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The novel synthesis of magnetically chitosan/carbon nanotube composites and their catalytic applications

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ABSTRACT

Chitosan-modified magnetic carbon nanotubes (CS-MCNTs) were synthesized and were investigated by FT-IR, EDX, FE-SEM, elemental analysis, XRD, VSM and TGA. In order to synthesize the CS-MCNTs composites, Fe_3O_4 decorated carbon nanotubes (CNTs-Fe_3O_4) were modified with a silica layer by the ammonia-catalysed hydrolysis of tetraethyl orthosilicate (CNTs-Fe_3O_4@SiO_2). Then, CS-MCNTs were successfully grafted on the surface of CNTs-Fe_3O_4@SiO_2 *via* a suspension cross-linking method. The CS-MCNT was found to be an excellent heterogeneous catalyst for the synthesis of 1,4-dihydropyridines (DHPs). The attractive advantages of the present process include short reaction times, milder and cleaner conditions, higher purity and yields, easy isolation of products, easier work-up procedure and lower generation of waste or pollutions. This catalyst was easily separated by an external magnet and the recovered catalyst was reused several times without any significant loss of activity. A combination of the advantages of CNTs, chitosan and magnetic nanoparticles provides an important methodology for carrying out catalytic transformations. Therefore, this method provides a green and much improved protocol over the existing methods.

1. Introduction

It is widely acknowledge that there is a growing need for more environmentally acceptable processes in the chemical reactions used in manufacturing. This trend towards what has become known as Green Chemistry, or environmentally benign chemistry, necessitates a paradigm shift from traditional concepts of process efficiency that focus largely on chemical yield to one that assigns economic value to eliminating waste at source and avoids the use of toxic and hazardous materials, as well as the design of eco-compatible chemicals [1]. One of the methods for implementing the principles of Green Chemistry is to use catalysis. Catalysis is one of the key underpinning technologies on which new approaches to sustainable chemistry are based. Recently, the development of eco-friendly, non-toxic, low cost, recyclable green catalysts, which give high productivity under mild reaction conditions, has received much attention in modern chemical synthesis [1b]. In particular, it is necessary to design catalysts and catalysis processes with environmental considerations for the preparation of compounds with pharmacological properties.

On the other hand, 1,4-dihydropyridines (DHPs) is one of the most important classes of heterocyclic compounds in the field of pharmaceutical and medicinal chemistry [2–6]. Due to the high medicinal and biological importance of DHPs derivatives, several methods have been developed for the synthesis of these heterocyclic compounds. Hantzsch DHPs synthesis is one of the most broadly used methods for the synthesis of structurally diverse DHPs. This classical method involves one-pot condensation of aldehydes with ethyl acetoacetate and ammonia in acetic acid or by refluxing in alcohol [7]. Up till now, numerous literature citations exist relating to various attempts to improve the Hantzsch reaction using alternative catalysts and greener protocols [8]. However, some drawbacks still exist, such as the use of expensive or toxic catalysts, high reaction temperatures, long reaction times, use of large quantities of volatile organic solvents, low yields and harsh reaction conditions [9]. Therefore, more general, efficient and viable routes employing recyclable catalysts in Hantzsch synthesis are very much desirable, in view of their broad array of biological activity and would be of great relevance to both synthetic and medicinal chemists.

The most recent efforts in the development of cleaner sustainable chemistry are being driven by a shift from petrochemical-based feed stocks toward biological compounds. Thus, there is a drive to produce raw materials from biofeed stocks, which in turn

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is stimulating considerable effort in new areas of chemistry and catalytic processes. Given these developments, it seems clear that the development of biopolymers as heterogeneous green catalytic systems will play a key role in this field [10]. Recently, biopolymers such as starch [11], cellulose [12], chitosan (CS) [13], or wool [14], have been used as catalysts in the organic reactions. In this context, chitosan can play a major role as a natural, biocompatible, biodegradable and bioactive polymer [15–17]. Chitosan, as a polyaminosaccharide, can be explored as a mild bi-functional heterogeneous catalyst in the organic reactions. In this regard, chitosan contains the primary amino groups at the C-2 position, the primary hydroxyl groups at the C-6 position and secondary hydroxyl groups at the C-5 in higher concentrations. Therefore, chitosan can activate the electrophilic and nucleophilic components of the reactions by hydrogen bonding and lone pairs, respectively [13a].

With the development of nanoscience and nanotechnology, chitosan nanostructures have received a great deal of attention because of their nano-size, large surface area and good biocompatibility. Moreover, unlike most other natural polymers, chitosan is a polymer with a positive charge in aqueous solution [18]. These characteristics favour the employment of nano-sized chitosan particles in a wide range of various applications, including drug delivery systems [19], gene delivery systems [20], sensors [16], protein carriers [18], tissue engineering [21] and catalysts [13]. Many recent attempts have been made to create chitosan nanoparticles through emulsion cross-linking [22], reverse micellar extraction [23], solvent evaporation [24], spray drying [25], coacervation [26] or thermal cross-linking [27]. These methods have intrinsic advantages, along with some limitations [18]. It should be noted that in spite of these favourable properties for chitosan, the poor mechanical strength and the loss of structural integrity especially under wet conditions, limits chitosan's application in various fields [28].

