by olefin metathesis

Scheme 1.28 Synthesis of organoboronates by borylation of hydrocarbons

1.5.1.7 Aromatic C-H Borylation

Organoboron compounds can be obtained by direct borylation of hydrocarbons. The first metal-catalyzed reaction of a borane and an arene was reported by Smith and coworkers (Scheme 1.28). The reaction was performed by using pre-catalyst 1 \(\text{Cp}^*\text{Ir(PMe}_3\text{)(H)(BPin)}\) \(52\) and pre-catalyst 2 \(\text{Cp}^*\text{Rh(η}^4\text{-C}_6\text{Me}_6)}\). Many reactions have been studied using various catalysts.
1.5.1.8 Miscellaneous Methods

The reaction of Grignard or lithium reagents with boron halides or borates was used for the preparation of 2-formylbezenboronic acid (55) in 57 % yield (Scheme 1.29).

**Scheme 1.29** Synthesis of organoboron compounds by lithium reagent

\[
\begin{align*}
\text{Br} & \quad \text{CHO} \\
54 & \quad \text{1. OHCH}_2\text{CH}_2\text{OH} \\
& \quad \text{2. } n\text{-BuLi} \\
& \quad \text{3. B(OR)}_3 \\
& \quad \text{4. H}_3\text{O}^+ \\
\text{CHO} & \quad \text{B(OH)}_2
\end{align*}
\]

The reaction between borane and arylmetallic derivatives leads to arylboronic acids, but in low yields (9-60%). This is due to the formation of other organoborane derivatives. Aryltrialkyltin compound 56 reacts with borane 57 in THF to give mixtures of trialkyltin hydrides 56a and arylboranes 57a, which on hydrolysis give the arylboronic acid 58 in high yields (Scheme 1.30).

**Scheme 1.30** The reaction between borane and arylmetallic derivatives

\[
\begin{align*}
\text{R}_3\text{SnAr} & \quad \text{BH}_3 \\
56 & \quad \text{THF} \\
\quad & \quad \text{R}_3\text{SnH} \quad \text{ArBH}_2 \\
56a & \quad 57a \\
\quad & \quad \text{H}_2\text{O} \quad \text{ArB(OH)}_2 \\
58 &
\end{align*}
\]

1.5.2 The Advantage of Organoboron Compounds

There are many advantages that Organoboron derivatives provide over other organometallic derivatives. They can tolerate a broad range of functional groups, such as organic halides, carbonyl, etc. The electronegativity of boron is about 2.0 which is close to the value of carbon of 2.5 and is higher than the electronegativities of lithium, magnesium, or most of the transition metals which range from 0.86 to 1.75. Therefore the boronic compounds are air-stable and also water tolerant. The starting materials and borate by-products are not toxic.
1.6 Reaction Conditions

1.6.1 The Catalyst

The most commonly used system is Pd(PPh₃)₄, but other palladium sources have been used including Pd^{II} pre-catalysts that are reduced to the active Pd⁰ in situ.⁷³

\[
\begin{align*}
-Pd₂(dba)_3 + PPh_3 & \quad 59 \\
-Pd(OAc)_2 + PPh_3 & \quad 60 \\
-PdCl₂(dpff) (for sp^3-sp^2 couplings) & \quad 61
\end{align*}
\]

In addition to that, N-heterocyclic carbenes are also used as an alternative to phosphine ligands. The nucleophilic N-heterocyclic carbene 62 is the active ligand and is formed in situ from 63 (Figure 1.4).⁷⁴

**Figure 1.4 N-heterocyclic carbene ligands 62, 63**

1.6.1.1 Tetrakis(triphenylphosphine)palladium(0) Pd(PPh₃)₄

This compound has the molecular formula Pd[P(C₆H₅)₃]₄, it is light-sensitive, unstable in air, and a coordinatively saturated Pd(0) complex. Sometimes, Pd(PPh₃)₄ is less active as a catalyst, because it is overligated and has too many ligands to allow the coordination of some reactants.⁷⁵

Malatesta and co-workers prepared the catalyst by reduction of chloropalladate 65 with hydrazine 66 in the presence of the phosphine (Scheme 1.31).⁷⁶
Background and Introduction

Scheme 1.31 Synthesis of 67

\[
PdCl_2 + 2 PPh_3 \rightarrow cis-PdCl_2(PPh_3)_2
\]

\[
cis-PdCl_2(PPh_3)_2 + 2.5 \text{N}_2\text{H}_4 \rightarrow Pd(PPh_3)_4 + 0.5 \text{N}_2 + 2 \text{N}_2\text{H}_5^+\text{Cl}^-
\]

The reaction is proceeding in one pot without isolation and purification of \textit{cis}-PdCl_2(PPh_3)_2 intermediate 64. Pd(PPh_3)_4 is widely used as a catalyst for palladium-catalyzed coupling reactions. Most applications include the Heck reaction and Suzuki-Miyaura coupling reaction.

1.6.2 Effect of Base and Water

The synthesis of trityl losartan 70 was studied by Smith and co-workers (Scheme 1.32). The product belongs to a new class of drugs (angiotensin II receptor antagonists) and was developed for the treatment of high blood pressure and heart failure.

Scheme 1.32 Synthesis of 70

They indicated that the Suzuki coupling reaction was efficient when the pKa of base was close to 10, whereas it failed when the base was a bicarbonate (pKa close to 6). Considering the pKa of phenylboronic acid 8.8, phenylboronic acid was transformed into trihydroxyphenylborate (PhB(OH)_3), showing a pH higher than 9. The authors supposed that this anion was the reactive species rather than the neutral boronic acid. Kinetic studies also proved that water and base are required to activate the boronic acid. They assumed that one mol of water and one mol of carbonate are required initially to activate the boronic acid and then to neutralize the produced boric acid.
1.6.3 Effect of Solvent

The Suzuki coupling reaction is unrivaled among metal-catalyzed cross-coupling reactions in that it can be run in biphasic (organic/aqueous) or aqueous environments in addition to organic solvents.\textsuperscript{79}

1.6.4 Microwave-Assisted Reactions\textsuperscript{48}

In 1996, Hallberg and co-workers reported the first application of microwaves to rapid carbon-carbon bond formation (Scheme 1.33).\textsuperscript{80} They confirmed that many metal-catalyzed reactions are completed within a few minutes and full conversion can be achieved in a few minutes. The reactions were carried out in water, ethylene glycol, or DMF, due to the ability of polar solvents to efficiently absorb microwaves irradiation.

\textbf{Scheme 1.33} Microwave-assisted Suzuki coupling reactions

\[
\begin{align*}
\text{H}_3\text{C} & \quad \text{ArB(OH)}_2 \\
\text{Br} & \quad \text{2.8 min 55w} \\
\text{Pd(PPh}_3\text{)}_4, \text{EtOH} & \quad \text{DME. H}_2\text{O} \\
\text{H}_3\text{C} & \quad \text{ArB(OH)}_2
\end{align*}
\]

71 72 (55%)

\[
\begin{align*}
\text{RAM} & \quad \text{NH} \\
\text{O} & \quad \text{Br} \\
\text{1. ArB(OH)}_2 & \quad \text{3.8 min. 45 W} \\
\text{Pd(PPh}_3\text{)}_4, \text{EtOH} & \quad 2\text{M Na}_2\text{CO}_3, \text{DME. H}_2\text{O} \\
\text{H}_2\text{N} & \quad \text{O}
\end{align*}
\]

73 74 (97%)

1.6.5 Coupling Reactions of $[\text{RBF}_3]\text{K}$\textsuperscript{48}

Potassium organotrifluoroborate salts are easily prepared\textsuperscript{81} and purified, and thus they are easier to handle compared to the preparation of the corresponding boronic acids. Potassium organotrifluoroborate salts are obtained by treatment of boronic acids with KHF\textsubscript{2}.\textsuperscript{82} Potassium salts are generally insoluble in common organic solvents and require polar solvents such as MeCN and H\textsubscript{2}O at high temperatures. Coupling reactions of organotrifluoroborates have several advantages including the simplicity of the preparation of pure and stable crystalline material
compared to the preparation of the corresponding boronic acids. Cross-coupling of arylboronate 75 and alkyl derivatives 78 with organic halides 76, 79 in the presence of bases resulted in successful coupling (Scheme 1.34).82,83

**Scheme 1.34** Coupling reactions of [RBF₃]K

```
BF₃K⁻ n-BuN₄⁺ + Br-CHO → Pd(OAc)₂ (5 mol%) dppb (5 mol%)
Cs₂CO₃, DME/H₂O (1:1) r.t.-50 °C, 12-24 h
75 76 77 (90%)
```

```
CH₃(CH₂)₇BF₃K + TFO-CN → PdCl₂(dpst).CH₂Cl₂
Cs₂CO₃, THF/H₂O (1:1) reflux, 18 h
78 79 80 (65%)
```

1.7 Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

Recently, site-selective Suzuki coupling reactions became important. Complex compounds can be prepared by successive coupling reactions of substrates containing one, two or more possible reactive sites. The first attack usually occurs at the more electron deficient and less sterically hindered position.84,85

Gronowitz and co-workers were able to convert 2,4-dibromofuran (81) into the 4-bromofuran (82) in high yield (Scheme 1.35). The electronic difference of the two positions resulted a higher yield and better selectivity as compared to 2,5-dibromofuran.86

**Scheme 1.35** Site-selective reaction of 81

```
Br       (HO)₂B
Br       OtBu
N        OtBu
81       Pd(PPh₃)₄ NaHCO₃, DME
Br                  OtBu
BuOf            82 (86%)
```

Page | 21
The reaction of 2,3-dibromobenzofuran (83) with one equivalent of boronic acids resulted in site-selective formation of 2-aryl-3-bromobenzofurans. The 2-position is less electron rich compared to the 3-position (Figure 1.5).\textsuperscript{87}

**Figure 1.5** Possible explanation for the site-selectivity of 83

Further studies towards site-selective Suzuki coupling reactions of imidazoles have been confirmed by Ohta and co-workers. Carbon atom C-2 is attacked first and then the second attack occurred at carbon atom C-5 (Scheme 1.36).\textsuperscript{88} Revesz and co-workers used similar Suzuki coupling reactions in order to synthesize potential kinase inhibitors and anti-inflammatory drugs.\textsuperscript{89}

**Scheme 1.36** Site-selective reaction of 84

Iwao and co-workers carried out the Suzuki coupling reaction of pyrroles containing two methoxycarbonyl groups at carbon atoms C-2 and C-5 (Scheme 1.37).\textsuperscript{90} The first attack occurred at carbon atom C-3 which can be explained by steric reasons. A further cross-coupling at C-4 is not preferred, due to the large aryl substituent present at carbon atom C-3.
The first attack of N-(TBDMS)-2,6-dibromoindole occurred at carbon atom C-6 (Scheme 1.38). Several boronic acids were used, providing the 6-substituted products in 52-78% yield.88

Langer and co-workers showed that the site-selective Suzuki coupling reaction of indole 91 was found to be in favour of the 2-position (Figure 1.6). This is due to the fact that the electronic character of C-2 and C-3 appears to be sufficiently different because site-selective transformations are observed.91
In addition, the substrates 2,3,4-tribromothiophene (92) and 2,3,5-tribromothiophene (93) showed very good site selectivity. For the 92 the first coupling occurred at the carbon atom C-2 then the second coupling took place at carbon atom C-4. In case of 93 the first coupling preferred to be at carbon atom C-5 and the second at carbon atom C-2 (Figure 1.7). The selectivity can be explained based on the different electronic and steric properties of the three different C–Br bonds of 92 and 93 (Figure 1.7).92

Guglielmetti and co-workers reported the site-selective Suzuki coupling reaction of 2,3-dibromobenzothiophene (94) (Scheme 1.39). They proved that the site-selective attack occurred at position 2 of the 2,3-dibromobenzothiophene (94). This reaction was used to synthesize 2,3-diarylbenzo[b]thiophenes 95 and 97 substituted by two different aryl rings.93
Corte and co-workers revealed that the site-selective Suzuki coupling reaction can depend on the type of catalyst in the reaction of 2,6-dichloropyridines (98) with boronic acids. The substrate reacted with distinct selectivity for 6-position using Pd(PPh$_3$)$_4$ as catalyst. On the other hand, in case of using the pre-catalyst PXPD$_2$ (Pd$_2$Cl$_4$(PtBu$_2$Cl)$_2$) or PdCl$_2$(dppf) preferentially the 2-substituted product 101 was obtained (Scheme 1.40). It was disputed that a chelation is responsible for the observed effect and that the chelation might be enhanced if coordinatively unsaturated Pd(0) intermediates are generated.$^{94}$

Scheme 1.40 Site-selective reaction of 98

\[ \text{98} \xrightarrow{\text{PhB(OH)$_2$, Pd(PPh$_3$)$_4$, K$_2$CO$_3$, THF}} \text{99} \]

\[ \text{100} \xrightarrow{\text{PhB(OH)$_2$, PXPD$_2$, K$_2$CO$_3$, THF}} \text{101 (61%)} \]
In order to synthesize the qindoline 105, Timari and co-workers studied a regioselective coupling reaction of 2,3-dibromoquinoline (102) with boronic acid taking into consideration the fact that the α-heteroaryl halogen atom is more reactive in such coupling reactions than the β-halogen atom (Scheme 1.41).95

**Scheme 1.41 Synthesis of 105**

Woodward and co-workers showed that the site-selective Suzuki coupling reaction of 1,3-dichloroisoquinoline (106) with boronic acids took place at the 1-position to give 107 (Scheme 1.42).96 These reactions were done by using Pd(PPh₃)₄ as a catalyst in the presence of CsF as a base. The carbon atom C-1 is more reactive than carbon atom C-3, due to the ease of oxidative addition at this electrophilic position.

**Scheme 1.42 Site-selective reaction of 106**
The Site-selective Suzuki coupling reaction of 2,4-dichloropyrimidine (108) with 2-thienylboronic acid (109) was confirmed by Gronowitz and co-workers (Scheme 1.43). They proved that the 4-position 110 is more reactive than the 2-position.

Scheme 1.43 Site-selective reaction of 108

For the reaction of 2,4′-bis(trifluoromethylsulfonyloxy)diphenylsulphone (111) with boronic acid derivatives, the Suzuki coupling reactions occurred at carbon atom C-4′ (Scheme 1.44). The oxidative addition of palladium usually occurs first at the most electron-deficient carbon atom. Carbon atoms C-2 and C-4′ of the bis(triflate) are expected to be equally electron deficient. The site-selective formation of 112 can be explained by the fact that the carbon atom C-4′ is less sterically hindered.

Scheme 1.44 Site-selective reaction of 111

Site-selective reactions of both chloro and fluoro-dihydroxyphthalate derivatives 113, 114 were also studied by Langer and co-workers. For both derivatives, the site-selective attack took place at C-5 and the formation of the opposite regioisomers was not observed (Scheme 1.45). The site-selectivity can be explained by steric reasons.
Scheme 1.45 Site-selective reaction of 113, 114

The reaction of the 3,4-bis(triflate) of benzophenone 115 with boronic acid derivatives provided very good site selectivity. The first attack occurred at C-4 which is located para to the keto group (Figure 1.8). Carbon C-4 is more electron deficient than C-3 which is located meta to the keto group. Steric parameters have presumably no effect, due to the similar steric environment of carbon atoms C-4 and C-3.

Figure 1.8 Possible explanation for the site-selectivity of 115

The attack of boronic acids in site-selective Suzuki coupling reactions of the bis(triflate) of phenyl 1,4-dihydroxynaphthoate 116 occurred at the sterically more hindered position C-1 (Figure 1.9). This was confirmed by Langer and co-worker. The reactions are an example of site-selectivity controlled by electronic parameters.
1.8 Applications of Suzuki-Miyaura Cross-Coupling Reactions

Since the Suzuki coupling reaction was discovered by Akira Suzuki and Norio Miyaura, it found multiple applications in many areas including total synthesis, pharmaceutics as well as polymer chemistry.

1.8.1 Total Synthesis

In 1981, Rossi and co-workers reported the first total synthesis of \((E)-9,11\)-dodecadien-1-yl acetate 119 which an insect sex pheromone isolated from Diparopsis castanet (Scheme 1.46). The key step in this elegant strategy was the Suzuki coupling reaction. It was prepared using the reaction between vinyl borane \((E)-120\) and vinyl bromide 117, followed by treatment of the resulting crude product mixture with acetic anhydride in acetic acid in order to convert the tetrahydropyranyl protecting group into the corresponding acetate.
Background and Introduction

Scheme 1.46 Total synthesis of 119

\[
\text{Br} \quad \xrightarrow{\text{Pd(PPh}_3)_4 (1 \text{ mol} \%) \atop \text{NaOH, THF/H}_2\text{O, } 50^\circ\text{C}} \quad \text{Ac}_2\text{O/AcOH, } 80^\circ\text{C} \quad \text{119 (54%)}
\]

The Palytoxin 120 (Figure 1.10) an extremely poisonous, water-soluble substance from marine coelenterates belonging to the genus *Palythoa*, was originally isolated in 1971 in Hawaii from the seaweed-like coral. Palytoxin is a complex marine natural product containing 71 asymmetric centers, cleaved into several compounds by sodium periodate. Kishi and co-workers first synthesized palytoxin in 1994.105

Figure 1.10 Structure of (120). The picture was taken from *Angew. Chem. Int. Ed.* 2005, 44, 4442-4489.
They concluded that the use of TIOH instead of KOH has many advantages. This method can be used in the presence of fragile functional groups as well as with large molecular weights in addition to formation of byproducts is nonexistent (Scheme 1.47).\textsuperscript{106}

**Scheme 1.47** Total synthesis of 120

\[
\begin{align*}
\text{B(OH)}_2 + \text{MeO} & \xrightarrow{\text{Pd(PPh}_3)_4, \text{TIOH, rt. 30 min}} \text{OY} \xrightarrow{\text{OMe}} \text{OX}
\end{align*}
\]

\[X= \text{Ac, } Y= \text{Si}(\text{Me})_2(\text{t-Bu})\]

\[\text{THF}\]

121 122 123 (94%)

FR182877 124 (Figure 1.11) is an antibiotic isolated from the fermentation broth of *Streptomyces* sp. No. 9885, in 1998.\textsuperscript{107} FR182877 exhibited potent antitumor activities against murine ascitic tumor and solid tumor in vivo.

**Figure 1.11** Structure of 124

Evans and Starr used the Suzuki coupling reaction between 125 and 126 to prepare regioselective product 127.\textsuperscript{108} They optimized this reaction by using Tl\textsubscript{2}CO\textsubscript{3} as a base which gave an excellent yield (84%) (Scheme 1.48).
And finally, they utilized the Suzuki methylation in order to convert 128 to 129. They used TMB as a methylating agent.\(^\text{109}\) Saponification of the ethyl ester (TMSOK, THF)\(^\text{110}\) and lactonization (1-methyl-2-chloropyridinium iodide, NaHCO\(_3\), 62\%, 2 steps)\(^\text{111}\) afforded FR182877 (Scheme 1.49).
Sugano and co-workers were isolated phomactin A 133, in the early 1990s.\textsuperscript{112} The phomactins show biological activity as platelet activating factor (PAF) antagonists. Halcomb and co-workers constructed the phomactin A 133 by using a regioselective hydroboration on the terminal olefin of 130 with 9-BBN to give an intermediate alkyl borane 131, which cyclized using a modification of Johnson’s conditions (Scheme 1.50).\textsuperscript{113} The Suzuki coupling reaction proceeded with the sensitive dihydrofuran ring in place. Treatment with TBAF then hydrolyzed both silyl groups to give phomactin A 133.
Danishefsky and Trauner synthesized (+)-Halichlorine, a marine alkaloid recently isolated from the sponge *Halichondria okadai*. Hydroboration of the protected amino alkene, followed by palladium-mediated Suzuki coupling reaction with methyl (Z)-3-iodoacrylate, afforded the α,β-unsaturated ester (Scheme 1.51). Upon deprotection of the amino function with TFA and subsequent basification, underwent a highly stereoselective intramolecular 1,4-addition to afford piperidine as the only isolated isomer. Intermediate was subsequently converted into the inhibitor (+)-halichlorine in eight steps.
Kündig and co-workers prepared vertine 142 in eleven steps including Suzuki coupling reaction and ring-closing metathesis. Vertine is classified as a member of the Lythraceae alkaloids isolated in 1962 by Ferris from Decodon verticillatus (L.) Ell. The reaction between 138 and 139 afforded the product 140 which was isolated as a mixture of two apparent atropisomers in a ratio of 3:1 (Scheme 1.52). To overcome the problem the best choice was choosing L-Selectride as a reducing agent to yield a single diastereomer in 62% yield. Aldehyde 141 was obtained by oxidation with MnO₂ in 98% yield.
Fostriecin 146 is a pyranone-containing natural product isolated from *Steptomyces pulveraceus*.119 Fostriecin has been shown to possess significant in vitro cytotoxic activity against a broad range of cell lines,120 such as leukemia, lung cancer, breast cancer, and ovarian cancer and also antitumor activity against leukemia in vivo.121 O’Doherty and Gao have been recently prepared the Fostriecin in 24 steps starting from enyne.122 The reaction of vinyl boronate 143 and vinyl iodide 144 led to (Z,Z,E)-triene 145 with excellent alkene stereoselectivity (>20:1) and 80% yield. The reaction has been achieved by using 20% Pd/PPh₃ system (20% Pd₂(dba)₃·CHCl₃/ 80% PPh₃) instead of using the Pd(PPh₃)₄/Ag₂O system which led to no reaction (Scheme 1.53).
Scheme 1.53 Total synthesis of 146

\[ \text{Scheme 1.53 Total synthesis of 146} \]

Diazonamide A 147 was isolated from the colonial ascidian *Diazona chinensis* (Figure 1.12).\(^{123}\) Diazonamide A possesses potent in vitro activity against HCT-116 human colon carcinoma and B-16 marine melanoma cancer-cell lines.\(^{124}\) Nicolaou and co-workers reported the synthesis of diazonamide A 147 by using also Suzuki coupling reaction.\(^{125,126}\)

Figure 1.12 Structures of 147
1.8.2 Synthesis of Pharmaceuticals

E2040 \(151\) is a potent antagonist of D3/D2/5-HT2 receptors being developed for the treatment and amelioration of mental disorders such as aggressive behavior, senile dementia, mental excitation, poriomania, delirium, hallucination, hyperkinesias, schizophrenia, emotional disturbance, depression, neurosis, psychophysiological disorder and anxiety.\(^{127}\) The intermediate \(150\) was synthesized by Urawa and co-workers at Eisai Co. in Japan.\(^{128}\) This reaction was achieved by the Suzuki coupling reaction of optically active \(148\) with boronate \(149\) (Scheme 1.54).

