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RESEARCH ARTICLE

SONOGASHIRA COUPLING REACTION CATALYZED BY GOLD NANOCATALYST UNDER MICROWAVE: EFFECT OF SIZE AND SHAPE.

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Abstract

Gold nanocatalysis is an increasingly popular field. In this paper, gold nanoparticles with different shape, size and capping agents were supported on lanthana. The gold nanocatalysts were explored for Sonogashira coupling. This category of gold nanocatalysts has not been systematically explored for the title reaction. When catalyzed Sonogashira coupling reaction of phenylacetylene and iodobenzene performed under microwave irradiation, all gold nanocatalysts resulted in the formation of the desired diphenylacetylene. The investigation demonstrates that the catalytic activities of various gold nanoparticles toward the Sonogashira coupling are shape and size-dependant. Meanwhile, the stability of gold nanoparticles on the support plays a critical role.

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Introduction:-

Bulk gold has long been classified as being catalytically far less active than other transition metals due to lack of partially filled *d*-orbital ($[Xe] 4f^{14}5d^{10}6s^1$), which results in limited affinity for catalytic adsorption. In 1987, however, Haruta *et al.* found that gold nanoparticles of small diameter supported on metal oxides can catalyze the oxidation of carbon monoxide to carbon dioxide at extremely low temperature (Haruta *et al.*, 1987). His work ignited many promising applications of gold nanoparticles in the field of catalysis. Many possible explanations have been suggested for the difference in catalytic activity between nanoparticle and bulk gold (Chen and Goodman, 2004, Valden *et al.*, 1998), such as nanoscale regime inherently provides high surface-to-volume ratio (Ma *et al.*, 2015).

Amongst chemical reactions known to be catalyzed by gold nanocatalysts are the selective oxidations of hydrocarbons with oxygen, selective hydrogenation of unsaturated hydrocarbons, fuel cell (Choudhary and Goodman, 2002), oxidation of carbon monoxide (Haruta *et al.*, 1987), reduction and decomposition of nitric and nitrous oxides (Daniel and Astruc, 2004) and Sonogashira coupling reaction (Sanz, M. Laguna, 2007). Interestingly, gold nanocatalysts have shown to be the best catalyst for some reactions (Hutchings, 1985, Shenhar, 2005, Boal, 2001) and, it is the only known catalyst for some chemical transformations (Hashmi, 2007). In addition to the high surface-to-volume ratio, nanocatalysis provides convenient means of separation and recyclability of the usually toxic and expensive species. Different separation methods, such as centrifugation, precipitation-flocculation, nanofiltration, or magnetic decantation are used to recycle the nanocatalysts.

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Sonogashira coupling is the formation of C-C bond via coupling reaction of terminal alkynes with aryl or vinyl halides involving Pd(0) as a catalyst in the presence Cu(I) and a base such as amine. This reaction was first reported by Sonogashira and Hagihara in 1975 (Sonogashira, 1975). Unfeasible economical, environmental concerns, long reaction times and the limited choice of reaction medium are the major disadvantages of the Pd(0) and Cu(I) based catalytic system.

Several reports have shown that Sonogashira coupling reactions can be effectively catalyzed by gold nanoparticles on solid such as lanthana, silica, and cerium oxide support (Mitsudome and Kaneda, 2013, de Souza *et al.*, 2008, da Silva and Antunes, 2008). Although, the effect of changing the size and shape of nanocatalysts on catalytic activity is a significant key step toward development of better catalyst, however in literature there have been few studies (Beaumont, 2010, Narayanan and El-Sayed, 2005). In this regards, the gold nanocatalyzed Sonogashira coupling is no exception. There have not been any studies comparing the catalytic activity using nanocatalysts with different shapes on Sonogashira coupling. It is extremely important to study changes in size and shape of gold nanoparticle on the reaction as the changes in size and shape lead to changes in nanoparticle properties, crystallographic facets and different fraction of surface atoms on their corners and edges.

Herein, spherical and hexagonal gold nanoparticles were prepared by seed-assisted method to give different sizes in which cetyltrimethyl ammonium bromide (CTAB) was the stabilizing agent (Kanuru *et al.*, 2009). Similarly, rod nanoparticle was prepared by silver ion-assisted seed-mediated method (Jana *et al.*, 2001). Moreover, spherical nanoparticle stabilized by polyethylene glycol (PEGylated) was prepared by Brust's synthesis methods (Chen *et al.*, 2001). The as prepared gold nanoparticles were then supported on lanthana and examined for Sonogashira coupling at different reaction conditions. The reaction conditions such as recyclability of nanocatalysts, temperature, microwave assistance and time of reaction were systematically investigated.

