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Synthesis and characterization of tetraarylporphyrins in the presence of nano-$TiCl_4 \cdot SiO_2$

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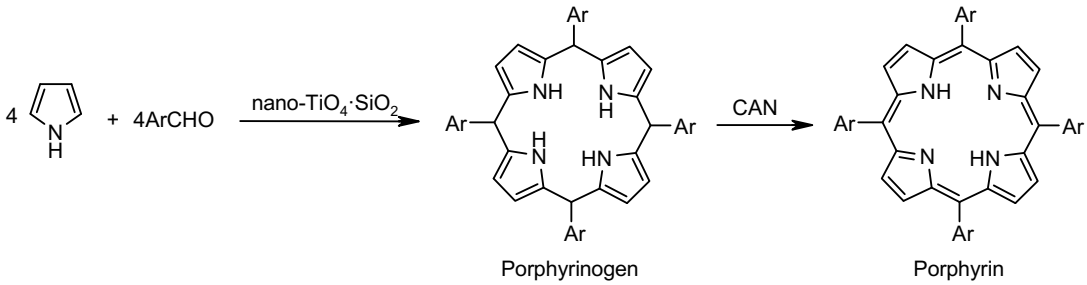


Synthesis of tetraarylporphyrins by the coupling of an aromatic aldehyde and pyrrole using nano-$TiCl_4 \cdot SiO_2$ as mild, inexpensive, and highly efficient catalyst is studied in the present article.

Keywords: aromatic aldehyde, pyrrole, tetraarylporphyrins, heterogeneous catalyst, nano-$TiCl_4 \cdot SiO_2$.

Porphyrins as important biogenic structures are found in various biologically active substances, such as hemoglobin, chlorophyll, vitamin B12, cytochromes, and are capable of DNA cleavage.[1,2] In recent years substituted porphyrins have been used in biomimetic chemistry,[3,4] medicinal chemistry,[5] analytical chemistry,[6] and molecular electronic devices.[7] Also, they are used for optical applications in e.g. data storage,[8] nonlinear optics,[9,10] electrochromism,[11] etc., which are just few of the many areas that have inspired the synthesis of porphyrin-based compounds. Porphyrins are used as catalysts,[12–14] photosensitizers,[15] nonlinear optical materials,[16] liquid crystals,[17,18] in photovoltaic cells,[19] light-harvesting complexes,[20] as well as in photodynamic therapy of cancer.[21] The increasing importance of these applications provides a continuous stimulus for intensive research towards artificial porphyrin assemblies.

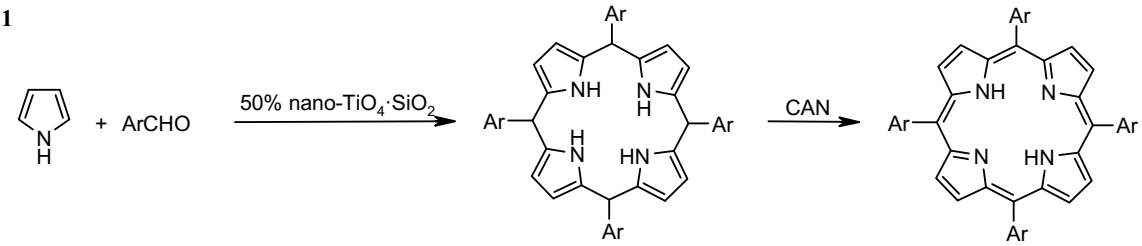
In recent years, the application of reusable heterogeneous catalysts has gained considerable importance in organic synthesis because of their environmental, economical, and industrial aspects.[22] Up to now, many reusable and heterogeneous catalysts have been designed and used. In particular, metal colloids, mineral clays, and immobilized reagents on silica gel, alumina, and other solid supports are some common examples of heterogeneous catalysts that have extensive applications in organic transformations. These catalysts have attracted a great deal of attention due to their ease of handling, enhanced reaction rates, greater selectivity, and simple work-up in most cases.

Several syntheses of *meso*-tetraarylporphyrins have been reported to proceed in the presence of catalysts such as $SOCl_2/SiO_2$,[23] PCl_5,[24] CF_3SO_2Cl,[25] silica-supported sulfuric acid (SSA),[26] and HBr/MeOH.[27] However, each method has certain restrictions with regards to scope and reaction conditions, such as costs of synthesis, unrecoverable catalysts, strong acidic conditions, long reaction times, low yields, difficult work-up, and harsh reaction conditions. To avoid these limitations, we are working towards the development of more efficient methods, that wood provide higher yields for the synthesis of tetraarylporphyrins in the presence of nano-$TiCl_4 \cdot SiO_2$.

