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DEVCOM ARMY RESEARCH LABORATORY

Synthesis of a Novel Hexa-functional Monomer for 2D Polymers: 2,4,6-Tris((diphenylmethylene) amino)benzene-1,3,5-tricarbaldehyde

by David C McLeod, Kätchen K Lachmayr, Robert H Lambeth, Adam Switek, Audrey Murphy, Rose A Pesce-Rodriguez, and Steven R Lustig

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14. ABSTRACT
This report details the synthesis, purification, and characterization of a novel hexa-functional monomer, 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde, which may be useful in the production of imine-based 2D polymers. Also detailed in this report are initial attempts to polymerize this monomer under acidic conditions. These attempts were unsuccessful, but did result in the stable, free amine form of the monomer, 2,4,6-triaminobenzene-1,3,5-tricarbaldehyde, which may also prove to be useful in the production of imine-based 2D polymers. To the best of our knowledge, this is the first report of the successful synthesis of a hexa-functional molecule consisting of a single benzene ring with three attached aldehyde groups alternating with either three attached benzophenone imine groups or three free primary amines.

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Executive Summary

Computational studies by US Army Combat Capabilities Development Command Army Research Laboratory scientists predict that films made of well-oriented, hydrogen-bonded, triangular-lattice 2D polymers, such as the theoretical "graphamid," will have excellent mechanical properties; however, the hexa-functional monomers containing the alternating reactive groups on a single benzene ring needed to construct such 2D polymers are not known to exist. This report details the synthesis, purification, and characterization of one such novel hexa-functional monomer, 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde, that may be useful for the production of the dense, triangular-lattice, imine-based 2D polymer "graphimine," which may further serve as a precursor to other 2D polymers of interest like graphamid. Also detailed in this report are initial attempts polymerize this monomer under acidic conditions to produce graphimine. These attempts were unsuccessful, but under certain conditions did result in the stable, free amine form of the monomer, 2,4,6-triaminobenzene-1,3,5-tricarbaldehyde, which may also prove to be useful for the production of graphimine and other 2D polymers. To the best of our knowledge, this is the first report of the successful synthesis of a hexa-functional molecule consisting of a single benzene ring with three attached aldehyde groups alternating with either three attached benzophenone imine groups or three free primary amines.

1. Introduction

Poly(*p*-phenylene terephthalamide) (PPTA) fibers, sold under the trade names Kevlar and Twaron, are among the stiffest and strongest synthetic materials per unit mass that are currently available.[1] PPTA fibers are especially notable because they maintain excellent mechanical properties even at elevated temperature, and are resistant to chemical degradation, moisture, and creep. These characteristics are enabled by two key features of the polymer: 1) a rigid aromatic backbone that provides stiffness and strength to the individual molecules, and 2) strong intermolecular hydrogen bonding between adjacent amide groups of the axially oriented polymers, which provides macroscopic strength and stiffness to the overall fiber.[1]

Inspired by the hydrogen-bonded aromatic networks found in PPTA fibers, a new high-performance material called "graphamid" was envisioned by US Army Combat Capabilities Development Command Army Research Laboratory researchers.[2,3] Graphamid is a sheet-like 2D polymer with a chemical makeup similar to PPTA, composed of benzene rings connected at each carbon by amide groups to six neighboring benzene rings. Rather than forming fibers like PPTA, graphamid 2D polymers could stack to form rigid, hydrogen-bonded ensembles, which would be especially advantageous in forming mechanically robust films. Films made from well-oriented 2D graphamid molecules are predicted to have significantly greater isotropic, in-plane stiffness and strength than woven PPTA fibers, making such films far more useful in situations where multiaxial loading occurs.[2]

A wide variety of 2D polymers, also known as covalent organic frameworks (COFs), are reported in the literature.[4] The vast majority of 2D COFs are designed to have relatively sparse, porous topologies, which are useful for selective chemical uptake and separation: however, this results in diminished mechanical properties, like lower molecular strength and stiffness, compared to denser 2D networks, such as graphene.[2] In order to construct the unusually dense, triangular topology of graphamid, a novel hexa-functional monomer made from a single benzene ring with alternating functionalities at each carbon position is needed. Also, most known 2D COFs are made of aromatic nodes connected by imine linkages (Ar–CH=N–Ar), which do not directly enable hydrogen bonding between layers; however, it has been reported that imine groups in 2D polymers can be converted to amide groups via oxidation.[5] Based on the existing literature, a synthetic route to graphamid was devised (Fig. 1), where a monomer with alternating aldehyde and benzophenone imine groups, 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde (**2**), would react via transimination to form a novel imine-linked 2D polymer

"graphimine" (**3**), which could later be oxidized to graphamid. Even without inherent hydrogen bonding, graphimine itself would likely be of significant interest given its unusually dense and rigid structure.[3]

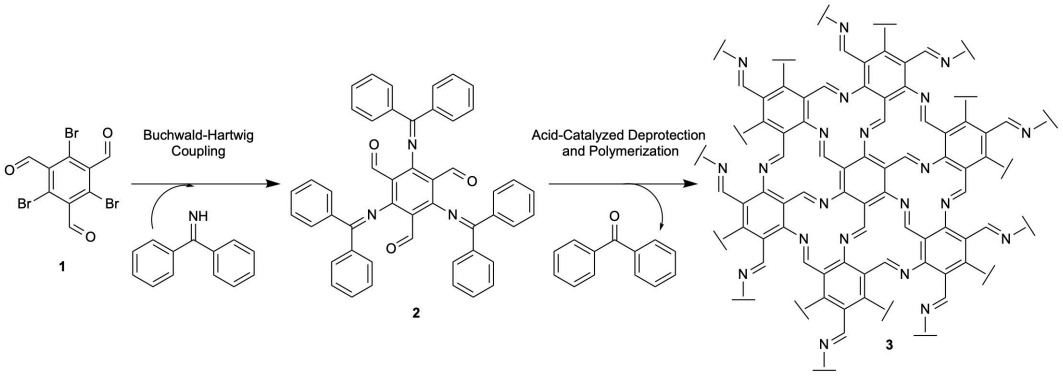

Fig. 1 Graphimine synthesis from Rubin's aldehyde (1), using Buchwald–Hartwig coupling to form 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde (2), followed by acid-catalyzed polymerization of 2 via transimination to yield graphimine (3)

The monomer **2** is not known in the literature, so this report primarily focuses on the synthesis, purification, and characterization of this compound. The synthesis of a monomer with two different functionalities that are reactive toward each other on alternating positions around a central benzene ring presents several synthetic challenges, such as controlling the positional selectivity so that each functionality alternates, ensuring the complete substitution of the ring in a sterically crowded environment so that there are no missing functional groups, and installing protective groups so that undesirable side reactions do not occur. This monomer contains alternative aldehyde and benzophenone imine functionalities. The advantage of using benzophenone imine as both the protecting group and amine source is that it can undergo simultaneous acid-catalyzed deprotection and react with the aldehydes of other monomers to form new imine linkages, leading to a 2D polymer. The synthesis of **2** begins with the formation of Rubin's aldehyde (**1**). 1,3,5-Tribromobenzene is transformed via Friedel-Crafts alkylation to 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene, which is then hydrolyzed to give the Rubin's aldehyde. The aryl-bromides of **1** are then substituted via Buchwald–Hartwig coupling with benzophenone imine to give the desired monomer **2**.

This report also details initial attempts to polymerize **2** via transimination using a variety of acid catalysts. The product of one such reaction is the deprotected, free amine version of the monomer, 2,4,6-triaminobenzene-1,3,5-tricarbaldehyde. This monomer is also unknown in the literature and will likely also be useful as a precursor to novel 2D polymers such as graphimine.

2. Experimental Methods

This section details the synthesis and purification of the hexa-functional monomer **2** and all intermediates starting with Rubin's aldehyde. Three methods for the attempted acid-catalyzed polymerization of **2** are also detailed. All reagents were purchased from commercial sources and used as received unless otherwise noted.

2.1 Monomer Synthesis

2.1.1 Synthesis of Rubin's Aldehyde

The synthesis of Rubin's aldehyde, **1**, as shown in Fig. 2, was done following a modified method described by Holst et al.[6] The synthesis began with Friedel–Crafts alkylation of 1,3,5-tribromobenzene. Chloroform was dried over 4-Å molecular sieves for a period of at least 24 h before use. Under a nitrogen atmosphere, the 1,3,5-tribromobenzene (25 g, 79.4 mmol) was dispensed into a 500-mL Schlenk flask equipped with a magnetic stir bar. Then, 250 mL of chloroform was added to the flask which dissolved the 1,3,5-tribromobenzene. Aluminum chloride (12.5 g, 93.7 mmol) was added to the flask, and then the reaction mixture was refluxed at 80 °C for 2 days. After 2 days, the reaction was cooled to room temperature and set on ice for 1 h. Residual aluminum chloride was quenched with the addition of 20 mL of water added over a period of 1 h. The reaction solution was then washed with 100 mL of cold deionized water. The organic fraction was collected, dried over sodium sulfate, and the chloroform was removed under reduced pressure by rotary evaporation (rotovap). The crude brown solid was then dissolved in dichloromethane (DCM) and passed through a plug of silica to remove residual salts, using DCM as the mobile phase, to produce the 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene as tan solid, yielding 33.6 g or 75.2%. ^{1}H NMR (500 MHz, $CDCl_3$) δ = 7.94 (s), 7.77 (s).

