



Selectivity engineered phase transfer catalysis in the synthesis of fine chemicals: reactions of *p*-chloronitrobenzene with sodium sulphide

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Abstract

Synthesis of chemicals from the same starting material wherein more than one step involving complex reactions are involved can be engineered to produce selectively the desired product by minimising both the by-product formation and separation stages. Several products of industrial importance can be produced from the same starting material by choosing proper conditions and nature and number of phases. The reduction of *p*-chloronitrobenzene with sodium sulphide was investigated in detail under different modes of phase transfer catalysis (PTC), such as liquid-liquid (L-L), liquid-solid (L-S reaction), and liquid-liquid-liquid (L-L-L) processes. This selectivity engineered PTC reaction has been investigated from mechanistic viewpoint and the rationale of selectivity is delineated.

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1. Introduction

In pharmaceutical and fine chemical industries, as also specialty, dyestuff, agrochemical and fragrance industries, multi-step and multi-phase batch reactions are frequently encountered [1,2]. A challenging aspect of multi-stage synthesis is that the complexity of the process goes on increasing with each additional stage thereby affecting the desired selectivity because as the number of functional groups and the number of chemically reactive centres in the molecule increase, steric

hindrances increase and the thermal stability of compounds decrease.

The basic building blocks in multi-step synthesis are mostly aromatic compounds with incorporation of such groups as halo, $-\text{NH}_2$, $-\text{OH}$, $-\text{NO}_2$, $-\text{SO}_3\text{H}$, alkyl, acyl, aryl, etc. which change the reactivity of the cyclic compound and some times the colour and odour of the final compound. Multi-step synthesis is typically done via routes which do not take into account the atom economy or the amount and nature of co-products or by-products. Catalysis, if any, is limited to homogeneous catalysis involving highly corrosive substances posing disposal problems. Use of solvents is also very common. Some of the important pre-cursors used in these industries are: aniline, acetanilide, benzyl chloride, benzoic acid,

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monochlorobenzene, chloronitrobenzenes, cresols, cresylic acid, cumene, cyclohexane, cyclohexanone, dichlorobenzenes, dihydroxbenzenes, dimethyl sulfate, ethylbenzene, bisphenol-A, α -methyl-styrene, nitrobenzene, nonylphenol, xylenes, phenol, phthalic anhydride, pyridine, picolines, salicylic acid, etc. [3]. From the process economics and environmental viewpoints, the intensification of reaction rates and enhancement of selectivities can be achieved through selectivity engineering principle [3] which adopts the following strategies:

- (a) in a biphasic reaction, addition of a third solid phase (porous or non-porous and/or catalytic or non-catalytic), with particle size smaller than diffusion film thickness. The triphasic system can lead to an enhancement in rates by orders of magnitude with reference to the original gas-liquid, and liquid-liquid systems (micro-phase catalysis);
- (b) converting a liquid-liquid reaction into liquid-liquid-liquid or liquid-liquid-solid phase transfer catalysis;
- (c) heterogenising a homogeneous catalyst;
- (d) cascade engineering or single pot synthesis;
- (e) eclectically engineered composite catalysts;
- (f) deliberate incorporation of mass transfer and/heat transfer resistance;
- (g) on a larger scale, integration of different plants on the same site to achieve environmental goals.

Phase transfer catalysis (PTC) is now a mature technique covering some 600 processes and majority of these are conducted under liquid-liquid conditions [4–6]. The intensification of L-L PTC reactions and the selectivity can be greatly altered by converting the same reaction as a solid-liquid reaction where either of the phases could be organic or inorganic. A small quantity of aqueous phase in a solid (inorganic)–organic liquid phase leads to enhancements in reaction rates and this is termed as the omega phase. A detailed mechanistic picture is provided recently [7]. In liquid-liquid-liquid phase transfer catalysis (L-L-L PTC), the third liquid phase is the main reaction phase [8–13]. The advantages of L-L-L PTC over normal PTC are: (i) increase in reaction rates by orders of magnitude; (ii) easier catalyst recovery and reuse; (iii) the catalyst need not be bound to a solid support; (iv) better selectivity, hence the attendant difficulties of reduced activity and me-

chanical strength associated with liquid-liquid-solid (L-L-S) PTC can be avoided. However, the disadvantages of L-L-L PTC are: (i) more amount of catalyst is required, which is expensive; (ii) the method is not applicable for systems where a very high temperature is required to carry out the reaction. As the temperature increases, the stability of third liquid phase decreases. However, if the catalyst is stable, then by lowering the temperature at the end of the reaction it could be easily separated into a third phase for recovery and reuse. Synthesis of *p*-nitroanisole (PNA), *p*-nitro-phenetole (PNP) and *p*-butoxynitrobenzene from *p*-chloronitrobenzene (PCNB), sodium hydroxide and methanol, ethanol, *n*-butanol, respectively, was found to be very selective and efficient with tetrabutylammonium bromide (TBAB) as catalyst under the L-L-L PTC systems [9,10] in comparison with the liquid-liquid PTC. The nature and concentration of catalyst and the amount of sodium hydroxide are important factors which influence the formation of the third liquid phase (catalyst-rich middle phase) and distribution of catalyst. It was observed that the third liquid phase was the main reaction phase but at a certain critical concentration of the catalyst, sodium hydroxide was formed as the third phase. The reuse of the third phase is important from economical point of view and it is found that the third phase can be reused effectively.