Recently, carbon nanotubes (CNTs)/chitosan nanocomposites have been researched to unite the interesting properties of CNTs and chitosan [16a,18,28,29]. CNTs possess high tensile strengths and are ultra-light weight with excellent thermal and chemical stability. CNTs have large length-to-diameter aspect ratios, which provide high surface-to-volume ratios, therefore, making them promising materials for catalytic applications [29]. On the other hand, CNTs are ideal reinforcing agents, which improve the mechanical properties of polymers. Incorporation of super strong lightweight CNT nanostructures into a chitosan matrix offers a novel approach to the design of high performance nanocomposite materials with superior mechanical properties [28].

Generally, the numerous hydroxyl and amino groups in the polymer chains of polyaminosaccharide resulted in an obvious enhancement in the absorption of pollutants on CNTs/chitosan nanocomposites in various fields, especially in catalytic processes. However, the difficulty in collecting these CNTs-chitosan nanocomposites from treated effluents can cause inconveniences in their practical application. Therefore, it is necessary and significant to explore novel modified CNTs/chitosan nanocomposites that can be easily separated from the treated solution, in addition to the excellent dispersion in solution and absorption properties [29]. Magnetic nanoparticles are another reinforcing nanostructure material used in chitosan; nanocomposites made with this material combine the excellent functional properties of nanoparticles in separation techniques. Magnetically supported chitosan can be recovered with an external magnetic field due to the paramagnetic character of the support, without the need for a filtration step [29]. Recently, magnetic chitosan and magnetic CNTs-chitosan nanocomposites for separation techniques have been obtained and studied, as the magnetic separation technique has some advantages, such as high efficiency and cost-effectiveness [30].

Based on the above considerations, CS-MCNTs were synthesized *via* a suspension cross-linking method in this study and CS-MCNTs were used as an efficient catalyst for the effective synthesis of DHPs through the solvent-free Hantzsch reaction. This new approach has several superiorities versus previous reports for the synthesis of DHPs and introduces the important field of the use of magnetically recoverable and environmentally benign heterogeneous nanocatalysts in the synthesis of pharmaceutically important heterocyclic compounds (Scheme 1).

2. Experimental

All chemicals were purchased from the Merck, Aldrich and Sigma Chemical Companies. Multi wall carbon nanotubes (MWNTs) with surface area of 136 m^2/g and 10–20 nm in diameter, used as a support, were supplied from Neutrino Company, Iran. Melting points (°C) were determined on an Electrothermal MK3 apparatus using an open-glass capillary and are uncorrected. ^1H NMR and ^{13}C NMR spectra were recorded with a Bruker DRX-400 spectrometer at 400 and 100 MHz respectively. FT-IR spectra were obtained with KBr pellets in the range 400–4000 cm^{-1} with a Perkin-Elmer 550 spectrometer. The magnetic measurement of samples were carried out in a vibrating sample magnetometer (VSM) (4 in., NDKF, Kashan, Iran) at room temperature. Nanostructures were characterized using a Holland Philips Xpert X-ray diffraction (XRD) diffractometer (CuK, radiation, $\lambda = 0.154056$ nm), at a scanning speed of 2°/min from 10° to 100° (2θ). The surface morphology of nanocomposites was analyzed by field emission scanning electron microscopy (FE-SEM) (MAIA). Thermogravimetric analysis (TGA) was performed on a Linseis-TGA at a heating rate of 15 °C/min under N_2 flow (40 cm^3/min).

2.1. Preparation of Fe_3O_4@SiO_2-CS

Fe_3O_4 nanoparticles were synthesized by a chemical coprecipitation process and the Fe_3O_4@SiO_2 core–shell nanoparticles were prepared according to the modified by the Stöber method [32]. Fe_3O_4@SiO_2-CS nanocomposites were prepared using the cross-linking method described in Ref. [33]. The details were as follows: 0.30 g of chitosan was firstly dissolved in 10.0 mL of acetic acid solution (2 wt.%), then 0.15 g of Fe_3O_4@SiO_2 nanoparticles were dispersed in the chitosan solution under ultrasound irradiation for 20 min, followed by the addition of 135 μL of glutaraldehyde solution (25 wt.%) and the black gels were formed after 4 h. Then, the gels were dried in a vacuum oven at 60 °C for 12 h, and washed with acetic acid solution (2 wt.%), hot water, and cool water several times to remove unreacted chitosan. The purified Fe_3O_4@SiO_2-CS was dried again in the vacuum oven at 50 °C for 12 h.

2.2. Synthesis of CNTs-Fe_3O_4@SiO_2 nanocomposite

0.5 g CNTs were added to 30 mL the mixture of 98% sulphuric acid and 70% nitric acid (volumetric ratio 3:1) at 50 °C under sonication for 6 h. Then, carboxylic acid-functionalized CNTs (CNTs-COOH) were centrifuged and washed with distilled water and oven dried at 100 °C for 24 h. CNTs-Fe_3O_4@SiO_2 nanocomposites were prepared by growing silica layers onto the surface of the CNTs-Fe_3O_4 as described by Zhang et al. [34]. $FeCl_2{\cdot}4H_2O$ and $FeCl_3.6H_2O$ precursors (2:1, molar ratio) were dissolved in 100 mL of water and heated to 90 °C. Then, 10 mL of ammonium hydroxide (25%) and 0.4 g of CNTs-COOH were dispersed in 50 mL of water, which was added rapidly under continuous Ar atmosphere bubbling. The mixture was stirred at 90 °C for 30 min. The black precipitate was then centrifuged, washed with distilled water and dried at 50 °C for 24 h. The obtained black precipitate was Fe_3O_4-CNTs nanocomposites. Finally, 25 mL of ethanol, 1.0 mL of double-distilled water,

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