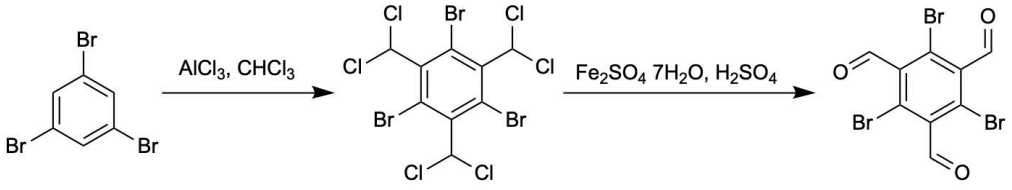

Fig. 2 Rubin's aldehyde synthesis

The second step of the Rubin's aldehyde synthesis was a hydrolysis reaction. As described by Holst et al.,[6] this was done in concentrated sulfuric acid at 130 °C for 4 h. However, the highest yields obtained for the hydrolysis were done at 135 °C for 5 h. For this method, the 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene (13.8 g, 24.6 mmol) was combined with iron (II) sulfate heptahydrate (0.68 g, 2.46 mmol), in 138 mL sulfuric acid (5 mL per 0.5 g of 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene). The reaction was vented into a 2 M aqueous NaOH solution, as HCl gas was produced over the course of the reaction. Effective stirring was critical to ensure all the 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene was completely dissolved once the reaction temperature of 135 °C has been reached. After 5 h, the reaction was cooled to 0 °C, and precipitated in large excess of cold deionized water (600 mL). The precipitate was collected via vacuum filtration and washed with two 15-mL aliquots of water to remove any remaining acid residue. The crude solid was then thoroughly dried and dissolved in DCM for purification by column chromatography where **2** was isolated in the first fraction (1.2 L of DCM). The organic fraction was dried using a rotovap before the resulting powder was re-dissolved in a minimal amount (550 mL) of hot DCM for crystallization. The solution was cooled to room temperature and then chilled at 4 °C for 16 h, which encourages the growth of white needle crystals. The crystals were then collected using a vacuum filtration with a fritted conical funnel and was washed with two aliquots (10 mL) of cold DCM, and recrystallized, as needed, to enhance purity, 8.37 g and 26.5%. ^{1}H NMR (500 MHz, deuterated dimethylsulfoxide [DMSO-d_6]) δ = 10.10 (s, 3H). ^{13}C NMR (400 MHz, DMSO-d_6) δ = 192.31, 136.98, 123.58.

2.1.2 Synthesis of 2,4,6-Tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde

Buchwald–Hartwig coupling of Rubin's aldehyde with benzophenone imine (or other amines, such as acetamide and tert-butyl carbamate) was attempted under a wide variety of conditions (time, temperature, solvent) and with a wide variety of catalysts, ligands, and bases. Most of these reactions gave low yield or no yield of the desired product. The details of these reactions are given in the Appendix, Supplementary Information, Tables A-1 through A-5.

Buchwald–Hartwig coupling of Rubin's aldehyde with benzophenone imine was conducted with palladium (II) acetate, $Pd(OAc)_2$, and the catalyst was with rac-BINAP (CAS: 98327-87-8) as the ligand (Fig. 3). Under a nitrogen atmosphere, the catalyst (0.73 g, 3.26 mmol) and ligand (2.54 g, 4.07 mmol) were combined in 50 mL of anhydrous toluene and activated at 50 °C for 15 min until a deep pink color persisted. Then, **1** (6.50 g, 16.3 mmol), Cs_2CO_3 (26.6 g, 81.5 mmol), and

benzophenone imine (10.3 g, 57.0 mmol) were added with an additional 100 mL of anhydrous toluene where **1** only dissolved fully once the reaction was heated. Once all reagents were combined, the flask was sealed with a Teflon cap and placed in a preheated oil bath at 90 °C. The reaction was then stirred vigorously for 40 h at 90 °C, and then was cooled to room temperature. The crude reaction solution was transferred to a separatory funnel, and the solution was washed twice with 100 mL of deionized water. The organic phase was then concentrated on a rotovap and redissolved in a minimal amount of ethyl acetate. The solution was chilled to 0 °C to encourage the precipitation of **2**. The precipitate was then collected via vacuum filtration and washed with two 5-mL aliquots of cold ethyl acetate. The crude product is then further dried under high vacuum before dissolving in DCM and purified via column chromatography using a CombiFlash (80-g flash silica column for 3.5 g of crude product). A mobile phase gradient started with 30:70 hexane:DCM for the first 5 min, or 0.4 L, which then transitions to 100% DCM over the next 5 min, or 0.4 L. The product begins to elute off the column once the mobile phase consists of at least 90% DCM. Identical fractions are combined and then dried on the rotovap, until a light-yellow powder is isolated, 1.89 g or 16.6%. The product is then stored in under a nitrogen environment until use. Note that **2** has a short lifetime, less than 3 days, when in solution state and is acid sensitive. ^{1}H NMR (500 MHz, DMSO-d_6) δ = 9.85 (s, 1H), 7.57–7.54 (t, J = 7.4 Hz, 2H), 7.39–7.36 (t, J = 7.7 Hz, 4H), 7.19–7.17 (d, J = 7.6 Hz, 4H). ^{13}C NMR (400 MHz, deuterated chloroform ($CDCl_3$) δ = 187.87, 169.04, 158.95, 136.87, 130.58, 129.16, 108.47. MALDI-TOF-MS = 699.23 m/z. Melting point, from differential scanning calorimetry (DSC) = 278.87 °C.

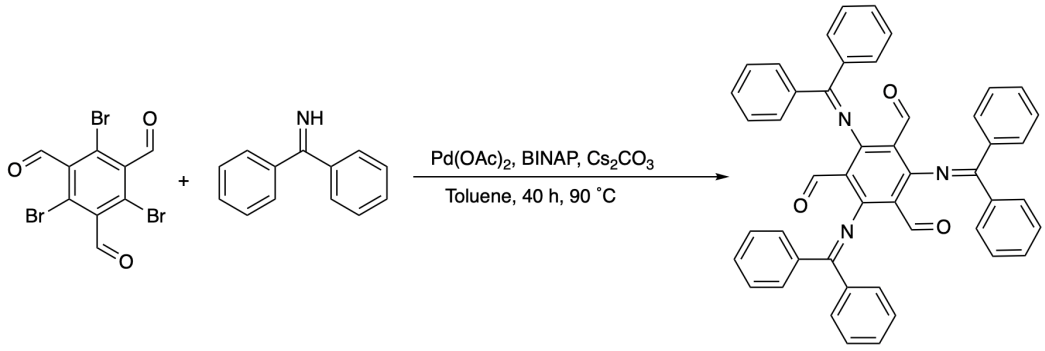

Fig. 3 Buchwald–Hartwig coupling for the synthesis of 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde, 2

2.2 Acid-Catalyzed Polymerization of Monomer 2

2.2.1 Acetic Acid Method

In a 25 mL Schlenk flask, 450 mg (0.644 mmol) of **2** was dissolved in 4 mL of 1:1 (v/v) solution of dioxane/mesitylene. Then 0.67 mL of a 6 M aqueous acetic acid solution was added to the flask. The reaction mixture was sonicated for 15 min, then heated to 120 °C for 20 h in the dark (no stirring). After 20 h, a brown solid, later determined to be 2,4,6-triaminobenzene-1,3,5-tricarbaldehyde, had formed on the bottom of the flask. The reaction mixture was cooled to room temperature and the solid was collected using vacuum filtration, 14 mg, 10%. ^{1}H NMR (500 MHz, DMSO-d_6) δ = 9.94 (s, 1H), 9.02 (exchange, 2H). ^{13}C NMR (400 MHz, DMSO-d_6) δ = 185.92, 160.68, 95.66.

2.2.2 Metal Triflate Method

Under a nitrogen atmosphere, 450 mg (0.644 mmol) of **2** was dissolved in 6 mL of 4:1 (v/v) solution of dioxane/mesitylene, in a 25-mL Schlenk flask. Then 29.5 g (0.0589 mmol) of $Sc(SO_3CF_3)_3$ was added to the reaction mixture. The reaction mixture was sonicated for 15 min, then heated to 50 °C for 18 h in the dark (no stirring). After 18 h, the reaction mixture was cooled to room temperature and dried under high vacuum for analysis.

2.2.3 Neat HCl Method

Under a nitrogen atmosphere and using air-free techniques, 410 mg (0.587 mmol) of **2** was added to a 25-mL Schlenk flask and dissolved in 5 mL of anhydrous toluene. Then 0.457 g (12.5 mmol) of neat HCl was added to the reaction mixture. The reaction mixture was sonicated for 15 min, degassed through three cycles of freeze-pump-thaw, and then heated to 50 °C for 30 min in the dark (no stirring). Within 30 min, the solution color changed from yellow to an orange-brown. The reaction mixture was cooled to room temperature and dried under high vacuum for analysis.

3. Analytical Techniques and Characterization

Nuclear magnetic resonance (NMR) spectroscopy was carried out with a 500 MHz Varian Inova or 400 MHz Varian Mercury spectrometer. DMSO-d_6 and $CDCl_3$ were used as the solvents. All spectra were referenced to tetramethylsilane using residual ^{1}H or ^{13}C chemical shifts of the deuterated solvent.

Matrix-assisted laser desorption ionization time-of-flight mass spectroscopy (MALDI-TOF-MS) was conducted using an SCIEX TOF/TOF 5800 system. The sample was prepared by dissolving 2 mg of the sample in 1 mL of 60:40 (v/v) dimethyl sulfoxide: acetonitrile solution. The matrix was prepared by dissolving 2 mg of alpha-cyano-4-hydroxycinnamic acid in 1 mL of 60:40 (v/v) DMSO:acetonitrile solution. Then 20 µL of the matrix and 5 µL of the sample were combined, and 0.6 µL of solution was spotted onto a steel 384-well target plate and dried completely at room temperature before analysis.