1.1. Selectivity engineered phase transfer catalysis (SEPTC)

The above mentioned selectivity engineered principles can be applied to PTC under L-L, L-S (reactant), L-L-S (bound catalyst) and L-L-L phase transfer catalysis for certain molecules such as chloronitrobenzenes or benzyl chloride to produce a variety of chemicals [14–16]. In order to study selectivity engineering with phase transfer catalysis, chlorobenzenes could be used as the starting materials. Both the chloro and nitro groups could be manipulated to obtain a variety of products, all having commercial values (Fig. 1). The sulphide reduction of chloronitrobenzenes could lead to chloroanilines, aminophenols, aminothiophenols or substituted diphenyl sulphides or polysulphides or mixture thereof in the presence of Na₂S under alkaline condition using a suitable PTC. The PTC could be used under L-L, S-L, L-L-L and

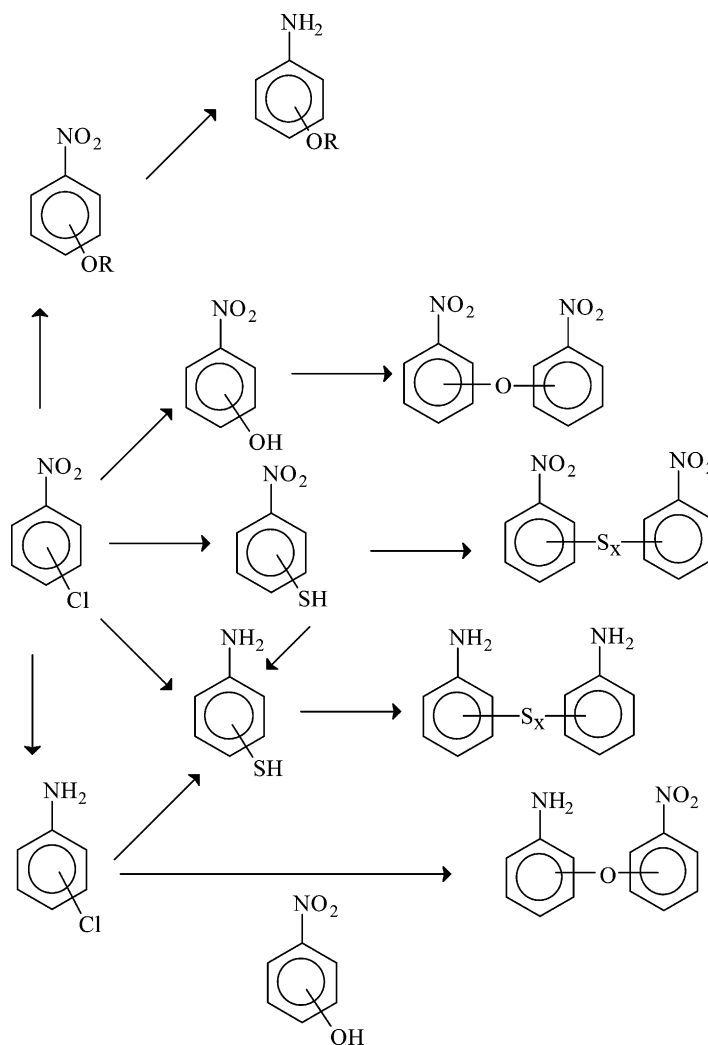


Fig. 1. Possible products of cascade engineered PTC reaction of chloronitrobenzene.

L-L-S (catalyst) and depending on the type of the system used, the product selectivity could be varied. Chloronitrobenzenes could be hydrolysed to form nitrophenols, which may give dinitrophenylethers by combining with either chloronitrobenzene or another molecule of nitrophenol. Nitrophenols and the corresponding ethers are important intermediates in organic process industry. Chloronitrobenzene could be reduced to form chloroaniline which could further yield aminothiophenol, if sodium sulphide or bisulphide is used as the reducing agent. Aminothiophenol is an important chemical used as photographic de-

veloper, intermediate in the manufacture of sulphur and azo-dyes and in the dyeing of furs and feathers. Aminothiophenol is mainly used as corrosion inhibitor in structural steels, copper and in preparation of many intermediate chemicals.

During sulphide reduction some other products are likely to be formed. These are the thioethers or sulphides, such as dinitrodiphenyl sulphide or polysulphides and diaminodiphenyl sulphide or its polysulphides, from the corresponding thiols. Certain other combinations are also possible, such as addition of one aminothiophenol and one nitrothiophenol to

yield aminonitro diphenyl sulphide or polysulphide. These are useful as corrosion inhibitors.

In this context, it would be worthwhile to review the earlier work on related compounds. Hydrolysis of *p*-chloronitrobenzenes with aqueous sodium hydroxide was studied at temperature of 100–160 °C using cuprous oxide and manganese dioxide as the catalyst to obtain more than 98% yield with complete conversion [17]. Reuter et al. [18] prepared alkali metal nitrophenolates from chloronitrobenzene using a vibrating tubular reactor. *p*-Aminothiophenol was prepared by using *p*-nitrochlorobenzene with aqueous Na₂S containing surfactant sodium dodecyl sulphate to give 95% *p*-aminothiophenol [19]. *o*-Aminothiophenol was prepared by alkali hydrolysis of 2-aminobenzothiazole in presence of ethylene glycol to give 89.4% product [20]. Thioethers as bis (*p*-nitrophenyl) sulphide was prepared in 42% yield by heating a mixture of *p*-chloronitrobenzene and aqueous Na₂S solution using tricaprylyl methyl ammonium chloride as PTC [21]. Bamfield and Sutcliffe [22] have prepared a number of organic sulphides/disulphides (formed in situ from Na₂S and S) in the presence of benzyltriethylammonium chloride as phase transfer catalyst. Non-ionic and ionic surfactants have also been used to catalyse the reaction of nitrochlorobenzene with alkali disulphide to give dinitrodiphenyl disulphide [23]. The reaction of *o*-chloronitrobenzene [24,25] and *p*-chloronitrobenzene [26] with sodium sulphide/disulphide have been carried out using polar solvents like dimethyl formamide and *N*-methylpyrrolidone with good yields of corresponding products. Reduction of *o*-nitro and *p*-chloronitrobenzene by sodium sulphide both in the absence and presence of TBAB is reported [27]. 2-2',dinitrodiphenyl disulphide was prepared in high yield and purity from 2-chloronitrobenzene in *N*-methylpyrrolidone and aqueous alkali metal disulphide (as sodium sulphide) in the presence of quaternary ammonium or phosphonium phase transfer catalyst [28]. Pradhan and Sharma [29] have reported the sulphide reduction of *p*-chloronitrobenzene with TBAB under certain set of conditions to get *p*-chloroaniline in the organic phase.

The foregoing suggests that the reaction is really a complex one and different products have been reported. Thus, it was thought desirable to address this problem and bring out the novelties of selectivity en-

gineered reduction of *p*-chloronitrobenzene with Na₂S under different set of conditions.

