

I₂/Nanostructured Pyrophosphate: A Mild and Efficient Catalyst for the Selective Protection of Carbonyl Compounds

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ABSTRACT

A new solvent free method for protection of carbonyl compounds as their thioacetals has been accomplished through the use of iodine supported on nanostructured pyrophosphate. Advantages of the methodology include very short reaction time, the requirement for minimum amounts of catalyst, the remarkably simple experimental procedure, and no necessity for solvents or inert atmospheres, excellent yields and recyclability of the catalyst used. An efficient method for the chemoselective thioacetalization of ketones in the presence of aldehydes using I₂/nanostructured pyrophosphate is also reported in this article. The nanostructured pyrophosphate was characterized by scanning electron microscopy, X-ray diffraction, infrared spectroscopy, Transmission electron microscopy and thermal gravimetric analysis, respectively.

Keywords: Catalyst; Free Solvent; Nanostructured Pyrophosphate; Protection of Carbonyl Compounds; Iodine

1. Introduction

Designing of new specific catalysts and exploring their catalytic activity has caused profound effects in optimizing the efficiency of a wide range of organic synthesis. Development of such catalysts has resulted in more economical and environmentally friendly chemistry through replacing nonselective, unstable, or toxic catalysts [1,2]. In the last few years, literature has highlighted the importance of nanosized materials in several scientific and technological areas, and many research councils have intensified investments in nanotechnology for the coming years [3].

The protection of carbonyl functionality as a dithioacetal or a thioketal is important in the multistep total synthesis of complex natural and non-natural products [4,5]. Among carbonyl protecting groups, 1,3-dithiolanes, 1,3-oxathiolanes, and 1,3-dithianes are important as they are inherently stable under both mildly acidic and basic conditions [6]. In addition, these are also utilized as masked acyl anions [7] or masked methylene functional groups [8] in carbon-carbon bond forming reactions. This

'umpolung' or inversion of polarity is an integral step of many multistep organic syntheses. In this view, there have been continued improvements in the methods of preparation of thioacetals. Generally, they are prepared by condensation of carbonyl compounds with thiols in the presence of strong acid catalysts such as AlCl₃ [9], LnCl₃ [10], ZnCl₂ [11], TiCl₄ [12], WCl₆ [13], InCl₃ [14], In(OTf)₃ [15], Sc(OTf)₃ [16,17], Bi(NO₃)₃ [18] and VO(OTf)₂ [19]. A number of milder procedures employing lithium salts [20-24], NiCl₂ [25], CoCl₂ [26], NBS [27], and I₂ [28] have also been reported for this purpose. Although some of these methods have been carried out under mild reaction conditions, most of them require [29] reflux temperature [30], long reaction times and use expensive and not readily available reagents [31]. They also suffer from a tedious work-up procedure [32] and require the use of stoichiometric reagents [11]. Some of the methods mentioned above are incompatible with other protecting groups and fail to protect deactivated aromatic substrates [33].

Recently, a number of solid supported reagents have also been used for thioacetalization of various types of carbonyl compounds, e.g. ZrCl₄-SiO₂ [33], SOCl₂-SiO₂

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[34], $\text{CoBr}_2\text{-SiO}_2$ [35], $\text{TaCl}_5\text{-SiO}_2$ [36], $\text{Cu}(\text{OTf})_2\text{-SiO}_2$ [37], $\text{NaHSO}_4\text{-SiO}_2$ [38], $\text{I}_2/\text{natural phosphate}$ [39], $\text{ZnCl}_2/\text{natural phosphate}$ [40] and $\text{Si}(\text{CH}_2)_2\text{SO}_3\text{H-SiO}_2$ [41].

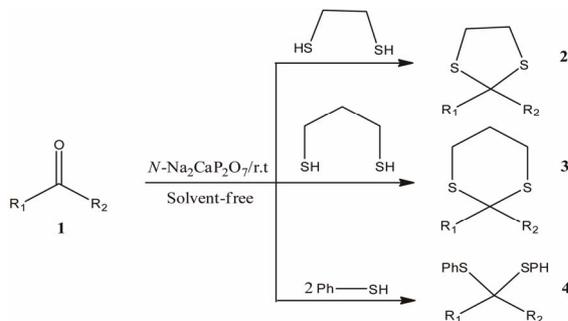
Finally, the main disadvantage of almost all the existing methods is that the catalysts are destroyed in the work-up procedure and cannot be recovered or reused. Therefore, there is further scope in exploring mild, chemoselective and efficient methods for thioacetalization of carbonyl compounds.

