A Novel One Step Synthesis of *trans*-1,4,6,9-tetraazabicyclo[4.4.0]decane over TiO$_2$/Zeolite Composite Photocatalysts

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A novel one step intermolecular cyclization of ethanol and ethylenediamine towards the formation of *trans*-1,4,6,9-tetraazabicyclo[4.4.0]decane (TAD) **3** has been achieved for the first time over TiO$_2$/zeolite composite photocatalysts using solar/artificial light at ambient temperature.

Solar energy applications cover the purification of contaminated water or air and also for the production of fine/commodity chemicals. In this regard, the SOLARIS-experiment[1,2] demonstrated the feasibility of solar photooxygenations and photocycloadditions, PROPHIS test facility for the synthesis of pyridines[3] are some of the examples demonstrated economically by solar photochemical reactions. Untill now, the only industrially important solar application is the synthesis of $\mathcal{E}$-caprolactam[4] from Toray Ltd, Japan. Also, the other classic reactions reported[5] are photoisomerizations, photoalkylation and heterocyclizations. The discovery of photo-Kolbe reaction by Kraeutler and Bard[6] using Pt/TiO$_2$ as a photocatalyst for the conversion of acetic acid to methane and CO$_2$ has resulted in many synthesis reactions in organic solvents.[7] There are few reports[8] available for the cyclization reactions on TiO$_2$ and the solar light induced synthesis of benzylated succinic acid is a recent example.[9] The reports on photocatalytic activity of TiO$_2$/zeolite composite catalyst for photoinduced organic synthesis are scarce.[10] The useful applications of TiO$_2$/zeolite composites for the organic synthesis reaction are to use the pore size and/or shape selectivity of zeolites and photocatalytic property of TiO$_2$.[11–13] Tetra-azadecalins (TAD's) have diversified applications such as vulcanization accelerators, electrographic developers and light resistant flourescent polymers.[14a] Phosphanes and polysulfides were used in earlier attempts for the synthesis of *trans*-1,4,6,9-tetraazabicyclo[4.4.0]decane resulting in small amounts and also known to be corrosive, hazardous and have detrimental effects on the environment.[14b] A group of substituted derivatives of the tetraazadecalin (TAD) system has been reported.[14c–d] As a part of our continued effort towards the synthesis of N-heterocyclization reactions[15] with TiO$_2$/zeolite composite catalysts, we report here the use of solar as well as an artificial light source for a novel and eco-friendly intermolecular cyclization of ethanol and ethylenediamine to form *trans*-1,4,6,9-tetra-azabicyclo[4.4.0]decane (TAD) **3** at ambient temperature for the first time to the best of our knowledge.

The catalysts were prepared as described elsewhere.[15] The respective catalysts were suspended in a mixture of ethanol (5.8 ml) and ethylenedia-mine (13.4 ml) in 1 : 2 molar ratio respectively in acetonitrile (20 ml) solvent. The suspension was magnetically stirred and irradiated under constant stream of molecular oxygen bubbles (20 ml h^{-1}) at room temperature using a 250 W high pressure mercury lamp ($\lambda > 300$ nm) in a cylindrical round bottomed quartz photoreactor of 200 ml capacity ($\varnothing = 2$ cm, L = 20 cm) equipped with a refluxing condenser at the top. The reaction mixture was centrifuged after the irradiation (ca. 15 h) to remove the catalyst.

Experiments using solar light optimised to ca. 40 h of exposure (May, 2001, Hyderabad) yielded compound **3**. The total acidity of the catalysts were measured as described elsewhere.[15] In order to ascertain the versatility of TiO$_2$ and TiO$_2$/zeolite composite catalysts parallel experiments were also carried out using ZnO,[16] along with ZnO/Zeolite composite catalysts and the results are depicted in Table 1.

Table 2 shows the control experiments performed to confirm the oxidative condensation of ethanol and ethylenediamine, which requires light, TiO$_2$/zeolite and oxygen for the formation of **3**. Irradiation, when

Table 1. The results on cyclization of ethanol and ethylenediamine (1:2 molar ratio) over TiO$_2$/zeolite composition catalysts