2. Experimental

2.1. Chemicals

p-Chloronitrobenzene was procured from M/s Aarti Industries Ltd., Mumbai, India. Toluene, sodium hydroxide and sodium sulphide, all AR grade were obtained from M/s s.d. Fine chemicals Ltd., Mumbai, India. Tetrabutylammonium bromide (TBAB) of pure grade was obtained from M/s Spectrochem Ltd., Mumbai, India and ethyltriphenylphosphonium bromide was obtained from M/s Dishman Pharmaceuticals and Chemicals Ltd., Ahmedabad, India.

2.2. Set-up

The reactions were studied in a 5 cm internal diameter, fully baffled mechanically agitated glass reactor of 100 cm³ capacity which was equipped with a six bladed-turbine impeller and a reflux condenser. The reactor was kept in a thermostatic bath whose temperature could be maintained within ± 1 °C of the desired value.

2.3. Procedure

Since there was a possibility of a combination of series and parallel or complex reactions occurring simultaneously under alkaline conditions, the following three steps were studied independently:

- Hydrolysis of *p*-chloronitrobenzene with aqueous NaOH under L-L PTC.
- Hydrolysis of *p*-chloronitrobenzene with aqueous NaOH under L-L PTC as the first step, upon completion of which the reduction of the nitro group with Na₂S in the same reactor under L-L PTC.
- Concomitant hydrolysis and reduction of *p*-chloronitrobenzene with aqueous alkaline Na₂S in the single pot under (i) L-L PTC, (ii) S-L PTC and (iii) L-L-L PTC.

2.3.1. Hydrolysis of *p*-chloronitrobenzene (*p*-CNB)

Hydrolysis of *p*-chloronitrobenzene was performed, by using aqueous NaOH and tetrabutylammonium

bromide as the catalyst. A standard experiment was carried out with 0.0625 mol of *p*-CNB in toluene (25 cm³ organic phase) with 0.125 mol of NaOH in water (25 cm³ aqueous phase) and 6.25×10^{-4} mol of catalyst TBAB for 5 h. Both aqueous and organic phases were analysed by HPLC and GC, respectively.

2.3.2. Reduction of *p*-nitrophenol

The aqueous phase from the above reaction was separated and it was confirmed to be only the sodium salt of *p*-nitrophenol. It was reacted with a saturated solution of Na₂S at 80 °C for 1 h in the same reactor and the reaction medium was analysed by HPLC.

2.3.3. Concomitant hydrolysis and reduction of *p*-chloronitrobenzene in a single pot

To study the hydrolysis and reduction reaction of *p*-chloronitrobenzene under PTC, alkaline sodium sulphide was taken as the reducing agent in the aqueous phase. Typical runs were conducted by taking 7.5×10^{-3} mol of *p*-chloronitrobenzene in 25 cm³ solution made in toluene and 7.5×10^{-3} mol of sodium hydroxide and 0.125 mol of sodium sulphide in 25 cm³ solution made in water. A known amount of catalyst (TBAB) was used and the mixture stirred. The aqueous phase was analysed by HPLC and the organic phase by GC. There was a formation of a distinct solid crystalline precipitate, which was separated and analysed by GC–MS.

In all above cases, a complete mass balance was done.

2.4. Method of analysis

The samples of the organic phase were analysed by gas chromatography on a Chemito 8510 model. A 2.0 m × 3.2 mm, i.d. stainless steel column packed with chromosorb WHP, which was impregnated with 10% SE-30, was used for analysis. The aqueous samples were analysed by HPLC on a Tosoh, UV-8010 model coupled with a Tosoh UV detector set at 254 nm, and a Merck 50983 column (stationary phase of Lichrospher 100 RP-18, particle size 5 μm, prepacked on a 250 × 4 mm, i.d.). Quantification of the data was done by comparison with standard samples and their synthetic mixtures.

3. Results and discussion

3.1. Hydrolysis of *p*-chloronitrobenzene

The hydrolysis of *p*-chloronitrobenzene was found to give *p*-nitrophenol as the sole product, which was extracted in to the aqueous phase as its sodium salt. It was observed that the conversion of *p*-chloronitrobenzene in 5 h was only 15.34%, thereby, indicating that this reaction would be slower in a single pot synthesis under reducing conditions. Further, there was no formation of any dinitrodiphenyl ether. Its absence was confirmed by the analysis of the organic phase by GC, GC–MS and NMR. It was indicative of the fact that no such ether would be formed under alkaline conditions in the presence of Na₂S.

3.2. Reduction of *p*-nitrophenol

The reduction of *p*-nitrophenol with Na₂S showed that the nitro and hydroxyl groups were reduced and substituted, respectively, to produce the sodium salt of *p*-aminothiophenol as product. There was no formation of any thioether or *p*-aminophenol. This would mean that the hydroxyl group gets replaced by SH group and the nitro group is reduced subsequently to the amino group. The formation of *p*-aminothiophenol in the aqueous phase was confirmed by extraction into an organic solvent followed by GC–MS analysis.

3.3. Improving selectivity of *p*-aminophenol

The single pot reaction was done to study the selectivity to *p*-aminophenol and *p*-aminothiophenol from *p*-chloronitrobenzene. It was confirmed that *p*-aminophenol was not at all formed in the reaction under alkaline conditions; instead only aminothiophenol was formed and it was extracted as the sodium salt in the aqueous phase. Different thioethers were also formed as a separate third phase precipitate.

A strategy was therefore adopted to make the formation of *p*-aminophenol possible and to avoid the formation of aminothiophenol. The hydrolysis of *p*-chloronitrobenzene was done as the first step under L-L PTC with TBAB as the catalyst, under otherwise similar conditions followed by the separation of organic and aqueous phases. The aqueous phase was

neutralised with hydrochloric acid and treated with sodium sulphide as the reducing agent. It was found that although in this process *p*-aminophenol was obtained in the aqueous phase as a sodium salt, the formation of *p*-aminothiophenol could not be avoided. However, the amount of *p*-aminothiophenol formed had reduced drastically. Aminophenol and aminothiophenol get extracted into the aqueous phase as sodium salts and could be separated upon acidification and extraction into a suitable solvent.

3.4. Single pot reaction of *p*-chloronitrobenzene with sodium sulphide under L-L PTC

The analysis of the aqueous and organic phases of single pot synthesis by HPLC and GC, respectively, and that of organic solids by GC–MS revealed that the following products were formed (Fig. 2).