Furthermore, many studies have been published describing the synthesis and use of the pyrophosphate ($\text{Na}_2\text{CaP}_2\text{O}_7$) in various fields, particularly in heterogeneous catalysis [42–45]. Bennazha *et al.* were able to synthesize and characterize a series of pyrophosphates by adopting a dry technique [46]. Recently, we have developed a method to tailor the nanostructure of this pyrophosphate by focusing on reactant crashing and the speed of calcination. This nanostructured phosphate has been used with great success to catalyze the synthesis of 2-amino-chromenes [47]. As a part of our continuing interest in the development of new synthetic methodologies; an efficient method for the chemoselective thioacetalization of aliphatic and both activated and deactivated aromatic carbonyl compounds using iodine supported on nanostructured pyrophosphate ($N\text{-Na}_2\text{CaP}_2\text{O}_7$) catalyst at room temperature under solvent-free is reported here (Scheme 1).

2. Experimental

2.1. General Remarks

All commercial reagents were purchased from Aldrich Chemical Company and were used without further purification. ^1H and ^{13}C NMR spectra were recorded at 400 and 100 MHz, respectively, on a Bruker DRX-400 spectrometer in CDCl_3 , using CDCl_3 as internal standard. IR spectra were obtained on a FTIR (Bruker Vector 22 spectrometer) and reported in wave numbers (cm^{-1}). Thermogravimetric analyses (TGA) were conducted under air using a TA Instruments Q 500 apparatus with $10^\circ\text{C}/\text{min}$ ramp between 25 and 1000°C . X-ray diffraction (XRD) patterns of the catalyst were obtained at room



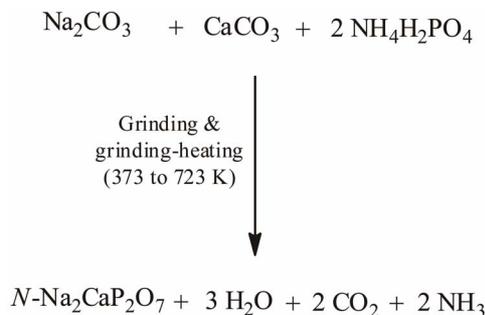
Scheme 1. Selective protection of carbonyl compounds $\text{I}_2/\text{nanostructured pyrophosphate}$.

temperature on a Bruker AXS D-8 diffractometer using Cu-K α radiation in Bragg-Brentano geometry ($q\text{-}2q$). Scanning electron microscopy (SEM) pictures were recorded on a FEI Quanta 200 microscope after carbon metallization. The TEM micrographs were obtained on a Tecnai G2 microscope at 120 kV. The specific surface areas were determined from the nitrogen adsorption/desorption isotherms (at -196°C) measured with a Quantachrome Autosorb-1 automatic analyzer, using the BET equation at $p/p_0 = 0.98$. Melting points were determined using a Stuart SN5228 apparatus. Melting points were determined with a ‘Thomas Hoover’ melting (capillary method) apparatus and are uncorrected.

2.2. Preparation of the Catalyst and Structural Characteristics

The synthesis of $\text{Na}_2\text{CaP}_2\text{O}_7$ was carried out by a dry technique. The pyrophosphate was prepared as a white powder starting from Na_2CO_3 , CaCO_3 and $\text{NH}_4\text{H}_2\text{PO}_4$ of high purity grade and in a 1:1:2 molar ratios, respectively (Scheme 2). These materials were ground together in an agate mortar and progressively heated to 723 K in a porcelain crucible. In order to obtain a homogeneous single phase product, additional grinding and progressive heating steps were carried out. The size of the final product does not only depend on the quality of the starting products but also on the precision of the weighing, grinding and grinding-heating from 373 to 723 K.