Experimental methods:-

General:-

Chloroauric acid tetra hydrate, CTAB, sodium borohydride, silver nitrate, decane, lanthana and tert-butyl hydroperoxide were purchased from Sinopharm Chemical Reagent Co. Ltd. (Shanghai, China). Ascorbic acid was purchased from Zhanyun Chemical Co. Ltd, Shanghai. Water used throughout this work was deionized and double distilled. Dimethylformamide, phenylacetylene and iodobenzene were purified by distillation. UV-VIS absorption spectra of gold nanoparticles were obtained by a Hitachi UV 3310 spectrophotometer. The scanning wavelength range was from 200 to 900 nm with the interval of 0.1 nm. The microwave assistant couplings were performed on an Emrys™ Creator using 5 mL sealed vessels. Gas chromatography measurements were obtained using Agilent 6890N GC (Agilent Technologies, USA).

Preparation of gold nanoparticles:-

Gold nanosphere:-

Gold nanoparticles were prepared using the seed-assisted method reported in the literature (Kanuru *et al.*, 2009). Briefly, gold nanosphere seed was prepared by mixing 4 mL aqueous solution containing 2.5×10^{-4} M HAuCl₄ and 2.5×10^{-4} M trisodium citrate in a conical flask. Next, 120 μ L of ice-cold, freshly prepared 0.1M NaBH₄ solution was added to the solution while stirring. The solution turned pink immediately after adding NaBH₄, indicating particle formation. The particles in this solution were used as seeds within 2-5 hour after preparation. The intermediate gold nanosphere was prepared by adding 2 mL of the gold nanoparticle seed solution to a rapidly stirred 18 mL of a solution containing 2.5×10^{-4} M HAuCl₄ and 0.08 M cetyltrimethylammonium bromide (CTAB) to which 0.1 M ascorbic acid solution (0.1 mL) had already been added, stirring being continued for 0.5 h. The large gold nanosphere was prepared by addition of 20 mL of the solution of the intermediate nanoparticles to the rapidly stirred 180 mL 2.5×10^{-4} M HAuCl₄ and 0.08 M CTAB to which 0.1 M ascorbic acid solution (1 mL) had already been added, stirring being continued for 0.5 h.

Gold nanorods:-

The gold nanorods were prepared using the silver ion-assisted seed-mediated method (Jana *et al.*, 2001). Specifically, the seed solution was prepared by the addition of HAuCl₄ (0.01 M, 250 μ L) into CTAB (0.1 M, 10 mL) in a 15 mL plastic tube with gentle mixing. A freshly prepared, ice-cold NaBH₄ solution (0.01 M, 0.6 mL) was then injected quickly into the mixture solution. The seed solution was kept at room temperature for 2-3 hours before use to allow decomposition of NaBH₄. Three gold nanorods growth solutions were obtained by adding HAuCl₄ (0.01 M,

2.0 mL), AgNO₃ (0.01 M, 0.4 mL) and CTAB (0.1 M, 40 mL) in three 50 mL plastic tubes. HCl (1.0 M, 0.8 mL) was then added to adjust the pH of these solutions to 1-2, thus enhancing solubility of AgNO₃, followed by the addition of ascorbic acid (0.1 M, 0.32 mL) to reduce Au³⁺ to Au⁺. Finally, the CTAB-stabilized seed solutions (0.096 mL) were injected into the growth solution to catalyze the Au⁺ to Au⁰ formation. The solution was gently mixed for 10 s and left undisturbed overnight.

Gold hexagons:-

The gold hexagons were prepared via reduction of HAuCl₄ by ascorbic acid with the addition of NaOH. Specifically, a mixture of 200 mL aqueous solution of 1.25×10⁻⁴ M HAuCl₄ and 10 mM cetyltrimethylammonium bromide CTAB was prepared and maintained at temperature 25°C using water bath. To this mixture, an aqueous solution of ascorbic acid (100 mM, 1 mL) was added. The light-yellow color of the gold salt in the CTAB solution disappeared when ascorbic acid was added (reduction of Au³⁺ to Au⁺). To this mixture, an aqueous solution of NaOH (100 mM, 1 mL) was quickly injected to induce particle formation.