- (i) *p*-Chloroaniline (*p*-CA)
- (ii) *p*-Aminothiophenol (*p*-ATP)
- (iii) *p*-*p'*-Dinitrodiphenyl thioether (DNDPTE)
- (iv) *p*-*p'*-Diaminodiphenyl thioether (DADPTE).

p-Aminophenol (*p*-AP) and *p*-*p'*-diaminodiphenyl ether (DADPE) were not formed in this reaction. It should be mentioned here that *p*-aminothiophenol was found as the sodium salt in the aqueous phase. Preliminary experiments had suggested that when stoichiometrically deficient amount of Na₂S was used, then only *p*-*p'*-dinitrodiphenyl thioether was formed instead of *p*-*p'*-diaminodiphenyl thioether. These two ethers were found to be insoluble in both the liquid phases and were isolated as solids.

3.5. Reduction of *p*-*p'*-dinitrodiphenyl thioether to *p*-*p'*-diaminodiphenyl thioether

In order to devise the mechanism of the reaction, separate experiments were conducted to study the reduction of *p*-*p'*-dinitrodiphenyl thioether to *p*-*p'*-diaminodiphenyl thioether. The formation of both the ethers was confirmed by GC–MS. After the reaction, *p*-*p'*-dinitrodiphenyl thioether was separated from the reaction mixture as solid and it was heated at 60 °C with fresh saturated Na₂S solution (25 cm³) with TBAB (1.5 × 10⁻⁵ mol/cm³) for 1 h. No sooner was the dinitrodiphenyl thioether added to the saturated solution of Na₂S, than the light yellow

coloured thioether was found to have changed to dark brown coloured compound. After the reaction mixture was refluxed for 1 h, it was fully converted to the brown coloured compound. The GC–MS analysis of the dark brown coloured compound showed it to be *p*-*p'*-diaminodiphenyl thioether.

3.6. Effect of different parameters on selectivity of products

Na₂S under alkaline conditions leads to the formation of SH⁻ anions which later combine with Q⁺ to give the ion-pair Q⁺SH⁻ for the reaction to proceed. Hence, it was thought worthwhile to study the reduction of *p*-CNB under L-L PTC and find out the various reaction products. The effect of various parameters on the rates of reactions and the product profile was studied under L-L PTC.

3.7. Effect of speed of agitation

The effect of speed of agitation on the conversion of *p*-chloronitrobenzene was studied under L-L PTC at 900, 1500 and 1800 rpm under otherwise similar conditions by using TBAB as catalyst (Fig. 3). It was confirmed that the conversion remained practically the same, which implied that there was no mass transfer resistance over this range for transfer of the ion-pairs across the liquid-liquid interface. All subsequent reactions were carried out at 1000 rpm.

3.8. Effect of *p*-chloronitrobenzene concentration

The effect of *p*-CNB concentration on the rate of reaction was studied in the range of 1 × 10⁻³ to 2.5 × 10⁻³ mol/cm³ organic phase with TBAB as the catalyst. The conversion was found to have decreased with an increase in the concentration of *p*-CNB because stoichiometrically lesser amount of Na₂S was available under otherwise similar conditions. The selectivities to *p*-chloroaniline (*p*-CA) and thioethers had increased with increasing concentration of *p*-CNB, but the selectivity of *p*-aminothiophenol (*p*-ATP) had decreased (Table 1).

3.9. Effect of concentration of Na₂S in L-L PTC

The effect of concentration of Na₂S was studied at 1.5 × 10⁻³, 2 × 10⁻³ and 2.5 × 10⁻³ mol/cm³ of

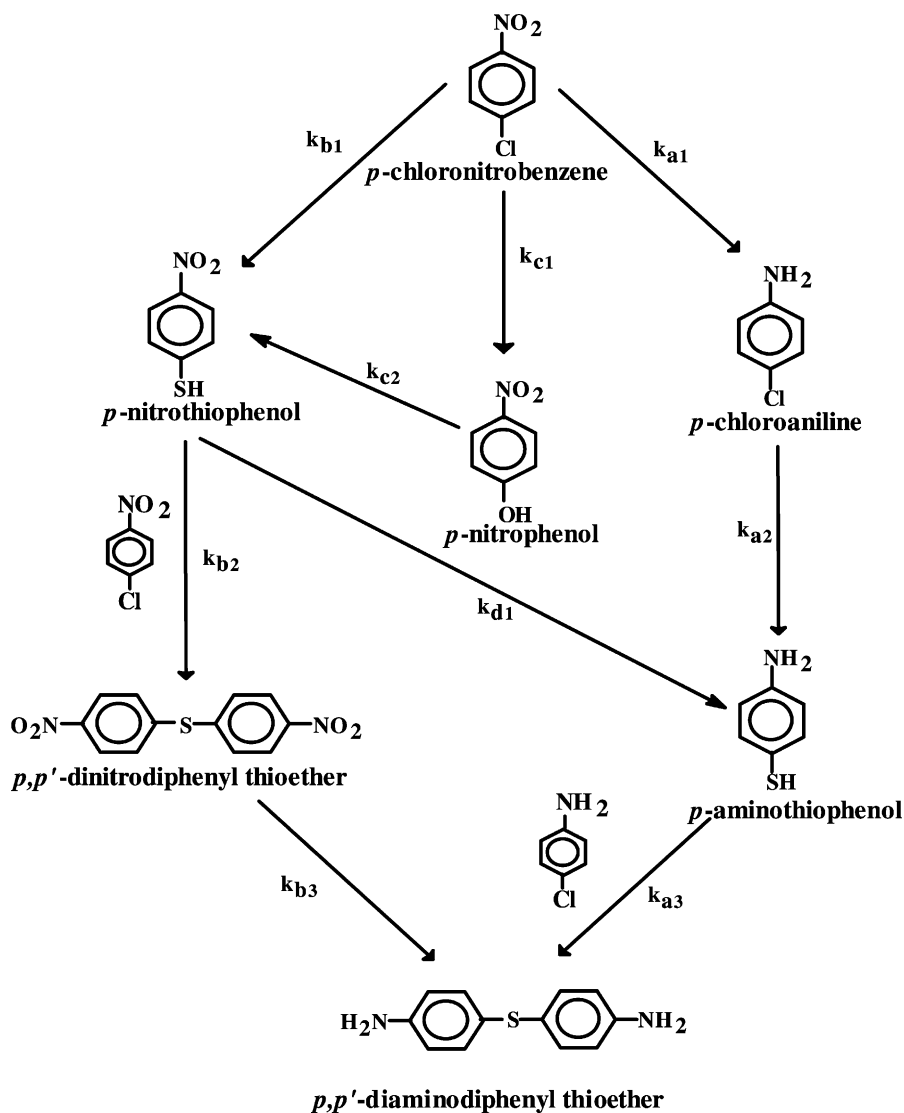


Fig. 2. Products of cascade engineered L-L PTC reaction of *p*-chloronitrobenzen with sodium sulphide.