**Scheme 1.54 Synthesis of \(151\)**

![Scheme 1.54 Synthesis of \(151\)](image)

They proposed mechanism for the Suzuki coupling reaction is shown below in Figure 1.13.
Larsen and co-workers synthesized the angiotensin II receptor antagonist Losartan 155 which is used mainly to treat high blood pressure (hypertension). The coupling between bromide 152 and boronic acid 153 is catalyzed by a palladium(0) catalyst in the presence of a base at 80 °C (Scheme 1.55).

Scheme 1.55 Synthesis of 155
The potent cathepsin K inhibitor 158 is used to treat osteoporosis. O’Shea and co-workers reported the synthesis of it by application of the Suzuki coupling reaction. They optimized the conditions of this coupling and found that the best conditions involve the use of 3 mol% PdCl2(dppf).CH2Cl2 as a catalyst with aqueous K2CO3 as a base in 10:1 Toluene/DMF at 80 °C. Under these conditions, the reaction was complete within 2 h to yield 158 in 89% (Scheme 1.56).

Scheme 1.56 Synthesis of 158

A useful application of the Suzuki coupling reaction is the synthesis of 2-amino-tetralin 161 which is a pharmaceutical ingredient that is useful in the treatment of epilepsy, stroke, and brain or spinal trauma. Coupling of arylobromide 159 with boronic acid 160, in the presence of K2CO3 (Scheme 1.57) and PS–Pd 162 as a catalyst (Figure 1.14).

Scheme 1.57 Synthesis of 161
1.8.3 Polymer Synthesis

1.8.3.1 Suzuki Poly-Condensation (SPC)

We can simply identify the Suzuki poly-condensation as a step-growth polymerization of bifunctional aromatic monomers of poly(arylene)s and related polymers. The required functional groups, boronic acid or esters on the one side and bromide or iodide, on the other, may be present in different monomers (AA/BB approach) or combined in the same monomer (AB approach). Most polymers prepared by this method are poly(paraphenylene)s, which are one of the most important classes of conjugated polymers.

Conjugated polymers have been identified as a fascinating class of novel conductors and semiconductors that have the electrical and optical properties of metals and semiconductors and, in addition, have the processing advantages and mechanical properties of molecular materials. The monomers of types AA and BB are widely used in Suzuki polycondensation. Among the most commonly used monomers of BB type is 2,5-dialkyl-1,4-benzene-bis(boronic) acid. The reaction conditions are like the ones Suzuki reported in his famous original article of 1981. The mechanism of SPC is supposed to involve the same steps of oxidative addition, transmetallation, and reductive elimination as for Suzuki cross-coupling. The standard catalyst precursor is Pd(PPh₃)₄.

Schlüter and co-workers used PSC in order to synthesize poly(para-2,5-di-n-hexylphenlene) (165) (Scheme 1.59). Starting from the suitable monomer 1,4-dibromo-di-2,5-n-hexylbeutene (163) which is then converted to boronic acid derivative 164. The monomer was treated with Pd(PPh3)4 under reflux for 2 days to afford poly(para-2,5-di-n-hexylphenlene) (165). A large number of poly(paraphenylene)s have been prepared based on this method.

![Scheme 1.58](image-url)
Scheme 1.59 Synthesis of 165

1. n-Butyllithium, Hexane/Ether
2. Ether, -60 °C
3. aq. HCl

163

164

164

165

1. n-Butyllithium, Hexane/Ether
2. Ether, -60 °C
3. aq. HCl

163

164

164

165
RESULTS AND DISCUSSION

CHAPTER TWO
Results and Discussion

2.1 Anthraquinones

Anthraquinones occur in many naturally occurring bioactive compounds.\(^{143}\) For instance, the anthracyclines are important as antitumor agents and antibiotics (e.g., the natural products daunorubicin, adriamycin, and aclorubicin).\(^{144}\) Anthraquinone containing natural products include chrysophanic acid, vismiaquinone, anthragallol, and questin.\(^{145}\) Anthraquinone derivatives show a very good antitumor activity against cancer cells.\(^{146}\) On the other hand, anthraquinones are widely using as antihelminthic as well as inhibitor agents.\(^{148}\) Many applications of aryl-substituted anthraquinones exist in material sciences, due to their redox,\(^{149a,b}\) UV and luminescence properties.\(^{149c,d}\) They have also been used as stabilizers of light-modulating fluids.\(^{149e}\)

2.1.1 Synthesis of 1,2-Diarylanthraquinones by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions of the Bis(triflate) of Alizarin

The phenol group can be transformed to triflates by treatment with triflic acid anhydride in the presence of pyridine.\(^ {150}\) The triflic anhydride was added at -78 °C and the mixture was allowed to warm to r.t.

My strategy is based on the above mentioned procedure to convert the alizarin 186 into the bis(triflate) of alizarin 187 which was isolated as a yellow solid in 81% yield (Scheme 2.1).

Scheme 2.1 Synthesis of 187

\[
\begin{array}{c}
\text{O} \\
\text{O} \\
\text{OH} \\
\text{OH} \\
\text{Tf}_2\text{O}, \text{CH}_2\text{Cl}_2 \\
\text{Pyridine, -78 °C to r.t.} \\
\text{14 h} \\
\end{array}
\]

\[
\begin{array}{c}
\text{O} \\
\text{O} \\
\text{OTf} \\
\text{OTf} \\
\end{array}
\]

2.1.1.2 Synthesis of 1,2-Diarylanthraquinones 189a-f

1,2-Diarylanthraquinones 189a-f were synthesized by using Suzuki coupling reactions of 1,2-bis(trifluoromethylsulfonyloxy)anthraquinone (187) and arylboronic acids (2.4 equiv) (Scheme 2.2). The best conditions for the completion of this coupling were the use of Pd(PPh\(_3\))\(_4\).
as the catalyst and K$_3$PO$_4$ as the base. I have done the Suzuki coupling reactions by using different substituted arylboronic acids including both electron-rich and electron-poor aryl groups. The coupling products were obtained in moderate to very good yields (40-81%).

Scheme 2.2 Synthesis of 189a-f

![Scheme 2.2 Synthesis of 189a-f]

The yield of 1,2-bis(4-methoxyphenyl)anthraquinone (189b) was low, due to hydrolysis of 187 to afford a monoarylhydroxyanthraquinone. The best yield was obtained for 1,2-bis(4-chlorophenyl)anthraquinone (189d) which resulted in 81% yield. 1,2-Diarylanthraquinones 189e,c,f were prepared in good yields. 1,2-Bis(4-trifluoromethylphenyl)anthraquinone (188a) also gave a good yield (77%) (Table 1).

Table 1 Synthesis of 189a-f

<table>
<thead>
<tr>
<th>188</th>
<th>189</th>
<th>Ar</th>
<th>% (189)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a</td>
<td>4-(F$_3$C)C$_6$H$_4$</td>
<td>77</td>
</tr>
<tr>
<td>b</td>
<td>b</td>
<td>4-(MeO)C$_6$H$_4$</td>
<td>40</td>
</tr>
<tr>
<td>c</td>
<td>c</td>
<td>4-t-BuC$_6$H$_4$</td>
<td>76</td>
</tr>
<tr>
<td>d</td>
<td>d</td>
<td>4-ClC$_6$H$_4$</td>
<td>81</td>
</tr>
<tr>
<td>e</td>
<td>e</td>
<td>4-MeC$_6$H$_4$</td>
<td>77</td>
</tr>
<tr>
<td>f</td>
<td>f</td>
<td>4-EtC$_6$H$_4$</td>
<td>60</td>
</tr>
</tbody>
</table>

$^a$Yields of isolated products.

The structure of 1,2-bis(4-tert-butylphenyl)anthraquinone (189c) was confirmed by X-ray crystal structure analysis as shown below in Figure 2.1. The anthraquinone unit is in plane. The tert-butyl-containing aromatic rings are twisted out of plane of the anthraquinone moiety.
2.1.1.3 Site-Selective Synthesis of 1-Aryl-2-(trifluoromethylsulfonyloxy) anthraquinones 190a-h

The reaction of 187 with one equivalent of arylboronic acids gives rise to the issue of site-selectivity. The conditions of these reactions were optimized in order to get the best yield of 1-aryl-2-(trifluoromethylsulfonyloxy)anthraquinones. The best yields were obtained when Pd(PPh3)4 and K3PO4 were used and when the reaction was carried out at 90 °C during 10 h (Scheme 2.3).

Scheme 2.3 Site-selective synthesis of 190a-h

Arylboronic acids 188d and 188g gave the best yields (85 and 84%). Arylboronic acids 188a,h and 188b,c were afforded in good yields. Moderate yields were obtained for reactions of 188i,j (50 and 52%) (Table 2).
The first nucleophilic attack occurred at carbon atom C-1. This can be explained by the \( \pi \)-acceptor effect of the carbonyl group (Figure 2.2). The site-selective formation of 190a-h can be explained by electronic reasons. The first attack of palladium(0)-catalyzed cross-coupling reactions generally occurs at the electronically more deficient and sterically less hindered position.\textsuperscript{151,152} Position 1 of 187 is sterically more hindered than position 2 (Figure 2.3). However, position 1 (located in \( \beta \)-position to the carbonyl group) is more electron-deficient than position 2. In fact, the \( ^1\text{H} \)-NMR signals of aromatic protons located at position 1 are generally shifted to lower field compared to the protons located at position 2.\textsuperscript{152} In addition, a neighboring group effect by the quinone carbonyl group (chelation of the approaching palladium complex) might play a role. In conclusion, the first attack occurs at the sterically more hindered position, due to electronic reasons.

\textbf{Figure 2.2} \( \pi \)-Acceptor effect of the carbonyl group

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{188} & \textbf{190} & \textbf{Ar} & \textbf{\% (190)\textsuperscript{a}} \\
\hline
a & a & 4-(F\textsubscript{3}C)C\textsubscript{6}H\textsubscript{4} & 74 \\
\hline
b & b & 4-(MeO)C\textsubscript{6}H\textsubscript{4} & 67 \\
\hline
c & c & 4-t-BuC\textsubscript{6}H\textsubscript{4} & 61 \\
\hline
d & d & 4-ClC\textsubscript{6}H\textsubscript{4} & 85 \\
\hline
g & e & 3-(F\textsubscript{3}C)C\textsubscript{6}H\textsubscript{4} & 84 \\
\hline
h & f & 3-(MeO)C\textsubscript{6}H\textsubscript{4} & 79 \\
\hline
i & g & 4-FC\textsubscript{6}H\textsubscript{4} & 50 \\
\hline
j & h & 4-(CF\textsubscript{3}O)C\textsubscript{6}H\textsubscript{4} & 52 \\
\hline
\end{tabular}
\caption{Synthesis of 190a-h}
\end{table}

\textsuperscript{a}Yields of isolated products.
**Figure 2.3** Possible explanation for the site-selectivity of 187

![Chemical structure diagram](image)

A $^1$H, $^1$H NOE experiment was used to confirm the structure of compound 190c. The $^1$H, $^1$H NOE spectrum does not provide us a real proof for the site-selectivity. The missing correlations give us an indirect hint to the structure of 190c (Figure 2.4).

**Figure 2.4** $^1$H, $^1$H NOE spectrum of 190c

![NMR spectrum](image)

In addition to the $^1$H, $^1$H NOE experiment, a better proof to the site-selective attack at carbon atom C-1 190b was obtained by using X-ray crystal structure analysis (Figure 2.5). The aromatic ring is perpendicular to the anthraquinone system.
2.1.1.4 Synthesis of Unsymmetrical 1,2-Diarylanthraquinones 191a-f

The possibilities of one-pot Suzuki coupling reactions of 187 with two different arylboronic acids were next studied. The boronic acids were added in a sequential manner. During the optimization, it proved to be important to carry out the first step of the one-pot reaction at 90 °C and the second step at 110 °C (Scheme 2.4).

![Scheme 2.4 Site-selective synthesis of unsymmetrical anthraquinones 191a-f](image)

Products 191a,c,d,e,f were isolated in moderate yields between 61-68%, except for 191b which resulted in a moderate yield (50%) (Table 3).
**Table 3 Synthesis of 191a-f**

<table>
<thead>
<tr>
<th>188</th>
<th>191</th>
<th>Ar&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Ar&lt;sup&gt;2&lt;/sup&gt;</th>
<th>% (191)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>a,c</td>
<td>a</td>
<td>4-(F&lt;sub&gt;3&lt;/sub&gt;C)C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4-&lt;i&gt;t&lt;/i&gt;-BuC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>65</td>
</tr>
<tr>
<td>b,c</td>
<td>b</td>
<td>4-(MeO)C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4-&lt;i&gt;t&lt;/i&gt;-BuC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>50</td>
</tr>
<tr>
<td>c,a</td>
<td>c</td>
<td>4-&lt;i&gt;t&lt;/i&gt;-BuC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4-(CF&lt;sub&gt;3&lt;/sub&gt;)C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>60</td>
</tr>
<tr>
<td>d,c</td>
<td>d</td>
<td>4-ClC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4-&lt;i&gt;t&lt;/i&gt;-BuC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>61</td>
</tr>
<tr>
<td>g,a</td>
<td>e</td>
<td>3-(F&lt;sub&gt;3&lt;/sub&gt;C)C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4-(CF&lt;sub&gt;3&lt;/sub&gt;)C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>61</td>
</tr>
<tr>
<td>g,c</td>
<td>f</td>
<td>3-(F&lt;sub&gt;3&lt;/sub&gt;C)C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4-&lt;i&gt;t&lt;/i&gt;-BuC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;</td>
<td>61</td>
</tr>
</tbody>
</table>

<sup>a</sup>Yields of isolated products.

For compound 191a an X-ray crystal structure was measured and the structure was confirmed (Figure 2.6). The aromatic rings are perpendicular to the anthraquinone moiety. Both the CF<sub>3</sub> and the <i>t</i>-Bu group are disordered.

**Figure 2.6 ORTEP plot of 191a**

![ORTEP plot of 191a](image-url)
2.1.2 Synthesis of 1,2,3-Triarylanthraquinones by Site-Selective Suzuki–Miyaura Cross-coupling Reactions of the Tris(triflate) of Purpurin

The reaction of commercially available purpurin with triflic acid anhydride, in the presence of pyridine, afforded the tris(triflate) of purpurin in 43% yield. The reaction was done at -78 °C and allowed to warm to r.t. under an inert atmosphere with stirring for 14 h (Scheme 2.5).

**Scheme 2.5 Synthesis of 193**

![Scheme 2.5 Synthesis of 193](image)

2.1.2.1 Synthesis of 1,2,3-Triarylanthraquinones 194a-f

The reaction of the tris(tiflate) of purpurin 193 with 4.0 equivelants of boronic acid derivatives afforded 1,2,3-triarylanthraquinones. In the reactions were used Pd(PPh₃)₄ as the catalyst and K₃PO₄ as the base. The best temperature was 120 °C (Scheme 2.6).

**Scheme 2.6 Synthesis of 194a-f**

![Scheme 2.6 Synthesis of 194a-f](image)

Arylboronic acids 188c,k gave very good yields (83 and 86%). Arylboronic acids 188b,d and 188a,i provided moderate to good yields (Table 4).
Results and Discussion

Table 4 Synthesis of 194a-f

<table>
<thead>
<tr>
<th></th>
<th>188</th>
<th>194</th>
<th>Ar</th>
<th>% (194)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a</td>
<td></td>
<td>4-(F(_3)C)C(_6)H(_4)</td>
<td>43</td>
</tr>
<tr>
<td>b</td>
<td>b</td>
<td></td>
<td>4-(MeO)C(_6)H(_4)</td>
<td>73</td>
</tr>
<tr>
<td>c</td>
<td>c</td>
<td></td>
<td>4-t-BuC(_6)H(_4)</td>
<td>83</td>
</tr>
<tr>
<td>d</td>
<td>d</td>
<td></td>
<td>4-ClC(_6)H(_4)</td>
<td>60</td>
</tr>
<tr>
<td>i</td>
<td>e</td>
<td></td>
<td>4-FC(_6)H(_4)</td>
<td>57</td>
</tr>
<tr>
<td>k</td>
<td>f</td>
<td></td>
<td>C(_6)H(_4)</td>
<td>86</td>
</tr>
</tbody>
</table>

\(^a\) Yields of isolated products.

2.1.2.2 Site-Selective Synthesis of 1,4-Diaryl-2-(trifluoromethylsulfonyloxy)anthraquinones 195a-e

The reaction of the tris(triflate) of purpurin 193 and 2.0 equivalents of arylboronic acids afforded 1,4-diaryl-2-(trifluoromethylsulfonyloxy)anthraquinones 195a-e. During the optimization, it was proved to be important to carry out the reaction at 105 °C and the reaction had to be stirred for 10 h (Scheme 2.7).

Scheme 2.7 Site-selective synthesis of 195a-e

Arylboronic acids 188c,f afforded the corresponding products in very good yield (83 and 86%). For 188l a moderate yield was obtained (60%). Moderate yields were observed for 188a,e (57 and 43%) (Table 5).
Results and Discussion

Table 5 Synthesis of 195a-e

<table>
<thead>
<tr>
<th>188</th>
<th>195</th>
<th>Ar</th>
<th>% (195)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a</td>
<td>4-(F(_3))C(_6)H(_4)</td>
<td>61</td>
</tr>
<tr>
<td>c</td>
<td>b</td>
<td>4-t-BuC(_6)H(_4)</td>
<td>81</td>
</tr>
<tr>
<td>e</td>
<td>c</td>
<td>4-MeC(_6)H(_4)</td>
<td>51</td>
</tr>
<tr>
<td>f</td>
<td>d</td>
<td>4-EtC(_6)H(_4)</td>
<td>74</td>
</tr>
<tr>
<td>l</td>
<td>e</td>
<td>3,5-MeC(_6)H(_4)</td>
<td>60</td>
</tr>
</tbody>
</table>

\(^a\) Yields of isolated products.

In order to determine the structure of compound 195e, a \(^1\)H, \(^1\)H NOE experiment was used. The correlation (black circle) shows that the attack of the boronic acid occurred at carbon atom C-4. The missing correlation (red circle) shows that carbon atom C-2 was not attacked (Figure 2.7).

Figure 2.7 \(^1\)H, \(^1\)H NOE spectrum of 195e

Inspection of the \(^1\)H-NMR shows that the aromatic protons are almost equivalent, which suggests a relatively symmetrical structure containing aryl groups located at carbon atom C-1 and C-4 (Figure 2.8)
The structure of 195a was confirmed by X-ray crystal structure analysis. Both CF$_3$ containing aromatic rings are perpendicular to the anthraquinone moiety (Figure 2.9).
2.1.2.3 Site-Selective Synthesis of 1,2-Bis(trifluoromethylsulfonyloxy)-4-arylanthraquinones 196a-f

Site-Selective Suzuki-Miyaura coupling reactions were achieved between tris(triflate) of purpurin 193 with 1.0 equivalent of arylboronic acids. The temperature was optimized to be 95 °C and the reaction was allowed to stir for 10 h (Scheme 2.8).

Scheme 2.8 Site-selective synthesis of 196a-f

![Scheme 2.8 Site-selective synthesis of 196a-f]

Arylboronic acids 188c,d resulted in moderate yields (61 and 65%). Arylboronic acid 188f gave 56% yield of product. Arylboronic acids 188b,c,g gave moderate yields (40, 38 and 40%) (Table 6).

Table 6 Synthesis of 196a-f

<table>
<thead>
<tr>
<th>188</th>
<th>196</th>
<th>Ar</th>
<th>% (196)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>a</td>
<td>4-(MeO)C₆H₄</td>
<td>38</td>
</tr>
<tr>
<td>c</td>
<td>b</td>
<td>4-t-BuC₆H₄</td>
<td>41</td>
</tr>
<tr>
<td>e</td>
<td>c</td>
<td>4-MeC₆H₄</td>
<td>61</td>
</tr>
<tr>
<td>f</td>
<td>d</td>
<td>4-EtC₆H₄</td>
<td>65</td>
</tr>
<tr>
<td>g</td>
<td>e</td>
<td>3-(F₃C)C₆H₄</td>
<td>40</td>
</tr>
<tr>
<td>m</td>
<td>f</td>
<td>3-ClC₆H₄</td>
<td>56</td>
</tr>
</tbody>
</table>

\(^a\)Yields of isolated products.

The first attack of palladium(0)-catalyzed cross-coupling reactions generally occurs at the electronically more deficient and sterically less hindered position.\(^{187,188}\) Position 2 and 4 of 193 are sterically less hindered than position 1 (Figure 2.10). Positions 1 and 4 of 193 are more electron-deficient than position 2. In conclusion, the first attack occurs at the sterically less
hindered and electronically deficient position 4. The second attack occurs at position 1 which is sterically hindered, but electron deficient. The third attack occurs at position 2 which is not electron deficient and not sterically hindered.

**Figure 2.10** Possible explanation for the site-selectivity of 193

![Possible explanation for the site-selectivity of 193](image)

The structure of 196f was determined by 2D NMR experiments. The \(^1\text{H}, \(^1\text{H}\) NOE correlation shows that the attack of the arylboronic acid occurred at carbon atom C-4 (Figure 2.11).

**Figure 2.11** \(^1\text{H}, \(^1\text{H}\) NOE spectrum of 196f
The $^1$H-NMR spectrum of 196f shows that two aromatic protons beside the carbonyl groups are not equivalent to each other, which suggests a relatively unsymmetrical structure containing the aryl groups located at position 4 (Figure 2.12).

**Figure 2.12** $^1$H-NMR spectrum of 196f

The structure of 196e was independently confirmed by X-ray crystal structure analysis. The aryl groups are twisted out of plane. The SO$_3$CF$_3$ group and the CF$_3$ group are disordered (Figure 2.13).
2.1.2.4 Synthesis of Unsymmetrical 1,4-Bis(4-tert-butylphenyl)-2-(4-chlorophenyl)anthraquinone (197)

The one-pot reaction of tris(tiflate) of purpurin 193 and different arylboronic acids afforded the 1,4-bis(4-tert-butylphenyl)-2-(4-chlorophenyl)anthraquinone (197). The first step of the reaction was carried out using 2.0 equivalents of arylboronic acid at 95 °C during 10 h. The second step was carried out at 110 °C during 10 h (Scheme 2.9). 1,4-Bis(4-tert-butylphenyl)-2-(4-chlorophenyl)anthraquinone (197) was obtained in 45% yield.

Scheme 2.9 Synthesis of unsymmetrical 197
2.2 Hydroxyphthalates

Functionalized hydroxylated benzoates and benzodioates and their derivatives are of great interest as lead structures in pharmaceutical, industrial and agricultural chemistry and constitute valuable synthetic building blocks in synthetic organic chemistry. Some of these molecules occur in natural products and have interesting pharmacological properties, including analgesic, antipyretic, antimicrobial and fungicidal properties. In addition, they act as inhibitors of some enzymes and as inhibitors for the absorption of steroids, such as, cholesterol and bile acids.