Fourier transform infrared (FTIR) spectroscopy was collected using Thermo Scientific Nicolet iS50R FTIR equipped with a single reflection diamond attenuated total reflectance (ATR) module.

DSC was used to obtain thermal transition values using a TA DSC 250 system, equipped was a finned-air cooling system. Samples were run in sealed hermetic aluminium sample pans with an empty pan as reference. A heat–cool–heat temperature program was used at a flow rate of 10 °C/min over the maximum range of 35–350 °C.

Thermal gravimetric analysis (TGA) of 3 mg of sample contained in a Pt pan was performed on a TA Systems Q500 TGA instrument. Analysis was performed under nitrogen atmosphere (flow rate: 60 mL/min sample gas, 40 mL/min balance gas), with a heating rate of 20 °C/min from ambient temperature to 1000 °C.

Pyrolysis (P) products were analyzed by means of a gas chromatography-mass spectroscopy (GC-MS) instrument with a desorption interface. Desorption was achieved via a CDS Analytical Model 2000 Pyroprobe (coil type) connected through a heated interface chamber to the splitless injector of an Agilent GC-MS system (Model 6890N GC and Model 5973N MSD). The GC column used was an HP-5 capillary column (0.25 mm × 30 m, 0.25-µm film). The injector temperature was 250 °C; the Pyroprobe interface was set to a temperature of 250 °C. The GC oven temperature program was as follows: 100 °C isothermal for 1 min, 100–250 °C at 40 °C/min, and 250 °C isothermal for 1 min. The Pyroprobe was programmed to give a 20-s desorption pulse at temperatures ranging from 175 to 450 °C at a heating rate of 1000 °C/s. All analyses were run sequentially on a single sample. The pulse temperature is based on calibration provided by the vendor and was not measured for this study. Samples (~1 mg) were held within the coil of the Pyroprobe by first placing them in a quartz tube containing a small plug of glass wool, and then inserting the entire tube into the coil.

4. Results and Discussion

4.1 Characterization of Monomer 2

The successful synthesis of **2** via Buchwald–Hartwig coupling of **1** with benzophenone imine was confirmed using ^{1}H NMR with the retention and shift of an aldehyde peak, initially at 10.10 ppm at **1** (Appendix, Fig. A-1), to 9.85 ppm in **2** (Fig. 4). The shift in the aldehyde position was accompanied by the addition of aromatic protons at 7.57–7.54 (t, J = 7.4 Hz, 2H), 7.39–7.36 (t, J = 7.7 Hz, 4H), 7.19–7.17 (d, J = 7.6 Hz, 4H), Fig. 4. The structure of **2** was further confirmed with ^{13}C NMR, which contains the distinct imine carbon (N = C) at 169.04 ppm, in addition to the aryl carbon adjacent to a nitrogen group at 158.95 ppm, and the distinctive aldehyde resonance at 187.87 ppm (Fig. 5).

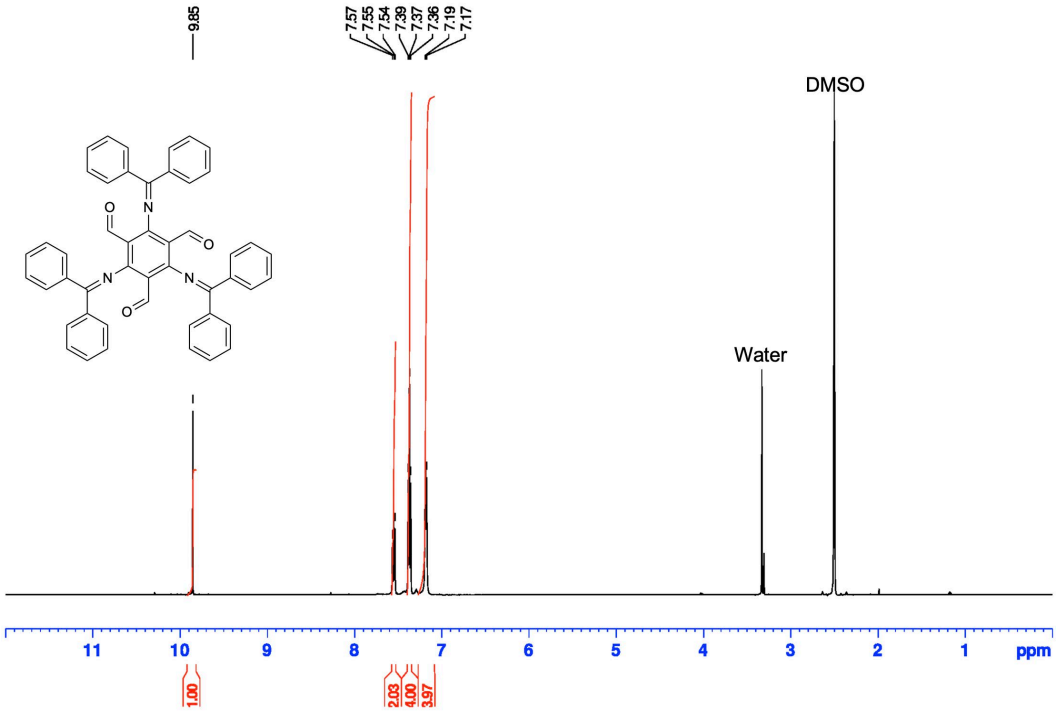

Fig. 4 ^{1}H NMR of 2, collected on a 500-MHz spectrometer in DMSO-d_6

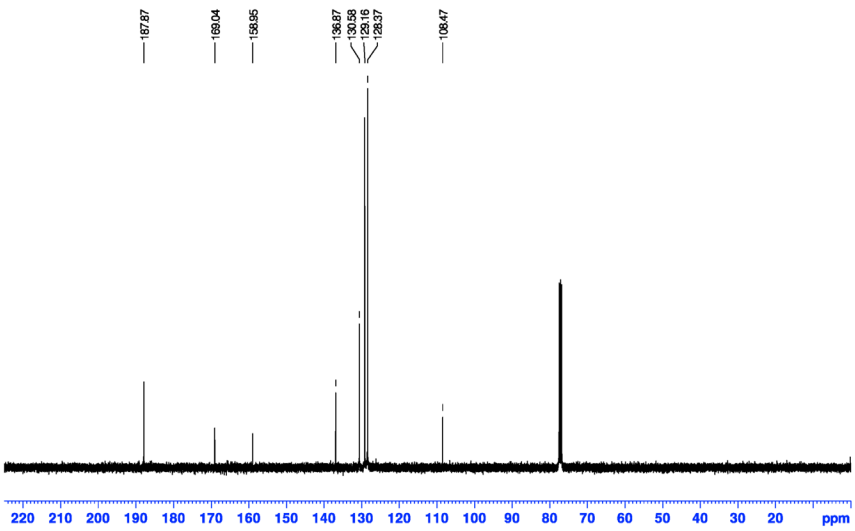

Fig. 5 **^{13}C NMR of 2, collected on a 400-MHz spectrometer in $CDCl_3$**

MALDI-TOF-MS was used to estimate the molecular weight of **2** (Fig. 6). From structural analysis, **2** is expected to have a molecular weight of 699.23 g/mol. This neutral compound was observed with a low relative intensity at 699.2281 m/z, and the protonated structure was observed at 700.2287 m/z with a high relative intensity. Additionally, the sodium and potassium adducts of **2** were observed at 722.2134 and 738.1831 m/z, respectively.

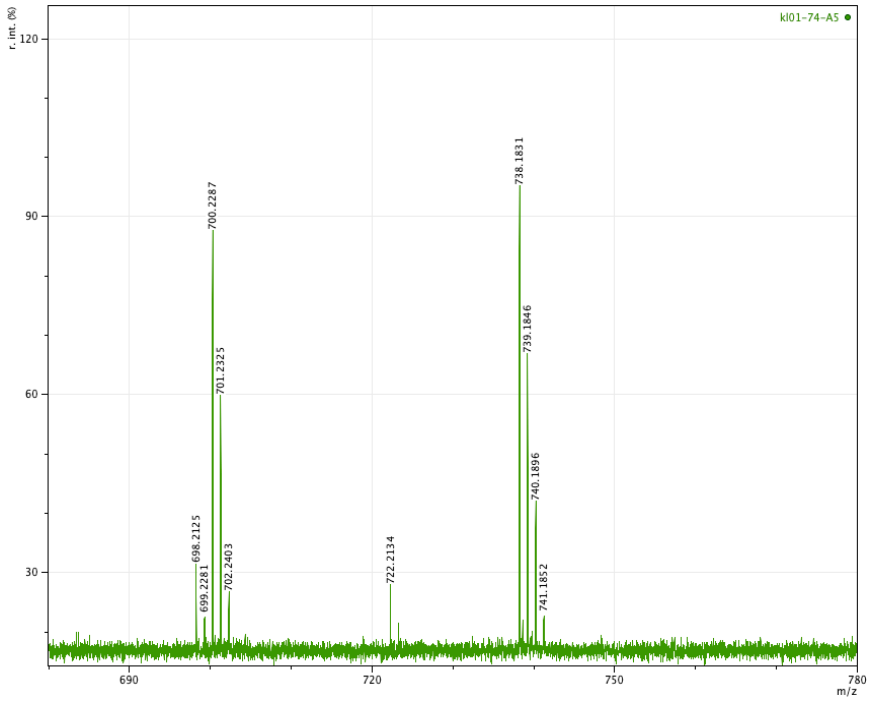

Fig. 6 MALDI-TOF-MS of 2, with neutral compound at 699.23 m/z, and a protonated peak (+H) at 700.23 m/z with additional ions at 701.23 and 702.24 m/z

FTIR spectroscopy was used to confirmed key functional groups (Fig. 7). The aldehyde group was seen as a doublet at 2850 and 2755 cm^{-1}, and as a single peak at 1684 cm^{-1}. The imine bond was identified at 1619 cm^{-1}.