Table 1
Effect of variation of *p*-CNB concentration

<i>p</i> -CNB concentrated (mol/cm ³)	Total conversion (%)	Yield (%)		
		<i>p</i> -CA	<i>p</i> -ATP	Thioethers
1×10^{-3}	29.82	17.18	35.00	47.82
1.5×10^{-3}	23.23	13.53	36.12	50.35
2.5×10^{-3}	22.80	9.61	26.04	64.35

Na₂S, 1.5×10^{-3} mol/cm³; TBAB, 0.375×10^{-3} mol; temperature, 80 °C; time, 2 h. Yields are based on converted reactant.

aqueous phase. It was seen that with an increase in the concentration of Na₂S, the total conversion had increased because of more availability of the reducing agent. Selectivities of *p*-CA and *p*-ATP had decreased. However, thioether formation had increased with increasing Na₂S concentration (Table 2).

3.10. Effect of different catalysts

Although tetrabutyl ammonium bromide (TBAB) was found to be an efficient catalyst, a phosphonium

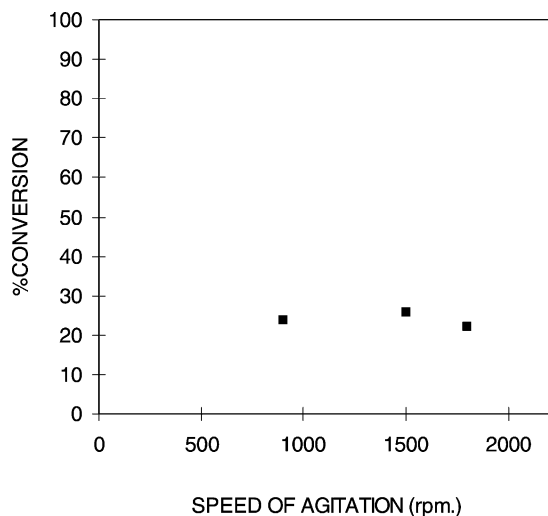


Fig. 3. Effect of speed of agitation. *p*-CNB, 0.0375 gmol; Na₂S, 0.0375 gmol; TBAB, 1.5×10^{-5} gmol/cm³ of organic phase, temperature, 80 °C.

Table 2
Effect of concentration of Na₂S

Na ₂ S concentrated (mol/cm ³)	Total conversion (%)	Yield (%)		
		<i>p</i> -CA	<i>p</i> -ATP	Thioethers
1.5×10^{-3}	23.23	13.53	36.12	50.35
2×10^{-3}	40.02	8.74	28.50	62.76
2.5×10^{-3}	54.78	7.62	22.78	69.60

p-CNB, 1.5×10^{-3} mol/cm³; TBAB, 0.375×10^{-3} mol; temperature, 80 °C; time, 2 h.

quaternary salt was also used for comparison. Ethyltriphenyl phosphonium bromide (ETPPB) was used as a catalyst under otherwise similar conditions. It was seen that total conversion in both the cases differed marginally but the selectivity to thioether was more with ETPPB. (Table 3).

Table 3
Effect of catalysts

Catalyst (mol)	Total conversion (%)	Yield (%)		
		<i>p</i> -CA	<i>p</i> -ATP	Thioethers
TBAB 3.75×10^{-4}	23.23	13.53	36.12	50.35
ETPPB 3.75×10^{-4}	21.45	6.23	25.70	68.07

p-CNB, 1.5×10^{-3} mol/cm³; Na₂S, 1.5×10^{-3} mol/cm³; temperature, 80 °C; time, 2 h.

Table 4
Effect of temperature

Temperature (°C)	Total conversion (%)	Yield (%)		
		<i>p</i> -CA	<i>p</i> -ATP	Thioethers
30	3.69	33.60	29.42	36.98
80	23.23	13.54	36.12	50.34

p-CNB, 1.5×10^{-3} mol/cm³; Na₂S, 1.5×10^{-3} mol/cm³; TBAB, 0.375×10^{-3} mol; time, 2 h.

3.11. Effect of temperature

Although the standard reaction was done at 80 °C, it was verified if it could occur at room temperature (30 °C). It was seen that as the temperature was increased from 30 to 80 °C, the conversion had increased almost four-fold which had resulted into the reduction of yields of *p*-CA and *p*-ATP, which reacts in situ to form the thioethers (Table 4).

3.12. Effect of type and number of phases

The effect of type and number of phases was also studied. By using TBAB as the catalyst, the reduction reaction was studied as a liquid-liquid-liquid (L-L-L) PTC and solid-liquid (S-L) PTC in comparison with liquid-liquid (L-L) PTC under otherwise similar conditions. Blank experiments were also done without a catalyst as a liquid-liquid reaction (Table 5).

3.13. Liquid-Liquid-Liquid PTC

Under L-L-L PTC, the reaction was done by employing 7.5×10^{-3} mol of TBAB, which resulted in the formation of a third liquid phase. The creation of a third liquid phase is discussed in our earlier work [9,10]. Beyond a critical concentration of TBAB, catalyst rich third phase separates out. Here the reactants are transferred to the middle catalyst-rich phase and hence almost complete conversion is obtained (Table 5). The conversion was 97% in 30 min showing intensification of reaction rate. In this case mostly thioethers were formed in a greater yield. This is consistent with the observations of Yadav and Reddy [9].