2.2.1 Synthesis of Dimethyl 3,5-Dihydroxyphthalates by [4+2]-Cycloaddition and Subsequent Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

I synthesized dimethyl 3,5-dihydroxyphthalate (200) by [4+2]-cycloaddition of 1-methoxy-1,3-bis(trimethylsilyloxy)-1,3-diene with dimethyl acetylenedicarboxylate (DMAD) in 32% yield. DMAD was added at r.t. and the mixture was allowed to stirr at 50 °C for 48 h. Toluene was used as the solvent (Scheme 2.10).

Scheme 2.10 Synthesis of 200

The reaction of dimethyl 3,5-dihydroxyphthalate (200) with triflic acid anhydride resulted in formation of dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (201) in good yield (78%) (Scheme 2.11).

Scheme 2.11 Synthesis of 201
The reaction of dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalates (201) with 2.4 equivalents of arylboronic acids afforded dimethyl 3,5-diarylphthalates 202a,b (Table 7). The temperature, which was selected, was 110 °C (8 h). Dioxane was used in this reaction as suitable solvent and the base K$_3$PO$_4$ was used (Scheme 2.12).

**Scheme 2.12 Synthesis of 202a,b**

![Scheme 2.12 Synthesis of 202a,b](image)

**Table 7 Synthesis of 202a,b**

<table>
<thead>
<tr>
<th>188</th>
<th>202</th>
<th>Ar</th>
<th>% (202)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>a</td>
<td>4-&lt;i&gt;t&lt;/i&gt;-BuC$_6$H$_4$</td>
<td>91</td>
</tr>
<tr>
<td>d</td>
<td>b</td>
<td>4-ClC$_6$H$_4$</td>
<td>88</td>
</tr>
</tbody>
</table>

$^a$Yields of isolated products.

The conditions were optimized for the reaction of dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (201) with 1 equivalent of arylboronic acids (Scheme 2.13). The reaction was carried out at 70 °C during 16 h. As the catalyst, 6 mol% of Pd(PPh$_3$)$_3$ was used. Products 203a,b were isolated in good yields (76 and 71%) (Table 8).

**Scheme 2.13 Site-selective synthesis of 203a,b**

![Scheme 2.13 Site-selective synthesis of 203a,b](image)
Table 8 Synthesis of 203a,b

<table>
<thead>
<tr>
<th>188</th>
<th>203</th>
<th>Ar</th>
<th>% (203)⁹</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a</td>
<td>4-(F₃C)C₆H₄</td>
<td>76</td>
</tr>
<tr>
<td>c</td>
<td>b</td>
<td>4-t-BuC₆H₄</td>
<td>71</td>
</tr>
</tbody>
</table>

⁹Yields of isolated products.

Based on a ¹H, ¹H NOE experiment for product 203b, it was confirmed that the first attack of the arylboronic acid occurred at carbon atom C-5 (Figure 2.14). The two protons at carbon atom C-4 and C-6, which appear as doublets at 7.62 and 8.11 ppm with coupling constants $J = 1.62$ Hz, correlate with the aromatic protons which appear as singlets.

**Figure 2.14** ¹H, ¹H NOE spectrum of 203b

2.3 Quinolines

Quinolines are the core for many naturally occurring compounds.¹⁵⁵ They are also very important as pharmacologically active substances. For example, pyrimidinylthiopyrimidyloxy
quinoline derivatives are active as herbicides, microbicides, and fungicides.\textsuperscript{156} Camptothecin is a natural product isolated in 1966 and shows excellent antitumor activity.\textsuperscript{157}

2.3.1 Synthesis of 5,7-Diaryl-8-(trifluoromethylsulfonyloxy)quinolines by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

5,7-Dibromo-8-(trifluoromethylsulfonyloxy)quinoline (205) was synthesized by reaction of 5,7-dibromo-8-hydroxyquinoline with triflic acid anhydride and afforded product 205 in very good yield (80\%) (Scheme 2.14).

Scheme 2.14 Synthesis of 205

\[
\begin{align*}
\text{Br} & \quad \text{Br} & \quad \text{Tf}_2\text{O}, \text{CH}_2\text{Cl}_2 & \quad \text{Br} \\
\text{Br} & \quad \text{OH} & \quad \text{Pyridine}, -78^\circ\text{C} & \quad \text{Br} \\
204 & \quad & 14 \text{ h} & \quad \text{N} \\
\text{Br} & \quad \text{Br} & \quad \text{OTf} & \quad 205
\end{align*}
\]

The reaction of 205 with 2.0 equivalent of 4-\textit{tert}-butylphenylboronic acid afforded product 206 in 81\% yield (Scheme 2.15). The optimization of the product 206 required to do this reaction at 70 °C and using K\textsubscript{2}CO\textsubscript{3} as the base. The first attack occurred at carbon atom C-5 and the second attack occurred at carbon atom C-7.

Scheme 2.15 Site-selective synthesis of 206

\[
\begin{align*}
\text{Br} & \quad \text{Br} & \quad \text{B(OH)}_2 & \quad \text{Pd(PPPh}_3)_4, \text{K}_2\text{CO}_3 & \quad \text{Br} \\
\text{Br} & \quad \text{OTf} & \quad \text{C(CH}_3)_3 & \quad \text{Dioxane}, 70^\circ\text{C}, 12 \text{ h} & \quad \text{C(CH}_3)_3 \\
205 & \quad 188c & \quad \text{Br} & \quad \text{C(CH}_3)_3 & \quad 206 \ (81\%)
\end{align*}
\]

The reaction of 5,7-dibromo-8-(trifluoromethylsulfonyloxy)quinoline (205) with 1 equivalent of 4-\textit{tert}-butylphenylboronic acid gave 5-(4-\textit{tert}-butylphenyl)-7-bromo-8-
(trifluoromethylsulfonyloxy)quinoline (207) in good yield (75%). I carried out this reaction at 50 °C for 20 h. I again used K₂CO₃ as the base (Scheme 2.16). The attack occurred selectively at carbon atom C-5.

**Scheme 2.16** Site-selective synthesis of 207

![Scheme 2.16 Site-selective synthesis of 207](image)

The structure of compound 207 was confirmed by using ¹H, ¹H NOE experiments. The ortho protons of the 4-tert-butylphenyl group correlate with proton H-4 of the quinoline moiety (Figure 2.15).

**Figure 2.15** ¹H, ¹H NOE spectrum of 207
Abstract

In English

Based on the methodology of Suzuki-Miyaura cross-coupling reactions, a wide range of substituted anthraquinones are now readily available including a few examples of phthalates and quinolines. The method provides new possibilities in carbon-carbon bond formation for the preparation of new materials. Due to the importance and useful properties of many anthraquinones, phthalates and quinolines, the chemistry of the bis(triflates) of anthraquinones, phthalates and 5,7-dibromo-8-(trifluoromethylsulfonyloxy)quinoline has been investigated in this thesis. The results for the synthesis and characterization of diarylanthraquinones, diarylphthalates and diarylquinolines are presented in this thesis.

In German

Basierend auf der Methode der Suzuki-Miyaura-Kreuzkupplungsreaktion ist nun eine große Auswahl substituierter Anthrachinone, einschließlich einiger Beispiele für substituierte Phthalate und Chinoline, leicht verfügbar. Die Methode bietet neue Möglichkeiten in der C-C-Bindungsknüpfung, um neue Materialien zu synthetisieren. Wegen der großen Bedeutung und den nützlichen Eigenschaften vieler Anthrachinone, Phthalate und Chinoline wurde die Chemie der Bis(triflate) von Anthrachinonen, Phthalaten und 5,7-Dibrom-8-(trifluormethylsulfonyloxy)chinolinen in der vorliegenden Arbeit untersucht. Die Ergebnisse der Synthese und der Charakterisierung von Diarylanthrachinonen, Diarylphthalaten und Diarylchinolinen werden in dieser Arbeit gezeigt und diskutiert.
3.1 Materials and Methods

3.1.1 General: Equipment, Chemicals and Work Technique

$^1$H-NMR Spectroscopy

Bruker: AM 250, Bruker ARX 300, Bruker ARX 500; $\delta = 0.00$ ppm for Tetramethylsilane; $\delta = 2.04$ ppm for Acetone d-6; $\delta = 7.26$ ppm for (CDCl$_3$); 2.50 ppm for d-6 DMSO-; Characterization of the signal fragmentations: s = singlet, d = doublet, dd = double of doublet, ddd = doublet of a double doublet, t = triplet, q = quartet, quint = quintet; sext = Sextet, sept = Septet, m = multiplet, br = broadly. Spectra were evaluated according to first order rule. All coupling constants are indicated as ($J$).

$^{13}$C-NMR Spectroscopy

Bruker: AM 250, (62.9 MHz); Bruker: ARX 300, (75.4 MHz), Bruker: ARX 500, (125 MHz) Ref: 29.84 ± 0.01 ppm and 206.26 ± 0.13 ppm for (CD$_3$)$_2$CO. $\delta = 128.00$ ppm for Acetone d-6; $\delta = 77.00$ ppm for CDCl$_3$. The multiplicity of the carbon atoms was determined by the DEPT 135 and APT technique (APT = Attached Proton Test) and quoted as CH$_3$, CH$_2$, CH and C for primary, secondary, tertiary and quaternary carbon atoms. Characterization of the signal fragmentations: quart = quartet the multiplicity of the signals was determined by the DEPT recording technology and/or the APT recording technology.

Mass Spectroscopy (MS)

AMD MS40, AMD 402 (AMD Intectra), Varian MAT CH 7, MAT 731.

High Resolution Mass Spectroscopy (HRMS)

Finnigan MAT 95 or Varian MAT 311; Bruker FT CIR, AMD 402 (AMD Intectra).
Infrared Spectroscopy (IR)

Bruker IFS 66 (FT IR), Nicolet 205 FT IR; Nicolet Protégé 460, Nicolet 360 Smart Orbit (ATR); KBr, KAP, Nujol, and ATR; Abbreviations for signal allocations: w = weak, m = medium, s = strong, br = broad.

Elementary Analysis

LECO CHNS-932, Thermoquest Flash EA 1112.

X-ray Crystal Structure Analysis

Bruker X8Apex Diffractometer with CCD-Kamera (Mo-Ka und Graphit Monochromator, $\lambda = 0.71073 \text{ Å}$).

Melting Points

Micro heating table HMK 67/1825 Kuestner (Büchi apparatus); Melting points are uncorrected.

Column Chromatography

Chromatography was performed over Merck silica gel 60 (0,063 - 0,200 mm, 70 - 230 mesh) as normal and/or over mesh silica gel 60 (0,040 - 0,063 mm, 200 - 400 mesh) as Flash Chromatography. All solvent were distilled before use.

TLC

Merck DC finished foils silica gel 60 F254 on aluminum foil and Macherey finished foils Alugram® Sil G/UV254. Detection under UV light with 254 nm and/or 366 nm without dipping reagent, as well as with anisaldehyde sulfuric acid reagent (1 mL anisaldehyde consisting in 100 mL stock solution of 85% methanol, 14% acetic acid and 1% sulfuric acid).
Chemicals and Work Technique

All solvents for using were distilled by standard methods. All reactions were carried out under an inert atmosphere, oxygen and humidity exclusion. All of the chemicals are standard, commercially available from Merck®, Aldrich®, Arcos® and others. The order of the characterized connections effected numerically, but does not correspond to the order in the main part of dissertation.

3.2 Preparative Procedures and Spectroscopic Data

3.3 Synthesis of 1,2-Bis(trifluoromethylsulfonyloxy)anthraquinone (187)

To a solution of 1,2-dihydroxyanthraquinone (186) (1.0 equiv) in CH₂Cl₂ (10 mL/mmol) was added pyridine (4.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf₂O (2.4 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc).

1,2-Bis(trifluoromethylsulfonyloxy)anthraquinone (187)

To a solution of 186 (1.0 equiv.) in CH₂Cl₂ (10 mL/mmol) was added pyridine (4.0 equiv.) at room temperature under an argon atmosphere. After 10 min, Tf₂O (2.4 equiv.) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc). Starting with 186 (1.9 g, 8.0 mmol), pyridine (2.6 mL, 32.0 mmol), CH₂Cl₂ (80 mL), Tf₂O (3.2 mL, 19.2 mmol), 187 was isolated as a yellow solid (3.25 g, 81%), mp 152-154 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.80-7.85 (m, 3H, ArH), 8.23-8.26 (m, 1H, ArH), 8.29-8.32 (m, 1H, ArH), 8.46 (d, J = 8.76 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 118.5 (q, J = 320.9 Hz, CF₃), 118.6 (d, J = 320.7 Hz, CF₃), 127.4 (CH), 127.8 (C), 128.0, 128.1, 128.9 (CH), 132.0, 133.7, 134.1 (C), 135.1, 135.2 (CH), 139.2, 145.0 (C), 180.2, 180.5 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.4 (q, J = 3.02, 6.02 Hz, 3F, CF₃), -72.58 (q, J =
Experimental Section

2.84, 5.83 Hz, 3F, CF₃). IR (KBr, cm⁻¹): \( \tilde{\nu} = 1674 \) (s), 1601, 1587, 1472 (w), 1427 (s), 1330, 1316, 1282, 1249 (w), 1208 (s), 1164, 1150 (m) 1124 (s), 1007, 998, 901, 856 (m), 807 (s), 795, 738 (m), 721, 708 (s), 684, 676, 655, 643 (w), 618, 606 (m), 589, 575, 569 (s), 543, 529 (m). GC-MS (EI, 70 eV): \( m/z \) (%) = 504 ([M+H]+, 36), 435 (05), 375 (08), 348 (23), 279 (100), 251 (76), 223 (26), 154 (26), 126 (60). HRMS (EI, 70 eV): calcd for C₁₆H₆O₈F₆S₂ [M]+: 503.94028, found 503.940108.

3.3.1 General Procedure for Suzuki-Miyaura Reactions

A 1,4-dioxane solution (4 mL per 3 mmol of 187) of 187, K₃PO₄, Pd(PPh₃)₄ and arylboronic acid 188 was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

1,2-Bis(4-trifluoromethylphenyl)anthraquinone (189a)

Starting with 187 (250 mg, 0.5 mmol), 188a (225 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 6 mol-%, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), 189a was isolated as a yellow solid (190 mg, 77%), mp 208-210 °C. \(^1\)H NMR (300 MHz, CDCl₃): \( \delta = 7.01-7.07 \) (m, 4H, ArH), 7.35 (d, \( J = 8.12 \) Hz, 2H, ArH), 7.42 (d, \( J = 8.12 \) Hz, 2H, ArH), 7.62-7.71 (m, 3H, ArH), 7.95-8.0 (m, 1H, ArH), 8.18-8.21 (m, 1H, ArH), 8.45 (d, \( J = 8.12 \) Hz, 1H, ArH). \(^1^3\)C NMR (62.9 MHz, CDCl₃): \( \delta = 123.8 \) (q, \( J_{F,C} = 272.2 \) Hz, CF₃), 124.1 (q, \( J_{F,C} = 272.1 \) Hz, CF₃), 124.7 (C), 124.7, 124.8, 126.7, 127.4, 127.7 (CH), 128.8 (C), 129.5, 129.7 (CH), 131.5, 132.6 (C), 134.0 (CH), 134.3 (C), 134.4 (CH), 134.5 (C), 135.1 (CH), 140.6, 143.0, 143.2, 147.3 (C), 182.7, 183.3 (CO). \(^1⁹\)F NMR (282 MHz, CDCl₃): \( \delta = -62.69 \) (s, 3F, CF₃), -62.37 (s, 3F, CF₃). IR (KBr, cm⁻¹): \( \tilde{\nu} = 1670 \) (m), 1633, 1615, 1580, 1416, 1397 (w), 1324, 1299 (s), 1281, 1261, 1212, 1199 (m), 1158, 1108, 1078, 1061, 1016 (s), 977 (w), 958, 947 (m), 900, 866 (w), 835, 825 (s), 797 (m), 787, 768, 757, 747, 740 (w), 720, 711 (s), 679 (w), 672 (m), 648 (w), 636 (m), 606 (s), 545 (w). GC-MS (EI, 70 eV): \( m/z \) (%) = 496 ([M]+, 78), 495 (100), 477 (09), 428 (25), 427 (86). HRMS (EI, 70 eV): calcd for C₂₅H₁₃O₂F₆ [M-H]+: 495.08143, found 495.081086.
1,2-Bis(4-methoxyphenyl)anthraquinone (189b)

Starting with 187 (250 mg, 0.5 mmol), 188b (180 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 6 mol-%, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), 189b was isolated as a red crystal (84 mg, 40%), mp 220-221 °C. ¹H NMR (300 MHz, CDCl₃): δ = 3.66 (s, 3H, OCH₃), 3.71 (s, 3H, OCH₃), 6.61 (d, J = 8.76 Hz, 2H, ArH), 6.71 (d, J = 8.73 Hz, 2H, ArH), 6.83 (d, J = 7.92 Hz, 4H, ArH), 7.60-7.65 (m, 3H, ArH), 7.97-8.0 (m, 1H, ArH), 8.15-8.18 (m, 1H, ArH), 8.30 (d, J = 8.07 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 54.0 (OCH₃), 54.1 (OCH₃), 112.1, 112.2, 125.4, 126.0, 126.3, 129.4, 129.6 (CH), 130.8, 131.0, 131.4, 131.7 (C), 132.4 (CH), 132.5 (C), 133.0 (CH), 134.0 (C), 134.2 (CH), 140.0, 148.0, 157.1, 157.5 (C), 182.3, 183.0 (CO). IR (KBr, cm⁻¹): ν = 2838 (w), 1671 (s), 1606 (s), 1588, 1550, 1516, 1464, 1451, 1440, 1412, 1394 (w), 1328, 1311 (m), 1297, 1240 (s), 1208, 1107, 1088, 1074 (m), 1027 (s), 977 (w), 954 (s), 858 (w), 840 (m), 828 (s), 811 (w), 800 (s), 767, 749 (w), 727 (m), 718 (s), 697 (m), 669, 649 (w), 640, 601, 588 (m), 537 (s). GC-MS (EI, 70 eV): m/z (%) = 420 ([M]+, 100), 419 (49), 405 (11), 390 (12), 389 (45), 345 (14), 312 (09). HRMS (EI, 70 eV): calcd for C₂₈H₂₀O₄ [M]+: 420.13561, found 420.134505.

1,2-Bis(4-tert-butylphenyl)anthraquinone (189c)

Starting with 187 (250 mg, 0.5 mmol), 188c (213 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 6 mol-%, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), 189c was isolated as an orange crystal (180 mg, 76%), mp 234-236 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.15 (s, 9H, 3CH₃), 1.20 (s, 9H, 3CH₃), 6.75-6.83 (m, 4H, ArH), 7.01-7.14 (m, 4H, ArH), 7.60-7.65 (m, 3H, ArH), 7.97 (d, J = 8.01 Hz, 1H, ArH), 8.01-8.03 (m, 1H, ArH), 8.17-8.23 (m, 1H, ArH), 8.34 (d, J = 8.05 Hz, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 31.2 (3CH₃), 31.4 (3CH₃), 34.4, 34.4 (C), 124.2, 124.3, 126.6, 127.0, 127.5, 129.0, 129.9 (CH), 131.3, 132.9 (C), 133.5 (CH), 133.6 (C), 134.1, 134.9 (CH), 135.0, 136.9, 137.2, 142.7, 149.1, 149.8 (C), 183.4, 183.7 (CO). IR (KBr, cm⁻¹): ν = 2959 (m), 2901, 2866 (w), 1675 (s), 1663, 1588 (m), 1575, 1566, 1548, 1513, 1475, 1456, 1410, 1394, 1360 (w), 1330, 1315 (m), 1298 (s), 1280, 1262, 1253, 1211, 1199 (m), 1185, 1160 (w), 1113 (m), 1072 (w), 1016 (m),
979 (w), 956 (m), 942, 904 (w), 860, 836 (m), 822(s), 795 (m), 774, 768, 755, 745 (w), 719 (s), 690 (m), 682 (w), 662, 645 (m), 587 (s), 568, 559, 543 (m). GC-MS (EI, 70 eV): m/z (%) = 472 ([M]+, 45), 457 (93), 439 (04), 415 (100), 401 (23), 383 (11). HRMS (EI, 70 eV): calcd for C_{14}H_{32}O_{2} [M]^{+}: 472.23968, found 472.238675.

1,2-Bis(4-chlorophenyl)anthraquinone (189d)

Starting with 187 (250 mg, 0.5 mmol), 188d (185 mg, 1.2 mmol), Pd(PPh_{3})_{4} (34 mg, 6 mol-%, 0.03 mmol), K_{2}PO_{4} (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), 189d was isolated as a yellow solid (174 mg, 81%), mp 208-210 °C. ¹H NMR (300 MHz, CDCl_{3}): δ = 6.82-6.87 (m, 4H, ArH), 7.06-7.16 (m, 4H, ArH), 7.61-7.70 (m, 3H, ArH), 7.95-8.02 (m, 1H, ArH), 8.15-8.18 (m, 1H, ArH), 8.34 (d, J = 8.01 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl_{3}): δ = 126.7, 127.4, 127.5, 128.1, 128.2, 130.5, 130.7 (CH), 131.6, 132.6, 132.8, 133.6 (C), 133.8 (CH), 134.0 (C), 134.3 (CH), 134.6 (C), 135.1 (CH), 137.9, 138.1, 140.8, 147.7 (C), 183.0, 183.5 (CO). IR (KBr, cm⁻¹): δ = 1673 (s), 1589 (m), 1576, 1551 (w), 1489 (m), 1478, 1451, 1410, 1388 (w), 1326 (m), 1308, 1297, 1267 (s), 1245, 1210 (m), 1181 (w), 1159 (m), 1091 (s), 1070 (m), 1014 (s), 972 (w), 954 (s), 938, 856, 846 (m), 834, 820 (s), 791, 774, 763, 729 (m), 714 (s), 698, 688 (m), 656 (w), 644 (m), 636, 573 (w), 559, 548 (m), 537 (w). GC-MS (EI, 70 eV): m/z (%) = 432 ([M]+, 2x ³⁷Cl, 12), 431 ([M+H]+, ³⁷Cl, 26), 430 ([M]+, ³⁷Cl, 67), 429 ([M+H]+, ³⁵Cl, 91), 428 ([M]+, ³⁵Cl, 93), 427 (100), 395 (30), 394 (24), 393 (91), 357 (17), 300 (26). HRMS (EI, 70 eV): calcd for C_{26}H_{13}Cl_{2}O_{2} ([M-H]+, ³⁵Cl): 427.02871, found 427.028111.