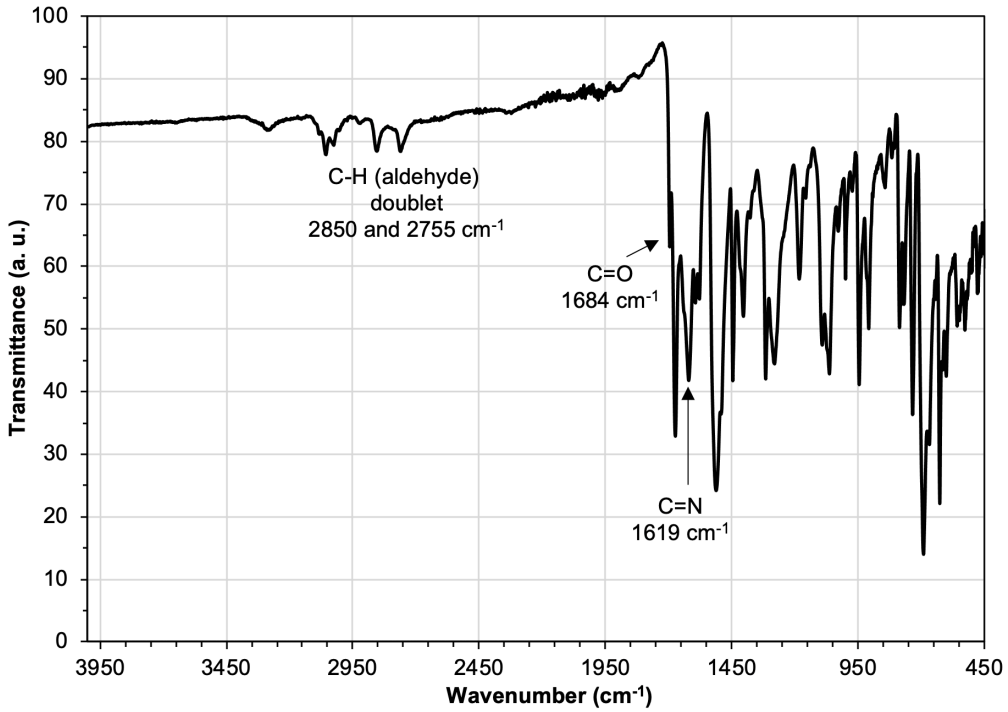

Fig. 7 FTIR spectrum of 2

DSC was used to estimate the melting point of **2**, which was found at 278.87 °C (Fig. 8). This melting point was only observed within the first heating cycle of the heat–cool–heat program. The maximum temperature of the program was 350 °C, which is well beyond the onset of thermal decomposition that was determined by TGA to be at 300 °C.

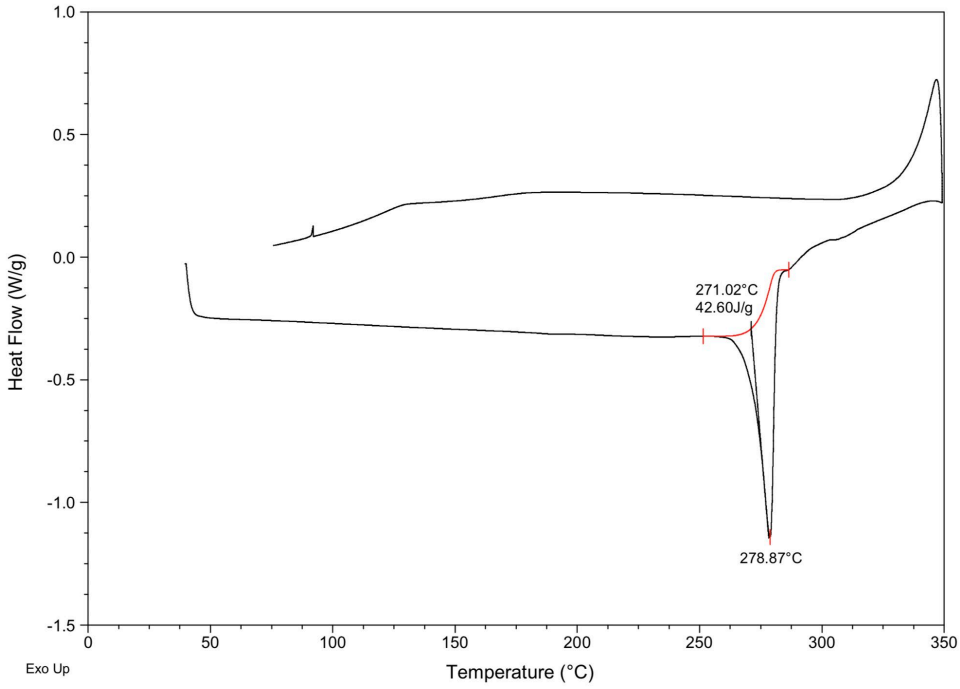

Fig. 8 DSC trace of 2, at a heating rate of 10 °C/min

The thermal stability of the compound **2** was examined by TGA (Fig. 9). In a nitrogen atmosphere at a heating rate of 20 °C/min, no significant weight loss was observed until 300 °C. From 300 to 500 °C, a continuous weight loss of 74% occurred with no further significant weight loss to 1000 °C.

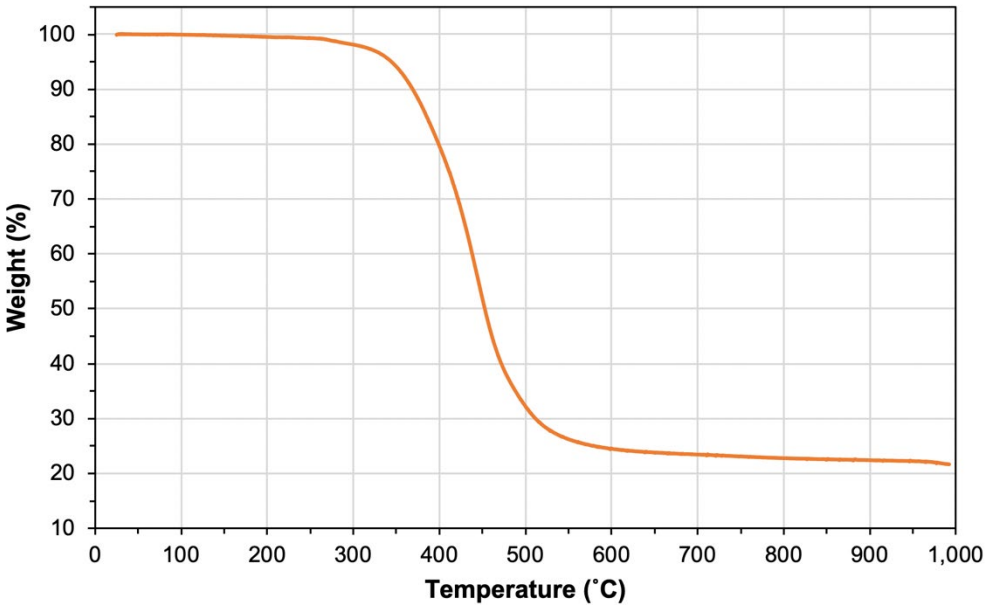

Fig. 9 TGA trace for 2 at a heating rate of 20 °C/min in nitrogen

The volatile products of thermal decomposition were elucidated using P-GC-MS (Fig 10). Initially, sequential 20-s heating pulses at 175 and 250 °C only showed trace amounts of residual ethyl acetate and benzophenone. Another pulse at 350 °C likewise showed trace signals of benzophenone and 2-methyl-1,1′-biphenyl. At 450 °C, where most decomposition occurred in the TGA, a significant amount of diphenylmethane with a relatively small amount of benzophenone was observed. It is possible that the benzophenone observed in all of these traces is residual from the synthesis of the compound, or it may be a product of heat-induced rearrangement with the oxygen-containing aldehyde moieties.