3.14. Solid-Liquid PTC

In this reaction *p*-CNB was taken as a solid. The conversion was 83.43% after 2 h (Table 5). However,

Table 5
Reaction under different PTC modes

Reaction type (reaction time)	TBAB (mol)	Total conversion (%)	Yield (%)		
			<i>p</i> -CA	<i>p</i> -ATP	Thioethers
L-L-L PTC (0.5 h)	0.75×10^{-2}	97.00	7.3	8	84.7
S-L PTC PTC (2 h)	0.375×10^{-3}	83.43	6.28	23.26	70.45
L-L PTC (2 h)	0.375×10^{-3}	65.25	8.3	26.3	65.4
L-L without catalyst (2 h)	0	41.5	9.45	12.9	77.5

p-CNB, 1.5×10^{-3} mol/cm³; Na₂S, 3.5×10^{-3} mol/cm³; temperature, 80 °C. In solid-liquid PTC, *p*-CNB was taken as a solid.

the selectivity of *p*-ATH increased drastically compared to that under L-L-L condition. The thioether selectivity had also decreased but *p*-CA selectivity almost remained the same as that of L-L-L PTC.

3.15. L-L reaction with and without PTC

The reaction was studied in L-L mode with as well as without TBAB under otherwise similar conditions (Table 5). It was seen that under otherwise similar conditions, the conversion was more in the case of PTC reaction compared to non-PTC reaction. The yields of thioethers and *p*-CA had increased in non-catalytic reaction, whereas *p*-ATP selectivity had decreased.

3.16. Selectivity patterns

With reference to Fig. 2, the product profile can be explained as follows:

- Under L-L PTC conditions, the nitro group reduction is faster and occurs first and thus *p*-chloroaniline is formed (path along k_{a1}). The formation of *p*-chloroaniline is faster than that of *p*-nitrothiophenol (path along k_{ba}). *p*-Chloroaniline remains in the organic phase whereas *p*-nitrothiophenol is extracted in to the aqueous phase as a sodium salt. The rates of formation are in the following order

$$r_{a1} > r_{b1} \quad (1)$$

where

$$r_{a1} = k_{a1}[pCNB][Q^+SH^-] \quad (2)$$

$$r_{b1} = k_{b1}[pCNB][Q^+SH^-] \quad (3)$$

- Formation of *p*-aminothiophenol takes place along path k_{a2} because the displacement of Cl from *p*-chloroaniline is easier under the PTC conditions.

p-Aminothiophenol formed goes in to the aqueous phase. Rate of formation of *p*-aminothiophenol along path k_{d1} is negligible since the formation of *p*-nitrophenol along path k_{c1} and its subsequent conversion to *p*-nitrothiophenol along path k_{c2} is also negligible because of the deficient quantities of Na₂S in the reaction mixture. In no experiment *p*-nitrophenol or *p*-nitrothiophenol was detected in the reaction mixture in any of the phases. This may be so because, as soon as *p*-nitrothiophenol is formed it immediately reacts with *p*-CNB along path k_{b2} to form *p*-*p'*-dinitrodiphenyl thioether under deficient quantities of Na₂S. As stated earlier, the independent experiment of *p*-nitrophenol reduction with excess Na₂S had shown that only *p*-aminothiophenol was formed.

Hence, $r_{a2} > r_{d1}$ and $r_{b2} > r_{d1}$.

Also r_{c1} and r_{c2} are very negligible.

Here,

$$r_{a2} = k_{a2}[pCA][Q^+SH^-] \quad (4)$$

$$r_{d1} = k_{d1}[pNTP][Q^+SH^-] \quad (5)$$

$$r_{c1} = k_{c1}[pCNB][Q^+SH^-] \quad (6)$$

$$r_{c2} = k_{c2}[pNTP][Q^+SH^-] \quad (7)$$

$$r_{b2} = k_{b2}[pCNB][p-NTP] \quad (8)$$

- p*-*p'*-Dinitrodiphenyl thioether is formed as a separate solid phase. Its subsequent reduction to *p*-*p'*-diaminodiphenyl thioether along path k_{b3} is therefore more difficult, since this has to happen by the S-L PTC mechanism under the depleted S⁻² concentration. Formation of *p*-*p'*-diaminodiphenyl thioether takes place by the interfacial reaction between *p*-chloroaniline in the organic phase and *p*-aminothiophenol in the aqueous phase along path k_{a3} . *p*-*p'*-Diaminodiphenyl thioether so formed

is obtained as a separate solid along with *p-p'*-dinitrodiphenyl thioether.

Therefore, $r_{a3} \gg r_{b3}$

$$r_{a3} = k_{a3}[pCA][p-ATP] \quad (9)$$

$$r_{b3} = k_{b3}[p-p' - DNDPTE][Q^+SH^-] \quad (10)$$

From the above discussion, it is evident that the product formation due to the reactions along path $k_{a1} \rightarrow k_{a2} \rightarrow k_{a3}$ shown in Fig. 2 is more prominent than those along all other paths. The trend in concentration profiles of reactants and products is shown in Fig. 4.

Based on the above considerations, the observations made while studying the effects of various parameters could be explained as follows.

It is seen that with the increase in *p*-CNB concentration, under otherwise similar conditions, the total conversion decreases because of the deficient quantity of Na_2S available for reduction. As the nitro reduction occurs first, *p*-CA is formed which is reduced further to *p*-ATP. This accounts for the decrease in *p*-CA concentration. Under L-L PTC conditions, *p*-ATP subsequently reacts with *p*-CA to form *p-p'*-diaminodiphenyl thioether. And so the thioether concentration goes on increasing with increasing *p*-CNB concentration.

With increasing Na_2S concentration, the total conversion increases because more Na_2S is available for reduction. The selectivities of *p*-CA, *p*-ATP and thioethers show similar trend as found with increasing *p*-CNB concentration.

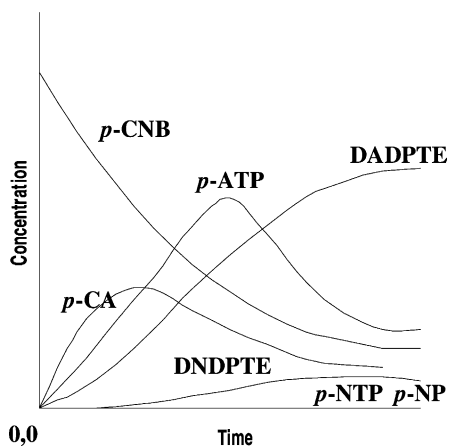


Fig. 4. Concentration profile of reactant and products.