1,2-Bis(4-methylphenyl)anthraquinone (189e)

Starting with 187 (250 mg, 0.5 mmol), 188e (162 mg, 1.2 mmol), Pd(PPh_{3})_{4} (34 mg, 6 mol-%, 0.03 mmol), K_{2}PO_{4} (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), 189e was isolated as a yellow solid (149 mg, 77%), mp 218-220 °C. ¹H NMR (300 MHz, CDCl_{3}): δ = 2.20 (s, 3H, CH₃), 2.27 (s, 3H, CH₃), 6.82-7.00 (m, 4H, ArH), 6.90 (d, J = 7.86 Hz, 2H, ArH), 6.98 (d, J = 7.88 Hz, 2H, ArH), 7.60-7.70 (m, 3H, ArH), 8.00-8.03 (m, 1H, ArH), 8.18-8.21 (m, 1H, ArH), 8.34 (d, J = 8.01Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl_{3}): δ = 21.1 (CH₃), 21.4 (CH₃), 126.5, 127.0, 127.4, 128.4, 128.5, 129.1, 129.3 (CH), 131.8, 132.8, (C), 133.5 (CH), 133.6 (C),
134.1 (CH), 135.1 (C), 135.3 (CH), 136.0, 136.7, 137.2, 142.4, 149.2 (C), 183.4, 183.9 (CO). IR (KBr, cm⁻¹): δ = 2920, 2851 (w), 1672, 1662 (s), 1590, 1574, 1548, 1512, 1478, 1445, 1414, 1385 (w), 1327, 1313 (m), 1293, 1278, 1260 (s), 1241, 1208 (m), 1182, 1159, 1112, 1070, 1039 (w), 1018 (m), 965 (w), 952, 939 (m), 896, 854, 832 (w), 811 (s), 794 (m), 762, 749 (w), 723, 713, 701 (s), 669, 650 (w), 642 (m), 595 (w), 580, 549, 540 (m). GC-MS (EI, 70 eV): m/z (%) = 388 ([M]⁺, 49), 374 (26), 373 (100), 371 (6). HRMS (EI, m, 70 eV): calcd for C₂₈H₂₀O₂ [M]⁺: 388.14578, found 388.144687.

1,2-Bis(4-ethylphenyl)anthraquinone (189f)

Starting with 187 (250 mg, 0.5 mmol), 189f (180 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), 189f was isolated as a brown solid (124 mg, 60%), mp 146-148 °C. 

¹H NMR (300 MHz, CDCl₃): δ = 1.03-1.14 (m, 6H, 2CH₃), 2.43-2.55 (m, 4H, 2CH₂), 6.76-6.87 (m, 6H, ArH), 6.95 (d, J = 8.07 Hz, 2H, ArH), 7.54-7.64 (m, 3H, ArH), 7.94-8.01 (m, 1H, ArH), 8.11-8.14 (m, 1H, ArH), 8.27 (d, J = 8.04 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 14.2 (CH₃), 14.4 (CH₃), 27.3 (CH₂), 27.5 (CH₂), 125.4, 125.8, 126.0 (d, J = 11.9 Hz), 126.3, 126.8, 128.1, 128.3 (CH), 130.5, 131.6 (C), 132.3 (CH), 132.5 (C), 133.0 (CH), 134.1 (C), 134.1 (CH), 136.0, 136.3, 141.2, 141.3, 142.0, 148.2 (C), 182.2, 182.6 (CO). IR (KBr, cm⁻¹): δ = 2962, 2849 (w), 1665 (s), 1630 (w), 1589 (m), 1572, 1512, 1478, 1470, 1454, 1434, 1409, 1392, 1358 (w), 1325, 1313 (m), 1294, 1288, 1262 (s), 1210, 1189, 1163, 1156 (m), 1114, 1089 (w), 1073 (m), 1051, 1041, 1017, 974 (w), 951, 943 (m), 889 (w), 871 (m), 832 (s), 791 (m), 761, 738 (w), 712 (s), 694, 669, 648, 583, 553, 533 (m). GC-MS (EI, 70 eV): m/z (%) = 416 ([M]⁺, 30), 388 (30), 387 (100), 372 (5), 357 (4). HRMS (EI, 70 eV): calcd for C₃₀H₂₄O₂ [M]⁺: 416.17708, found 416.176631.
1-(4-Trifluoromethylphenyl)-2-trifluoromethylsulfonyloxy)anthraquinone (190a)

Starting with 187 (250 mg, 0.5 mmol), 188a (95 mg, 0.5 mmol), Pd(PPh3)4 (17 mg, 3 mol-%, 0.015 mmol), K3PO4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190a was isolated as a yellow solid (186 mg, 74%), mp 135-136 °C. 1H NMR (300 MHz, CDCl3): δ = 7.29 (d, J = 8.24 Hz, 2H, ArH), 7.64-7.71 (m, 5H, ArH), 7.94-7.96 (m, 1H, ArH), 8.14-8.17 (m, 1H, ArH), 8.43 (d, J = 8.57 Hz, 1H, ArH). 13C NMR (75.4 MHz, CDCl3): δ = 117.0 (q, JF,C = 321.0 Hz, CF3), 123.1 (q, JF,C = 271.3 Hz, CF3), 124.3 (q, J = 272.0 Hz), 125.4, 126.0, 126.5, 128.1, 129.1 (CH), 129.2, 129.6, 131.1, 132.2, 133.0 (d, J = 1.7 Hz, C), 133.4, 133.7 (CH), 134.7, 136.7 (d, J = 1.1 Hz), 151.1 (C), 180.4, 180.8 (CO). 19F NMR (282 MHz, CDCl3): δ = -74.03 (s, 3F, CF3), -62.57 (s, 3F, CF3). IR (KBr, cm⁻¹): ν = 1674 (s), 1617, 1589, 1572, 1479, 1452, 1433, 1418 (w), 1402 (m), 1326 (s), 1301, 1273 (m), 1249 (w), 1219, 1165, 1125, 1107, 1085, 1061 (s), 1018 (m), 1000 (w), 946 (m), 793, 770, 743 (w), 723, 711 (s), 676, 651 (w), 601 (s), 572, 528 (m). GC-MS (EI, 70 eV): m/z (%) = 500 ([M]+, 48), 499 (13), 431 (25), 368 (24), 367 (100), 366 (24), 298 (23). HRMS (EI, 70 eV): calcd for C22H10O5F6S1 [M]+: 500.01476, found 500.013920.

1-(4-Methoxyphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190b)

Starting with 187 (250 mg, 0.5 mmol), 188b (76 mg, 0.5 mmol), Pd(PPh3)4 (17 mg, 3 mol-%, 0.015 mmol), K3PO4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190b was isolated as an orange crystal (154 mg, 67%), mp 140-142 °C. 1H NMR (300 MHz, CDCl3): δ = 3.82 (s, 3H, OCH3), 6.94 (d, J = 8.76 Hz, 2H, ArH), 7.07 (d, J = 8.76 Hz, 2H, ArH), 7.60-7.67 (m, 3H, ArH), 7.96-8.00 (m, 1H, ArH), 8.11-8.14 (m, 1H, ArH), 8.36 (d, J = 8.67 Hz, 1H, ArH). 13C NMR (75.4 MHz, CDCl3): δ = 55.2 (OCH3), 113.8, (CH), 118.2 (q, JF,C = 320.4 Hz, CF3), 125.4 (C), 126.2, 126.8, 127.5, 129.2, 130.0 (CH), 132.3, 133.5 (C), 134.0 (CH), 134.1, 134.5 (C), 134.6 (CH), 137.3, 152.0, 159.6 (C), 182.0, 182.1 (CO). 19F NMR (282 MHz, CDCl3): δ = -74.04 (s, 3F, CF3). IR (KBr, cm⁻¹): ν = 2838 (w), 1671 (s), 1606 (m), 1588, 1550, 1516, 1464, 1451, 1440, 1412, 1394 (w), 1328, 1311 (m), 1297, 1240 (s), 1208, 1107, 1088, 1074 (m), 1027 (s), 977 (w), 954 (s), 858 (w), 840 (m), 828 (s), 811 (w), 800 (s), 767, 749 (w), 727, 718 (s), 697 (m), 669, 649 (w), 640, 601, 588 (m), 537

1-(4-tert-Butylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190c)

Starting with 187 (250 mg, 0.5 mmol), 188c (90 mg, 0.5 mmol), Pd(PPh3)4 (17 mg, 3 mol-%, 0.015 mmol), K3PO4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190c was isolated as a yellow crystal (149 mg, 61%), mp 160-162 °C. ¹H NMR (250 MHz, CDCl₃): δ = 1.31 (s, 9H, 3CH₃), 7.07 (d, J = 8.4 Hz, 2H, ArH), 7.42 (d, J = 8.5 Hz, 2H, ArH), 7.58-7.67 (m, 3H, ArH), 7.96-8.0 (m, 1H, ArH), 8.11-8.14 (m, 1H, ArH), 8.36 (d, J = 8.81 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 31.3 (3CH₃), 118.2 (q, JF,C = 318.5 Hz, CF₃), 125.2, 126.3, 126.9, 127.7, 128.3, 129.3 (CH), 130.5, 132.4, 133.4 (C), 134.1 (CH), 134.1 (C), 134.5 (CH), 134.6, 137.6, 151.2, 151.8 (C), 181.9, 182.0 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.2 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2960, 2930, 2869, 1675, 1665, 1590, 1580, 1573, 1429 (w), 1410 (m), 1362, 1329, 1316, 1297 (w), 1267 (m), 1205 (s), 1165 (m), 1129 (s), 1079, 1040, 1017, 997 (w), 946, 879, 843 (m), 820 (s), 792, 775, 767, 757, 745 (w), 725 (m), 713 (s), 683, 671 (w), 642 (m), 603 (s), 573 (m). GC-MS (EI, 70 eV): m/z (%) = 488 ([M]+, 18), 473 (100), 431 (31), 325 (58), 299 (26), 239 (08). HRMS (EI, 70 eV): calcd for C25H19O5F3S [M]+: 488.08998, found 488.090070.

1-(4-Chlorophenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190d)

Starting with 187 (250 mg, 0.5 mmol), 188d (78 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190d was isolated as a yellow solid (199 mg, 85%), mp 160-162 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.08-7.11 (m, 2H, ArH), 7.38-7.40 (m, 2H, ArH), 7.62-7.71 (m, 3H, ArH), 7.96-8.0 (m, 1H, ArH), 8.14-8.17 (m, 1H, ArH), 8.41 (d, J = 8.68 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 118.1 (q, JF,C = 320.5 Hz, CF₃), 126.3, 127.0, 127.6, 128.7, 129.9, 130.0 (CH), 132.1, 132.3, 133.3, 134.1, 134.2 (C), 134.3 (CH), 134.5 (C), 134.7 (CH), 136.1, 151.4 (C), 181.6, 182.0 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.92 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 1676 (s), 1589, 1579, 1570, 1492, 1477, 1453 (w), 1408 (m), 1327, 1314, 1300 (w), 1270 (m), 1253 (w), 1212, 1170, 1132 (s), 1089, 943 (m), 883 (s), 854 (w), 827 (s), 793, 775 (w), 713 (s), 640 (m). GC-MS (EI, 70 eV): m/z (%) = 468 ([M+H]+, 37Cl, 21),
467 ([M]$^+$, $^{37}$Cl, 14), 466 ([M+H]$^+$, $^{35}$Cl, 53), 465 ([M]$^+$, $^{35}$Cl, 09), 431 (09), 335 (32), 334 (25), 333 (100), 332 (14), 298 (35), 297 (15), 270 (19). HRMS (EI, 70 eV): calcd for C$_{21}$H$_{10}$Cl$_1$F$_3$O$_5$S$_1$ ([M]$^+$, $^{35}$Cl): 465.98841, found 465.987508.

1-(3-Trifluoromethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190e)

Starting with 187 (250 mg, 0.5 mmol), 188g (95 mg, 0.5 mmol), Pd(PPh$_3$)$_4$ (17 mg, 3 mol-%, 0.015 mmol), K$_3$PO$_4$ (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190e was isolated as a yellow solid (209 mg, 84%), mp 115-117 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.35$ (d, $J = 7.62$ Hz, 1H, ArH), 7.42 (s, 1H, ArH), 7.52 (t, $J = 7.76$ Hz, 1H, ArH), 7.60-7.73 (m, 4H, ArH), 7.89-7.92 (m, 1H, ArH), 8.08-8.10 (m, 1H, ArH), 8.38 (d, $J = 8.64$ Hz, 1H, ArH). $^{13}$C NMR (62.9 MHz, CDCl$_3$): $\delta = 117.0$ (q, $J_{F,C} = 320.6$ Hz, CF$_3$), 123.0 (q, $J_{F,C} = 272.2$ Hz, CF$_3$), 124.1 (q, $J = 3.8$ Hz), 124.6 (q, $J = 3.8$ Hz), 125.4, 126.0, 126.5, 127.8 (d, $J = 4.0$ Hz), 129.1 (CH), 129.5, 130.0 (C), 131.2 (CH), 132.2, 133.0 (d, $J = 5.5$ Hz, C), 133.3 (CH), 133.6 (C), 133.7 (d, $J = 4.4$ Hz, CH), 134.4, 144.0, 150.2 (C), 180.4, 180.7 (CO). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta = -74.10$ (s, 3F, CF$_3$), -62.70 (s, 3F, CF$_3$). IR (KBr, cm$^{-1}$): $\nu = 1673$ (s), 1589, 1492, 1479 (w), 1418, 1308 (m), 1277, 1274 (w), 1250 (m), 1213, 1167, 1121, 1099, 1069 (s), 1001 (w), 955 (m), 883, 839, 804 (s), 770 (w), 727, 712, 702 (s), 689, 652 (w), 628, 598 (s), 572 (m). GC-MS (EI, 70 eV): $m/z$ (%) = 500 ([M]$^+$, 34), 431 (12), 368 (21), 367 (100), 266 (16), 347 (24). HRMS (EI, 70 eV): calcd for C$_{22}$H$_{10}$O$_8$F$_6$S$_1$ [M]$^+$: 500.01476, found 500.015351.

1-(3-Methoxyphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190f)

Starting with 187 (250 mg, 0.5 mmol), 188h (76 mg, 0.5 mmol), Pd(PPh$_3$)$_4$ (17 mg, 3 mol-%, 0.015 mmol), K$_3$PO$_4$ (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190f was isolated as a yellow solid (183 mg, 79%), mp 115-116 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 3.72$ (s, 3H, OCH$_3$), 6.69-6.73 (m, 2H, ArH), 6.91-6.95 (m, 1H, ArH), 7.31 (t, $J = 8.76$ Hz, 1H, ArH), 7.58-7.66 (m, 3H, ArH), 7.94-8.01 (m, 1H, ArH), 8.10-8.13 (m, 1H, ArH), 8.36 (d, $J = 8.70$ Hz, 1H, ArH) $^{13}$C NMR (62.9 MHz, CDCl$_3$): $\delta = 55.2$ (OCH$_3$), 113.8, 114.3 (CH), 118.2 (q, $J_{F,C} = 320.5$ Hz, CF$_3$), 120.8, 126.1, 126.8, 127.5, 129.4, 129.5 (CH), 132.2, 133.3, 134.0 (C), 134.1 (CH), 134.3 (C), 134.6 (CH), 135.0, 137.1, 151.5, 159.5 (C), 181.7, 181.8 (CO). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta = -74.02$ (s, 3F, CF$_3$). IR (KBr, cm$^{-1}$):
Experimental Section

δ = 1679 (m), 1606, 1571, 1488, 1455 (w), 1422 (s), 1327, 1300 (w), 1270 (m), 1250 (w), 1210, 1166, 1152, 1132 (s), 1096, 1076 (w), 1038 (m), 1000 (w), 959 (m), 892, 848 (s), 825, 810, 780, 769 (m), 742 (w), 725 (m), 707, 701 (s), 671 (m), 627, 597 (s), 571 (m). GC-MS (EI, 70 eV): m/z (%) = 462 ([M]+, 40), 330 (21), 329 (100), 314 (28), 298 (10), 286 (14), 202 (13).


1-(4-Fluorophenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190g)

Starting with 187 (250 mg, 0.5 mmol), 188i (70 mg, 0.5 mmol), Pd(PPh3)4 (17 mg, 3 mol-%, 0.015 mmol), K3PO4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190g was isolated as a yellow solid (113 mg, 50%), mp 136-138 °C. 1H NMR (300 MHz, CDCl3): δ = 7.11-7.14 (m, 4H, ArH), 7.63-7.72 (m, 3H, ArH), 7.97-8.00 (m, 1H, ArH), 8.16-8.20 (m, 1H, ArH), 8.42 (d, J = 8.70 Hz, 1H, ArH). 13C NMR (62.9 MHz, CDCl3): δ = 115.4, 115.7 (CH), 118.1 (q, JF,C = 318.3 Hz, CF3), 126.3, 127.0, 127.5 (CH), 129.4 (d, JF,C = 3.7 Hz, C), 129.7, 130.4, 130.5 (CH), 132.2, 133.4, 134.1 (C), 134.2 (CH), 134.3 (C), 134.6 (CH), 136.3, 151.5 (C), 162.7 (d, JF,C = 247.7 Hz, CF), 181.7, 182.0 (CO). 19F NMR (282 MHz, CDCl3): δ = -113.01 (s, 1F, CF), -74.00 (s, 3F, CF3). IR (KBr, cm⁻¹): δ = 1674 (m), 1589, 1568, 1510. 1479, 1450 (w), 1420 (m), 1329, 1315, 1298, 1271, 1249 (w), 1206 (s), 1162 (m), 1130 (s), 1096 (m), 1080, 1038, 1015, 999, 974, 945 (w), 879 (s), 856 (m), 832, 809 (s), 770, 752 (w), 729 (m), 717, 708 (s), 681, 669 (w), 646 (m), 637, 621 (w), 603, 578 (s), 541 (m). GC-MS (EI, 70 eV): m/z (%) = 450 ([M]+, 46), 449 (09), 318 (23), 317 (100), 316 (14), 260 (10), 233 (20), 231 (14). HRMS (EI, 70 eV): calcd for C21H10O5F4S1 [M]+: 450.01796, found 450.017099.

1-(4-Trifluoromethoxyphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190h)

Starting with 187 (250 mg, 0.5 mmol), 188j (102 mg, 0.5 mmol), Pd(PPh3)4 (17 mg, 3 mol-%, 0.015 mmol), K3PO4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), 190h was isolated as a yellow solid (135 mg, 52%), mp 108-110 °C. 1H NMR (300 MHz, CDCl3): δ = 7.17-7.28 (m, 4H, ArH), 7.66-7.70 (m, 3H, ArH), 7.96-8.00 (m, 1H, ArH), 8.16-8.18 (m, 1H, ArH), 8.43 (d, J = 8.65 Hz, 1H, ArH). 13C NMR (75.4 MHz, CDCl3): δ = 118.1 (q, JF,C = 320.6 Hz, CF3), 120.5 (q, JF,C = 257.6 Hz, OCF3), 120.8, 126.4, 127.0, 127.6, 129.9, 130.1 (CH), 132.3, 133.3, 134.1, 134.2 (C), 134.3, 134.7 (CH), 135.8,
149.2, 149.3, 151.3 (C), 181.6, 182.0 (CO). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta$ = -74.10 (s, 3F, CF$_3$), -57.78 (s, 3F, OCF$_3$). IR (KBr, cm$^{-1}$): $\tilde{\nu}$ = 1681 (m), 1609, 1588, 1570, 1510, 1450 (w), 1425 (m), 1409, 1329, 1315, 1298 (w), 1250, 1204, 1167, 1152, 1131, 1105 (s), 1081 (m), 1038 (w), 1019 (m), 999 (w), 946 (m), 920 (w), 877 (s), 852 (m), 820 (s), 805 (m), 771 (w), 722, 711 (s), 681, 668, 655 (w), 628 (m), 599 (s), 571, 553, 527 (m). GC-MS (EI, 70 eV): m/z (%) = 516 ([M]$^+$, 43), 431 (10), 384 (22), 383 (100), 382 (13). HRMS (EI, 70 eV): calcd for C$_{22}$H$_{10}$O$_6$F$_6$S$_1$ [M]$^+$: 416.00968, found 416.010762.

3.3.2 General procedure for the synthesis of 191a-f

The reaction was carried out in a pressure tube. To a dioxane suspension (3 mL) of 187 (0.5 mmol), Ar$_1$B(OH)$_2$ (0.5 mmol) and Pd(PPh$_3$)$_4$ (3 mol-%) was added K$_3$PO$_4$ (0.75 mmol), and the resultant solution was degassed by bubbling argon through the solution for 10 min. The mixture was heated at 90 °C under an argon atmosphere for 10 h. The mixture was cooled to 20 °C. Ar$_2$B(OH)$_2$ (0.55 mmol), Pd(PPh$_3$)$_4$ (3 mol-%), K$_3$PO$_4$ (0.75 mmol) and dioxane (2 mL) were added. The reaction mixtures were heated under an argon atmosphere for 10 h at 110 °C. They were diluted with H$_2$O and extracted with CH$_2$Cl$_2$ (3 x 25 mL). The combined organic layers were dried (Na$_2$SO$_4$), filtered and the filtrate was concentrated in vacuo. The residue was purified by flash chromatography (flash silica gel, heptanes/EtOAc).

1-(4-Trifluoromethylphenyl)-2-(4-tert-butylphenyl)anthraquinone (191a)

Starting with 187 (252 mg, 0.5 mmol), 188a (95 mg, 0.5 mmol), Pd(PPh$_3$)$_4$ (17 mg, 3 mol-%, 0.015 mmol), K$_3$PO$_4$ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and 188c (98 mg, 0.55 mmol), 191a was isolated as a yellow crystal (157 mg, 65%), mp 225-227 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 1.15 (s, 9H, 3CH$_3$), 6.76-6.80 (m, 2H, ArH), 7.03-7.10 (m, 4H, ArH), 7.38 (d, $J = 8.1$ Hz, 2H, ArH), 7.61-7.66 (m, 2H, ArH), 7.70 (d, $J = 8.0$ Hz, 1H, ArH), 7.94-7.98 (m, 1H, ArH), 8.16-8.20 (m, 1H, ArH), 8.36 (d, $J = 8.0$ Hz, 1H, ArH). $^{13}$C NMR (75.4 MHz, CDCl$_3$): $\delta$ = 31.2 (3CH$_3$), 34.4 (C), 124.3 (q, $J_{F,C} = 272.3$ Hz, CF$_3$), 124.4 (dq, $J_{F,C} = 7.6$, 2.2 Hz), 124.7, 126.7, 127.4, 127.6 (CH), 128.5 (q, $J = 32.8$ Hz, C), 129.0, 129.7 (CH), 131.3, 132.8, 133.6 (C), 133.8, 134.3 (CH), 134.6 (C), 135.4 (CH), 136.3, 140.8, 144.0 (d, $J = 1.7$ Hz), 149.1, 150.5 (C), 183.0, 183.6 (CO). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta$ = -62.3 (s, 3F, CF$_3$). IR (KBr, cm$^{-1}$): $\tilde{\nu}$ = 2962, 2905, 2869 (w), 1672 (m), 1613, 1588, 1552,
Experimental Section

1513, 1462, 1399, 1363 (w), 1321 (s), 1300, 1278, 1263 (m), 1213, 1186 (w), 1158 (s), 1118 (m), 1105 (s), 1087, 1075, 1059, 1016 (m), 976 (w), 954 (m), 899, 864 (w), 837, 824 (m), 796, 784, 767, 758, 744 (w), 718 (s), 688, 671, 662, 640, 605 (w), 584 (m), 566, 564, 532 (w).

