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Practical synthesis of silyl-protected and functionalized propargylamines using nanostructured Ag/TiO₂ and Pt/TiO₂ as active recyclable catalysts

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Abstract

Herein we report the use of Ag/TiO_2 and Pt/TiO_2 nanocatalysts to promote the synthesis of a series of silyl-protected and functionalized propargylamine derivatives through alkyne–amine–aldehyde (A^3) coupling under microwave condition using water as solvent in short reaction times with high yielding production. A comparative study between the two catalysts was also demonstrated to prove that Pt/TiO_2 nanocomposite has higher potential effect for propargylamines synthesis more than Ag/TiO_2 . The main features of the investigated method for propargylamines synthesis were easy handling, low catalyst loading as well as the feasibility of catalyst recyclability. The prepared compounds are potentially beneficial with possible pharmacological and biological properties, which that could be used in several disciplines including medicinal and agricultural applications.

Graphical abstract



Keywords Metal-doped TiO₂ · Nanocatalysis · Propargylamine · Multicomponent reaction · Recyclability

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Introduction

Multicomponent reactions are an important protocol in modern synthetic chemistry, and are utilized in the synthesis of highly functionalized organic products (Haji 2016; Abbiati and Rossi 2014). However, some important factors, such as reaction conditions, temperature and catalyst, must be taken into considerations for enabling multicomponent reactions to produce one single product (Wender 2014). One of the best examples of this type of reactions is the one-pot synthesis of propargylamine as main product from the catalytic coupling reaction of aldehyde, amine and alkyne (Abbiati and Rossi 2014). Recently, propargylamine moieties have been found in some bioactive pharmaceuticals such as rasagiline (Oldfield et al. 2007) and selegiline (Riederer and Lachenmayer 2003) (Fig. 1).

Furthermore, propargylamines were used as versatile building blocks in organic synthesis (Vessally et al. 2016). Hence, due to the importance of these compounds, a variety of synthetic approaches have been investigated for the synthesis of these motifs. Several examples using Cu(I) salts (Gommermann et al. 2003; Li and Li 2004; Xu and Li 2009; Okamura et al. 2010), Cu(II) salts (Meyet et al. 2012), Zn(II) salts (Zani et al. 2006; Sarode et al. 2016; Kano et al. 2016), In(III) salt (Sakai et al. 2005), Au(III) salts (Lo et al. 2006), Ag(I) salt (Wei et al. 2003), [IrCl(COD)]₂/MgI₂ (Fischer and Carreira 2004), [Ru(bpy)₃]/CuI (Zhang et al. 2017) as well as nanocatalysts such as Au⁰ NPs (Borah et al. 2014), and Ag^0 NPs have been reported (Borah and Das 2016). However, these methods suffer from drawbacks such as long reaction time (e.g., 1-6 days) (Gommermann et al. 2003; Meyet et al. 2012; Zani et al. 2006; Lu et al. 2009), the utility of strong bases such as alkyllithium reagents (Qi et al. 1988; Riederer and Lachenmayer 2003; Merino et al. 1996), the use of auxiliary substances with the catalyst (Gommermann et al. 2003; Fischer and Carreira 2004; Zhang et al. 2017; Cardoso et al. 2013). Hence, the search for an efficient approach for the synthesis of these compounds is required. Lately, there has been an increasing interest in nanocatalysts as active heterogeneous catalysts (Nguyen et al. 2017; Okamura et al. 2010). One of the defects which occurred during the reaction processes is the agglomeration of catalyst particles that may block the active sites of the catalyst, which effect on its instability. Titanium dioxide (TiO₂) was found to be good supported metal catalysts due to its high surface area, which can be stabilizing the catalysts in its mesoporous framework, which leads to strong metal support interaction and high chemical stability (Bagheri et al. 2014). Hence, due to the mentioned properties, the activity of TiO₂