PEGylated gold nanoparticle:-

Specifically the PEGylated gold nanoparticle was prepared as reported earlier by adding 5 mL MeOH and 1 mL acetic acid in 10 mL flask and stirred for 2-5 minutes (Chen *et al.*, 2008). Then, 14.75 mg (0.225 mmol) tetrachloroauric acid and 20 mg of PEG-thiol were added to the above mixed solvents and dissolved by stirring for 5 minutes. 12.5 mg (2.0 mmol) sodium borohydride was dissolved in one mL nanopure water. The NaBH₄ solution was drop-wise added into the above solution with rapid stirring. With the first drop of NaBH₄ was added, the HAuCl₄ solution was immediately turned to dark red from yellow. Rapid stirring was continued for two hours to ensure complete decomposition of NaBH₄. The particle solution was purified by centrifugation and washing with distilled water several times.

Preparation of gold nanocatalyst supported on lanthana:-

Before supporting gold nanoparticles on lanthana, the pH of gold colloid was brought to neutral value and the excess CTAB was removed by cold crystallization and filtration. Then the colloid was mixed with 100 mg of lanthana to give suspension which was sonicated for 2 h under inert atmosphere followed by repeated washing to remove any remaining contaminants and then dried under vacuum.

Testing of the nanocatalysts:-

The coupling was performed under conventional heating and microwave irradiation in 5 mL sealed vessels. In a typical microwave assisted coupling reaction, 68 mM iodobenzene, 68 mM phenylacetylene, and gold nanocatalysts containing 10 wt% gold, 34 mM K₂CO₃ and 3 ml of dimethylformamide were allowed to react at different temperature and reaction times. The reaction was also preformed in conventional heating system for 6 days at temperature 145 °C. The argon gas was purged through the reaction mixture for 10 minutes before each reaction and then the reaction tube was well sealed. After the completion of the reaction, samples were taken and analyzed by gas chromatography (column HP-5 crosslinked 5% PH ME siloxane) with decane as internal standard. The product yields were calculated by means of an internal standard.

Transmission Electron Microscopy (TEM):-

TEM imaging of the gold nanocatalysts was carried out using a Tecnai G² 20 S-TWIN FEI microscope at 200 kV. The samples were dispersed in water, sonicated and deposited lacey-formvar copper grid stabilized with a thin layer of carbon followed by solvent evaporation at room temperature and atmospheric pressure. The TEM images were used to determine the mean particle size and dispersity of the nanoparticles.

Results and Discussion:-

Preparation of gold nanocatalysts:-

Spherical gold nanocatalysts with size of 17 and 40 nm were prepared and then supported on lanthana. Similarly PEGylated, rod and hexagon (45 and 56 nm) nanocatalysts were supported on lanthana. Fig 1, presents TEM images of gold nanocatalysts, which reveals monodispersed nanoparticles with absence of aggregation. Table 1 presents the various gold nanocatalysts involved in the catalysis reaction.

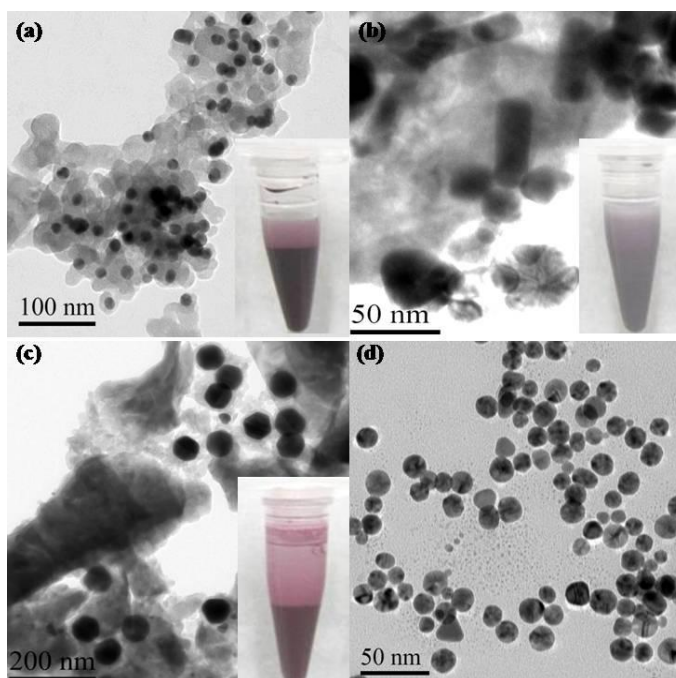


Fig 1:- TEM image of some gold nanocatalysts supported on lanthana and corresponding picture, (a) sphere (17 nm), (b) rod, (c) hexagon (56 nm) and (d) TEM image of PEGylated (17 nm) dispersed in water.

Table 1:- Gold nanocatalysts involved in the coupling reaction.