GC-MS (EI, 70 eV): \( m/z \) (%) = 484 ([M]+, 43), 469 (100), 449 (10), 427 (08), 383 (02), 357 (03). HRMS (EI, 70 eV): calcd for C\(_{31}\)H\(_{23}\)O\(_2\)F\(_3\) [M]+: 484.16447, found 484.164850.

1-(4-Methoxyphenyl)-2-(4-tert-butylphenyl)anthraquinone (191b)

Starting with 187 (252 mg, 0.5 mmol), 188b (76 mg, 0.5 mmol), Pd(PPh\(_3\))\(_4\) (17 mg, 3 mol-%, 0.015 mmol), K\(_3\)PO\(_4\) (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and 188c (98 mg, 0.55 mmol), 191b was isolated as a red solid (111 mg, 50%), mp 221-222 °C. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \( \delta = 1.18 \) (s, 9H, 3CH\(_3\)), 3.71 (s, 3H, OCH\(_3\)), 6.70 (d, \( J = 8.58 \) Hz, 2H, ArH), 6.84 (d, \( J = 7.26 \) Hz, 4H, ArH), 7.10 (d, \( J = 8.58 \) Hz, 2H, ArH), 7.58-7.68 (m, 3H, ArH), 7.98-8.01 (m, 1H, ArH), 8.16-8.20 (m, 1H, ArH), 8.32 (d, \( J = 8.58 \) Hz, 1H, ArH). \(^{13}\)C NMR (62.9 MHz, CDCl\(_3\)): \( \delta = 30.2 \) (3CH\(_3\)), 33.4 (C), 54.0 (OCH\(_3\)), 112.1, 123.5, 125.4, 125.9, 126.3, 128.1, 129.4 (CH), 130.8, 130.9, 131.7 (C), 132.4 (CH), 132.6 (C), 133.0 (CH), 134.1 (C), 134.2 (CH), 136.1, 141.0, 148.3, 149.0, 157.2 (C), 182.3, 183.0 (CO). IR (KBr, cm\(^{-1}\)): \( \tilde{\nu} = 2956, 2865, 2839, 2042, \) (w), 1671 (s), 1658, 1609, 1586 (w), 1573 (m), 1547 (w), 1513 (m), 1477, 1465, 1451, 1439, 1415, 1405, 1390, 1361 (w), 1329, 1315 (m), 1297, 1277, 1241 (s), 1206 (m), 1176 (s), 1159, 1115 (m), 1088, 1071 (w), 1024 (s), 1014 (m), 977 (w), 953 (m), 941, 931, 901, 859, (w), 836 (m), 823 (s), 795 (m), 767, 752, 747 (w), 718 (s), 686, 661 (w), 648 (m), 634 (w), 597, 578, 569 (m), 540 (s). GC-MS (EI, 70 eV): \( m/z \) (%) = 446 ([M]+, 100), 445 (12), 432 (16), 431 (40), 416 (10), 415 (23), 390 (13). 389 (18), HRMS (EI, 70 eV): calcd for C\(_{31}\)H\(_{26}\)O\(_3\) [M]+: 446.18765, found 446.187401.
1-(4-tert-Butylphenyl)-2-(4-trifluoromethylphenyl)anthraquinone (191c)

Starting with 187 (252 mg, 0.5 mmol), 188c (90 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and 188a (104 mg, 0.55 mmol), 191c was isolated as a yellow solid (143 mg, 60%), mp 220-222 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.20 (s, 9H, 3CH₃), 6.81 (d, J = 8.59 Hz, 2H, ArH), 6.98 (d, J = 8.12 Hz, 2H, ArH), 7.14 (d, J = 8.59 Hz, 2H, ArH), 7.28 (d, J = 8.12 Hz, 2H, ArH), 7.60-7.68 (m, 3H, ArH), 8.00-8.02 (m, 1H, ArH), 8.17-8.20 (m, 1H, ArH), 8.36 (d, J = 8.12 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 30.2 (3CH₃), 33.4 (C), 122.9 (q, J = 272.2 Hz, CF₃), 123.3 (q, J_F,C = 7.4, 3.7 Hz), 123.5, 125.6, 126.1, 126.5 (CH), 127.7 (C), 127.8 (CH), 128.2 (C), 128.7 (CH), 130.4, 131.7 (C), 132.6, 133.2, 133.6 (CH), 133.8, 141.5, 142.8 (d, J = 1.3 Hz), 146.9, 148.7 (C), 182.1, 182.4 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -62.68 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 1674 (s), 1615, 1576, 1551, 1511, 1461, 1456, 1415, 1393, 1364, 1359 (w), 1323, 1300 (s), 1283, 1258 (m), 1210, 1198, 1184 (w), 1155, 1109 (s), 1085 (m), 1073, 1061, 1014 (s), 978, 967 (w), 956, 941 (m), 903, 861 (m), 837, 823 (s), 796 (m), 780, 766, 753, 739 (w), 720, 714, 700 (s), 678 (w), 646 (m), 632 (w), 605, 585, 563, 545 (m). GC-MS (EI, 70 eV): m/z (%) = 485 ([M+H]+, 10), 484 ([M]+, 29), 470 (34), 469 (100), 428 (22), 427 (65). HRMS (EI, 70 eV): calcd for C₃₁H₂₄F₃O₂ [M+H]+: 485.1723, found 485.1713.

1-(4-Chlorophenyl)-2-(4-tert-butylphenyl)anthraquinone (191d)

Starting with 187 (252 mg, 0.5 mmol), 188d (78 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and 188c (98 mg, 0.55 mmol), 191d was isolated as a yellow solid (137 mg, 61%), mp 245-246 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.30 (s, 9H, 3CH₃), 6.92-7.00 (m, 4H, ArH), 7.21-7.26 (m, 4H, ArH), 7.75-7.82 (m, 4H, ArH), 8.09-8.12 (m, 1H, ArH), 8.30-8.33 (m, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 31.2 (3CH₃), 34.5 (C), 124.7, 126.6, 127.3, 127.4, 128.0, 129.1, 130.7 (CH), 131.6, 132.5, 132.7, 133.6 (C), 133.7, 134.2 (CH), 134.8 (C), 135.5 (CH), 136.6, 138.4, 141.0, 149.1, 150.3 (C), 183.1, 183.8 (CO). IR (KBr, cm⁻¹): ν = 1667 (s), 1588, 1575, 1549, 1513, 1492, 1477, 1461, 1409, 1391, 1360 (w), 1332
Experimental Section

Starting with $187$ (252 mg, 0.5 mmol), $188g$ (95 mg, 0.5 mmol), Pd(PPh$_3$)$_4$ (17 mg, 3 mol-%, 0.015 mmol), K$_3$PO$_4$ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and $188a$ (104 mg, 0.55 mmol), $191e$ was isolated as a yellow solid (169 mg, 68%), mp 255-256 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.02$ (d, $J = 8.23$ Hz, 2H, ArH), 7.14 (d, 7.65 Hz, 1H, ArH), 7.27-7.45 (m, 5H, ArH), 7.65-7.77 (m, 3H, ArH), 8.00-8.03 (m, 1H, ArH), 8.23-8.26 (m, 1H, ArH), 8.46 (d, $J = 8.10$ Hz, 1H, ArH). $^{13}$C NMR (62.9 MHz, CDCl$_3$): $\delta = 122.8$ (q, $J_{F,C} = 321.2$ Hz, CF$_3$), 123.1 (q, $J_{F,C} = 272.0$ Hz, CF$_3$), 123.6 (d, $J = 4.1$ Hz), 124.8 (d, $J = 3.7$ Hz), 126.2 (d, $J = 3.8$ Hz), 126.8, 127.4, 127.8, 128.2, 129.7 (CH), 130.0, 130.5, 131.5 (C), 132.5 (CH), 132.6 (C), 134.0 (CH), 134.3 (C), 134.4 (CH), 134.6 (C), 134.9 (CH), 140.1, 140.5, 143.0, 147.6 (C) 182.8, 183.3 (CO). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta = -62.79$ (s, 3F, CF$_3$), -62.78 (s, 3F, CF$_3$). IR (KBr, cm$^{-1}$): $\nu = 1669$ (s), 1617, 1589, 1574, 1533, 1490, 1432, 1414, 1399 (w), 1328, 1302 (s), 1285, 1263, 1244, 1291, 1212 (w), 1161, 1109, 1081, 1066 (s), 1018 (m), 1002, 981 (w), 961 (m), 923, 893, 863 (w), 849 (m), 836 (w), 825, 805 (m), 792, 767, 752, 746, 725 (w), 712, 706 (s), 686 (w), 675 (m), 655, 629, 605, 567, 542 (w). GC-MS (EI, 70 eV): $m/z$ (%) = 496 ([M$^+$], 80), 495 (100), 477 (09), 428 (21), 427 (72), 407 (08). HRMS (EI, 70 eV): calcd for C$_{28}$H$_{13}$O$_2$F$_6$ [M-H]$^+$: 495.08143, found 495.080798.
1-(3-Trifluoromethylphenyl)-2-(4-tert-butylphenyl)anthraquinone (191f)

Starting with 187 (252 mg, 0.5 mmol), 188g (95 mg, 0.5 mmol), Pd(PPh3)4 (17 mg, 3 mol-%, 0.015 mmol), K3PO4 (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and 188c (98 mg, 0.55 mmol), 191f was isolated as a yellow solid (148 mg, 61%), mp 227-229 °C. 1H NMR (300 MHz, CDCl3): δ = 1.16 (s, 9H, 3CH3), 6.75 - 6.77 (m, 2H, ArH), 7.07 - 7.10 (m, 3H, ArH), 7.17 (d, J = 8.34 Hz, 1H, ArH), 7.27 (t, J = 7.68 Hz, 1H, ArH), 7.40 (d, J = 7.86 Hz, 1H, ArH), 7.60 - 7.70 (m, 2H, ArH), 7.73 (d, J = 7.86 Hz, 1H, ArH), 7.96 - 8.00 (m, 1H, ArH), 8.18 - 8.21 (m, 1H, ArH), 8.37 (d, J = 8.04 Hz, 1H, ArH). 13C NMR (75.4 MHz, CDCl3): δ = 30.1 (3CH3), 33.4 (C), 122.2 (q, JFC = 3.84 Hz, CH), 122.9 (q, J = 272.4 Hz, CF3), 123.6, 125.3 (q, J = 3.8 Hz), 125.6, 126.3, 126.5, 126.7, 128.0 (CH), 128.7, 129.1, 130.4, 131.7 (C), 131.9 (CH), 132.6 (C), 132.7, 133.2 (CH), 133.7 (C), 134.2 (CH), 135.2, 139.6 (d, J = 9.8 Hz), 148.3, 149.4 (C), 182.0, 182.6 (CO). 19F NMR (282 MHz, CDCl3): δ = -62.68 (s, 3F, CF3). IR (KBr, cm⁻¹): δ = 2957, 2907, 2872, 2134 (w), 1671 (s), 1589, 1574, 1549, 1513, 1479, 1460, 1433, 1407, 1393, 1365 (w), 1329, 1316, 1302 (s), 1279 (m), 1258, 1245 (s), 1211, 1183 (w), 1159, 1116, 1100, 1068 (s), 1017 (m), 1001, 986, 973 (w), 961 (m), 917, 892 (w), 861, 838 (m), 824, 801 (s), 792 (m), 768, 751, 744 (w), 715, 702 (s), 688 (w), 679, 666, 652 (m), 628 (w), 580, 566, 545 (m). GC-MS (EI, 70 eV): m/z (%) = 484 ([M]+, 43), 470 (33), 469 (100). HRMS (EI, 70 eV): calcd for C31H23O2F3 [M]+: 484.16447, found 484.164011.

3.4 Synthesis of 1,2,4-Tris(trifluoromethylsulfonyloxy)anthraquinone (193)

To a solution of 1,2,4-trihydroxyanthraquinone (192) (1.0 equiv) in CH2Cl2 (10 mL/mmol) was added pyridine (7.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf2O (5.0 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptane/EtOAc).
Experimental Section

1,2,4-Tris(trifluoromethylsulfonyloxy)anthraquinone (193)

Starting with 1,2,4-trihydroxyanthraquinone 192 (1.00 g, 3.90 mmol), pyridine (2.2 mL, 27.3 mmol), CH2Cl2 (40 mL), Tf2O (3.3 mL, 19.5 mmol), 193 was isolated as a yellow solid (1.10 g, 43%), mp 162-164 °C. 1H NMR (300 MHz, CDCl3): δ = 7.66 (s, 1H, ArH), 7.80-7.86 (m, 2H, ArH), 8.22-8.36 (m, 2H, ArH). 13C NMR (62.9 MHz, CDCl3): δ = 118.3 (d, JF,C = 313.5 Hz, CF3), 118.4 (d, JF,C = 316.0 Hz, CF3), 118.6 (d, JF,C = 319.0 Hz, CF3), 123.3 (CH), 126.8 (C), 127.7, 127.8 (CH), 129.6, 132.5, 132.6 (C), 135.5, 135.6 (CH), 138.9, 144.5, 146.6 (C), 178.4, 179.9 (CO). 19F NMR (282 MHz, CDCl3): δ = -73.02 (q, JF = 2.82, 5.28 Hz, 3F, CF3), -72.83 (s, 3F, CF3), -72.24 (q, JF = 2.73, 5.07 Hz, 3F, CF3). IR (KBr, cm⁻¹): ν = 3100 (w), 1682 (s), 1589 (m), 1440, 1428 (s), 1310 (m), 1278 (w), 1208, 1182, 1170, 1127 (s), 1071, 1039, 1018 (m), 974 (w), 929, 904, 851, 812, 780, 763 (s), 756, 740 (m), 719 (s), 712, 695, 674 (m), 653, 635 (s), 623 (m), 597, 534 (s). GC-MS (EI, 70 eV): m/z (%) = 652 ([M]+, 100), 583 (13), 519 (11), 455 (46), 427 (16), 391 (14), 363 (85), 336 (11), 335 (74). HRMS (EI, 70 eV): calcd for C17H5F9O11S3 [M]+: 651.88448, found 651.883916.

3.4.1 General Procedure for Suzuki-Miyaura Reactions

A 1,4-dioxane solution (4 mL per 3 mmol of 193) of 193, K3PO4, Pd(PPh3)4 and arylboronic acid 188 was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH2Cl2. The combined organic layers were dried (Na2SO4), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.
1,2,4-Tris(4-trifluoromethylphenyl)anthraquinone (194a)

Starting with 193 (100 mg, 0.15 mmol), 188a (114 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), 194a was isolated as a yellow solid (43 mg, 43%), mp 237-238 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.03-7.12 (m, 4H, ArH), 7.35-7.47 (m, 6H, ArH), 7.48 (s, 1H, ArH), 7.64-7.67 (m, 4H, ArH), 7.94-8.02 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 123.7 (q, Jₑ,C = 272.3 Hz, CF₃), 124.0 (q, Jₑ,C = 272.1 Hz, CF₃), 124.2 (q, Jₑ,C = 272.1 Hz, CF₃), 124.9 (t, J = 3.5 Hz), 125.0, 125.2 (d, J = 3.8 Hz), 126.8, 127.0, 128.3 (CH), 128.9 (C), 129.4, 129.6 (CH), 129.8, 130.1, 132.1, 133.4, 133.7, 133.9 (C), 134.1, 134.2, 138.0 (CH), 140.8, 142.4, 143.0, 143.1, 145.4, 146.2 (C), 183.2, 183.7 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -62.77 (s, 3F, CF₃), -62.41 (s, 3F, CF₃), -62.38 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3067, 2929, 2581 (w), 1673 (m), 1616, 1592, 1531, 1407, 1372 (w), 1285, 1251 (m), 1211 (w), 1167, 1108 (s), 1089 (m), 1081, 1060, 1017 (s), 966 (m), 937, 919, 866 (w), 839 (m), 801, 766, 746 (w), 726 (m), 711, 684, 660, 644, 622, 604, 551, 539 (w). GC-MS (EI, 70 eV): m/z (%) = 640 ([M]+, 98), 639 (100), 638 (13), 621 (15), 572 (28), 571 (81), 570 (36). HRMS (EI, 70 eV): calcd for C₃₅H₁₆F₉O₂ [M-H]⁺: 639.10011, found 639.099492.

1,2,4-Tris(4-methoxyphenyl)anthraquinone (194b)

Starting with 193 (100 mg, 0.15 mmol), 188b (91 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), 194b was isolated as an orange solid (59 mg, 73%), mp 240-242 °C. ¹H NMR (300 MHz, CDCl₃): δ = 3.67 (s, 3H, OCH₃), 3.74 (s, 3H, OCH₃), 3.80 (s, 3H, OCH₃), 6.61-6.64 (m, 2H, ArH), 6.72-6.75 (m, 2H, ArH), 6.85-6.90 (m, 6H, ArH), 7.21-7.24 (m, 2H, ArH), 7.49 (s, 1H, ArH), 7.58-7.61 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 55.0 (OCH₃), 55.1 (OCH₃), 55.2 (OCH₃), 113.2, 113.3, 113.6, 126.5, 126.6, 129.3, 130.5, 130.7 (CH), 131.3, 132.1, 132.2 (C), 133.5, 133.6 (CH), 134.0, 134.9, 134.4, 134.5 (C), 138.8 (CH), 141.2, 143.3, 147.5, 158.2, 158.6, 158.9 (C), 184.1, 185.0 (CO). IR (KBr, cm⁻¹): ν = 3318, 3068, 3033, 3012, 2952, 2918, 2849,
Experimental Section

2833, 2539 (w), 1665, 1606 (s), 1592, 1575 (m), 1508 (s), 1461, 1454, 1435 (m), 1410, 1368 (w), 1330, 1310 (m), 1289, 1239, 1173 (s), 1107, 1085, 1076 (m), 1027, 1010, 963 (s), 938 (m), 917, 907, 862 (w), 829, 802, 796 (s), 773, 763 (m), 749 (w), 736 (m), 722 (s), 686 (w), 653, 645, 628, 621 (m), 594 (w), 572 (m), 548 (s). GC-MS (EI, 70 eV): m/z (%) = 526 ([M]⁺, 100), 525 (40), 495 (15), 285 (12). HRMS (EI, 70 eV): calcd for C₃₅H₂₆O₅ [M]⁺: 526.17748, found 526.176367.

1,2,4-Tris(4-tert-butylphenyl)anthraquinone (194c)

Starting with 193 (100 mg, 0.15 mmol), 188c (107 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), 194c was isolated as an orange solid (77 mg, 83%), mp 244-246 °C.

1H NMR (300 MHz, CDCl₃): δ = 1.13 (s, 9H, 3CH₃), 1.20 (s, 9H, 3CH₃), 1.31 (s, 9H, 3CH₃), 6.75-6.76 (m, 2H, ArH), 6.84-6.87 (m, 2H, ArH), 6.99-7.02 (m, 2H, ArH), 7.12-7.15 (m, 2H, ArH), 7.21-7.24 (m, 2H, ArH), 7.36-7.39 (m, 2H, ArH), 7.53 (s, 1H, ArH), 7.55-7.58 (m, 2H, ArH), 7.93-8.03 (m, 2H, ArH). 13C NMR (62.9 MHz, CDCl₃): δ = 31.2 (CH₃), 31.4 (CH₃), 31.5 (CH₃), 34.3, 34.4, 34.6, 124.2, 124.4, 125.0, 126.6, 126.8, 127.7, 127.9, 128.6 (C), 129.0 (CH), 131.4 (C), 133.5, 133.5 (CH), 133.6, 134.0, 134.4, 136.8, 137.1 (C), 138.8 (CH), 139.3, 142.0, 143.7, 148.2, 149.1, 149.8 (C), 184.1, 184.6 (CO). IR (KBr, cm⁻¹): δ = 2952 (s), 2902, 2864 (m), 1677, 1669 (s), 1607 (w), 1592 (m), 1574, 1512, 1504, 1475 (w), 1462 (m), 1440, 1392 (w), 1360 (m), 1327 (s), 1309, 1301, 1279, 1266 (m), 1241 (s), 1212, 1201, 1165, 1155 (w), 1114, 1081, 1016, 966 (m), 944, 934, 918, 898, 863 (w), 831 (s), 796 (m), 772, 764, 740 (w), 725 (s), 705, 681 (w), 651, 625 (m), 615 (w), 580 (m), 567 (s), 551 (m). GC-MS (EI, 70 eV): m/z (%) = 604 ([M]⁺, 31), 590 (11), 589 (24), 548 (14), 547 (33), 532 (03), 490 (04), 287 (11), 69 (06), 57 (100). HRMS (EI, 70 eV): calcd for C₄₄H₄₄O₂ [M]⁺: 604.33358, found 604.3345.
1,2,4-Tris(4-chlorophenyl)anthraquinone (194d)

Starting with 193 (100 mg, 0.15 mmol), 188d (94 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), 194d was isolated as a yellow solid (50 mg, 60%), mp 293-295 °C. ¹H NMR (300 MHz, CDCl₃): δ = 6.84-6.92 (m, 4H, ArH), 7.07-7.11 (m, 2H, ArH), 7.18-7.23 (m, 4H, ArH), 7.34-7.38 (m, 2H, ArH), 7.44 (s, 1H, ArH), 7.62-7.65 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 126.7, 126.8, 128.2, 128.4, 129.3, 130.5, 130.6 (CH), 131.9, 132.9, 133.5, 133.7, 133.8 (C), 133.9, 134.0 (CH), 134.1, 137.5, 138.0 (C), 138.3 (CH), 141.2, 140.2, 140.7, 142.9, 145.5 (C), 183.8, 184.1 (CO). IR (KBr, cm⁻¹): δ = 3320, 3065, 2923, 2853 (w), 1670 (s), 1650, 1644, 1632 (w), 1591 (m), 1524 (w), 1492 (s), 1470, 1441, 1397, 1370 (w), 1328 (m), 1311 (s), 1282 (m), 1247 (s), 1209, 1158 (w), 1089, 1013, 962 (s), 935, 918, 862 (w), 818 (s), 810, 766 (m), 733 (s), 718 (m), 700, 687, 671, 656 (w), 647 (m), 636, 618, 593 (w), 551 (m). GC-MS (EI, 70 eV): m/z (%) = 542 ([M]+, 2x ³⁷Cl, 29), 541 ([M]+, ³⁷Cl, 50), 540 ([M]+, ³⁷Cl, 92), 539 ([M+H]+, ³⁵Cl, 100), 538 ([M]+, ³⁵Cl, 93), 537 (78), 505 (24), 504 (26), 503 (37), 502 (25). HRMS (EI, 70 eV): calcd for C₃₂H₁₇Cl₃O₂ ([M]+, ³⁷Cl): 540.02591, found 540.024908, C₃₂H₁₇Cl₃O₂ ([M]+, 2x ³⁷Cl): 542.02296, found 542.023142.