supported metal catalysts was explored in the literature for various organic transformations (Oi et al. 2016). In this protocol, different molecules containing propargylamine moiety have been synthesized conducting alkyne-aldehyde-amine coupling (A³ coupling) reaction utilizing Ag/TiO₂ and Pt/ TiO₂ in water as heterogeneous catalysts under both thermal and microwave irradiation. In addition, we investigated the effect of metal doping on the catalytic activity of TiO_2 nanoparticles. Furthermore, by carrying out the reactions in water this protocol offers advantages, from the green chemistry point of view, compared to those performed in organic solvents (Kashid and Balakrishna 2018; Shah et al. 2018; Loukopoulos et al. 2017; GhavamiNejad et al. 2016; Trivedi and Singh 2015; Zhao and Seidel 2015; Sharma et al. 2014). A literature survey on some reported approaches for the synthesis of propargylamines is shown in Table 1.

Continuing to our studies for the development and application of heterogeneous catalysts in new synthetic routes in organic reactions (Mohamed and Solum 2017; Mohamed and Hansen 2013; Attia et al. 2017; Petroff et al. 2017), herein we set an eco-friendly reaction condition that has the following features: (1) recyclable heterogeneous nanocatalyst which is easy to prepare and to handle (2) the use of microwave irradiation which shortens the reaction time; (3) no co-catalysts or auxiliary substances have been used, (4) the reaction is carried out in water as solvent, and (5)obtaining variety of propargylamine derivatives with high yields. To the best of our knowledge, Ag and Pt doped on TiO₂ nanocatalysts have not previously been employed in the A^3 coupling reaction. It was demonstrated in this report that Pt/TiO₂ is a more practical nanocatalyst under microwave irradiation condition in water, compared to Ag/TiO₂. The Pt/TiO₂ catalyst surface was in addition easier to regenerate which leads to far greener outcomes.

Experimental

All solvents, amines and paraformaldehyde were purchased from supplier and used without further purification. Anatase titanium dioxide (Aldrich) having the specific surface area of $(35-65 \text{ gm}^{-2})$ was used. 2-(prop-2-yn-1-yl)isoindoline-1,3-dione (**1c**) and (prop-2-yn-1-yloxy)benzene (**1d**) were prepared according to the literature procedures (Menon et al. 2009; Al-Qaisi et al. 2014). Melting points (mp) were measured by an electrothermal (variable heater) melting point apparatus and were uncorrected. Thin layer chromatography (TLC) was performed on silica gel plates 60 GF254, cellulose plates (20 × 20 cm). ¹H NMR (300 MHz) and ¹³C NMR (75 MHz) spectra were recorded on Bruker-Avance DPX (300 MHz for ¹H and 75 MHz for and ¹³C, respectively). CDCl₃ was used as partial deuterated-NMR solvent.

 Table 1
 Some literature reports

 for catalyzed A³ coupling
 reaction

Catalyst	Rx. conditions	Isolated yield	Refs.
CuBr	Catalyst (20	R ₃	Sharma et al. (2014)
	mol%), toluene,	R ₂	
	100 °C, 4 h		
		н ö 51-89%	
Nano-Ag ₂ O	Catalyst (2	R	Trivedi et al. (2015)
C	mol%), MW	N ^{Et}	
	condition,	R ₁ 72-94% Ét	
	CH ₃ Cl, 5 min		
Cu(I)/Acid-	Catalyst (4	\Box	Zhao et al. (2015)
Thiourea	mol%),	Ň	
Catalyst	cocatalyst (3	R ₂	
	$mol\%$), CH_2Cl_2 ,	^R 1 63-92%	
	<u>0°C, 12 h</u>		
ZSM-5-AgNPs	Catalyst (100)	^R 1 ^N ^{R2}	GhavamiNejad et. al
	mg, 5% Ag),	R ₃	(2016)
	glycol, 75 C	Ph 84-96%	
	min		
Cu(II)	Catalyst (2	R ₃ , R ₂	Loukopoulos et al
Coordination	mol%). 2-	N -	(2017)
Polymers	propanol, 90 °C,	R ₁	()
2	5 h	R ₄ 57-100%	
$[{Cu(\mu-I)_2Cu}(P)]$	Catalyst (0.1	R'	Kashid et al. (2018)
$Ph_3)_4$	mol%), CH ₃ CN,	R R"	
-/ -	MW condition,	72-99%	
	5 min		
CuNPs@ZnO-	Catalyst (20	R _{1`N} ^{_R} 2	Shah et.al. (2018)
PTh	mg), ethylene		
	glycol, MW	R ₂ 74 000	
	condition, 15	11-98%	
			т (1 ч
Pt/11O ₂	Catalyst (0.25)	N ^R 2	In this report
nanocomposite	mol%), NIW	R ₃ R ₁	
	condition,	00-30%	
	water, o min		