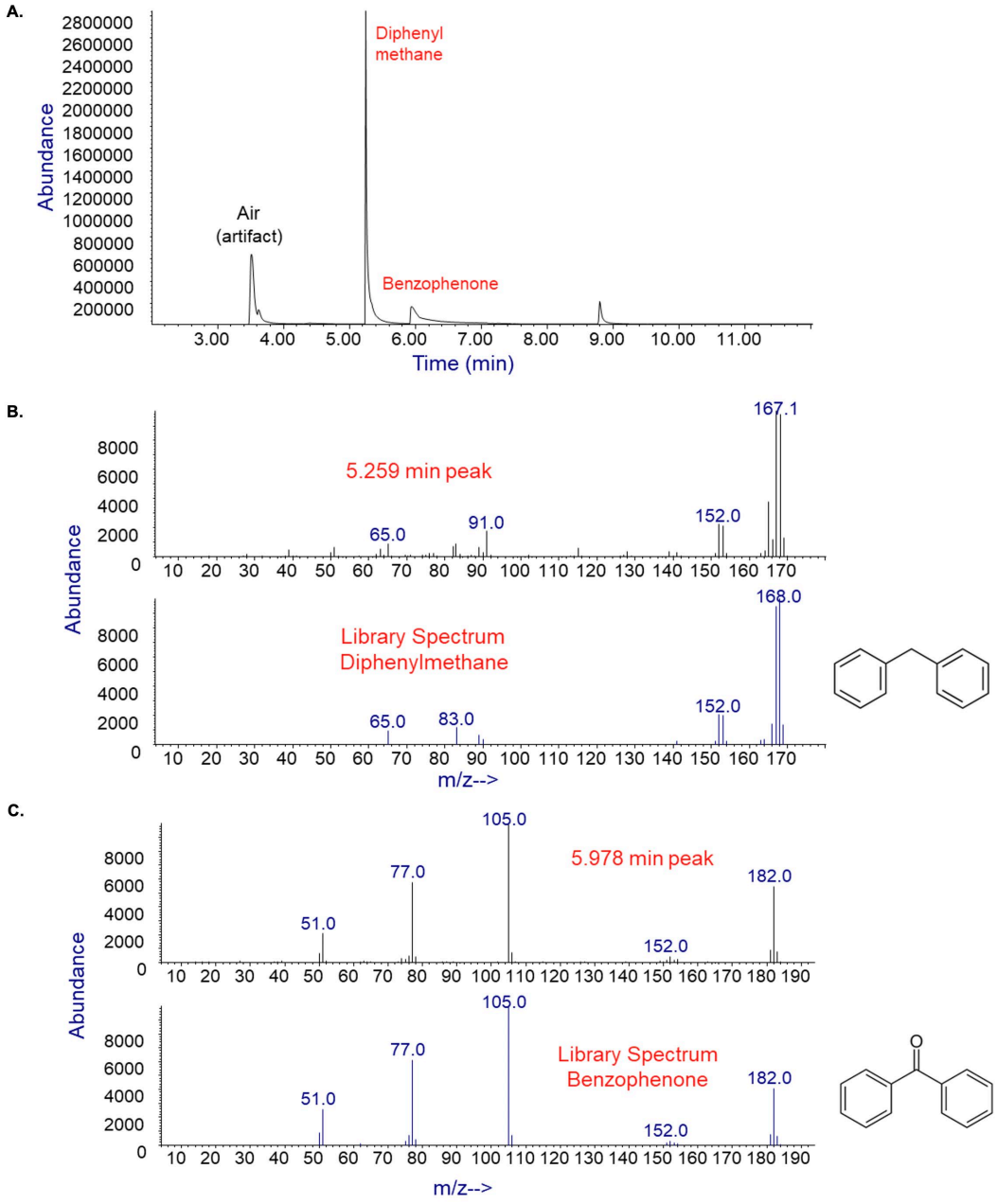

Fig. 10 (A) GC trace of pyrolysis desorption products of 2 obtained at 450 °C. Mass spectra and comparative library spectra of 5.258 min peak (B) identified as diphenylmethane and 5.978 min peak (C) identified as benzophenone.

Given that the three diphenylmethyl protecting groups attached to the nitrogen atoms of the compound constitute ca. 71% of the molecular weight of the compound, and a similar loss of mass was observed by TGA by 550 °C, the black residue produced by TGA of the compound taken to 600 °C was analyzed using ATR-FTIR. This was done to determine if removal of the diphenylmethyl protecting groups, or direct polymerization of compound to give an imine-linked

polymer, could be achieved through heat alone. The infrared spectrum of the black residue was relatively featureless, giving no indication of intact amine or aldehyde groups, nor of imine (or other) groups that could result from reaction of deprotected amines with aldehydes. The compound appears to be entirely carbonized after 600 °C is reached.

4.2 Polymerization of 2 via Acid-Catalyzed Transimination

Three different acid catalysts were employed under various conditions to attempt the simultaneous deprotection and polymerization of **2** via transimination reaction to the desired 2D polymer **3**. The NMR spectra of the products of these reactions indicate that deprotection of the benzophenone imine groups to free amines occurred without further polymerization, ultimately resulting either in undesirable byproducts or in the completely deprotected monomer, 2,4,6-triaminobenzene-1,3,5-tricarbaldehyde (**4**).

The first method utilized 6 M acetic acid solution in a 1:1 mixture of 1,4-dioxane/mesitylene. The solvents 1,4-dioxane and mesitylene were selected because they are thought to be excellent solvents for traditional covalent organic framework formation and have been used in the past for successful imine COF synthesis from removal of benzophenone imine groups.[7] The acetic acid method resulted in the production a brown solid, which was identified as the completely deprotected monomer **4** by ^{1}H and ^{13}C NMR (Figs. 11 and 12). Figure 11 shows the distinctive aldehyde resonance at 9.94 ppm and NH_2 exchange peak at 9.02 ppm, and lacks any additional resonances, indicating the successful cleavage of benzophenone. Complete hydrolysis of the benzophenone imine groups to free amine and benzophenone can probably be attributed to the presence of water in the 6 M acetic acid, which is more reactive toward the benzophenone imine groups than are the imine groups toward each other. The integration values of the aldehyde and amine exchange are 1:1.69, which is close the expected ratios of 1:2. The integration ratio discrepancy can likely be attributed to solvent interaction with the exchange peaks resulting in a deduction in its total integration value.

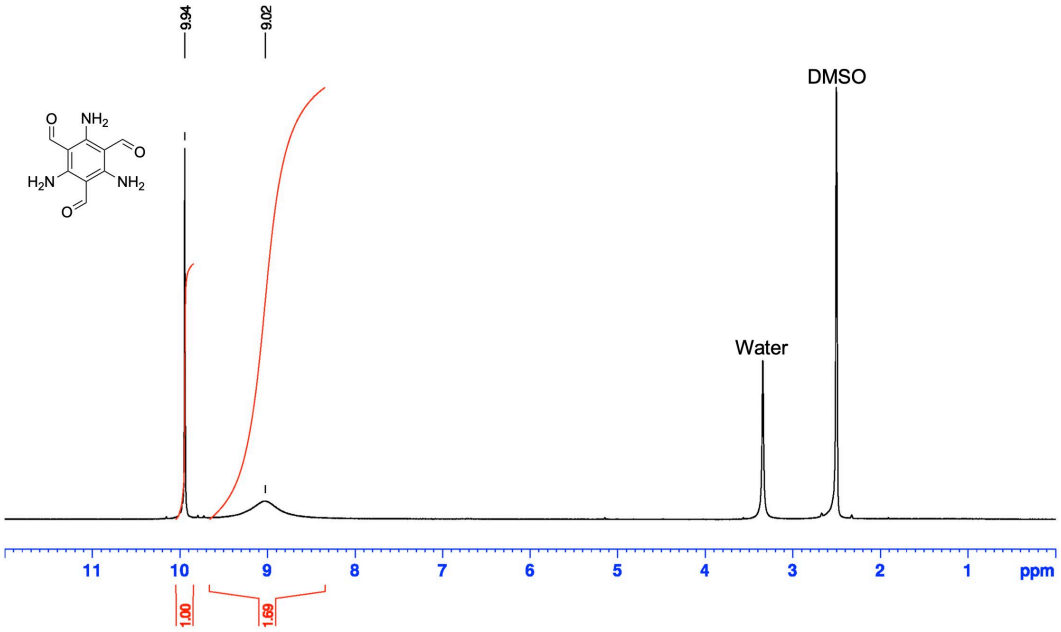

Fig. 11 ^{1}H NMR of 4, collected on a 500-MHz spectrometer in DMSO-d_6

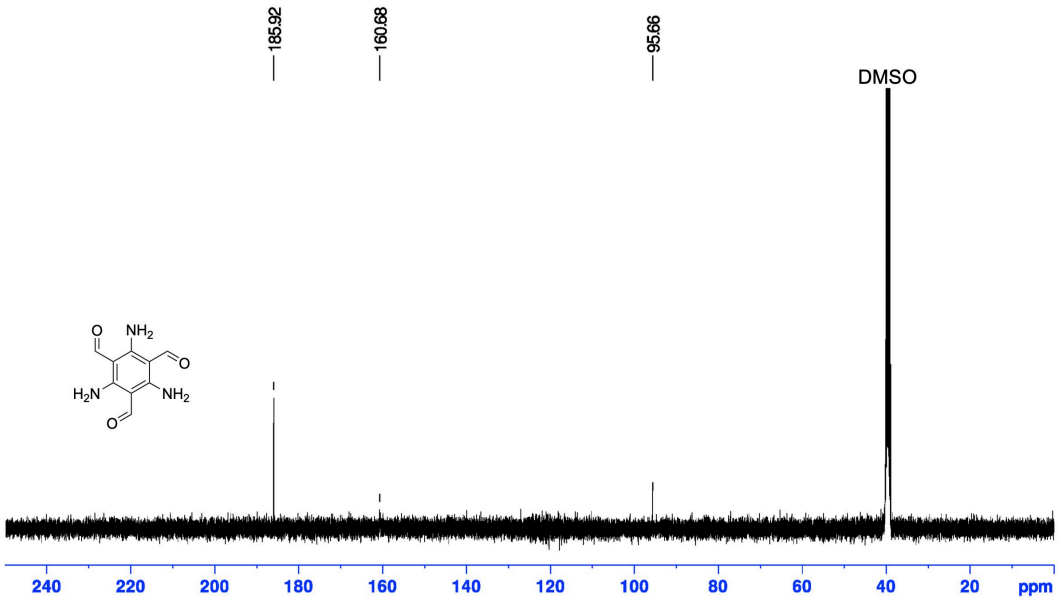

Fig. 12 ^{13}C NMR of 4, collected on a 400-MHz spectrometer in DMSO-d_6

^{1}H NMR analysis of the remaining reaction solutions from the acetic acid method indicated formation of benzophenone (500 MHz, $CDCl_3$) δ = 7.80–7.78 (d, 4H), 7.59–7.56 (t, 2H), 7.48–7.45 (t), where the last peak integrates to a value of 7.51 as it is shared with residual **2** (Fig. 13). Three distinct aldehyde peaks are also

observed, which corresponded to 1) unreacted **2**, 2) partly deprotected **2**, and 3) the aldehyde neighboring a protonated imine bond (NH–CH), which also result in the appearance of the single at 5.11 ppm (benzene–NH–C**H**).