1,2,4-Tris(4-fluorophenyl)anthraquinone (194e)

Starting with 193 (100 mg, 0.15 mmol), 188i (84 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), 194e was isolated as an orange crystal (43 mg, 57%), mp 204-206 °C. ¹H NMR (300 MHz, CDCl₃): δ = 6.77-6.83 (m, 2H, ArH), 6.86-6.93 (m, 6H, ArH), 7.04-7.11 (m, 2H, ArH), 7.23-7.27 (m, 2H, ArH), 7.47 (s, 1H, ArH), 7.61-7.64 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 114.7, 114.8, 115.0, 115.1, 115.2, 115.3, 126.6, 126.8, 129.6, 129.7, 130.7, 130.8, 131.0, 131.1 (CH), 131.8, 133.8 (C), 133.8, 133.9 (CH), 133.9, 134.2, 135.2 (d, J = 3.3 Hz), 135.5 (d, J = 3.6 Hz), 137.7 (d, J = 3.6 Hz, C), 138.5 (CH), 140.9, 143.0, 146.9, 161.7 (d, J_F,C = 246.4 Hz), 161.9 (d, J_F,C = 248.0 Hz), 162.2 (d, J_F,C
Experimental Section

= 246.6 Hz, CF), 183.7, 184.3 (CO). $^1$F NMR (282 MHz, CDCl$_3$): $\delta = -115.07$ (s, F, CF), -114.85 (s, F, CF), -114.14 (s, F, CF). IR (KBr, cm$^{-1}$): $\delta = 3069, 3041, 2920, 2852$ (w), 1673 (s), 1604 (w), 1592 (m), 1530 (w), 1510 (s), 1442, 1402, 1370 (w), 1328, 1308 (m), 1278 (w), 1245 (m), 1222, 1157 (s), 1092, 1083, 1073, 1014 (w), 963 (m), 945, 927, 866 (w), 829, 817 (s), 786, 766, 745 (w), 734, 721 (m), 709, 701, 686, 658, 650, 642, 624, 617, 587, 560 (w), 551 (m), 534 (w). GC-MS (EI, 70 eV): $m/z$ (%) = 490 ([M]$^+$, 83), 489 (100), 488 (18), 394 (18). HRMS (EI, 70 eV): calcd for C$_{32}$H$_{17}$O$_2$F$_3$ [M]$^+$: 490.11752, found 490.116052.

1,2,4-Tris(phenyl)anthraquinone (194f)

Starting with 193 (100 mg, 0.15 mmol), 188k (73 mg, 0.6 mmol), Pd(PPh$_3$)$_4$ (17 mg, 10 mol-%, 0.015 mmol), K$_3$PO$_4$ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), 194f was isolated as a yellow solid (58 mg, 86%), mp 228-230 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 6.92-7.00$ (m, 4H, ArH), 7.06 (t, $J = 2.61$ Hz, 3H, ArH), 7.16-7.18 (m, 3H, ArH), 7.28-7.38 (m, 5H, ArH), 7.52 (s, 1H, ArH), 7.57-7.60 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). $^{13}$C NMR (62.9 MHz, CDCl$_3$): $\delta = 126.5, 126.6, 126.8, 127.1, 127.2, 127.6, 127.7, 128.0, 128, 129.3, 129.4 (CH), 131.6 (C), 133.6, 133.7 (CH), 133.8, 133.9, 134.4 (C), 138.6 (CH), 139.6, 139.9, 141.8, 142.2, 143.8, 147.7 (C), 183.8, 184.5 (CO). IR (KBr, cm$^{-1}$): $\delta = 3329, 3065, 3054, 3022, 2953, 2919, 2850$ (w), 1677 (s), 1633 (w), 1590 (m), 1557, 1537, 1524, 1494, 1455, 1443, 1431, 1370 (w), 1322, 1302 (s), 1277 (m), 1243 (s), 1206, 1160 (w), 1085, 1077, 1071 (m), 1034 (w), 1024 (m), 1001, 975 (w), 959 (m), 938, 915, 899, 857, 842, 825 (w), 801, 774, 760, 750, 742 (m), 728 (s), 711 (m), 691 (s), 671 (m), 652 (s), 637, 614, 570 (m), 554 (w), 541 (s). GC-MS (EI, 70 eV): $m/z$ (%) = 436 ([M]$^-$, 78), 435 (100), 434 (18), 358 (19), 218 (19), 217 (44). HRMS (EI, 70 eV): calcd for C$_{32}$H$_{19}$O$_2$ [M-H]$^-$: 435.13796, found 435.137591.
1,4-Bis(4-trifluoromethylphenyl)-2(trifluoromethylsulfonyloxy)anthraquinone (195a)

Starting with 193 (100 mg, 0.15 mmol), 188a (57 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), 195a was isolated as an orange solid (61 mg, 61%), mp 168-170 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.32-7.40 (m, 4H, ArH), 7.48 (s, 1H, ArH), 7.66-7.72 (m, 6H, ArH), 7.94-8.00 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 118.0 (q, J₉,₁₃C = 320.4 Hz, CF₃), 119.7 (q, J₉,₁₃C = 272.2 Hz, CF₃), 125.4 (t, J = 3.8 Hz), 127.0, 127.1, 128.1 (CH), 128.5 (q, J₉,₁₃C = 286.2 Hz, CF₃), 128.9, 129.2 (CH), 129.9, 130.2, 130.4, 132.2, 133.2, 133.3 (C), 134.5, 134.6 (CH), 135.3, 135.7, 137.7, 143.9, 145.6, 149.6 (C), 182.2, 182.2 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.86 (s, 3F, CF₃), -62.59 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2917 (w), 1675 (m), 1618, 1591, 1541, 1428, 1408 (w), 1321 (s), 1241 (m), 1217 (s), 1190 (w), 1163 (m), 1122, 1108, 1080, 1059 (s), 1040 (w), 1017, 948, 900 (m), 854 (w), 834, 823, 799, 786, 763, 753, 744 (s), 731 (m), 713, 692, 682, 662, 641, 630 (w), 599 (s), 571, 535 (w). GC-MS (EI, 70 eV): m/z (%) = 644 ([M⁺, 100), 643 (68), 625 (11), 576 (14), 575 (48), 512 (21), 511 (56), 510 (29), 509 (13). HRMS (EI, 70 eV): calcd for C₂₉H₁₃F₉O₅S1 [M⁺]: 644.03345, found 644.03239.

1,4-Bis(4-tert-butylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195b)

Starting with 193 (100 mg, 0.15 mmol), 188c (54 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), 195b was isolated as a yellow solid (77 mg, 81%), mp 245-247 °C. ¹H NMR (300 MHz, CDCl₃): δ = 0.59 (s, 9H, 3CH₃), 0.60 (s, 9H, 3CH₃), 6.37-6.40 (m, 2H, ArH), 6.46-6.48 (m, 2H, ArH), 6.68-6.74 (m, 4H, ArH), 6.74 (s, 1H, ArH), 6.86-6.90 (m, 2H, ArH), 7.21-7.27 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 31.3 (3CH₃), 31.4 (3CH₃), 34.7, 34.8 (C), 117.5 (q, J₉,₁₃C = 318.5 Hz, CF₃), 125.2, 125.3, 126.8, 127.0, 127.6, 128.3, 129.5 (CH), 130.8, 132.3, 133.7, 133.8 (C), 133.9, 134.0 (CH), 135.5, 136.5, 137.5, 146.5, 150.1, 150.8, 151.0 (C), 182.8, 182.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.69 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2917 (w), 1677 (m), 1590, 1536, 1531, 1462 (w), 1425 (s), 1404, 1360 (w), 1319 (s), 1268 (m), 1239, 1214 (s), 1177 (m), 1159 (w), 1137, 1115 (s), 1040, 1015, 1004, 977, 966 (w), 947, 900, 844, 825,
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812, 803 (s), 776 (w), 746 (m), 732, 722 (s), 699 (w), 686 (m), 661 (w), 642 (m), 608 (s), 597 (m), 566 (s), 528 (m). GC-MS (EI, 70 eV): m/z (%) = 620 ([M]+, 06), 606 (13), 605 (34), 565 (10), 564 (32), 563 (100), 571 (09), 457 (10). HRMS (EI, 70 eV): calcd for C_{35}H_{31}F_{3}O_{5}S [M]+: 620.18388, found 620.183785.

1,4-Bis(4-methyllphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195c)

Starting with 193 (100 mg, 0.15 mmol), 188e (41 mg, 0.3 mmol), Pd(PPh_3)_4 (10 mg, 6 mol-%, 0.009 mmol), K_3PO_4 (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), 195c was isolated as a yellow solid (42 mg, 51%), mp 186-188 °C. ¹H NMR (300 MHz, CDCl_3): δ = 2.39 (s, 3H, CH_3), 2.40 (s, 3H, CH_3), 7.07-7.10 (m, 2H, ArH), 7.14-7.17 (m, 2H, ArH), 7.22-7.26 (m, 4H, ArH), 7.46 (s, 1H, ArH), 7.59-7.66 (m, 2H, ArH), 7.94-7.98 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl_3): δ = 21.4 (CH_3), 21.5 (CH_3), 118.1 (q, J_{F,C} = 320.7 Hz, CF_3), 126.9, 127.0, 127.8, 128.5, 129.1, 129.2, 129.3 (CH), 130.8, 132.4, 133.7, 133.8 (C), 134.0, 134.1 (CH), 135.5, 136.7, 137.6, 137.8, 137.9, 146.5, 150.1 (C), 182.8, 182.9 (CO). ¹⁹F NMR (282 MHz, CDCl_3): δ = -73.96 (s, 3F, CF_3). IR (KBr, cm⁻¹): υ = 3022, 2960, 2920, 2860 (w), 1675 (s), 1651, 1592, 1538, 1446 (w), 1420 (s), 1403, 1379 (w), 1312 (m), 1272, 1261 (w), 1239 (m), 1220, 1205 (s), 1161 (w), 1131 (s), 1037, 1019, 1005, 962 (w), 946, 896 (s), 848 (m), 829, 819, 810, 798 (s), 769 (w), 752 (m), 729 (s), 715 (m), 689, 659, 650, 631 (w), 599 (s), 570, 558, 538, 530 (m). GC-MS (EI, 70 eV): m/z (%) = 536 ([M]+, 85), 535 (23), 523 (10), 522 (26), 521 (100), 404 (10), 403 (48), 402 (33), 401 (20), 389 (18), 388 (77), 387 (61), 386 (27). HRMS (EI, 70 eV): calcd for C_{29}H_{15}F_{3}O_{5}S [M]+: 536.08998, found 536.090080.
1,4-Bis(4-ethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195d)

Starting with 193 (100 mg, 0.15 mmol), 188f (45 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), 195d was isolated as a yellow solid (64 mg, 74%), mp 142-144 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.24 (t, J = 7.62 Hz, 3H, CH₃), 1.28 (t, J = 7.60 Hz, 3H, CH₃), 2.70 (q, J = 15.18, 7.59 Hz, 4H, 2CH₂), 7.08-7.12 (m, 2H, ArH), 7.17-7.20 (m, 2H, ArH), 7.24-7.28 (m, 4H, ArH), 7.47 (s, 1H, ArH), 7.60-7.63 (m, 2H, ArH), 7.94-7.99 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 15.2 (CH₃), 15.3 (CH₃), 28.6 (CH₂), 28.7 (CH₂), 118.1 (q, J_{F,C} = 320.1 Hz, CF₃), 126.9, 127.0, 127.8, 127.9, 128.2, 128.5, 129.4 (CH), 131.0, 132.4, 133.7, 133.8 (C), 134.0, 134.1 (CH), 135.5, 136.7, 137.8, 143.9, 144.2, 146.6, 150.1 (C), 182.8, 182.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.01 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3024, 2962, 2932, 2874 (w), 1677 (s), 1641, 1610, 1591, 1536, 1460 (w), 1427 (s), 1410, 1373, 1320, 1311 (m), 1260 (w), 1206 (s), 1173, 1160 (w), 1133 (s), 1050, 1038 (w), 1018 (m), 1005, 977 (w), 946, 899 (s), 846 (m), 823, 802 (s), 766 (w), 752 (m), 729 (s), 703, 688, 663, 642 (m), 631 (w), 599, 569 (s), 541 (m). GC-MS (EI, 70 eV): m/z (%) = 564 ([M]⁺, 43), 563 (11), 537 (11), 536 (32), 535 (100), 403 (17), 402 (50), 401 (28), 387 (16), 386 (11), 374 (25), 373 (86). HRMS (EI, 70 eV): calcd for C₃₁H₂₃F₃O₅S₁ [M]⁺: 564.12128, found 564.121848.

1,4-Bis(3,5-dimethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195e)

Starting with 193 (100 mg, 0.15 mmol), 188l (45 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), 195e was isolated as a yellow solid (52 mg, 60%), mp 211-213 °C. ¹H NMR (300 MHz, CDCl₃): δ = 2.31 (s, 6H, 2CH₃), 2.32 (s, 6H, 2CH₃), 6.79 (b, 2H, ArH), 6.86 (b, 2H, ArH), 7.03 (b, 2H, ArH), 7.44 (s, 1H, ArH), 7.61-7.64 (m, 2H, ArH), 7.96-7.99 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 21.4 (2CH₃), 21.4 (2CH₃), 118.1 (q, J_{F,C} = 320.2 Hz, CF₃), 125.5, 126.2, 126.9, 127.0, 129.1, 129.6, 129.8 (CH), 132.2, 133.7, 133.7, 133.8 (C), 134.0, 134.1 (CH), 135.3, 136.8, 137.7, 137.9, 140.5, 146.7, 149.9 (C), 182.7, 182.8 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.51 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3024, 2962, 2932, 2874 (w), 1677 (s), 1641, 1610, 1591, 1536, 1460 (w), 1427 (s), 1410, 1373 (w), 1320, 1311 (m), 1260 (w), 1206 (s), 1173, 1160 (w), 1133 (s), 1050, 1038 (w), 1018 (m), 1005, 977 (w), 946, 899 (s), 846 (m), 823, 802 (s), 766 (w), 752 (m), 729 (s), 703, 688, 663, 642 (m), 631 (w), 599, 569 (s), 541 (m). GC-MS (EI, 70 eV): m/z (%) = 564 ([M]⁺, 43), 563 (11), 537 (11), 536 (32), 535 (100), 403 (17), 402 (50), 401 (28), 387 (16), 386 (11), 374 (25), 373 (86). HRMS (EI, 70 eV): calcd for C₃₁H₃₂F₃O₅S₁ [M]⁺: 564.12128, found 564.121848.
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1331, 1294 (m), 1267 (w), 1206 (s), 1173, 1162 (m), 1134, 1026, 1010 (s), 968 (m), 920, 898, 883 (w), 848, 814, 796 (s), 771, 752 (w), 729, 723 (s), 708 (w), 692, 648, 631, 604 (s), 570, 552, 530 (m). GC-MS (EI, 70 eV): m/z (%) = 564 ([M]+, 66), 550 (22), 549 (80), 432 (14), 431 (49), 430 (21), 417 (34), 416 (86), 415 (36), 402 (16), 401 (57), 387 (14), 215 (14), 208 (100), 207 (15). HRMS (EI, 70 eV): calcd for C_{31}H_{23}F_{3}O_{5}S [M]+: 564.12128, found 564.122443.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-methoxyphenyl)anthraquinone (196a)

Starting with 193 (100 mg, 0.15 mmol), 188b (23 mg, 0.15 mmol), Pd(PPh3)4 (5 mg, 3 mol-%, 0.0045 mmol), K3PO4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), 196a was isolated as a red solid (36 mg, 38%), mp 87-88 °C. 1H NMR (300 MHz, CDCl3): δ = 3.82 (s, 3H, OCH3), 6.91-6.93 (m, 1H, ArH), 6.94-6.96 (m, 1H, ArH), 7.13-7.14 (m, 1H, ArH), 7.16-7.18 (m, 1H, ArH), 7.59 (s, 1H, ArH), 7.69-7.78 (m, 2H, ArH), 7.99-8.01 (m, 1H, ArH), 8.21-8.24 (m, 1H, ArH). 13C NMR (62.9 MHz, CDCl3): δ = 55.3 (OCH3), 114.0 (CH), 115.9 (q, J_{F,C} = 318.4 Hz, CF3), 121.0 (q, J_{F,C} = 320.2 Hz, CF3), 127.2, 127.4, 129.2 (CH), 129.3 (C), 131.1 (CH), 131.2, 131.9, 132.9, 133.4 (C), 134.5, 135.0 (CH), 138.1, 143.1, 146.2, 159.9 (C), 181.1, 181.4 (CO). 19F NMR (282 MHz, CDCl3): δ = -73.33 (q, J_{F} = 5.33, 2.45 Hz, 3F, CF3), -72.56 (q, J_{F} = 5.70, 2.79 Hz, 3F, CF3). IR (KBr, cm−1): δ = 2961, 2916, 2840 (w), 1680 (s), 1607, 1593, 1579, 1513 (w), 1432 (s), 1323 (m), 1303 (w), 1243, 1204, 1177, 1168, 1126 (s), 1044, 1030 (m), 1013, 996 (s), 905 (w), 865, 830, 805, 784, 760, 723 (s), 684, 654, 644, 622 (m), 593, 579 (s), 534 (m). GC-MS (EI, 70 eV): m/z (%) = 610 ([M+H]+, 100), 479 (10), 478 (27), 477 (82), 385 (10), 346 (12), 345 (24), 317 (28), 316 (93), 315 (10). HRMS (EI, 70 eV): calcd for C_{32}H_{22}F_{6}O_{9}S_{2} [M]+: 609.98214, found 609.981630.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-tert-butylphenyl)anthraquinone (196b)

Starting with 193 (100 mg, 0.15 mmol), 188c (27 mg, 0.15 mmol), Pd(PPh3)4 (5 mg, 3 mol-%, 0.0045 mmol), K3PO4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), 196b was isolated as a yellow solid (40 mg, 41%), mp 80-81 °C. 1H NMR (300 MHz, CDCl3): δ = 1.33 (s, 9H, 3CH3), 7.13-7.17 (m, 2H, ArH), 7.41-7.44 (m, 2H, ArH), 7.60 (s, 1H, ArH), 7.69-7.78 (m, 2H, ArH), 7.99-8.02 (m, 1H, ArH), 8.22-8.25 (m, 1H, ArH). 13C NMR (62.9 MHz, CDCl3): δ = 30.31 (3CH3), 33.75 (C), 115.0 (q, J_{F,C} = 319.4
Hz, CF₃), 120.0 (q, $J_{F,C} = 321.7$ Hz, CF₃), 124.5, 126.2, 126.4, 126.5 (CH), 128.2 (C), 130.2 (CH), 131.0, 132.0, 132.4 (C), 133.5, 134.0 (CH), 135.1, 137.2, 142.1, 145.5, 150.5 (C), 180.1, 180.3 (CO). $^{19}$F NMR (282 MHz, CDCl₃): $\delta = 73.32$ (q, $J_F = 5.31, 2.52$ Hz, CF₃), $-72.56$ (q, $J_F = 6.09, 2.97$ Hz, 3F, CF₃). IR (KBr, cm⁻¹): $\nu = 2963$ (m), 1684 (s), 1594, 1577 (w), 1436 (s), 1364 (w), 1325 (m), 1303 (w), 1245, 1218 (s), 1169 (w), 1135 (s), 1105, 1045, 1018, 1000, 906 (w), 870 (m), 839 (w), 806 (m), 783, 763, 727, 703, 685, 655, 644, 624 (w), 598 (m), 575 (w). GC-MS (EI, 70 eV): $m/z$ (%) = 636 ([M]+, 53), 623 (12), 622 (27), 621 (90), 581 (14), 580 (27), 579 (100), 447 (26). HRMS (EI, 70 eV): calcd for C₂₆H₁₈F₆O₈S₂ [M]+: 636.03418, found 636.033895.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-methylphenyl)anthraquinone (196c)

Starting with 193 (100 mg, 0.15 mmol), 188e (20 mg, 0.15 mmol), Pd(PPh₃)₄ (5 mg, 3 mol-%, 0.0045 mmol), K₃PO₄ (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), 196c was isolated as a yellow solid (56 mg, 61%), mp 79-80 °C. $^1$H NMR (300 MHz, CDCl₃): $\delta = 2.37$ (s, 3H, CH₃), 7.09-7.11 (m, 2H, ArH), 7.20-7.23 (m, 2H, ArH), 7.58 (s, 1H, ArH), 7.67-7.76 (m, 2H, ArH). $^{13}$C NMR (62.9 MHz, CDCl₃): $\delta = 21.36$ (CH₃), 113.4 (q, $J_{F,C} = 318.8$ Hz, CF₃), 123.6 (q, $J_{F,C} = 319.1$ Hz, CF₃), 127.2, 127.4, 127.6 (CH), 128.3 (C), 129.3, 131.1 (CH), 132.0, 132.9, 133.4 (C), 134.6, 135.0 (CH), 136.2, 138.3, 138.4, 143.1, 146.5 (C), 181.1, 181.3 (CO). $^{19}$F NMR (282 MHz, CDCl₃): $\delta = -73.33$ (q, $J_F = 5.13, 2.34$ Hz, 3F, CF₃), $-72.58$ (d, $J_F = 2.88$ Hz, 3F, CF₃). IR (KBr, cm⁻¹): $\nu = 3070, 3027, 2924, 2871$ (w), 1680 (s), 1593, 1578, 1513 (w), 1432 (s), 1322 (m), 1303 (w), 1243 (m), 1203 (s), 1168 (m), 1126 (s), 1044, 1021, 1015 (w), 998 (m), 946, 905 (w), 865, 818, 805 (s), 783, 760 (m), 723 (s), 708, 684, 645, 627 (w), 593, 576 (s), 532 (w). GC-MS (EI, 70 eV): $m/z$ (%) = 594 ([M+H]+, 17), 579 (14), 461 (19), 369 (10), 330 (19), 329 (32), 316 (10), 315 (45), 301 (19), 300 (31), 215 (31), 64 (100), 48 (58). HRMS (EI, 70 eV): calcd for C₂₆H₁₈F₆O₈S₂ [M]+: 593.98723, found 593.985244.
1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-ethylphenyl)anthraquinone (196d)