Titanium tetrachloride, as a powerful Lewis acid, is a liquid that is highly volatile, corrosive, and difficult to handle. It is readily hydrolyzed to produce HCl in the presence of moisture. Silica-supported $TiCl_4$ has several advantages as a catalyst which makes it economically and environmentally attractive. It can be stored at ambient temperatures for months without losing its catalytic activity. This catalyst does not need special precautions for preparation, handling, storage, and use.[28–32]

In continuation of our investigations on solid-supported acids in organic synthesis,[28–32] we have investigated the synthesis of tetraarylporphyrins in the presence of various acids.

Scheme 1



1a–j **2a–j**

Table 1. Synthesis of tetraphenylporphyrin (**2a**) under various conditions. Optimization study*

Entry	Catalyst (g)	Quantity, g	Oxidant	Solvent	Tempetature	Time, h	Yield, %
1	SiO_2	0.5	CAN	CH_2Cl_2	rt	1	10
2	50% nano-$TiCl_4$·SiO_2	0.4	CAN	CH_2Cl_2	rt	1	70
3	50% nano-$TiCl_4$·SiO_2	0.2	CAN	CH_2Cl_2	rt	1	82
4	50% nano-$TiCl_4$·SiO_2	0.15	CAN	CH_2Cl_2	rt	1	81
5	50% nano-$TiCl_4$·SiO_2	0.1	CAN	CH_2Cl_2	rt	1	81
6	50% nano-$TiCl_4$·SiO_2	0.05	CAN	CH_2Cl_2	rt	1	78
7	30% nano-$TiCl_4$·SiO_2	0.1	CAN	CH_2Cl_2	rt	1	60
8	50% nano-$TiCl_4$·SiO_2	0.1	DDQ	CH_2Cl_2	rt	1	70
9	50% nano-$TiCl_4$·SiO_2	0.1	TCM	CH_2Cl_2	rt	1	65
10	50% nano-$TiCl_4$·SiO_2	0.1	Chloranil	CH_2Cl_2	rt	1	64
11	50% nano-$TiCl_4$·SiO_2	0.1	CAN	Solvent-free	rt	1	50
12	50% nano-$TiCl_4$·SiO_2	0.1	CAN	MeOH	Reflux	3	52
13	50% nano-$TiCl_4$·SiO_2	0.1	CAN	Solvent-free	rt**	1	14
14	50% nano-$TiCl_4$·SiO_2	0.1	CAN	EtOAc	rt***	30	10
15	50% nano-$TiCl_4$·SiO_2	0.1	CAN	Acetone	Reflux	3	64
16	50% nano-$TiCl_4$·SiO_2	0.1	CAN	Et_2O	Reflux	2	52
17	50% nano-$TiCl_4$·SiO_2	0.1	CAN	THF	Reflux	2	47
18	PCl_5	0.04	Aair	CH_2Cl_2	Reflux	4	62[24]
19	CF_3SO_2Cl	0.1 ml	Air	CH_2Cl_2	Reflux	4	65[25]
20	SSA	0.05	Air	CH_2Cl_2	rt	4	60[26]

* The amounts of starting materials: benzaldehyde (0.1 ml, 1 mmol, 10^{-2} M), pyrrole (0.07 ml, 1 mmol, 10^{-2} M). The resulted tetraphenylporphyrinogen (**1a**) was oxidized into the porphyrin **2a** by treating with 0.1 g of the respective oxidant in the presence of air.
** Grinding in MM 400 mixer mill at 25 Hz frequency.
*** Sonication with BANDELIN Sonopulse HD 3200 Ultrasonic apparatus at 20 KHz frequency.

Herein, we report that nano-$TiCl_4$·SiO_2 is an efficient catalyst for the synthesis of tetraarylporphyrinogens, and its efficiency is comparable with some other catalysts such as $SiO_2/SOCl_2$,[23] PCl_5,[24] CF_3SO_2Cl,[25] and SSA.[26] The synthesis and characterization of nano-$TiCl_4$·SiO_2 is published in literature.[32]

To optimize the reaction conditions, the condensation of benzaldehyde and pyrrole was used as a model reaction (Scheme 1, Table 1). Performing the process under different conditions revealed that the best result was achieved by stirring the reactants in dichloromethane in the presence of 50% nano-$TiCl_4$·SiO_2 at room temperature, while optimal catalyst loading was 0.1 g of 50% nano-$TiCl_4$·SiO_2 per 1 mmol of starting material (Table 1, entry 5). The initially formed tetraphenylporphyrinogen (**1a**) was then aerobically oxidized into tetraphenylporphyrin (**2a**) in the presence of various oxidants, among which ceric ammonium nitrate (CAN) was found to be the best one.