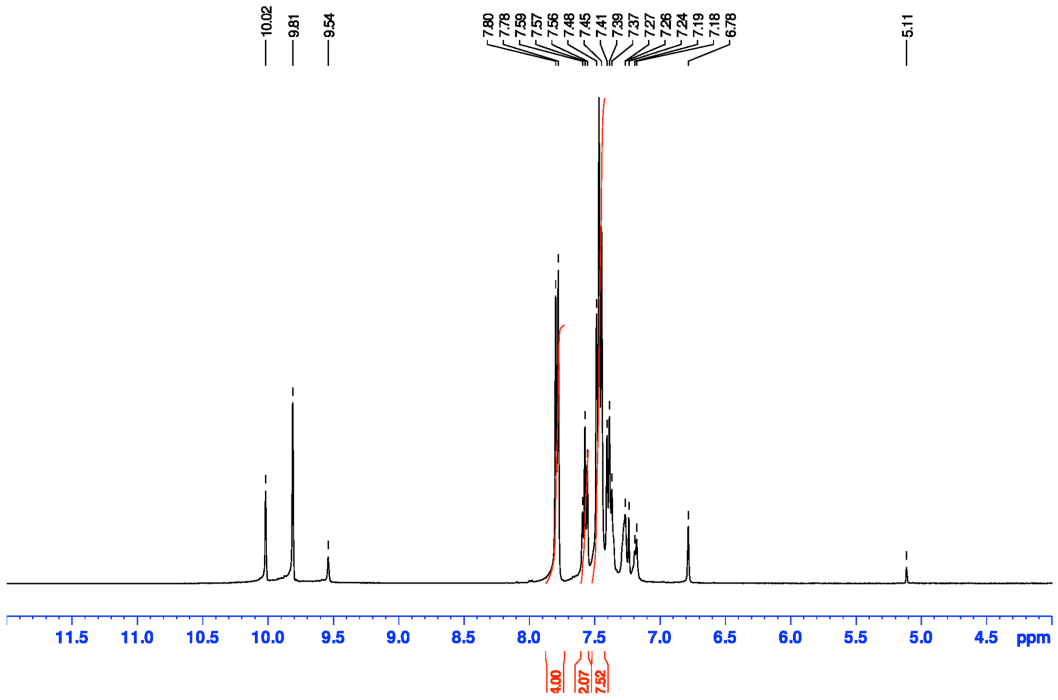

Fig. 13 **^{1}H NMR filtrate from acetic acid method, collected on a 500-MHz spectrometer in $CDCl_3$**

The second method utilized $Sc(SO_3CF_3)_3$ as the acid catalyst under anhydrous conditions. Past reports indicate that metal triflates are more efficient than acetic acid for the production of imine-linked covalent organic frameworks.[8] As with the first method, benzophenone was produced, as indicated by the NMR spectrum (500 MHz, $CDCl_3$) δ = 7.80–7.78 (d, 4H), 7.59–7.56 (t, 2H), 7.48–7.45 (t, 4H) (Fig. 14). Furthermore, the appearance of a singlet at 5.11 ppm indicates the formation of an imine bond complexed with an acid catalyst, as previously seen with the first method. However, there appears to be limited evidence of free amine formation, as seen by the exchange peak at 9.52 ppm, which is overlapped by an additional peak at 9.58 ppm. The majority of the product appears to have been converted to 2,4,6-tris(benzhydrylamino)benzene-1,3,5-tricarbaldehyde, containing a protonated imine.

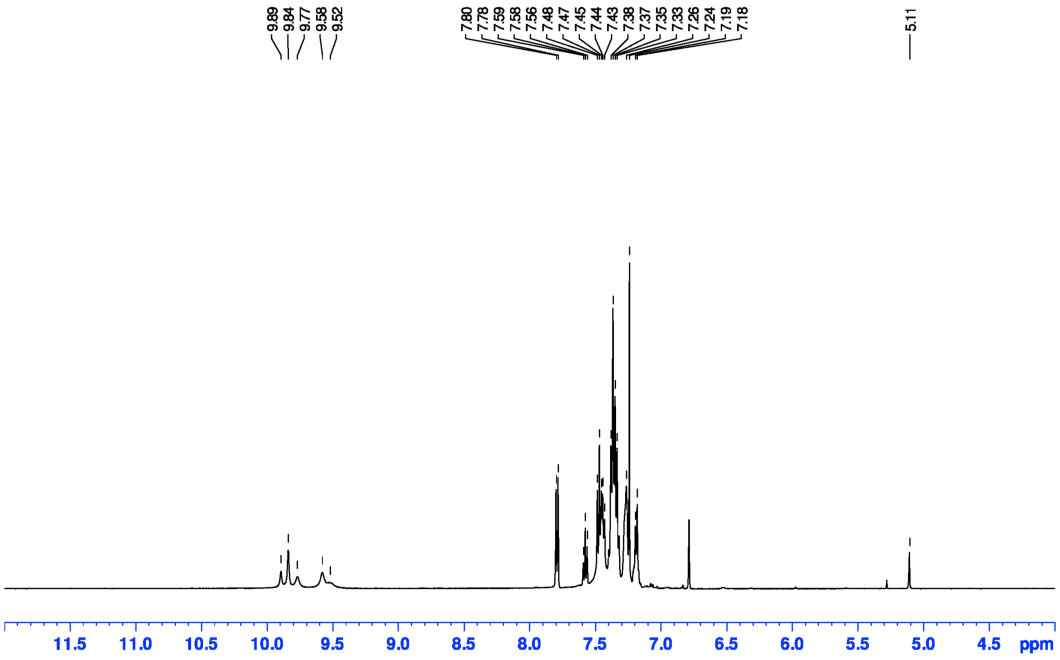

Fig. 14 ^{1}H NMR of the crude reaction mixture from metal triflate method, collected on a 500-MHz spectrometer in $CDCl_3$

The third method, which used neat HCl as the acid catalyst to avoid the introduction of water to the reaction, also did not produce the desired 2D polymer, and the free amine monomer **4** was not isolated from the reaction. Benzophenone from the partial deprotection of **2** was observed in the NMR spectrum (500 MHz, $CDCl_3$) δ = 7.80–7.78 (d, 4H), 7.59–7.56 (t, 2H), 7.48–7.45 (t, 4H), as well as NH_2- exchange peaks at 9.60 and 9.17 ppm, as a result of the partial deprotection of **2** (Fig. 15). Additionally, residual **2** is seen with aldehyde resonances at 10.04 ppm and aromatic resonances at 7.53–7.51 and 7.47–7.46 ppm.

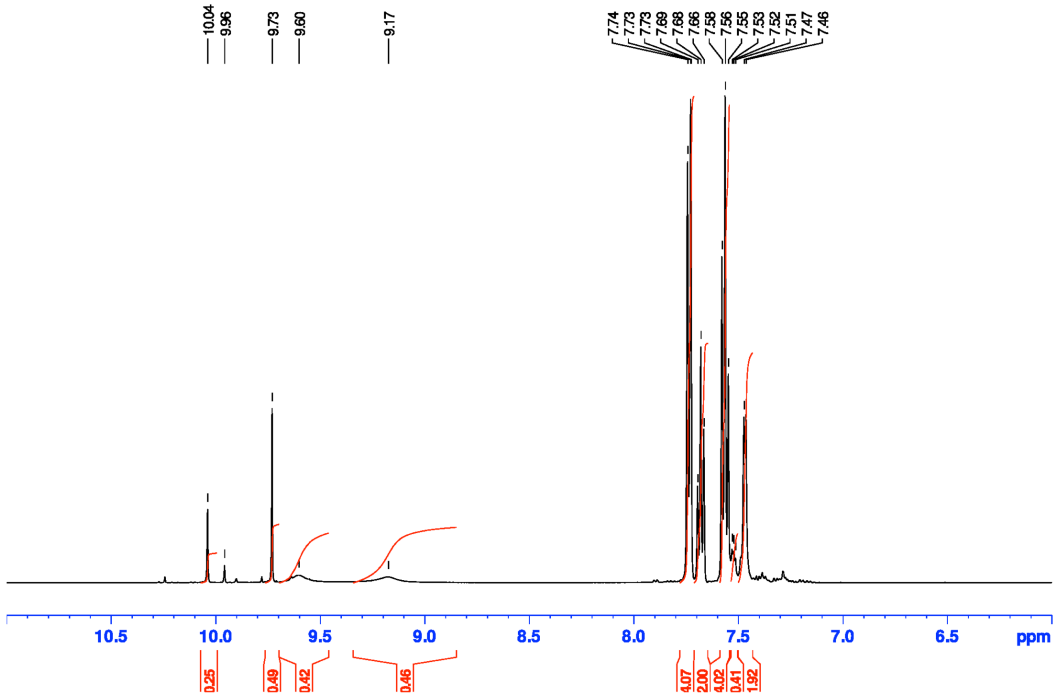

Fig. 15 **^{1}H NMR of mixture of reaction products from neat HCl method, collected on a 500-MHz spectrometer in $CDCl_3$**

5. Conclusions and Future Directions

Starting from Rubin's aldehyde, **1**, Buchwald–Hartwig coupling with benzophenone imine was used to synthesize the novel, hexa-functional monomer 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde, **2**. Several acid catalysts were used to attempt simultaneous deprotection of the benzophenone imine and polymerization of **2** via transimination reaction. There is no indication that these initial attempts resulted in the desired 2D polymer graphimine **3**; however, reaction of the monomer with water in the presence of an acid catalyst produced to varying degrees the completely deprotected, free amine monomer 2,4,6-triaminobenzene-1,3,5-tricarbaldehyde **4**. As it is now evident that **4** is relatively stable, future efforts are being directed toward synthesizing this molecule directly in a much more atom-efficient manner than is possible with the benzophenone-protected monomer **3**, and subsequently polymerizing it to form graphimine **3**, which may then be further transformed to graphamid.