Starting with 193 (100 mg, 0.15 mmol), 188f (22 mg, 0.15 mmol), Pd(PPh3)4 (5 mg, 3 mol-%, 0.0045 mmol), K3PO4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), 196d was isolated as an orange solid (61 mg, 65%), mp 101-103 °C. 1H NMR (300 MHz, CDCl3): δ = 1.25 (t, J = 7.65 Hz, CH3), 2.69 (q, J = 14.94, 7.62 Hz, 2H, CH2), 7.12-7.15 (m, 2H, ArH), 7.24-7.26 (m, 2H, ArH), 7.59 (s, 1H, ArH), 7.68-7.77 (m, 2H, ArH), 7.98-8.01 (m, 1H, ArH), 8.21-8.24 (m, 1H, ArH). 13C NMR (75.4 MHz, CDCl3): δ = 15.2 (CH3), 28.6 (CH2), 113.2 (q, JF,C = 321.0 Hz, CF3), 121.7 (q, JF,C = 321.0 Hz, CF3), 126.2, 126.4, 126.7, 127.0 (CH), 128.2, 130.1 (C), 131.0 (CH), 131.9, 132.4 (C), 133.5, 134.0 (CH), 135.4, 137.3, 142.1, 143.6, 145.5 (C), 180.1, 180.3 (CO). 19F NMR (282 MHz, CDCl3): δ = -73.32 (q, JF = 5.31, 2.76 Hz, 3F, CF3), -72.56 (q, JCF = 6.09, 2.94 Hz, 3F, CF3). IR (KBr, cm⁻¹): 554, 3075, 3027, 2965, 2931, 2874 (w), 1681 (s), 1611, 1593, 1577, 1512 (w), 1433 (s), 1323 (m), 1303 (w), 1243 (m), 1205 (s), 1168 (m), 1128 (s), 1044 (w), 1015, 998 (m), 905 (w), 865 (s), 826 (m), 803 (s), 783, 760, 754 (m), 723 (s), 684, 654, 645, 626 (w), 594 (s), 533 (w). GC-MS (EI, 70 eV): m/z (%) = 608 ([M]+, 32), 581 (11), 580 (20), 579 (85), 475 (14), 447 (14), 383 (12), 382 (12), 354 (25), 344 (13), 343 (23), 316 (18), 315 (100), 314 (36), 313 (14). HRMS (EI, 70 eV): calcd for C24H14F6O8S2 [M]+: 608.00288, found 608.003921.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(3-trifluoromethylphenyl)anthraquinone (196e)

Starting with 193 (100 mg, 0.15 mmol), 188g (28 mg, 0.15 mmol), Pd(PPh3)4 (5 mg, 3 mol-%, 0.0045 mmol), K3PO4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), 196e was isolated as a yellow crystal (40 mg, 40%), mp 169-171 °C. 1H NMR (300 MHz, CDCl3): δ = 7.41 (d, J = 7.71 Hz, 1H, ArH), 7.47 (b, 1H, ArH), 7.59 (s, 1H, ArH), 7.68-7.71 (m, 1H, ArH), 7.73-7.81 (m, 2H, ArH), 7.97-8.00 (m, 1H, ArH), 8.23-8.26 (m, 1H, ArH). 13C NMR (62.9 MHz, CDCl3): δ = 117.5 (q, JF,C = 321.3 Hz, CF3), 121.2 (q, JF,C = 272.3 Hz, CF3), 123.5 (d, J = 3.8 Hz), 124.2 (d, J = 3.7 Hz), 126.3, 126.6 (CH), 127.3 (q, JF,C = 265.5 Hz, CF3), 128.0 (CH), 128.4 (C), 129.8 (d, J = 5.1 Hz), 129.9, 130.3, 131.0 (C), 131.9, 132.0, 133.9, 134.2 (CH), 138.0, 138.8, 142.4, 143.3 (C), 179.8, 179.9 (CO). 19F NMR (282 MHz, CDCl3): δ = -73.25 (q, JF = 5.78, 2.84 Hz, 3F, CF3), -72.48 (q, JF = 5.16, 2.25 Hz, 3F, CF3). IR (KBr, cm⁻¹): 554, 2954, 2923, 2852 (w), 1690
Experimental Section

Starting with 193 (100 mg, 0.15 mmol), 188m (23 mg, 0.15 mmol), Pd(PPh₃)₄ (5 mg, 3 mol-%, 0.0045 mmol), K₃PO₄ (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), 196f was isolated as a yellow crystal (53 mg, 56%), mp 78-80 °C. ¹H NMR (300 MHz, CDCl₃): δ = 6.58 (dt, J = 7.17, 1.65 Hz, 1H, ArH), 6.68-6.70 (m, 1H, ArH), 6.81-6.90 (m, 2H, ArH), 7.06 (s, 1H, ArH), 7.19-7.28 (m, 2H, ArH), 7.47-7.50 (m, 1H, ArH), 7.71-7.74 (m, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 114.0 (q, J_F,C = 316.2 Hz, CF₃), 120.0 (q, J_F,C = 320.2 Hz, CF₃), 124.8, 126.3, 126.5, 126.6, 127.5 (CH), 128.3 (C), 128.8, 129.8 (CH), 130.9, 131.9, 132.0 (C), 133.5 (CH), 133.8 (C), 134.1 (CH), 137.8, 139.8, 142.2, 143.5 (C), 179.8, 179.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.90 (q, J_F = 4.99, 2.85 Hz, 3F, CF₃), -73.11 (q, J_F,C = 5.53, 2.85 Hz, 3F, CF₃). IR (KBr, cm⁻¹): v = 3070, 2961 (w), 1680 (s), 1592, 1577 (w), 1433 (s), 1323 (m), 1303 (w), 1244, 1205 (s), 1169 (m), 1127, 1093, 1080 (s), 1045 (m), 1008, 876, 837, 799, 784, 761, 711, 689, 654 (s), 623 (m), 593, 572 (s), 535 (m). GC-MS (EI, 70 eV): m/z (%) = 617 ([M]+, 2x ³⁷Cl, 07), 616 ([M+H]+, ³⁷Cl, 32), 615 ([M]+, ³⁷Cl, 24), 614 ([M+H]+, ³⁵Cl, 82), 613 ([M]+, ³⁵Cl, 16), 579 (15), 483 (12), 482 (12), 481 (29), 446 (16), 382 (18), 355 (18), 354 (100), 350 (12), 349 (20). HRMS (EI, 70 eV): calcd for C₂₂H₉Cl₁F₆O₈S₂ ([M]+, ³⁵Cl): 613.93261, found 613.932573. calcd for C₂₂H₉Cl₁F₆O₈S₂ ([M]+, ³⁷Cl): 615.92966, found 615.931303.

3.4.2 General Procedure for the Synthesis of 197

The reaction was carried out in a pressure tube. To a dioxane suspension (4 mL) of 193 (100 mg, 0.15 mmol), Ar¹B(OH)₂ (0.3 mmol) and Pd(PPh₃)₄ (6 mol-%) was added K₃PO₄ (96 mg, 0.45 mmol), and the resultant solution was degassed by bubbling argon through the solution for 10 min. The mixture was heated at 95 °C under an argon atmosphere for 10 h.
mixture was cooled to 20 °C. Ar²B(OH)₂ (0.15 mmol), Pd(PPh₃)₄ (3 mol-%), K₂PO₄ (48 mg, 0.225 mmol) and dioxane (2 mL) were added. The reaction mixtures were heated under an argon atmosphere for 10 h at 110 °C. They were diluted with H₂O and extracted with CH₂Cl₂ (3 × 25 mL). The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by flash chromatography (flash silica gel, EtOAc/heptanes).

1,4-Bis(4-tert-butylphenyl)-2-(4-chlorophenyl)anthraquinone (197)

Starting with 193 (100 mg, 0.15 mmol), 188c (54 mg, 0.3 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₂PO₄ (143 mg, 0.675 mmol) and 1,4-dioxane (5 mL), and 188d (23 mg, 0.15 mmol), 197 was isolated as a yellow solid (40 mg, 45%), mp 288-290 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.25 (s, 9H, 3CH₃), 1.32 (s, 9H, 3CH₃), 6.80-6.83 (m, 2H, ArH), 6.84-6.88 (m, 2H, ArH), 6.98-7.01 (m, 2H, ArH), 7.17-7.24 (m, 4H, ArH), 7.39-7.41 (m, 2H, ArH), 7.48 (s, 1H, ArH), 7.58-7.62 (m, 2H, ArH), 7.94-8.01 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 31.3 (3CH₃), 31.4 (3CH₃), 34.5, 34.6 (C), 124.7, 125.1, 126.6, 126.8, 127.6, 127.8 (CH), 128.2 (C), 128.9, 130.7 (CH), 131.8, 133.1 (C), 133.5, 133.6 (CH), 133.9, 134.4, 136.5, 138.2 (C), 138.6 (CH), 139.0, 141.7, 143.8, 146.5, 149.5, 150.0 (C), 183.9, 184.5 (CO). IR (KBr, cm⁻¹): δ = 3076, 3025 (w), 2958, 2902, 2865 (w), 1677 (s), 1591 (m), 1529 (m), 1490, 1471, 1462, 1443, 1423, 1400, 1358 (w), 1329, 1306, 1269, 1248, 1217 (m), 1158, 1137, 1115 (w), 1092 (m), 1039 (w), 1013 (m), 964, 946, 935, 915, 899, 863, 846, 836 (w), 822 (s), 800 (m), 768, 746 (w), 730 (s), 721 (m), 697, 669, 658, 647, 631, 621, 608 (w), 575, 568 (m), 531 (w). GC-MS (EI, 70 eV): m/z (%) = 585 ([M+H]+, 37Cl, 08), 584 ([M]+, 37Cl, 22), 583 ([M+H]+, 35Cl, 22), 582 ([M]+, 35Cl, 46), 581 (10), 570 (15), 569 (30), 568 (40), 567 (63), 566 (10), 565 (10), 528 (20), 527 (44), 526 (56), 525 (100), 524 (11), 513 (10), 512 (23), 511 (27), 510 (43). HRMS (EI, 70 eV): calcd for C₄₀H₃₅ClO₂ [M]+: 582.23201, found 582.231833.

3.5 Synthesis of Dimethyl 3,5-dihydroxyphthalate (200)

To a solution of Diene 198 (1 equiv) in toluene (0.5 mL/mmol) was added to DMAD 199 (1.5 equiv) at -78 °C. The mixture was allowed to warm to 50 °C during 48 h with stirring.
To the mixture were added hydrochloric acid (10%) and dichloromethane (10 mL/2 mmol). The organic and the aqueous layer were separated and the latter was extracted with CH\textsubscript{2}Cl\textsubscript{2}. The combined organic layers were dried (Na\textsubscript{2}SO\textsubscript{4}), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (flash silica gel, heptanes/EtOAc).

**Dimethyl 3,5-dihydroxyphthalate (200)**

Starting with 198 (5.0 g, 19.19 mmol), Toluene (5 mL), 199 (4.1 g, 3.5 mL, 43.2 mmol), 200 was isolated as colorless solid (1.45 g, 33%), mp 127-129 °C. \textsuperscript{1}H-NMR (300 MHz, CDCl\textsubscript{3}): \( \delta = 3.80 \) (s, 3H, OCH\textsubscript{3}), 3.81 (s, 3H, OCH\textsubscript{3}), 6.34 (d, \( J = 2.35 \) Hz, 1H, ArH), 6.40 (d, \( J = 2.35 \) Hz, 1H, ArH), 6.95 (s, 1H, OH), 10.89 (s, 1H, OH). \textsuperscript{13}C-NMR (62.9 MHz, CDCl\textsubscript{3}): \( \delta = 52.6 \) (OCH\textsubscript{3}), 53.0 (OCH\textsubscript{3}), 102.6 (C), 104.8, 108.1 (CH), 137.1, 161.4, 163.6 (C), 169.0, 170.2 (CO). IR (KBr, cm\textsuperscript{-1}): \( \delta = 3201 \) (m), 3074, 2954, 2851 (w), 1726 (w), 1690 (m), 1667, 1621 (s), 1586 (m), 1567, 1536, 1515 (w), 1493 (m), 1435 (s), 1383, 1337 (m), 1302, 1238, 1195, 1182, 1165 (s), 1108, 1024, 994, 948, 917, 865, 855, 850 (m), 833 (w), 799, 782 (m), 724, 703 (s), 643, 615, 578, 543 (m). GC-MS (EI, 70 eV): \texttt{m/z (%)} = 226 ([M]\textsuperscript{+} 34), 195 (46), 194 (42), 164 (14), 137 (12), 136 (100), 135 (17). HRMS (EI, 70 eV): calcd for C\textsubscript{10}H\textsubscript{10}O\textsubscript{6} [M\textsuperscript{+}]: 226.04719, found 226.046991.

**3.5.1 Synthesis of Dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (201)**

To a solution of 200 (1.0 equiv) in CH\textsubscript{2}Cl\textsubscript{2} (10 mL/mmol) was added pyridine (4.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf\textsubscript{2}O (2.4 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc).
**Experimental Section**

**Dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (201)**

Starting with **200** (1.76 g, 7.8 mmol), pyridine (2.5 mL, 31.2 mmol), CH$_2$Cl$_2$ (80 mL), Tf$_2$O (3.15 mL, 18.74 mmol), **201** was isolated as viscous red oil (3.00 g, 78%). $^1$H-NMR (300 MHz, CDCl$_3$): $\delta$ = 3.87 (s, 3H, OCH$_3$), 3.93 (s, 3H, OCH$_3$), 7.43 (d, $J$ = 2.34 Hz, 1H, ArH), 7.86 (d, $J$ = 2.34 Hz, 1H, ArH). $^{13}$C-NMR (62.9 MHz, CDCl$_3$): $\delta$ = 53.5 (OCH$_3$), 53.6 (OCH$_3$), 118.3 (q, $J_{FC}$ = 320.6 Hz, CF$_3$), 118.6 (q, $J_{FC}$ = 321.1 Hz, CF$_3$), 119.2, 122.8 (CH), 129.3, 132.3, 146.4, 149.2 (C), 162.7, 163.2 (CO). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta$ = -72.25 (d, $J_F$ = 2.34 Hz, 3F, CF$_3$), -73.23 (d, $J_F$ = 2.25 Hz, 3F, CF$_3$). IR (KBr, cm$^{-1}$): $\tilde{\nu}$ = 3102, 3011, 2960, 2904, 2848 (w), 1737 (s), 1610, 1587, 1476 (w), 1428, 1298, 1245, 1205, 1125 (s), 1082, 1002 (m), 980 (s), 954, 913 (m), 878 (w), 841 (m), 818, 791 (s), 772 (w), 755 (s), 743 (m), 700, 676, 639 (w), 597 (s). GC-MS (EI, 70 eV): $m/z$ (%) = 490 ([M+H]$^+$ 07), 461 (11), 460 (14), 459 (100), 395 (11), 268 (14). HRMS (EI, 70 eV): calcd for C$_{12}$H$_8$F$_6$O$_{10}$S$_2$ [M]$^+$: 489.94576, found 489.945970.

**3.5.2 General Procedure for Suzuki-Miyaura Reactions**

A 1,4-dioxane solution (4 mL per 3 mmol of **201**), K$_2$CO$_3$, Pd(PPh$_3$)$_4$ and arylboronic acid **188** was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH$_2$Cl$_2$. The combined organic layers were dried (Na$_2$SO$_4$), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

**Dimethyl 3,5-bis(4-tert-butylphenyl)phthalate (202a)**

Starting with **201** (200 mg, 0.40 mmol), **188c** (171 mg, 0.96 mmol), Pd(PPh$_3$)$_4$ (28 mg, 6 mol%, 0.024 mmol), K$_3$PO$_4$ (255 mg, 1.2 mmol) and 1,4-dioxane 4 mL, **202a** was isolated as colorless oil (171 mg, 91%). $^1$H-NMR (300 MHz, CDCl$_3$): $\delta$ = 1.24 (s, 18H, 6CH$_3$), 3.60 (s, 3H, OCH$_3$), 3.81 (s, 3H, OCH$_3$), 7.24-7.66 (m, 8H, ArH), 8.10 (s, 1H, ArH), 8.11 (s, 1H, ArH). $^{13}$C-NMR (62.9 MHz, CDCl$_3$): $\delta$ = 30.2, 30.2 (6CH$_3$), 33.5, 33.5 (2C), 51.2, 51.5 (OCH$_3$), 124.2, 124.8, 125.8, 126.0, 127.2 (CH), 127.6 (C), 131.5 (CH), 132.0, 135.1, 135.3, 140.0, 140.9, 149.7, 150.3 (C), 165.2, 168.4 (CO). IR (KBr, cm$^{-1}$): $\tilde{\nu}$ = 3030 (w), 2951, 2903, 2867 (m), 2255, 1911 (w), 1726 (s), 1600, 1514, 1460 (w), 1431 (m), 1393, 1362.
Experimental Section

(w), 1343 (m), 1264, 1242, 1199 (s), 1176 (m), 1122, 1067 (s), 1056 (m), 1016, 976, 963 (w), 906 (m), 874, 854 (w), 832 (s), 805 (w), 793 (m), 775 (w), 729 (s), 707 (m), 696, 647, 625 (w), 589, 555 (m). GC-MS (EI, 70 eV): m/z (%) = 458 ([M]⁺, 44), 444 (31), 443 (100), 214 (10). HRMS (EI, 70 eV): calcd for C₃₀H₃₄O₄ [M]⁺: 458.24516, found 458.244023.

Dimethyl 3,5-bis(4-chlorophenyl)phthalate (202b)

Starting with 201 (200 mg, 0.40 mmol), 188d (150 mg, 0.96 mmol), Pd(PPh₃)₄ (28 mg, 6 mol%, 0.024 mmol), K₂PO₄ (255 mg, 1.2 mmol) and 1,4-dioxane (4 mL), 202b was isolated as colorless oil (150 mg, 88%). ¹H-NMR (300 MHz, CDCl₃): δ = 3.62 (s, 3H, OCH₃), 3.84 (s, 3H, OCH₃), 7.26-7.36 (m, 6H, ArH), 7.44-7.47 (m, 2H, ArH), 7.57 (d, J = 1.86 Hz, 1H, ArH), 8.09 (d, J = 1.86 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 52.5 (OCH₃), 52.7 (OCH₃), 127.5, 128.4, 128.6 (CH), 129.1 (C), 129.2, 129.9, 132.2 (CH), 133.6, 134.3, 134.6, 137.3, 137.5, 140.1, 141.1 (C), 165.8, 168.8 (CO). IR (KBr, cm⁻¹): ν = 3067, 3030, 2997, 2949, 2840 (w), 1723 (s), 1601 (w), 1494 (m), 1458 (w), 1398, 1380 (w), 1341 (m), 1269, 1241 (s), 1199, 1175 (m), 1119, 1090, 1066 (m), 1054 (m), 1012 (s), 973, 960, 904, 872, 845 (w), 825 (s), 806 (w), 792 (m), 772 (w), 755 (m), 729 (s), 705, 692, 646, 633, 618, 566 (w). GC-MS (EI, 70 eV): m/z (%) = 418 ([M]⁺, 2x ³⁷Cl, 07), 417 ([M+H]⁺, ³⁷Cl, 09), 416 ([M]⁺, ³⁷Cl, 40), 415 ([M+H]⁺, ³⁵Cl, 14), 414 ([M]⁺, ³⁵Cl, 60), 387 (12), 386 (14), 385 (67), 384 (23), 383 (100), 226 (15). HRMS (EI, 70 eV): calcd for C₂₂H₁₆Cl₂O₄ ([M]⁺, ³⁵Cl): 414.04202, found 414.041035.

Dimethyl 3-(trifluoromethylsulfonyloxy)-5-(4-trifluoromethylphenyl)phthalate (203a)

Starting with 201 (200 mg, 0.40 mmol), 188a (76 mg, 0.40 mmol), Pd(PPh₃)₄ (18 mg, 4 mol%, 0.016 mmol), K₂PO₄ (127 mg, 0.6 mmol) and 1,4-dioxane (3 mL), 203a was isolated as colorless solid (152 mg, 76%), mp 103-104 °C. ¹H-NMR (300 MHz, CDCl₃): δ = 3.88 (s, 3H, OCH₃), 3.92 (s, 3H, OCH₃), 7.61-7.68 (m, 4H, ArH), 7.72 (d, J = 1.56 Hz, 1H, ArH), 8.14 (d, J = 1.56 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 53.1, 53.3 (OCH₃), 118.4 (q, J_F,C = 320.5 Hz, CF₃), 122.0 (C), 123.8 (CH), 125.6 (C), 126.3 (d, J = 3.76 Hz), 127 (CH), 128.2 (C), 128.3 (CH), 131.5, 140.8, 143.3, 146.5 (C), 164.3, 164.4 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.46 (s, 3F, CF₃), -62.77 (s, 3F, CF₃). IR
Experimental Section

(KBr, cm\(^{-1}\)): \(\delta = 3088, 3009, 2956, 2923, 2815\) (w), 1738 (m), 1728 (s), 1613, 1562, 1481 (w), 1427 (s), 1394 (w), 1324, 1292 (s), 1260 (w), 1246 (m), 1206, 1163, 1142, 1115, 1098, 1069, 1055 (s), 1016 (m), 992 (s), 952 (w), 920 (m), 897, 870 (w), 842 (m), 823, 804, 791 (s), 772 (m), 758 (s), 742 (m), 671, 663, 637 (w), 599 (s), 568 (w). GC-MS (EI, 70 eV): \(m/z\) (%): 486 ([M]^+, 43), 456 (17), 455 (100), 264 (830), 263 (12). HRMS (EI, 70 eV): calcd for C\(_{18}\)H\(_{12}\)F\(_6\)O\(_7\)S\(_1\) [M^+]: 486.02024, found 486.020205.