Next, various aldehydes and pyrrole were used as substrates for the synthesis of tetraarylporphyrinogens (Table 2). All the products are known and were characterized by

Table 2. Synthesis of tetraarylporphyrins **2a**–**j***

Porphyrin	Ar	Time, h	Yield, %	Porphyrin	Ar	Time, h	Yield, %
2a	Ph	1.0	80	**2f**	4-$O_2NC_6H_4$	0.5	94
2b	4-MeC_6H_4	1.5	74	**2g**	4-(*i*-Pr)C_6H_4	1.5	60
2c	4-ClC_6H_4	1.0	87	**2h**	2-ClC_6H_4	1.0	81
2d	4-$MeOC_6H_4$	1.0	88	**2i**	2-$MeOC_6H_4$	2.0	70
2e	4-BrC_6H_4	2.0	74	**2j**	2,4-$Cl_2C_6H_3$	1.0	91

* Reaction conditions: pyrrole (1 mmol), arylaldehydes (1 mmol), 50% nano-$TiCl_4$·SiO_2 (0.1 g). The resulted tetraarylporphyrinogens **1** were oxidized into the respective porphyrins **2** by treating with of CAN (0.1 g, 5 mol %) for 20 min in the presence of air.

IR spectra, UV-Visible and ^{1}H NMR spectra and by comparison of their physical properties with those reported in the literature.

Thus, 50% nano-$TiCl_4 \cdot SiO_2$ as an efficient, cheap, noncorrosive, and available catalyst has been used for the synthesis of tetraarylporphyrins. High to excellent yields, ease of work-up, mild reaction conditions, short reaction times, environmentally friendly procedures, and the ability to tolerate a diversity of substituents in aldehyde are features of this new procedure.

Experimental

FT-IR (ATR) spectra were recorded on a Bruker Eqinox 55 spectrometer. UV/Vis spectra were recorded on an Ultrospec 3000 V/Visible spectrometer in 1 mol/l CH_2Cl_2 solutions. ^{1}H NMR spectra were recorded on a Bruker Avance DRX-400 (400 MHz) instrument in $CDCl_3$ using TMS as internal standard. Melting points were measured with a Thermo Scientific Electrothermal digital apparatus. The chemicals were purchased from Merck and used without any additional purification.

Preparation of 50% nano-$TiCl_4 \cdot SiO_2$. To a mixture of silica gel (0.5 g) and $CHCl_3$ (5 ml), $TiCl_4$ (0.5 g, 0.29 ml) was added dropwise with stirring. The resulting suspension was further stirred for 1 h at room temperature, filtered, washed with $CHCl_3$, and dried at room temperature in air.

Synthesis of porphyrins 2a–j (General method). Pyrrole (0.07 ml, 1 mmol), aldehyde (1 mmol), 50% nano-$TiCl_4 \cdot SiO_2$ (0.1 g), and CH_2Cl_2 (20 ml) were placed in a 50 ml beaker. The mixture was stirred at room temperature within the time specified in Table 2. The progress of the reaction was monitored by TLC. After the reaction was finished, CAN (0.1 g, 5 mol %) was added to the reaction mixture and stirred at room temperature for 20 min in the presence of air while the reaction mixture became dark-purple indicating porphyrinogen conversion into porphyrin under aerobic oxidation. The solution was concentrated under reduced pressure and chromatographed on neutral alumina column eluting with CH_2Cl_2–petroleum ether, 1:1.5. Alternatively, crude solid residues obtained by the evaporation of the corresponding reaction mixtures were sequentially washed with Et_2O, hot H_2O, and cold MeOH to give pure porphyrins as purple solid.

5,10,15,20-Tetraphenylporphyrin (2a). Mp >300°C (mp >300°C)[26]. IR spectrum, ν, cm^{-1}: 3311 (br, N–H), 3053 (C–H aromatic), 2923 (C–H aliphatic), 1595 (aryl stretch), 1469 (NH bend), 1440 (C=N), 965, 792, 726, 696. UV spectrum, λ_{max}, nm (log ε): 418 (4.52), 517 (4.01), 549 (3.84), 591 (3.73), 647 (3.42). ^{1}H NMR spectrum, δ, ppm: 2.98 (2H, s, 2NH); 7.56–7.59 (12H, m, H Ar); 8.01–8.03 (8H, m, H Ar); 8.65 (8H, s, H Ar).

5,10,15,20-Tetrakis(4-methylphenyl)porphyrin (2b). Mp >300°C (mp >300°C)[26]. IR spectrum, ν, cm^{-1}: 3250 (br, N–H), 3050 (C–H aromatic), 2950 (C–H aliphatic), 1595 (aryl stretch), 1469 (NH bend), 1440 (C=N), 1100, 965, 844. UV spectrum, λ_{max}, nm (log ε): 422 (4.95), 518 (4.33), 560 (4.15), 595 (4.11), 655 (3.75). ^{1}H NMR spectrum, δ, ppm: 3.05 (2H, s, 2NH); 2.42 (12H, s, H Ar); 7.35–7.37 (8H, m, H Ar); 7.89–7.91 (8H, m, H Ar); 8.66 (8H, s, H Ar).