Thermogravimetric analysis (TGA) of a mixture of these three reagents showed that the thermal behavior of this blend was suitable to form the desired pyrophosphate (Figure 1). Three major mass losses were observed and corresponded to the dehydration reaction, the loss of NH_3 and CO_2 as well as the crystallization of this material. X-ray diffraction (XRD) of $\text{Na}_2\text{CaP}_2\text{O}_7$ showed that this system crystallized in the triclinic system with the space group $P1bar$ (Figure 2). The lattice parameters of the prepared $\text{Na}_2\text{CaP}_2\text{O}_7$ were in excellent agreement with standard data: $a = 5.361 \text{ \AA}$, $b = 7.029 \text{ \AA}$ and $c = 8.743 \text{ \AA}$, with the characteristic peaks of this pyrophosphate all present [Green].



Scheme 2. Synthesis of nanostructured pyrophosphate ($N\text{-Na}_2\text{CaP}_2\text{O}_7$).

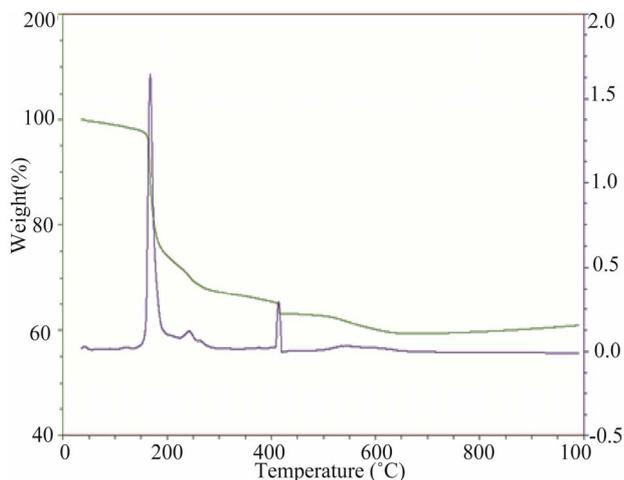


Figure 1. Thermal gravimetric analysis (TGA) of $\text{Na}_2\text{CaP}_2\text{O}_7$.

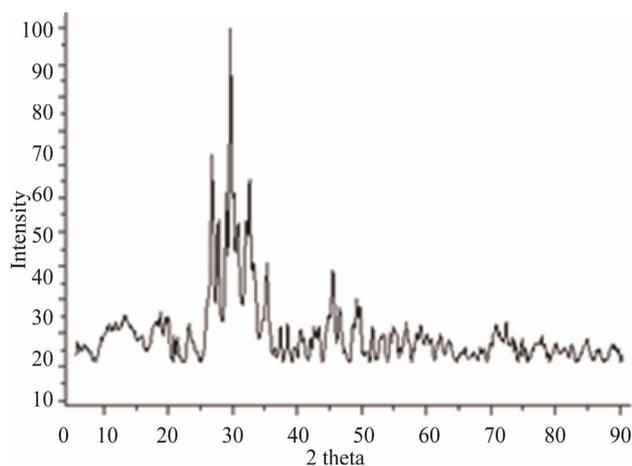


Figure 2. XRD pattern of $\text{Na}_2\text{CaP}_2\text{O}_7$.

The FTIR spectrum of $N\text{-Na}_2\text{CaP}_2\text{O}_7$ is presented on the **Figure 3**. The existence of P_2O_7 units was confirmed by the symmetrical vibration bands of P-O-P at 720 cm^{-1} as well as the *anti*-symmetric vibration bands at 893 cm^{-1} . The related vibrations of the PO_4 groups were shared between two fields: a field of symmetrical vibrations at 996 cm^{-1} and 1031 cm^{-1} and another that ranged from 1130 to 1278 cm^{-1} (**Figure 3**). Scanning Electronic Microscopy (SEM) was used to study the morphology of the surface of $N\text{-Na}_2\text{CaP}_2\text{O}_7$ (**Figure 4**). This micrograph shows a homogeneous microstructure that consisted of layers of various sizes and forms.

The shape, size, and morphology of $N\text{-Na}_2\text{CaP}_2\text{O}_7$ particles were revealed by Transmission electron microscopy "TEM" (**Figure 5**). The micrograph shows nanoparticles that are rod-like which agglomerate to form superstructures with different aspect ratios of grain crystals (*i.e.* length/diameter). $N\text{-Na}_2\text{CaP}_2\text{O}_7$ is characterized by an average grain diameter and length of 15 nm and 40 nm, respectively.