6. References

1. Garcia JM, Garcia FC, Serna F, de la Pena JL. High-performance aromatic polyamides. Prog Polymer Sci. 2010;35:623–686.
2. Sandoz-Rosado E, Beaudet TD, Andzelm JW, Wetzel ED. High strength films from oriented, hydrogen-bonded "graphamid" 2D polymer molecular ensembles. Sci Rep. 2018;8:3708.
3. Lustig SR, Andzelm JW, Wetzel ED. Highly thermostable dynamic structures of polyaramid two-dimensional polymers, Macromolecules. 2021;54:1291–1303.
4. Geng K, He T, Liu R, Dalapata S, Tan KT, Li Z, Tao S, Gong Y, Jiang Q, Jiang D. Covalent organic frameworks: design, synthesis, and functions. Chem Rev. 2020;120:8814–8933.
5. Waller PJ, Lyle SJ, Osborn Popp TM, Diercks CS, Reimer JA, Yaghi OM. Chemical conversion of linkages in covalent organic frameworks. J Am Chem Soc. 2016;138:15519–15522.
6. Holst C, Schollmeyer D, Meier HZ. An efficient synthesis of Rubin's aldehyde and its precursor 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene. Naturforsch. 2011;66b:935–938.
7. Vitaku E, Dichtel WR. Synthesis of 2D imine-linked covalent organic frameworks through formal transimination reactions. J Am Chem Soc. 2017;139:12911–12914.
8. Matsumoto M, Dasari RR, Ji W, Feriante CH, Parker TC, Marder SR, Dichtel WR. Rapid, low temperature formation of imine-linked covalent organic frameworks catalyzed by metal triflates. J Am Chem Soc. 2017;139:4999–5002.

Appendix. Supplementary Information

Figures A-1 through A-3 are additional ^{1}H and ^{13}C nuclear magnetic resonance (NMR) spectra, and Figure A-4 includes photographs of isolate products.

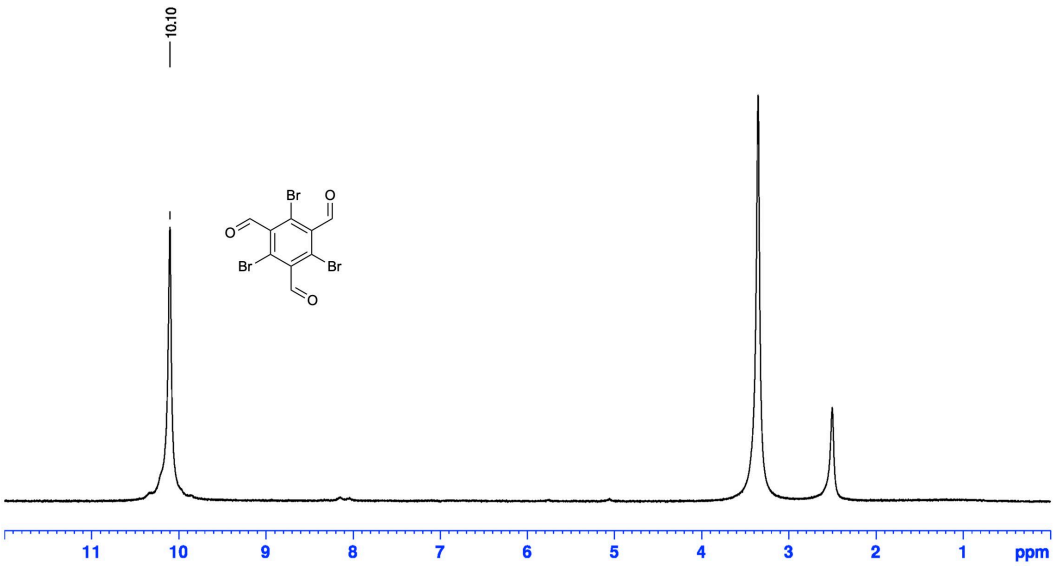

Fig. A-1 ^{1}H NMR (400-MHz) of Rubin's aldehyde, 1, in deuterated dimethylsulfoxide (DMSO-d_6)

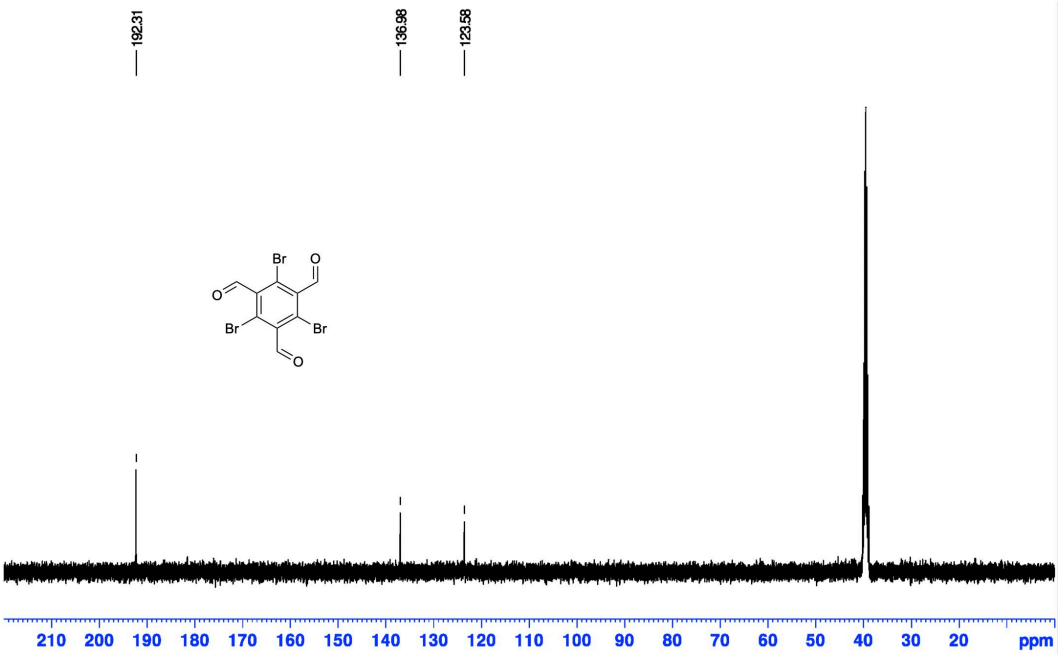

Fig. A-2 ^{13}C NMR (400-MHz) of 1 in DMSO-d_6

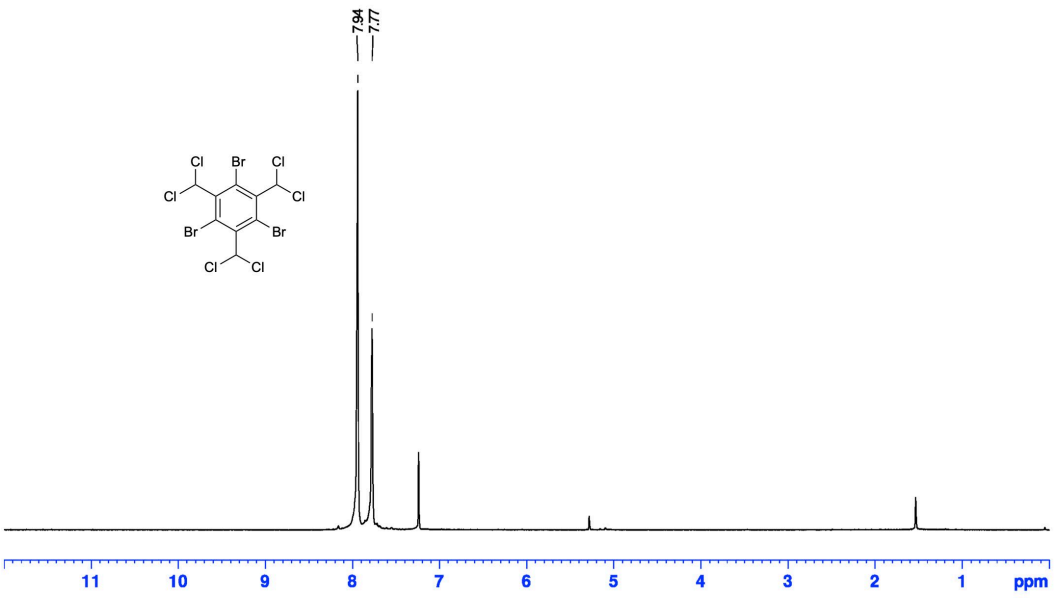

Fig. A-3 ^{1}H NMR (500-MHz) of 1,3,5-tribromo-2,4,6-tris(dichloromethyl)benzene in $CDCl_3$