Catalyst	Surface Area[a] m^2 g^{-1}	Acidity[b] mmol g^{-1}	Yield of **3**[c] /%[e]	Yield of **3**[d] /%[e]
2 wt% TiO$_2$-HZSM-5(30)[f]	350	0.37	16.8	14.5
5 wt% TiO$_2$-HZSM-5(30)	320	0.32	19.5	16.5
2 wt% TiO$_2$-HZSM-5(90)	340	0.44	18.9	15.3
5 wt% TiO$_2$-HZSM-5(90)	326	0.40	20.6	17.9
2 wt% TiO$_2$-HY(4.4)	400	0.25	12.8	10.5
5 wt% TiO$_2$-HY(4.4)	341	0.20	13.5	11.6
2 wt% TiO$_2$-Hβ(20)	406	0.26	21.5	18.6
5 wt% TiO$_2$-Hβ(20)	400	0.24	28.6	21.6
2 wt% TiO$_2$-Hβ(30)	495	0.43	23.0	20.0
5 wt% TiO$_2$-Hβ(30)	485	0.47	35.0	25.6
2 wt% ZnO-HZSM-5(30)	326	0.13	10.5	8.5
2 wt% ZnO-HY(4.4)	336	0.18	6.0	2.0
2 wt% ZnO-Hβ(30)	490	0.40	13.5	10.0
TiO$_2$	50	—	—	—
ZnO	30	—	—	—

[a]BET techinique measured with liquid N$_2$ at -196 °C. [b]TPD of NH$_3$ measured on AutoChem 2910 (Micromeritics U.S.A.). [c]Artificial irradiation (15 h; 250 W HP mercury lamp.). [d]Solar irradiation (40 h). [e]Isolated yield and reproduced for 3 cycles of catalyst reuse. [f]SiO$_2$/Al$_2$O$_3$ ratios of zeolites are shown in parenthesis.

Table 2. Control experiments for the photocatalytic synthesis of compound **3**

Conditions	Irradiation Period /h	Yield of **3** /%
TiO$_2$/Zeolite, Light, O$_2$	15[a], 40[b]	35.0[a]; 25.6[b]
TiO$_2$/Zeolite, Dark, O$_2$	> 15 and 40	0
Light, O$_2$	> 15 and 40	0
Zeolite, Light, O$_2$	> 15 and 40	0
TiO$_2$ or ZnO, Light, O$_2$	> 15 and 40	0

[a]Artificial irradiation (15 h; 250 W HP mercury lamp). [b]Solar irradiation (40 h).
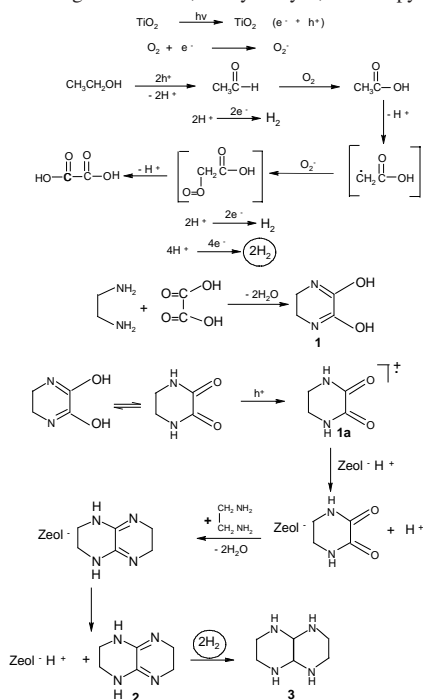
carried out using a conventional liquid acid (HCl) or silicagel (soid acid) as a photocatalyst did not yield any product. However, when ethylenediamine and oxalic acid were irradiated with similar conditions as mentioned above, it was observed that the formation of **3** resulted in a very low yield (2%).

The evaluation of the TiO$_2$/zeolite composite catalysts in the present cyclization of ethanol and ethylenediamine show alterations in the yields (Table 1) of compound **3** over the three zeolites studied and light source. The internal structure of the three different types of zeolites (Y, HZSM-5 and Hβ) which are utilized to support TiO$_2$ vary in pore size and shape. The zeolite supports reveal that, to obtain a high selectivity of the product, one should utilize a reaction cavity that was large enough to respond to the shape changes that occured along the reaction coordinate but at the same time were hard and small enough to provide relatively different extents of restriction on various reaction pathways available to the reactive intermediates[17–19] existing during the reaction. It seems that the moderate hydrophobicity and acid site strength of the TiO$_2$/zeolite composite is favouring the present cyclization reaction. Also the structure of the Hβ-zeolite may be helping to attain the maximum yield of **3** with artificial (35.0%) and solar light (25.6%), as it is known that Hβ is a combination of both HZSM-5 (channel pore system, high Si/Al ratio) and Y (12-ring pore system) zeolites.[20] Also, the high yield of **3** obtained with artificial light source in comparison to solar light may be attributed due to the high intensity of the UV component in artificial light. The amount of UV radiation in sunlight is less than 5%, in particular at $\lambda < 350$ nm it is almost negligible. In view of this, higher exposure times (ca. 40 h) are required for the product formation **3** with sunlight. The stoichiometry of the reaction requires one mole of ethanol and