Nanocatalyst	Shape	Size (nm)
sphere (17 nm)	sphere	17
sphere (40 nm)	sphere	40
PEGylated	sphere	17
rod	rod	50x15
hexagon (45 nm)	hexagon	45
hexagon (56 nm)	hexagon	56

The effect of the nanoparticle shape:-

When the coupling reaction was performed in conventional heating system temperature at 145°C and a period of 6 days afforded low yields 15-20%. However, applying microwave irradiation has tremendous effect on the reaction. The reaction time has shortened to 2 hours instead of several days. This is consistent with early observation on the role of microwave irradiation on catalyzed Sonogashira coupling reaction (de Souza *et al.*, 2008). Control experiments confirmed that no reaction occurred in the absence of a catalyst or when only the support material was present. The catalyzed coupling reaction results are summarized in table 2.

Table 2:-Summary of Sonogashira coupling reaction of phenylacetylene and iodobenzene catalyzed by various gold nanocatalysts. The reaction was carried in DMF under microwave irradiation at temperature 200 °C for 2 hours. [phenylacetylene] = [iodobenzene] = 68 mM.

Nanocatalyst	[DPA] (mM)	Yield (%)
sphere (17 nm)	55	81.0
sphere (40 nm)	36	53.0
recycled sphere (15 nm)	23	34.0
PEGylated	40	58.0
rod	38	56.0
hexagon (45 nm)	12	18.0
hexagon (56 nm)	06	08.4

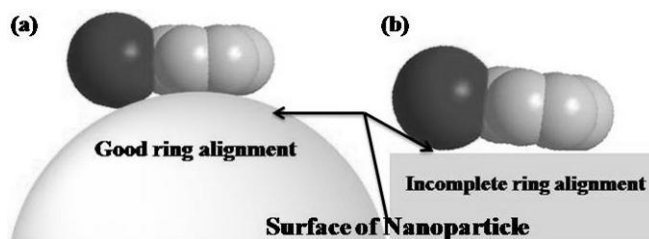


Fig 2:- The alignment of iodobenzene on the (a) rounded (nanosphere) and (b) flat (hexagon) structure.

The result of having spherical nanocatalyst more effective in the coupling reaction than other nanocatalysts is consistent with similar observation on platinum nanoparticles. Tetrahedral platinum nanocatalysts have been found less catalytically active than the spherical palladium nanocatalysts in Suzuki reaction (Zheng and Huang, 2004). Obviously, the sphere (40 nm), which almost has similar size to hexagon (45 nm) catalytically more effective. The only structural difference between hexagon and spherical gold nanoparticle, the first is regular flat while the later has rounded structure. Thus, the high catalytic activity of spherical gold nanocatalyst could not only be related to the large reaction footprint as has been reported before (Narayanan and El-Sayed, 2005), probably due to the rounded structure of the spherical catalyst surface, which could provide good alignment of reactant rings, especially iodobenzene as the iodine atom is suited at angle of 120° to the ring. The good alignment of iodobenzene makes the oxidative addition reaction as initial process to conveniently proceed by weakening the iodine-carbon bond when adsorbed to the surface. Fig 2, provides illustration for the alignment of the iodobenzene ring on the surface of rounded and regular flat nanocatalysts. Another possible reason for low catalytic activity of hexagon could be due the leaching of gold into reaction mixture, and probably the hexagon with regular shape unlike rounded sphere, adsorbed less effectively to the support defect. Leaching of gold was also observed when the coupling reaction was catalyzed by rod and PEGylated nanocatalyst. The leaching of gold from the nanocatalysts was clearly evident by the loss or faint color of nanoparticles. Under the reaction conditions of the experiment, the gold could leach. The leaching of gold from the support has been undoubtedly proved by XPS and ICP-MS techniques and has been considered as the main reason for the loss of catalytic activity from recycled gold nanocatalysts as reported earlier (da Silva and Antunes, 2008, Narayanan and El-Sayed, 2005). In this study, the comparison of TEM images of fresh and recycled sphere nanocatalyst obviously confirmed leaching of gold as shown in Fig 3. This is evident by reduction in the size of gold nanocatalyst and less intense color characteristic of adsorbed gold nanoparticle. Although the spherical and the PEGylated nanocatalyst have similar shape and size (17 nm), the PEGylated nanocatalyst resulted in low catalysis yield as shown in table 2. The low catalytic activity of the PEGylated gold nanocatalyst is due to leaching of gold during the course of reaction. This was evident by complete loss of nanoparticle coloration and retaining the white color of lanthana when the by recycled PEGylated gold nanocatalyst was washed by centrifugation. The removal of gold nanoparticle could take place at the early stage of the reaction, thus the reaction yielded less product. Undoubtedly, the polyethylene glycol polymers stabilizing the nanoparticle don't allow strong adsorption to the support and during the course of reaction act as spring thus negatively affecting the stability of nanoparticle on the solid support. The PEG polymer is also well known to resist non-specific adsorption (Kyriakou, 2010). Consequently, the leaching of gold from solid support could roughen the gold nanoparticle surface leading to loss of catalytic activity. The rough gold surface, unlike smooth surface has been proved to be catalytically less effective (Zheng *et al.*, 2003). Thus the roundness and the stability of nanocatalyst are important key factors of the catalytic activity.