There is a marginal difference in the total conversion with TBAB or ETPPB as catalysts but the selectivities suggest that the reduction of *p*-CA to *p*-ATP and their subsequent conversion to thioethers is faster in the case of ETPPB. This may be due to the unsymmetrical nature of ETPPB as against the symmetrical TBAB, which makes the former more reactive.

As the reaction temperature increases from 30 to 80 °C, the total conversion increases which is typical of a PTC reaction. With the rise in temperature, more of *p*-CA and *p*-ATP will react to form thioethers.

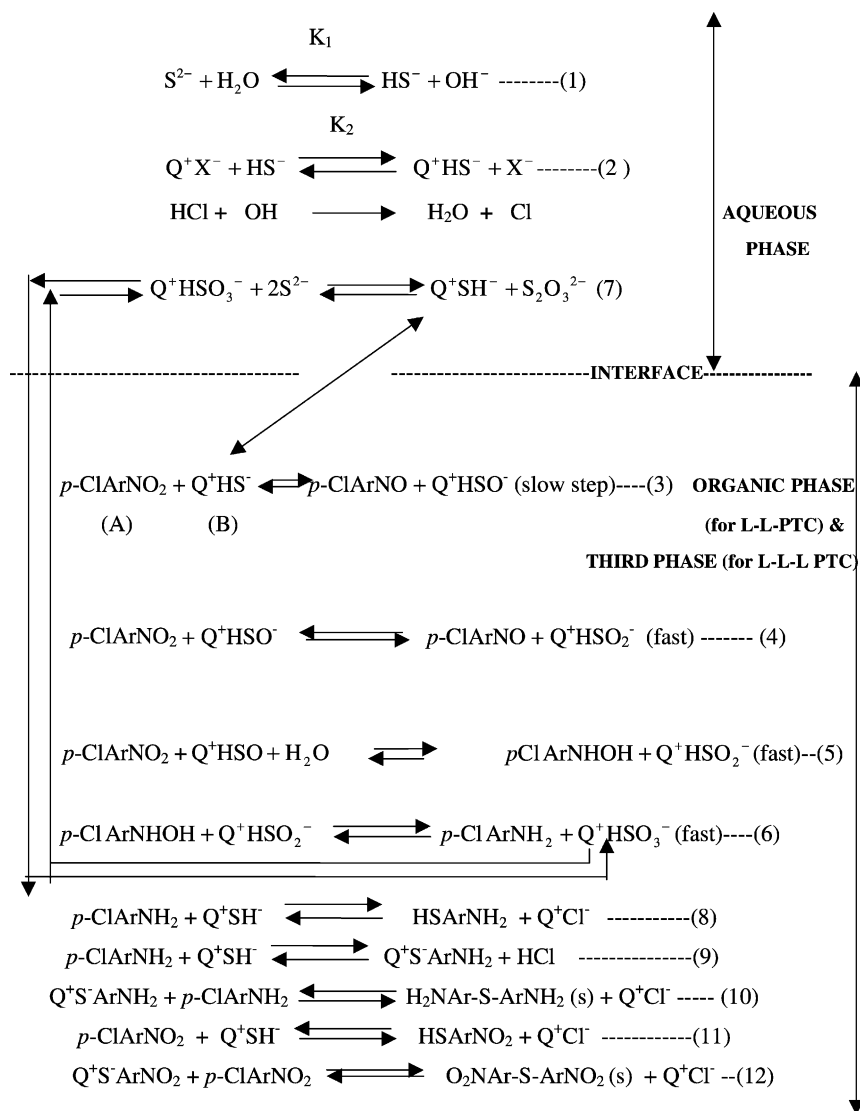
The reaction under different PTC condition shows that the total conversion decreases in the following order L-L-L PTC > S-L PTC > L-L PTC > uncatylsed reaction. This is typical of PTC reactions, since in a triphasic reaction, the creation of a third liquid phase, which is the main reaction phase, enhances the rate of the reaction. We have reported this already for alkoxylation reactions [14]. In the case of S-L PTC the reaction occurs due to the homogeneous solubilisation of solid *p*-CNB followed by its reduction.

3.17. Mechanism of reaction

With reference to Fig. 2, a mechanism was proposed as depicted in Fig. 5.

From the model of the reaction, it is seen that the quaternary ion of PTC, Q^+ takes up different anions for its reaction with the substrate. S is a multivalent species and thus different mono-valent anions, such as HS^- , HSO^- , HSO_2^- and HSO_3^- , can be formed sequentially which are capable of producing ion-pairs with single quaternary cations more readily than those multi-valent anions which require ion-pairing with multiple quaternary cations. In the aqueous phase S^{2-} reacts with H_2O to form HS^- which further reacts with the quaternary salt Q^+X^- to form Q^+HS^- . The Q^+HS^- , which is then transferred to the organic phase undergoes a series of reactions with *p*-CNB, *p*-CA and *p*-ATP forming different ion-pairs mono-valent S^- anions in combination with the cation Q^+ of quaternary salt.

In the case of S-L PTC, the following mechanism is proposed. The quaternary salt Q^+SH^- diffuses to the solid particle of *p*-CNB. The solid particle is surrounded by a thin film of aqueous phase, through which Q^+SH^- diffuses to the exterior surface of the particles of *p*-CNB where the reaction takes place due

Fig. 5. Mechanism of reduction reaction of *p*-CNB with Na_2S .

to solubilisation of the nitroaromatic followed by the subsequent reduction. In this reaction, the formation of *p*-aminothiophenol takes place immediately which is subsequently converted to *p-p'*diaminodiphenyl thioether. This reaction happens in the vicinity of the solid *p*-CNB particle. Therefore, the selectivity to the thioether increases.

In the case of L-L-L PTC, all the reactants and catalyst were available in the catalyst-rich third phase

and therefore the formation of *p-p'*diaminodiphenyl thioether was very high and so its selectivity was also high.

4. Conclusions

The reduction of *p*-chloronitrobenzene with sodium sulphide is a reaction of great industrial relevance,

which could lead to different products of commercial value. This reaction was investigated in detail under different modes of PTC, such as liquid-liquid, solid-liquid and liquid-liquid-liquid and also without PTC. The concept of selectivity engineered PTC has been well developed to effect different product selectivities. A systematic study was undertaken to understand the reaction mechanism.