2 moles of ethylenediamine for the formation of **3**. The intermediates observed are oxalic acid (m/z – M^+ 90, GC/MS) and 2,3-dihydroxy 5,6-dihydropyrazine **1** (m/z – M^{+1} 117, GC/MS). Compound **1** formed during the photocatalytic reaction of ethylenediamine and ethanol is due to the reaction between ethylenediamine and oxalic acid (generated *in situ*) as shown in Scheme 1. It is believed that in all probability the tendency of desorbing the formed oxalic acid (*in situ*) by the TiO$_2$/zeolite composite catalyst in a controlled way of release to react with ethylenediamine is helping to obtain the desired product **3** in said yields (Table 1) while minimizing the unwanted reactions when compared to the yields (2%) of reaction between ethylenediamine and oxalic acid.

The ^{1}H-NMR, ^{13}C-NMR and elemental analysis (C, H, N) data for compound **3** obtained are in well agreement (with only small differences in the ^{13}C chemical shifts) with the literature reported data.[14]

It is reported that alcohols are oxidized to aldehydes or ketones on TiO$_2$ upon irradiation and the oxidation is accompanied by liberation of hydrogen[21] as shown in Scheme 1. In the presence of oxygen, the electrons in the conduction band of the excited TiO$_2$ are captured by oxygen to give oxidative species capable of oxidizing the adsorbed aldehyde to carboxylic acid.[22] Our control experiments also demonstrate that photooxidation of alcohol is initiated by the excitation of the semiconductor only, and no oxidation products of the ethylenediamine were observed. As reported earlier[23] in the preparation of substituted benzimidazoles *via* a semiconductor mediated photocatalytic process, the reduction product of *o*-dinitrobenzene and the oxidation product of an alcoholic solvent are coupled. Although the coupled reactive intermediate can be easily hydrolyzed via an equilibrium with water, the ring closure process pushes the reaction further to the final product. As mentioned by Somrani *et al.* and even in the present case it is attributed that the acidity of zeolite is influencing the reaction and the corresponding oxidation.[10] A plausible reaction mechanism for the formation of **3** is outlined in Scheme 1. It has been observed and presumed that ethylenediamine being a basic reactant completely is adsorbed on the acidic zeolite, while the ethanol undergoes oxidation to acetaldehyde[21] and aldehyde in turn is oxidized to acetic acid.[24] The acid by subsequent loss of H^+ and immediate attack of oxygen affords in *endo* peroxide moiety and on further loss of another H^+ forms oxalic acid. The oxalic acid generated *in situ* reacts with the first molecule of ethylenediamine to give rise to 2,3-dihydroxy-5,6-dihdropyrazine **1** (first

ring closure reaction). The water that has been formed (Scheme 1) subsequently, neither deactivates the catalyst nor interferes in the forward reaction being highly miscible in the reaction medium. In turn **1** is attacked by the hole created on the titania and forms 2,3-dihydroxy-5,6-dihydropyrazine radical **1a**, and it is stabilized by the zeolite which ultimately looses a proton as reported by Beaune *et al.*[10] It is recognized that zeolite catalysts can stabilize the reactive intermediates in several photochemical reactions.[25] The zeolite bound **1** may exist in keto-enol forms and react with the second molecule of ethylenediamine to yield pyrazino[2,3-b] piperazine **2** (second ring closure) and is released from the zeolite. Subsequently, it is assumed that the *in situ* absorbed and diffused H$_2$ (reduction process) in the reaction medium forms the desired product **3** as shown in Scheme 1.

In conclusion, the present results provide potentially new mode of photocatalytic synthetic application for N-heterocyclic compounds. For the first time the formation of **3**[26] by cyclization at ambient temperature is reported in photocatalysis. Further work is in progress for the synthesis of **3** (TAD) derivatives.

Scheme 1. A plausible reaction mechanism for the formation of *trans*-1,4,6,9-tetraazabicyclo[4.4.0]decane.

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26 Compound **3** (TAD) was characterized by (^{1}H-NMR, ^{13}C-NMR, MS), elemental analysis (CHN) and melting point. ^{1}H-NMR (D$_2$O): δ = 2.79 (dd, J = 13.0, 13.0 Hz, 4H), 2.94 (dd, J = 13.0, 13.0 Hz, 4H), 3.24 (s, 2H); ^{13}C-NMR (D$_2$O): δ = 47.40, 75.72; MS (EI): m/z 142 [M^+]; Found: C, 50.10; H, 9.83; N, 39.87%. Calcd for C$_6$H$_{14}$N$_4$: C, 50.70; H, 9.85; N, 39.43%. m.p. = 164–166 °C.