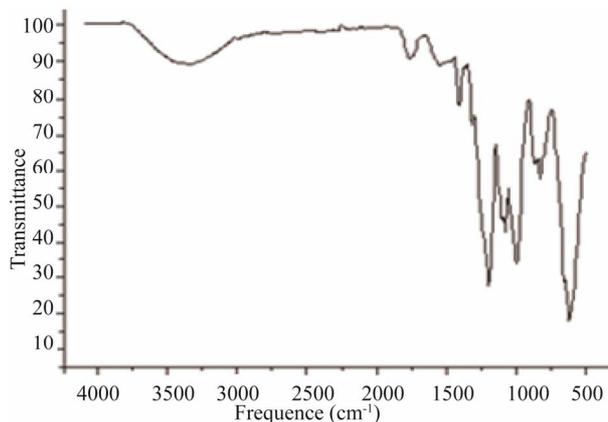


Figure 3. FTIR spectrum of $\text{Na}_2\text{CaP}_2\text{O}_7$.

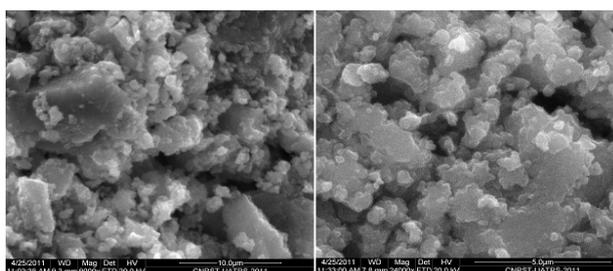


Figure 4. SEM images of $\text{Na}_2\text{CaP}_2\text{O}_7$ nanopowder.

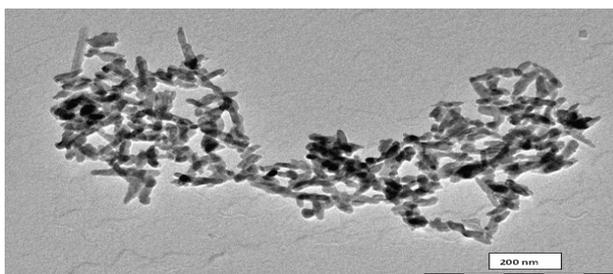


Figure 5. TEM of $\text{Na}_2\text{CaP}_2\text{O}_7$.

2.3. General Procedure for the Thioacetalization of Carbonyl Compounds

To a freshly prepared catalyst (0.2 g, 0.2 mmol of iodine) under stirring, a mixture of carbonyl compound **1** (2 mmol) and monothiol or dithiol (4.2 or 2.1 mmol, respectively) was added and the mixture was stirred at room temperature and the progress was monitored by TLC using hexane: dichloromethane as an eluent. Following completion of the reaction, the crude reaction mixture was filtered and the catalyst washed with dichloromethane. After concentration of the filtrate under reduced pressure the residue was subjected to chromatography (eluent: 95% hexane and 5% ethyl acetate) leading to the respective thioacetal (**2**, **3** or **4**, **Scheme 1**). The product structure was analysed by ^1H , ^{13}C NMR, IR spectrometry and melting points. When NP and I_2 are mixed one pot in the reaction mixture without previous

absorption the thioacetal (**2**, **3** or **4**) was obtained in slightly lower yields.

2.4. Typical Procedure for the Recycling of the $N\text{-Na}_2\text{CaP}_2\text{O}_7$ (Catalyst)

After completion of the reaction, the reaction mixture was filtered and the catalyst washed with dichloromethane. The $N\text{-Na}_2\text{CaP}_2\text{O}_7$ was washed with acetone 3 - 4 times and drying at 423 K in vacuum or calcined at 723 K to confirm the complete removal of any residual material. The same process was repeated after each reaction cycle to isolate and reuse the $N\text{-Na}_2\text{CaP}_2\text{O}_7$ as catalyst.