The hydrolysis of *p*-chloronitrobenzene with aqueous sodium hydroxide under L-L PTC yields *p*-nitrophenol as the sole product, which is instantly extracted into the aqueous phase as a sodium salt. No *p-p'*-dinitrodiphenyl ether is formed. When *p*-nitrophenol is reduced by aqueous sodium sulphide, it gives *p*-aminothiophenol as the only product, no formation of *p*-aminophenol is detected. For producing *p*-aminophenol, the reaction should be conducted starting from *p*-nitrophenol or from *p*-chloronitrobenzene, which is converted, to *p*-nitrophenol in situ under L-L PTC, followed by neutralisation of the aqueous phase and subsequent reduction with sodium sulphide under L-L PTC. Both *p*-aminophenol and *p*-aminothiophenol are formed as sodium salts, which could be separated from the reaction mixture by dissociation extraction because their pK_a values are different.

The liquid-liquid PTC reaction was studied in detail and the effects of different parameters were studied on the product profile and thereafter a mechanism was developed. *p*-Chloronitrobenzene was reduced with sodium sulphide to give *p*-chloroaniline in the organic phase, *p*-aminothiophenol in the aqueous phase. *p-p'* Dinitrodiphenyl thioether or *p-p'* diaminodiphenyl thioether or their mixture was obtained as solid precipitate depending on the stoichiometric ratio of *p*-chloronitrobenzene and sodium sulphide. A mechanistic model was also proposed which shows how the reaction proceeds in phase transfer catalysis to yield various products in this reaction. In the case of S-L PTC and L-L-L PTC, the thioethers were the main products. The results are novel.

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References

- [1] R.A Sheldon, H. van Bekkum (Eds.), *Fine Chemicals Through Heterogeneous Catalysis*, Wiley, Weinheim, Toronto, 2001.
- [2] R.A. Sheldon, J. Moulijn, M.M. Sharma, *Fine Chemicals Manufacture Technology and Engineering*, first ed., Elsevier, Amsterdam, The Netherlands, 2001.
- [3] G.D. Yadav, *Chimica & Industria*, July 2000, 1–7.
- [4] C.M. Starks, C. Liotta, M. Halpern, *Phase Transfer Catalysis: Fundamentals, Applications, and Perspectives*, Chapman and Hall, New York, 1994.
- [5] Y. Sasson, R. Neumann (Eds.), *Handbook of Phase transfer Catalysis* Blackie Academic and Professional: London, 1997.
- [6] E.V. Dehmlo, S.S. Dehmlo, *Phase Transfer Catalysis*, third ed., VCH, New York, 1993, pp. 2.
- [7] G.D. Yadav, Y.B. Jadhav, *Langmuir* 18 (16) (2002) 5995–6002.
- [8] D.H. Wang, H.S. Weng, *Chem. Eng. Sci.* 43 (1988) 2019.
- [9] G.D. Yadav, C.A. Reddy, *Ind. Eng. Chem. Res.* 38 (6) (1999) 2249.
- [10] G.D. Yadav, S.S. Naik, *Cat. Today* 2357 (2001) 1–10.
- [11] G.D. Yadav, T. Radhika, in: *Proceedings of the Paper Presented at Fall Meeting, AIChE, Reno, Nevada, 6–11 November 2001*.
- [12] G.D. Yadav, S. Sengupta, in: V. Murugeson, B. Arabindoo, M. Palanichamy (Eds.), *Recent Trends in Catalysis*, Narosa Publishing House, New Delhi, 1999, pp. 645–650.
- [13] R. Neumann, Y. Sasson, *J. Org. Chem.* 49 (1984) 3448.
- [14] S.S. Naik, *Insights In Catalysis: Novelties of Multi-Phase Transfer Catalysis*, Ph.D. Thesis, University of Mumbai, Mumbai, India, 1998.
- [15] S. Sengupta, *Selectivity Engineering Via Catalysis*, Ph.D. (Tech.) Thesis, University of Mumbai, Mumbai, India, 1999.
- [16] Y.B. Jadhav, *Insight into Catalytic Synthesis of Fine Chemicals*, Ph.D. Thesis, University of Mumbai, Mumbai, India, 2001.
- [17] M.D. Bhawe, S.B. Chandalia, *J. Appl. Chem. Biotechnol.* 26 (1976) 167–170.
- [18] E. Reuter H. Kaerst, K. Mechel W. Rauner, DE 4037286, 27 May 1992.
- [19] M. Imanary, K. Iwane, T. Sugawara, T.CI.C07C323/34, 22 January 1990, Appl. 88/167, 247, 5 July 1988, Chem. Abstr. 113 (1990) 40141e.
- [20] Y. Kawaoka, K. Takashita, JP 07,278,100, 24 October 1995 Chem. Abstr. 124 (1995) 201777m.
- [21] I.K. Kim, J.S. Noh, *Tachan Hwahak Hoechi* 18 (6) (1974) 421–422 (Korean); I.K. Kim, J.S. Noh, *Chem. Abstr.* 82 (1975) 124967h.
- [22] P. Bamfield, D. Sutcliffe, *British Patent* 1,498,410, 1978.

- [23] V. Sartori, European Patent, 156,769, 1985, Chem. Abstr. 104 (1986) 148486.
- [24] A. Koller, P. Jaegar, C. Berther, Ger.Offen. 2,204,726, Chem. Abstr. 77 (1972) 139604.
- [25] A.V. Ivanov, T.M. Beregovykh, USSR Patent 529,156, Chem. Abstr. 85 (1976) 192365.
- [26] S.S. Gitis, A.V. Ivanov, E.G. Kaminskaya, N. Udris, V.I. Nikolaev, Nauch. Tr. Tul. Gos. Pedagog. Inst. 1968, 109-15 (Russian), Chem. Abstr. 73 (1970) 120230d.
- [27] V.F. Shener, N.N. Artamonova, I.I. Petrunina, V.F. Seregina, B.V. Salov, Zh. Org. Khim. 28,879 (1989) Chem. Abstr. 112 (1990) 55111y.
- [28] F. Hagedorn, H. Fiege, et al., European Patent Appl. EP 658,544, 21 June 1995, De Appl. 4,342,619, 14 December 1993, 6 pp.
- [29] N.C. Pradhan, M.M. Sharma, Ind. Eng. Chem. Res. 31 (1992) 1610–1614.