Dimethyl 3-(trifluoromethylsulfonyloxy)-5-(4-tert-butylphenyl)phthalate (203b)

Starting with 201 (200 mg, 0.40 mmol), 188c (71 mg, 0.40 mmol), Pd(PPh\(_3\))\(_4\) (18 mg, 4 mol%, 0.016 mmol), K\(_2\)PO\(_4\) (127 mg, 0.6 mmol) and 1,4-dioxane (3 mL), 203b was isolated as colorless oil (139 mg, 71%). \(^1\)H-NMR (300 MHz, CDCl\(_3\)): \(\delta = 1.28\) (s, 9H, 3CH\(_3\)), 3.86 (s, 3H, OCH\(_3\)), 3.91 (s, 3H, OCH\(_3\)), 7.45 (s, 4H, ArH), 7.62 (d, \(J = 1.62\) Hz, 1H, ArH), 8.11 (d, \(J = 1.62\) Hz, 1H, ArH). \(^{13}\)C-NMR (62.9 MHz, CDCl\(_3\)): \(\delta = 31.2\) (3CH\(_3\)), 34.7 (C), 53.0, 53.1 (OCH\(_3\)), 118.5 (q, \(J_{F,C} = 320.3\) Hz, CF\(_3\)), 123.2, 126.2 (CH), 126.8 (C), 126.9, 127.9 (CH), 131.2, 134.4, 144.8, 146.5, 152.6 (C), 165.8, 168.8 (CO). \(^{19}\)F NMR (282 MHz, CDCl\(_3\)): \(\delta = -73.57\) (s, 3F, CF\(_3\)). IR (KBr, cm\(^{-1}\)): \(\delta = 3033\) (w), 2955 (m), 2906, 2870 (w), 1731 (s), 1612 (m), 1573, 1553, 1521, 1479 (w), 1425 (s), 1318 (m), 1267, 1245, 1206, 1156, 1135, 1115 (s), 1093, 1057 (m), 997 (s), 959 (w), 925 (s), 890, 872 (w), 834 (m), 820, 804, 789 (s), 765, 749 (m), 704, 664, 640 (w), 602 (s), 571, 551 (m). GC-MS (EI, 70 eV): \(m/z\) (%): 474 ([M]^+, 23), 460 (22), 459 (100). HRMS (EI, 70 eV): calcd for C\(_{21}\)H\(_{21}\)F\(_3\)O\(_7\)S\(_1\) [M^+]: 474.09546, found 474.095709.

3.6 Synthesis of 5,7-Dibromo-8-(trifluoromethylsulfonyloxy)quinoline (205)

To a solution of 204 (1.0 equiv) in CH\(_2\)Cl\(_2\) (10 mL/mmol) was added pyridine (7.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf\(_2\)O (5.0 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc).
5,7-Dibromo-8-(trifluoromethylsulfonyloxy)quinoline (205)

Starting with 204 (1.00 g, 3.30 mmol), pyridine (0.7 mL, 8.25 mmol), CH₂Cl₂ (40 mL), Tf₂O (0.7 mL, 3.96 mmol), 205 was isolated as colorless solid (1.15 g, 80%), mp 119-120 °C. ¹H-NMR (300 MHz, CDCl₃): δ = 7.54 (dd, J = 8.61, 4.23 Hz, 1H, ArH), 8.00 (s, 1H, ArH), 8.44 (dd, J = 8.58, 7.05 Hz, 1H, ArH), 8.97 (dd, J = 4.23, 2.67 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 117.6 (d, J₁,F₁ = 290.9 Hz, CF₃), 114.9, 120.5 (C), 122.6 (CH), 126.8 (C), 132.3, 134.7 (CH), 140.8, 143.0 (C), 151 (CH). ¹⁹F NMR (282 MHz, CDCl₃): δ = -72.36 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3084, 2961, 2850, 1599, 1584, 1472, 1449 (w), 1420, 1405 (m), 1347, 1334, 1291, 1249 (w), 1229 (m), 1202, 1179, 1129, 1057 (s), 1035, 962, 933 (w), 873 (m), 825, 809, 784 (s), 765 (m), 692 (s), 641 (m), 609, 601, 584 (s), 584, 553, 546 (m). GC-MS (EI, 70 eV): m/z (%) = 435 ([M+H]⁺, 81Br, 26), 433 ([M+H]⁺, 79Br, 13), 304 (49), 303 (10), 302 (100), 276 (37), 275 (07), 274 (73), 272 (39). HRMS (EI, 70 eV): calcd for C₁₀H₅Br₂F₃N₁O₃S₁ ([M+H]⁺, 79Br): 433.8304, found 433.8299, calcd for C₁₀H₅Br₂F₃N₁O₃S₁ ([M+H]⁺, 81Br): 435.8283, 435.8283.

3.6.1 General Procedure for Suzuki–Miyaura Reactions

A 1,4-dioxane solution (4 mL per 3 mmol of 205) of 205, K₂CO₃, Pd(PPh₃)₄ and arylboronic acid 188 was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

5,7-Bis(4-tert-buty]phenyl)-8-(trifluoromethylsulfonyloxy)quinoline (206)

Starting with 205 (100 mg, 0.22 mmol), 188c (78 mg, 0.44 mmol), Pd(PPh₃)₄ (15 mg, 6 mol%, 0.0132 mmol), K₂CO₃ (2 mL), and 1,4-dioxane (3 mL), 206 was isolated as colorless solid (101 mg, 81%), mp 150-152 °C. ¹H-NMR (300 MHz, CDCl₃): δ = 1.30 (s, 9H, 3CH₃), 1.33 (s, 9H, 3CH₃), 7.33-7.36 (m, 2H, ArH), 7.40 (dd, J = 8.61, 4.23 Hz, 1H, ArH), 7.45-7.48 (m, 6H, ArH), 7.54 (s, 1H, ArH), 8.24 (dd, J = 8.55, 7.11 Hz, 1H, ArH), 8.99 (dd, J = 4.05, 2.67 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 31.2, 31.35 (6CH₃), 34.7 (C), 118.5 (q, J₁,F₁ = 320.5 Hz, CF₃), 121.9, 125.4, 125.6 (CH), 126.9 (C), 129.3, 129.6
Experimental Section

(CH), 132.3 (C), 134.0, 134.5 (CH), 134.8, 135.0, 140.3, 141.7, 142.1 (C), 151.0 (CH), 151.3, 151.9 (C). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta = -75.06$ (s, 3F, CF$_3$). IR (KBr, cm$^{-1}$): $\tilde{\nu} = 3037$ (w), 2952, 2924, 2903, 2866 (m), 1619, 1596, 1568, 1555, 1513, 1485, 1454 (w), 1416 (s), 1392 (m), 1363, 1342, 1311, 1266, 1241 (w), 1220, 1203 (s), 1170, 1153 (m), 1135 (s), 1106, 1097, 1065 (w), 1043, 1034, 1021, 1014 (m), 968, 940, 922, 900, 880 (w), 849 (m), 838, 828, 793 (s), 774, 763, 755, 747, 723, 706, 687, 665, 642, 631 (w), 607, 597 (s), 577, 563, 555, 540, 529 (w). GC-MS (EI, 70 eV): $m/z$ (%) = 541 ([M$^+$]), 353 (22), 352 (100), 336 (14). HRMS (EI, 70 eV): calcd for C$_{30}$H$_{30}$F$_3$N$_1$O$_3$S$_1$ [M$^+$]: 541.18930, found 541.188400.

5-(4-tert-Butylphenyl)-7-bromo-8-(trifluoromethylsulfonyloxy)quinoline (207)

Starting with 205 (100 mg, 0.22 mmol), 188c (39 mg, 0.22 mmol), Pd(PPh$_3$)$_4$ (8 mg, 3 mol%, 0.0066 mmol), K$_2$CO$_3$ (1 mL), and 1,4-dioxane (2 mL), 207 was isolated as colorless solid (85 mg, 75%), mp 111-113 °C. $^1$H-NMR (300 MHz, CDCl$_3$): $\delta = 1.33$ (s, 9H, 3CH$_3$), 7.28-7.32 (m, 2H, ArH), 7.41 (dd, $J = 8.64, 4.17$ Hz, 1H, ArH), 7.45-7.50 (m, 2H, ArH), 7.65 (s, 1H, ArH), 8.20 (dd, $J = 8.61, 6.99$ Hz, 1H, ArH), 8.95 (dd, $J = 4.17, 2.58$ Hz, 1H, ArH). $^{13}$C-NMR (62.9 MHz, CDCl$_3$): $\delta = 30.31$ (3CH$_3$), 33.75 (C), 114.4 (q, $J_{F,C} = 320.5$ Hz, CF$_3$), 121.3, 124.7 (CH), 126.0 (C), 128.5, 129.6 (CH), 132.8 (C), 133.8 (CH), 140.3, 140.8, 142.3 (C), 150.3 (CH), 150.8, 151.2 (C). $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta = -72.49$ (s, 3F, CF$_3$). IR (KBr, cm$^{-1}$): $\tilde{\nu} = 2956$ (m), 2922 (s), 2852 (m), 1743, 1728, 1693, 1665, 1630, 1602, 1589, 1515 (w), 1462, 1451 (m), 1426 (s), 139, 1376, 1307, 1261 (w), 1241 (m), 1209 (s), 1183 (m), 1136 (s), 1193 (w), 1055 (s), 1034 (w), 1019, 942, 881, 865 (w), 832 (s), 788, 766, 754, 746, 720, 697, 684, 644, 619, 613 (w), 599 (s), 565, 541 (w). HRMS (EI, 70 eV): calcd for C$_{20}$H$_{18}$BrF$_3$N$_1$O$_3$S$_1$ ([M+H]$^+$, $^{79}$Br): 488.0137, found 488.0145, calcd for C$_{20}$H$_{18}$BrF$_3$N$_1$O$_3$S$_1$ ([M+H]$^+$, $^{81}$Br): 490.0118, found 490.0129.
NOTES AND REFERENCES


139. Treacher, K.; StPssel, P.; Spreitzer, H.; Becker, H.; Falcou, A.; PCT Int. Appl. WO 03/048225A2, **2003**.


143. Steglich, W.; Fugmann, B.; Lang-Fugmann, S. In *Natural Product*; Eds.; Thieme: Stuttgart, **1997**.


146. Nair, M. G.; Cichewicz, R. H.; Seeram, N. P.; Zhang, Y. US Patent.6,875,746 B1, **2005**.

147. Cichewicz, R. H.; Nair, M. G.; McKerrow, J. US Patent. 6,903,076 B2, **2005**.


152. For a simple guide for the prediction of the site selectivity of palladium(0)-catalyzed cross-coupling reactions based on the ¹H-NMR chemical shift values, see: Handy, S. T.; Zhang, Y. *Chem. Commun.* **2006**, 299-301.


X-Ray Crystallography Reports

APPENDIX
### Crystal Data and Structure Refinement for Compound 189c

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Identification code</td>
<td>is_a14</td>
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<tr>
<td>Empirical formula</td>
<td>C_{34}H_{32}O_{2}</td>
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<tr>
<td>Formula weight</td>
<td>472.60</td>
</tr>
<tr>
<td>Temperature</td>
<td>173 (2) K</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.71073 Å</td>
</tr>
<tr>
<td>Crystal system</td>
<td>Triclinic</td>
</tr>
<tr>
<td>Space group (H.-M.)</td>
<td>P-1</td>
</tr>
<tr>
<td>Space group (Hall)</td>
<td>-P1</td>
</tr>
<tr>
<td>Unit cell dimensions</td>
<td></td>
</tr>
<tr>
<td>(a)</td>
<td>9.106 (6) Å</td>
</tr>
<tr>
<td>(b)</td>
<td>10.813 (6) Å</td>
</tr>
<tr>
<td>(c)</td>
<td>14.071 (8) Å</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>105.943 (11)°</td>
</tr>
<tr>
<td>(\beta)</td>
<td>93.339 (13)°</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>97.190 (16)°</td>
</tr>
<tr>
<td>Volume</td>
<td>1315.4 (13) Å³</td>
</tr>
<tr>
<td>(Z)</td>
<td>2</td>
</tr>
<tr>
<td>Density (calculated)</td>
<td>1.193 Mg m(^{-3})</td>
</tr>
<tr>
<td>Absorption coefficient</td>
<td>0.07 mm(^{-1})</td>
</tr>
<tr>
<td>F(000)</td>
<td>504</td>
</tr>
<tr>
<td>Crystal size</td>
<td>0.74 × 0.57 × 0.37 mm</td>
</tr>
<tr>
<td>(\Theta) range for data collection</td>
<td>0 = 6.4-59.9°</td>
</tr>
<tr>
<td>Index ranges</td>
<td>(-11 \leq h &lt; 11, -14 \leq k &lt; 14, -18 \leq l \leq 18)</td>
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<tr>
<td>Reflections collected</td>
<td>23152</td>
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<tr>
<td>Independent reflections</td>
<td>5994 [R(int) = 0.037]</td>
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</table>
Completeness to $\Theta = 29.82^\circ$ 99.2%

Absorption correction Semi-empirical from equivalents

Max. and min. transmission 0.978 and 0.948

Refinement method Full-matrix least-squares on F2

Data/ restraints / parameters 5175/0/331

Goodness-of-fit on F2 1.097

Final R indices [I>2\sigma(I)] R1 = 0.0555, wR2 = 0.1476

R indices (all data) R1 =0.0482, wR2 = 0.1398

Largest diff. peak and hole 0.336 and -0.294 e Å$^{-3}$
Crystal Data and Structure Refinement for Compound 190b

Identification code                     is_a17
Empirical formula C_{22}H_{13}F_{3}O_{6}S
Formula weight 462.38
Temperature 173 (2) K
Wavelength 0.71073 Å
Crystal system Triclinic
Space group (H.-M.) P1
Space group (Hall) -P 1
Unit cell dimensions
\begin{align*}
a &= 10.2281 (4) \text{ Å} & \alpha &= 85.020 (2)° \\
b &= 10.8657 (4) \text{ Å} & \beta &= 87.467 (2)° \\
c &= 19.2816 (7) \text{ Å} & \gamma &= 67.002 (2)° \\
\end{align*}
Volume 1964.98 (13) Å$^3$
Z 4
Density (calculated) 1.563 Mg m$^{-3}$
Absorption coefficient 0.23 mm$^{-1}$
F(000) 944
Crystal size 0.60 × 0.35 × 0.08 mm$^3$
\( \Theta \) range for data collection \( \theta = 4.7-60.5° \)
Index ranges \(-14 \leq h \leq -14, -15 \leq k \leq -14, -20 \leq l \leq 27 \)
Reflections collected 42358
Independent reflections 11784 [R(int) = 0.025]
Completeness to $\Theta = 29.82^\circ$ 98.6%

Absorption correction Semi-empirical from equivalents

Max. and min. transmission 0.982 and 0.873

Refinement method Full-matrix least-squares on F2

Data / restraints / parameters 5175/0/579

Goodness-of-fit on F2 1.064

Final R indices [I>2\sigma(I)] R1 = 0.0598, wR2 = 0.1145

R indices (all data) R1 = 0.0412, wR2 = 0.1067

Largest diff. peak and hole 0.39 and -0.36 e Å$^{-3}$
Crystal Data and Structure Refinement for Compound 191a

Identification code  
is_a24

Empirical formula  
C$_{31}$H$_{23}$F$_3$O$_2$

Formula weight  
484.49

Temperature  
173(2) K

Wavelength  
0.71073 Å

Crystal system  
Triclinic

Space group (H.-M.)  
P̅1

Space group (Hall)  
-P 1

Unit cell dimensions  
\(a = 9.0823 \text{ (18) Å, } \alpha = 76.95 \text{ (3)°}
\)

\(b = 11.869 \text{ (2) Å, } \beta = 88.73 \text{ (3)°}
\)

\(c = 12.460 \text{ (3) Å, } \gamma = 73.54 \text{ (3)°}
\)

Volume  
1253.6 (4) Å$^3$

Z  
2

Density (calculated)  
1.284 Mg m$^{-3}$

Absorption coefficient  
0.09 mm$^{-1}$

F(000)  
504

Crystal size  
0.38 × 0.37 × 0.07 mm

Θ range for data collection  
\(\theta = 4.7\text{-}55.4°\)

Index ranges  
\(-11\leq h\leq 11, -14\leq k\leq 15, -16\leq l\leq 16\)

Reflections collected  
21238

Independent reflections  
5706 [R(int) = 0.0245]
Completeness to $\Theta = 29.82^\circ$ 98.9%

Absorption correction Semi-empirical from equivalents

Max. and min. transmission 0.993 and 0.965

Refinement method Full-matrix least-squares on F2

Data / restraints / parameters 3766/0/87

Goodness-of-fit on F2 1.093

Final R indices [I>2$\sigma$(I)] $R1 = 0.0860$, $wR2 = 0.1480$

R indices (all data) $R1 = 0.0499$, $wR2 = 0.1332$

Largest diff. peak and hole 0.31 and -0.21 e Å$^{-3}$
Crystal Data and Structure Refinement for Compound 195a

Identification code is_a136

Empirical formula C_{29}H_{13}F_{9}O_5S

Formula weight 651.78

Temperature 173 (2) K

Wavelength 0.71073 Å

Crystal system Monoclinic

Space group (H.-M.) P 21/n

Space group (Hall) -P 2yn

Unit cell dimensions

\[ a = 14.4439 (7) \text{ Å} \quad \alpha = 90.00^\circ \]

\[ b = 11.2736 (5) \text{ Å} \quad \beta = 101.911 (2)^\circ \]

\[ c = 33.9566 (16) \text{ Å} \quad \gamma = 90.00^\circ \]

Volume 5410.3 (4) Å³

Z 8

Density (calculated) 1.600 Mg m⁻³

Absorption coefficient 0.239 mm⁻¹

F(000) 2621

Crystal size 0.60 × 0.17 × 0.09 mm³

Θ range for data collection θ = 1.91-24.98°

Index ranges -17 ≤ h ≤ 17, -13 ≤ k ≤ 13, -40 ≤ l ≤ 40

Reflections collected 39066

Independent reflections 9445 [R(int) = 0.0495]
Completeness to $\Theta = 29.82^\circ$ = 99.4%

Absorption correction Semi-empirical from equivalents

Max. and min. transmission 0.9788 and 0.8698

Refinement method Full-matrix least-squares on F2

Data / restraints / parameters 6265/7/846

Goodness-of-fit on F2 1.049

Final R indices [I>2\sigma(I)] $R1 = 0.0934$, $wR2 = 0.1228$

R indices (all data) $R1 = 0.0517$, $wR2 = 0.1228$

Largest diff. peak and hole 0.380 and -0.395 e Å$^{-3}$
Crystal Data and Structure Refinement for Compound 196e

Identification code                      is_a106
Empirical formula                     C_{23}H_{9}F_{9}O_{8}S_{2}
Formula weight                        648.42
Temperature                          173 (2) K
Wavelength                           0.71073 Å
Crystal system                       Triclinic
Space group (H.-M.)                  P -1
Space group (Hall)                   -P 1
Unit cell dimensions
\[ a = 8.5921 (2) \, \text{Å} \quad \alpha = 79.2310 (10)^{\circ} \]
\[ b = 11.1466 (3) \, \text{Å} \quad \beta = 80.2880 (10)^{\circ} \]
\[ c = 13.0127 (3) \, \text{Å} \quad \gamma = 85.0560 (10)^{\circ} \]
Volume                                1204.84 (5) Å³
Z                                      2
Density (calculated)                  1.787 Mg m⁻³
Absorption coefficient               0.342 mm⁻¹
F(000)                                 648
Crystal size                          0.34 \times 0.18 \times 0.14 \, \text{mm}³
θ range for data collection          \theta = 2.24-30.00^{\circ}
Index ranges                          -15 \leq h \leq 15, -12 \leq k \leq 12, -16 \leq l \leq 18
Reflections collected                 26483
Independent reflections              6942 [R(int) = 0.0279]
Completeness to $\Theta = 29.82^\circ$ 98.7%

Absorption correction Semi-empirical from equivalents

Max. and min. transmission 0.9537 and 0.8927

Refinement method Full-matrix least-squares on F2

Data / restraints / parameters 5429/0/462

Goodness-of-fit on F2 1.027

Final R indices [I>2\sigma(I)] R1 = 0.0655, wR2 = 0.1174

R indices (all data) R1 = 0.0469, wR2 = 0.1079

Largest diff. peak and hole 0.587 and -0.476 e Å$^{-3}$
**About the Author**

<table>
<thead>
<tr>
<th>Name</th>
<th>Ahmed Salem Ahmed Mahal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of Birth</td>
<td>Sept. 06, 1976</td>
</tr>
<tr>
<td>Place of Birth</td>
<td>Mosul, Iraq</td>
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<td>Nationality</td>
<td>Iraqi</td>
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**Professional Qualifications**

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<tr>
<td>1994-1998</td>
<td>B.Sc. in Chemistry, University of Mosul, Iraq</td>
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<tr>
<td>2001-2004</td>
<td>M.Sc. in Chemistry, Al al-Bayt University, Jordan</td>
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<tr>
<td>2007-2011</td>
<td>Ph.D. in Chemistry, University of Rostock, Germany</td>
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**Thesis Title:** Synthesis of Functionalized Anthraquinones, Phthalates and Quinolines by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

**Employment Details**

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**Teaching Duties**

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<td>1. Practical Inorganic Chemistry, Chemistry Laboratories 2&lt;sup&gt;ed&lt;/sup&gt; Class, Department of Chemistry, University of Mosul, Iraq</td>
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<td>2. Practical Inorganic Chemistry, Chemistry Laboratories 3&lt;sup&gt;rd&lt;/sup&gt; Class, Department of Chemistry, University of Mosul, Iraq</td>
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**Scholarships**

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<td>2001-2004</td>
<td>Ministry of Higher Education and Scientific Research Fellowship (Iraq), Al al-Bayt University, Jordan</td>
</tr>
<tr>
<td>2007-2011</td>
<td>German Academic Exchange Service (DAAD) Fellowship, University of Rostock, Germany</td>
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### Research Interest

1. Total Synthesis of Natural Products  
2. New Synthetic Methods for Organic Synthesis  
3. Catalysts  
4. Medicinal Chemistry  
5. Asymmetric Synthesis

### Membership in Societies

1. Membership in Iraqi Chemists Union, Iraq, 1998  
2. Member of the Gesellschaft Deutscher Chemiker GDCh (German Chemical Society) and its division: Liebig-Vereinigung für Organische Chemie (Liebig-Union for Organic Chemistry), 2008  
3. IUPAC Sponsored Affiliate Member, 2010
LIST OF
PUBLICATION

DECLARATION/
ERKLÄRUNG
Here by I declare that this work has so for neither submitted to the Faculty of Mathematics and Natural Sciences at the University of Rostock nor to any other scientific Institution for the purpose of doctorate. Furthermore, I declare that I have written this work by myself and that I have not used any other sources, other than mentioned earlier in this work.

Hiermit erkläre ich, daß diese Arbeit bisher von mir weder an der Mathematisch-Naturwissenschaftlichen Fakultät der Universität Rostock noch einer anderen wissenschaftlichen Einrichtung zum Zwecke der Promotion eingereicht wurde.

Ferner erkläre ich, dass ich diese Arbeit selbständig verfasst und keine anderen als die darin angegebenen Hilfsmittel benutzt habe

I hereby apply irrevocably to take oral examination in the form of a private viva voce and a public presentation.

Ahmed Mahal