3. Results and Discussion

The scope and failure of the catalyst nanostructured pyrophosphate ($N\text{-Na}_2\text{CaP}_2\text{O}_7$) as a heterogeneous catalyst in dithioacetalization of a variety of carbonyl compounds under solvent-free examined. Benzaldehyde, thiophenol and iodine (**Scheme 1**) were chosen as model substrates to determine suitable conditions. The optimum weight of

$N\text{-Na}_2\text{CaP}_2\text{O}_7$ is 200 mg. In a blank reaction (20 min), $N\text{-Na}_2\text{CaP}_2\text{O}_7$ alone or 0.1 mmol alone the thioacetal **4a** was obtained with low yields 13% or 31%, respectively. The $N\text{-Na}_2\text{CaP}_2\text{O}_7$ was the preferred choice as a catalyst and support to keep the reaction medium under mild and neutral conditions.

Interestingly, the experimental procedure for thioacetalization is remarkably simple and does not require the use of solvents or inert atmospheres. A catalytic quantity of I_2 supported on nanostructured pyrophosphate was added to the carbonyl compound, to this was added the required monothiols or dithiols (2.1 or 1.1 equiv., respectively) and the mixture was stirred at room temperature. The generality of this process has been proved in a wide range of aromatic, aliphatic and, α,β -unsaturated carbonyl compounds. Accordingly, dithioacetals, 1,3-dithiolanes and 1,3-dithianes have been obtained by the reaction of thiophenol, 1,2-ethanedithiol and 1,3-propanedithiol, respectively, in the presence of catalytic amounts of $\text{I}_2/N\text{-Na}_2\text{CaP}_2\text{O}_7$ (**Scheme 1**); the results are illustrated in **Table 1**.

Table 1. I_2 supported on nanostructured pyrophosphate ($\text{I}_2/N\text{-Na}_2\text{CaP}_2\text{O}_7$) catalysed selective dithioacetalization of carbonyl compoundsa.

Entry	Substrate	Reagent	Products	Yield ^a (%) (time/min)
1	Benzaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2a	90 (5)
2	<i>p</i> -Methoxybenzaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2b	95 (2)
3	<i>p</i> -Methylbenzaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2c	93 (3)
4	<i>p</i> -Chlorobenzaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2d	91 (5)
5	<i>p</i> -Nitrobenzaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2e	92 (9)
6	Acetophenone	$\text{HS}(\text{CH}_2)_2\text{SH}$	2f	90 (20)
7	Cyclohexanone	$\text{HS}(\text{CH}_2)_2\text{SH}$	2g	93 (20)
8	Cinnamaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2h	94 (3)
9	Pentaldehyde	$\text{HS}(\text{CH}_2)_2\text{SH}$	2i	89(25)
10	Benzaldehyde	$\text{HS}(\text{CH}_2)_3\text{SH}$	3a	92 (5)
11	<i>p</i> -Methoxybenzaldehyde	$\text{HS}(\text{CH}_2)_3\text{SH}$	3b	96 (3)
12	<i>p</i> -Methylbenzaldehyde	$\text{HS}(\text{CH}_2)_3\text{SH}$	3c	92 (4)
13	<i>p</i> -Chlorobenzaldehyde	$\text{HS}(\text{CH}_2)_3\text{SH}$	3d	91 (5)
14	<i>p</i> -Nitrobenzaldehyde	$\text{HS}(\text{CH}_2)_3\text{SH}$	3e	92 (10)
15	Acetophenone	$\text{HS}(\text{CH}_2)_3\text{SH}$	3f	93 (25)
16	Cyclohexanone	$\text{HS}(\text{CH}_2)_3\text{SH}$	3g	90 (25)
17	Pentaldehyde	$\text{HS}(\text{CH}_2)_3\text{SH}$	3h	88 (30)
18	Benzaldehyde	PhSH	4a	92 (20)
19	<i>p</i> -Methoxybenzaldehyde	PhSH	4b	95 (10)
20	<i>p</i> -Methylbenzaldehyde	PhSH	4c	93 (13)
21	<i>p</i> -Chlorobenzaldehyde	PhSH	4d	95 (20)
22	<i>p</i> -Nitrobenzaldehyde	PhSH	4e	93 (25)
23	Acetophenone	PhSH	4f	90 (60)
24	Cyclohexanone	PhSH	4g	91 (45)
25	Pentaldehyde	PhSH	4h	82 (60)

We observed that the reaction of aldehydes takes place rapidly in the presence of $I_2/N-Na_2CaP_2O_7$ when compared to that of ketones (see **Table 1**). This method is suitable for aldehydes and ketones both aromatic and aliphatic as well as, α,β -unsaturated carbonyl compounds. It is free from the problem of Michael addition encountered in some case of, α,β -unsaturated carbonyl systems (**Table 1**, Entry 8) with some reagents [48].