5,10,15,20-Tetrakis(4-chlorophenyl)porphyrin (2c). Mp >300°C (mp >300°C)[24]. IR spectrum, ν, cm^{-1}: 3350 (br, N–H), 3050 (C–H aromatic), 1550 (aryl stretch), 1469 (br, NH bend), 1440 (br, C=N), 1250, 966, 799, 750 (C–Cl). UV spectrum, λ_{max}, nm (log ε): 422 (4.88), 518 (4.35), 560 (4.12), 595 (3.84), 655 (3.62). ^{1}H NMR spectrum, δ, ppm: 3.15 (2H, s, 2NH); 7.70–7.72 (8H, m, H Ar); 7.87–7.88 (8H, m, H Ar); 8.65 (8H, s, H Ar).

5,10,15,20-Tetrakis(4-methoxyphenyl)porphyrin (2d). Mp >300°C (mp >300°C)[26]. IR spectrum, ν, cm^{-1}: 3350 (br, N–H), 3007 (C–H aromatic), 2931 (C–H aliphatic), 1460 (NH bend, C=N), 1246 (C–O), 832. UV spectrum, λ_{max} (log ε): 424 (4.85), 449 (5.23), 519 (4.47), 555 (4.24), 595 (3.84), 670 (3.36).

5,10,15,20-Tetrakis(4-bromophenyl)porphyrin (2e). Mp >300°C (mp >300°C)[25]. IR spectrum, ν, cm^{-1}: 3340 (br, N–H), 3050 (C–H aromatic), 1585 (aryl stretch), 1486 (br, NH bend), 1250, 965, 799. UV spectrum, λ_{max}, nm (log ε): 421 (5.17), 518 (5.31), 550 (4.82), 591 (4.61), 649 (3.54). ^{1}H NMR spectrum, δ, ppm: 3.17 (2H, s, 2NH); 7.54–7.55 (8H, m, H Ar); 7.92–7.93 (8H, m, H Ar); 8.65 (8H, s, H Ar).

5,10,15,20-Tetrakis(4-nitrophenyl)porphyrin (2f). Mp >300°C (mp >300°C)[26]. IR spectrum, ν, cm^{-1}: 3360 (br, N–H), 3050 (C–H aromatic), 2923 (C–H aliphatic), 1585 (aryl stretch), 1515 and 1345 (N–O stretch), 1469 (NH bend), 1200 (C=N), 785. UV spectrum, λ_{max}, nm (log ε): 422 (4.75), 517 (4.52), 548 (4.33), 590 (4.15), 650 (3.41), 676 (2.43).

5,10,15,20-Tetrakis(4-isopropylphenyl)porphyrin (2g). Mp >300°C (mp >300°C)[29]. IR spectrum, ν, cm^{-1}: 3320 (br, N–H), 3050 (C–H aromatic), 2959 (C–H aliphatic), 1500 (br, aryl stretch, C=N, NH bend), 1370 and 1380 (CH bend, *i*-Pr), 832. UV spectrum, λ_{max}, nm (log ε): 420 (5.21), 518 (4.94), 52 (4.28), 599 (3.43), 652 (2.19).

5,10,15,20-Tetrakis(2-chlorophenyl)porphyrin (2h). Mp >300°C (mp >300°C)[26]. IR spectrum, ν, cm^{-1}: 3431 (br, N–H), 3050 (C–H aromatic), 2924 (C–H aliphatic), 1564 (aryl stretch), 1468 (NH bend), 1432 (C=N), 1044, 965, 747, 707 (C–Cl). UV spectrum, λ_{max}, nm (log ε): 418 (5.80), 515 (5.51), 550 (4.22), 590 (3.81), 643 (1.20).

5,10,15,20-Tetrakis(2-methylphenyl)porphyrin (2i). Mp >300°C (mp >300°C)[26]. UV spectrum, λ_{max}, nm (log ε): 418 (5.57), 514 (4.80), 545 (4.63), 591 (4.33), 646 (3.26).

5,10,15,20-Tetrakis(2,4-dichlorophenyl)porphyrin (2j). Mp >300°C (mp >300°C)[26]. IR spectrum, ν, cm^{-1}: 3427 (br, N–H), 3090 (C–H aromatic), 1564 (aryl stretch), 1469 (NH bend), 1440 (C=N), 997, 725. UV spectrum, λ_{max}, nm (log ε): 418 (5.30), 450 (5.02), 515 (4.83), 550 (4.18), 591 (3.91), 646 (3.44).

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