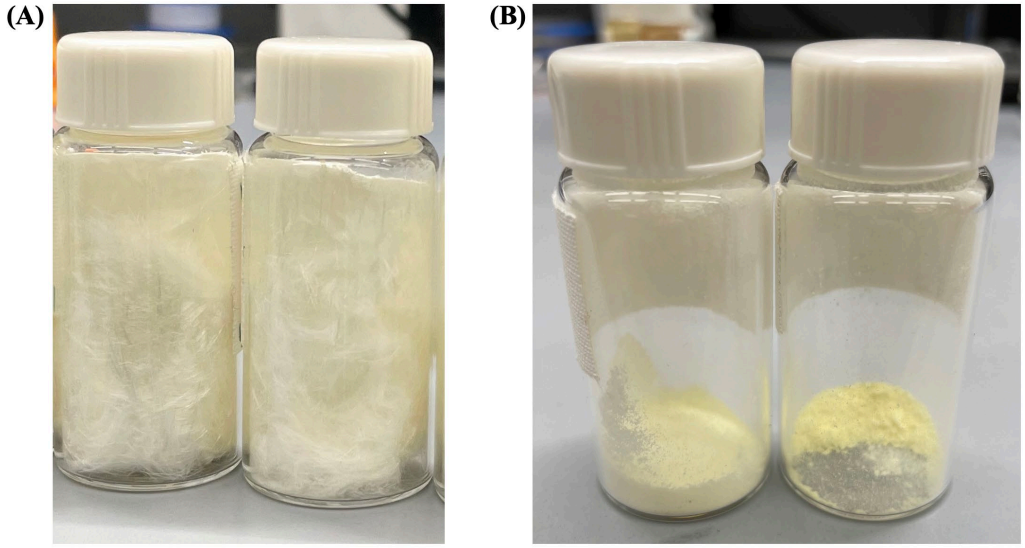

Fig. A-4 Isolate products: (A) Rubin's aldehyde, 1, as white needle crystals and (B) 2,4,6-tris((diphenylmethylene)amino)benzene-1,3,5-tricarbaldehyde, 2, as light-yellow powder

In addition to the successful Buchwald–Hartwig coupling method that is documented within the Section 2, Experimental Methods, of the main report, many additional base-ligand combinations were tried and largely found to be unsuccessful. Table A-1 first documents the attempts made with 2-bromobenzaldehyde, as a simplified substrate used for initial screening of successful catalyst-ligand combinations, that were then tried with **1** as documented in Table A-2. Table A-3 then catalogs optimization of different solvent, base, time, and temperature conditions, which have resulted in the synthetic processes described in detail within Section 2 of the main report. After optimal conditions were obtained for solvent, base, and time, Table A-4 revisited additional catalyst and ligand combinations to determine if alternative routes of synthesis were viable for obtaining higher yields than the 16.6% obtained from $Pd(OAc)_2$, with 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (BINAP) and Cs_2CO_3 at 90 °C for 48 h.

Table A-1 Buchwald–Hartwig coupling reaction of 2-bromobenzaldehyde with benzophenone imine using Cs_2CO_3 as the base and toluene as the solvent

Entry	Catalyst	Ligand	Time (h)	Temperature (°C)	Yield (%)
kl01-19	$Pd(OAc)_2$	BrettPhos	3	110	8.4
kl01-27	$Pd(OAc)_2$	BINAP	48	110	97
kl01-23	BrettPhos Pd-G3	BrettPhos	16	110	0
kl01-34	$Pd(OAc)_2$	RuPhos	20	110	98
kl01-38[a]	BrettPhos 3G Pd	RuPhos	24	90	37

Notes: Reactions were performed with 150 mg of 2-bromobenzaldehyde (0.811 mmol), 1.5 eq of benzophenone imine (220 mg, 1.22 mmol), 4 mol% of catalyst, 8 mol% of ligand, and 1.4 eq of base (1.14 mmol). Yields were determined from ^{1}H NMR.
[a] kl01-38 used t-BuOH as a base instead of Cs_2CO_3.

Table A-2 Initial Buchwald–Hartwig coupling reaction conducted with 1 and benzophenone imine for 48 h at 110 °C

Entry	Catalyst	Ligand	Base	Solvent	Yield (%)
kl01-31	$Pd(OAc)_2$	BINAP	Cs_2CO_3	Toluene	10.4
kl01-38	$Pd(OAc)_2$	RuPhos	Cs_2CO_3	Toluene	0
kl01-39[a]	BrettPhos 3G Pd	RuPhos	Cs_2CO_3	t-BuOH	0
kl01-41	PEPPSI-*i*Pr-Pd	. . .	K_2CO_3	DME	0

Notes: Reactions were performed with 200 mg of **1** (0.50 mmol), 4 eq of benzophenone imine (363 mg, 2.00 mmol), 4 mol % of catalyst, 8 mol % of ligand, and 4.5 eq of base (2.25 mmol). Yields were determined from ^{1}H NMR.
[a] kl01-39 was run at 85 °C.

Table A-3 Optimization of Buchwald–Hartwig coupling reactions with 1 and benzophenone imine. Reactions were all conducted for a length of 48 h with $Pd(OAc)_2$ as the catalyst and BINAP as the ligand.

Entry	Solvent	Base	Temperature (°C)	Yield (%)
kl01-56	Mesitylene	Cs_2CO_3	130	30
kl01-57	1,4-dioxane	Cs_2CO_3	110	16.6
kl01-59	t-BuOH	Cs_2CO_3	85	0
kl01-60	Toluene	Cs_2CO_3	110	47.7
kl01-66	Toluene	K_2CO_3	110	12

Notes: The catalyst and ligand were combined first for 30 min at 50 °C, followed by aryl-halide, base, and amine addition. Reactions were performed with 350 mg of **1** (0.878 mmol), 3.5 eq of benzophenone imine (557 mg, 3.07 mmol), 0.2 eq of $Pd(OAc)_2$ (39.4 mg, 0.176 mmol), 5 eq of BINAP (1.43 g, 4.39 mmol) and 0.25 eq of base (0.220 mmol). Yields were determined from ^{1}H NMR.

Table A-4 Further optimization of Buchwald–Hartwig coupling reactions with 1 and benzophenone imine

Entry	Catalyst	Ligand	Conditions	Yield (%)
kl01-65[a]	$Pd(OAc)_2$	BINAP	48 h, toluene, 90 °C, K_2CO_2	13
as01-08	$Pd(OAc)_2$	BrettPhos	48 h, toluene, 90 °C, Cs_2CO_2	0
as01-10	$Pd(OAc)_2$	RuPhos	48 h, toluene, 90 °C, Cs_2CO_2	4
kl01-98	$Pd_2(dba)_3$	BINAP	48 h, toluene, 90 °C, Cs_2CO_2	6
as01-12	PEPPSI-*i*Pr-Pd	. . .	48 h, toluene, 90 °C, Cs_2CO_2	5

Notes: Reactions were performed with 250 mg of **1** (0.632 mmol), 3.5 eq of benzophenone imine (400 mg, 2.21 mmol), 0.2 eq of catalyst (0.126 mmol), 5 eq of ligand (3.16 mmol) and 0.25 eq of base (0.16 mmol). Yields were determined from ^{1}H NMR.

[a] 360 mg of **1** was used and all equivalents scaled likewise.

For the Buchwald–Hartwig coupling methods, benzophenone imine was not the only amine source utilized; two additional amines sources in the form of acetamide and tert-butyl carbamate (NH_2-Boc) were briefly explored in an effort to use less-bulky protecting groups to reduce the steric strain and crowding around the central benzene ring. These efforts, although largely unsuccessful, are documented in Table A-5.

Table A-5 Buchwald–Hartwig coupling reactions with 1, using acetamide or tert-butyl carbamate as amine sources. Reactions were run for 20 h each.

Entry	Amine source	Ligand	Catalyst	Conditions	Result
kl01-47	NH_2-Boc	BrettPhos	$Pd(OAc)_2$	Cs_2CO_3, 80 °C, DME	No reaction
kl01-48	NH_2-Boc	. . .	PEPPSI-*i*Pr-Pd	K_2CO_3, 110 °C, DME	New amine peak in ^{1} NMR – low yieldin
kl01-49	NH_2-Boc	BrettPhos	BrettPhos G3 Pd	K_2CO_3, 90 °C, t-BuOH	Catalyst activation issues
kl01-51[a]	Acetamide	BrettPhos	$Pd(OAc)_2$	K_2CO_3, 85 °C, t-BuOH	No reaction
kl01-54[a]	NH_2-Boc	BINAP	$Pd(OAc)_2$	Cs_2CO_3, 125 °C, Toluene	Destruction of aldehyde

Notes: Reactions were performed with 200 mg of **1** (0.801 mmol), 4 eq of amine (3.20 mmol), 5 mol % of catalyst, 7 mol % of ligand, and 5 eq of base (4.01 mmol).
[a] 150 mg of **1** was used and all equivalents scaled likewise.

List of Symbols, Abbreviations, and Acronyms

2D	two-dimensional
ARL	Army Research Laboratory
ATR	attenuated total reflectance
BINAP	2,2′-bis(diphenylphosphino)-1,1′-binaphthyl
$CDCl_3$	deuterated chloroform
COF	covalent organic framework
DCM	dichloromethane
DEVCOM	US Army Combat Capabilities Development Command
DME	dimethoxyethane
DMSO	dimethylsulfoxide
DSC	differential scanning calorimetry
FTIR	Fourier transform infrared
GC	gas chromatography
MALDI	matrix-assisted laser desorption ionization
MS	mass spectroscopy
NMR	nuclear magnetic resonance
P	pyrolysis
PPTA	poly(*p*-phenylene terephthalamide)
rotovap	rotary evaporation
TGA	thermal gravimetric analysis
TOF	time-of-flight

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3 (PDF) DEVCOM ARL FCDD RLA MA DC MCLEOD FCDD RLA WA RA PESCE-RODRIGUEZ FCDD RLB D RH LAMBETH