It is clear from the mechanism (**Figure 6**), that the corresponding methyl ketones show a lower yield as compared to the aldehydes (**Table 1**, Entry-1 and 6; 10 and 15; 18 and 23 can be chosen as representative examples of aromatic and aliphatic carbonyl compounds for proving this point). This might have been because of steric factors (the extra bulk imposed by the methyl group on the attaching thiol nucleophile), or electronic factors (the electron-donating inductive effect of methyl

group renders the carbonyl carbon less electrophilic) or a combination of both.

Amongst the aromatic carbonyl compounds, the reaction mechanism suggests that the electron donating substituents would activate the benzene ring and thus increase the yield of the products. On the other hand, the electron withdrawing substituents (**Table 1**, Entry-2 and 5, 11 and 14) would show a slight decrease in the yield of the corresponding 1,3-dithiolanes.

The difference in reactivity of the $I_2/N-Na_2CaP_2O_7$ catalyst towards aldehydes and ketones gave us impetus to study chemoselective reactions. With this objective, as a representative example we carried out some experiments with equimolar mixtures of an aldehyde and a ketone (**Scheme 3**). It was observed that in this mixture, the corresponding aldehyde formed the 1,3-dithiolane whilst the ketone was almost completely recovered.

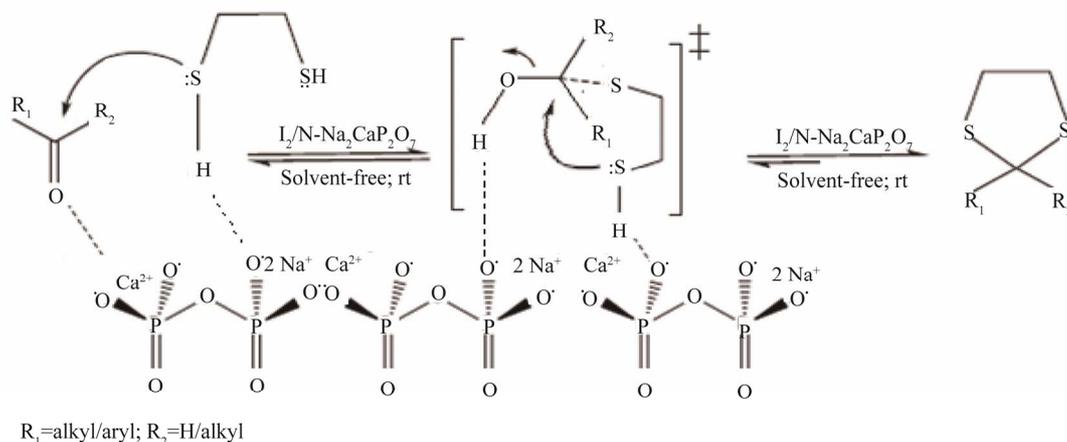
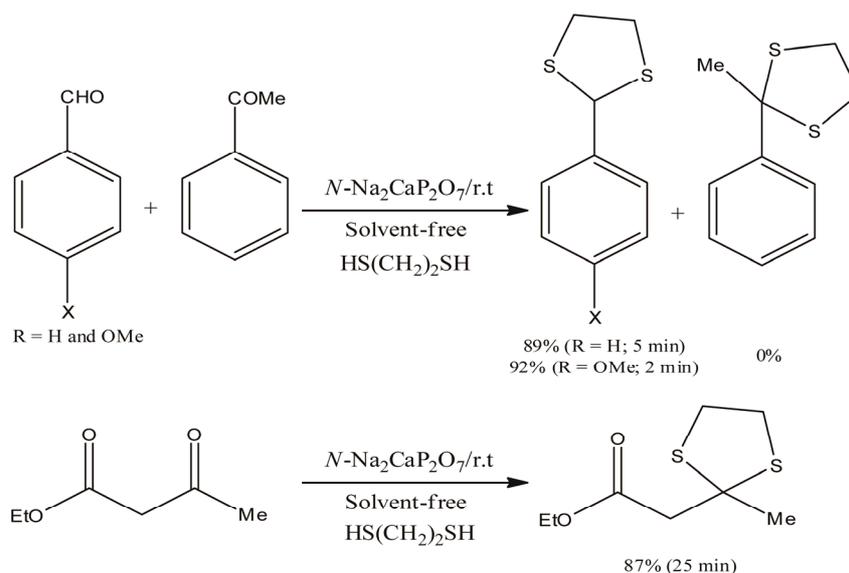