The effect of the nanoparticle size:-

As there no work on size effect beyond 20 nm, spherical (17 and 40 nm) and hexagon (45 and 56 nm) gold nanocatalysts have been investigated for the catalysis of the coupling reaction. Table 2 reveals a pronounced particle size effect on the coupling reaction. The small size gold nanocatalysts revealed better catalytic activity compared to corresponding large ones. Apparently these results contradict to the hypothesis that steric limitations of small size particle adversely affect the catalytic activity and the large size gold nanoparticle should be more effective catalyst (da Silva and Antunes, 2008, Narayanan and El-Sayed, 2005, (Zheng *et al.*, 2003)]. However, taking into account the low stability of gold nanoparticle on the solid support and the ease with which larger nanoparticle leaches into the reaction mixture, the low catalytic activity of large nanoparticles is reasonably anticipated. The large size gold nanoparticles on the support are more fragile and susceptible to desorption into the reaction mixture, thus their catalytic activities are less than the small ones.

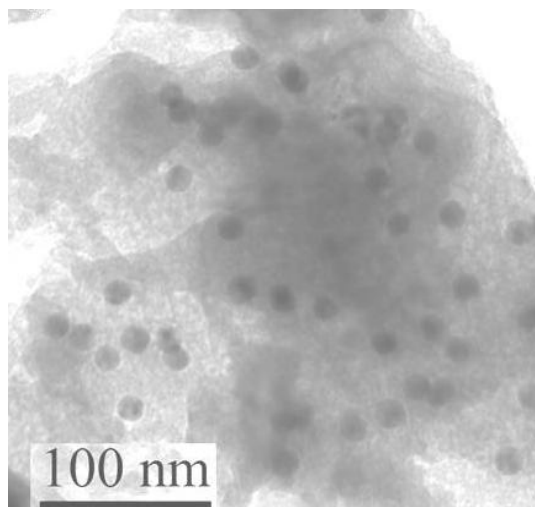


Fig 3:- TEM image of recycled gold nanosphere supported on lanthana, indicating an average diameter reduction of 2 nm from the starting nanosphere.

The effect of temperature:-

The effect of temperature on the microwaved catalyzed coupling reaction is shown in table 3. Due to development of potentially risk pressure in the reaction vessel, the reaction was not performed at temperature higher than 220 °C. However, the yields of reaction performed at 180 and 200 °C were found higher than that at 220 °C. The results of table 3 clearly indicate that the reaction yield increases with increasing the temperature up to 200 °C and then decreases with increasing the temperature. Again the stability of gold nanoparticles on the solid support is probably the main cause of low catalytic activity at high temperature.

Table 3:- The coupling reaction catalyzed by spherical gold nanoparticles at different temperatures. The reaction was carried in DMF under microwave irradiation for 2 h. [phenylacetylene] = [iodobenzene] = 68 mM.

Temperature (°C)	Yield %
220	33
200	81
180	65
145	10

Conclusions:-

Gold nanoparticles with different size, shape, capping agents were supported on lanthana. The resulting gold nanocatalysts were characterized by TEM and tested for Sonogashira coupling at various reaction conditions. Microwaved-assisted reaction compared to conventional heating system, resulted in a very noticeable yield and shortened the reaction time. The catalytic performance of these nanocatalysts was found to vary with shape and size. The stability of the gold nanocatalyst on the solid support is suggested as significant key factor. Specifically the coupling reaction was found to favor by spherical nanocatalyst. The nanocatalysts were found poorly recyclable except the small nanoparticle due to leaching of gold. The study of gold nanocatalysts with various shape and size provide better understanding of the catalytic process of the coupling reaction. In comparison to the tradition catalysts for these reactions, the synthesized gold nanocatalysts are promising and operate in environmentally clean system and deserved further development.

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