Figure 6. Proposed mechanism for the protection of carbonyl compound using ethane dithiol over I_2 supported on nanostructured pyrophosphate ($I_2/N-Na_2CaP_2O_7$) catalyst.



Scheme 3. Chemoselective protection in presence I_2 /Nanostructured Pyrophosphate catalyst.

This method has also been extended to the intramolecular chemoselectivity between keto and ester functionalities (**Scheme 3**). Only keto functionality was thioacetalized by this method in a short period (25 min) with a high yield (87%). When compared with the existing method, the present method was found to be superior in many respects.

In all these cases, the aldehyde reacted in almost quantitative yields while the ketone remained unreacted. These reactions are kinetically controlled. The reaction time is only 10 min and thus equilibrium is not allowed to set in. The final step of the reaction mechanism is irreversible as the water which is eliminated separates out from the organic phase into an aqueous phase. In this way, our claim of having developed a gentle methodology for the chemoselective protection of aldehydes using 1,3-dithiolanes in the presence of ketones is justified.

The $N\text{-Na}_2\text{CaP}_2\text{O}_7$ could be recycled by separating them from the reaction mixture by simple filtration. They could be used as a catalyst for the same reaction again and the change in their catalytic activity was studied. The relation between the number of cycles of the reaction and the catalytic activity in terms of yield is presented in the **Figure 7**. The catalyst can be recovered and reused at least six times without appreciable loss of activity.

It was observed that with the increasing number of cycles of the reaction, the catalytic activity of the $N\text{-Na}_2\text{CaP}_2\text{O}_7$ slightly decreased. This might have been due to the slow poisoning of $N\text{-Na}_2\text{CaP}_2\text{O}_7$.

4. Conclusion

In conclusion a new solvent free method for protection of carbonyl compounds as their thioacetals has been accomplished through the use of iodine supported on nanos

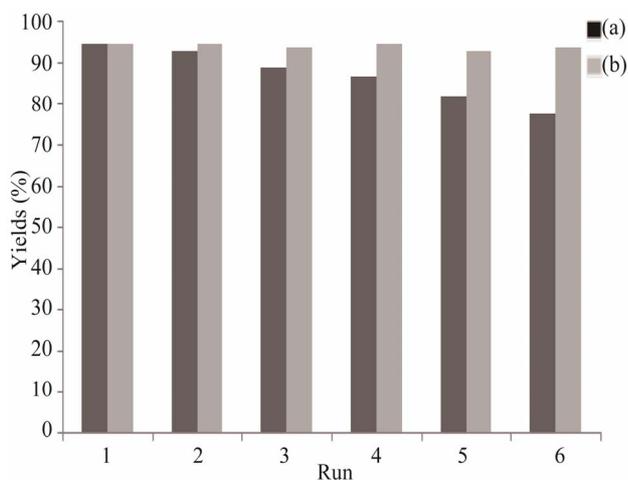


Figure 7. Recycling of the $N\text{-Na}_2\text{CaP}_2\text{O}_7$ catalyst in the synthesis of **2a**. (a) Catalyst recoverable dried at 423 K for 1 h; (b) Catalyst recoverable, washed with acetone, dried and calcined at 723 K for 15 - 30 min.

structured pyrophosphate. Advantages of the methodology include very short reaction time, the requirement for minimum amounts of catalyst, the remarkably simple experimental procedure, and no necessity for solvents or inert atmospheres, excellent yields and recyclability of the catalyst used. Furthermore, the relatively slow reaction rate of ketones allows chemoselective protection of aldehydes in the presence of ketones, making this an important tool in the synthetic organic chemistry.

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