Chemical shifts (δ) are given in parts per million (ppm) downfield from tetramethylsilane. High-resolution mass (ESI/MS) spectra were recorded on Agilent; 6230 Series Accurate-Mass Time-of-Flight (TOF) LC/MS. The used microwave oven is a Milestone Italy; StartSynth model accompanied with Pack2B Basic Single Vessel Kit reactor. The microstructure of the prepared powders was examined using high resolution transmission electron microscope (HRTEM), JEOL, JEM-2100 working voltage at 200 kV. The metal content was observed by energydispersive X-ray spectroscopy (EDX). The EDX spectra of the TiO₂ doped with Pt and Ag were recorded on a JOEL Model JED-2300 instrument.

Preparation of metal-doped TiO₂

 TiO_2 (5 g), ethanol (500 mL) and the appropriate amounts of metal salts (corresponding to 0.5 wt% metal loading) were added to 1 L of distilled water and placed in a 1.5-L cylindrical photoreactor equipped with a medium pressure Hg lamp (500 W). The suspension was bubbled by helium atmospheric pressure for 30 min before irradiation. The suspensions were irradiated for 6 h (Bellardita et al. 2017).

General procedure for the synthesis of propargylamines

A mixture of a terminal alkyne (2.0 mmol), paraformaldehyde (180.2 mg, 2.0 mmol), amine (2 mmol) and Pt/TiO₂ (5.0 mg, 0.25 mol%) loaded in distilled H₂O (3 mL) and heated under microwave condition at 140 °C and 250 W for appropriate reaction time (the reaction was monitored by TLC). After the completion of the reaction, the mixture was allowed to cool down and then extracted with EtOAc (3 × 20 mL). The combined organic extracts were dried (MgSO₄) and filtered. The solvent was evaporated under reduced pressure and the resulting crude product was purified by column chromatography (silica gel) to obtain the corresponding products **4a**–**4 I**.

Catalyst recovery procedure

After completion of the reaction, Pt/TiO_2 nanocatalyst was collected by filtration and then washed with water (30 mL) and $CHCl_3$ (30 mL). The recovered catalyst was reused in another A^3 coupling reaction.

Characterization data for the synthesized propargylamines 4a–4 l

N,N-dimethyl-3-(trimethylsilyl)prop-2-yn-1-amine (4a)

(Bieber and Da Silva 2004): Colorless oil; yield 98%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 3.48 (s, 2H), 2.36 (s, 6H), 0.14 (s, 9H); ¹³C NMR (CDCl₃, 75 MHz): δ (ppm) 85.2, 82.6, 56.1, 44.3, 0.38; HRMS (ESI) m/z calcd. for C₈H₁₈NSi [M+H]⁺ 156.1209, found 156.1216.

1-(3-(Trimethylsilyl)prop-2-yn-1-yl)piperidine (4b)

(Aguilar et al. 2010) Colorless oil, yield 91%; ¹H NMR (300 MHz, CDCl₃): δ (ppm) 3.25 (s, 2H), 2.61–2.57 (m, 4H), 1.67–1.61 (m, 4H), 1.46–1.43 (m, 2H), 0.15 (s, 9H); ¹³C NMR (75 MHz, CDCl₃): δ (ppm) 84.6, 82.2, 56.3, 49.7, 25.9, 24.6, 0.41. HRMS (ESI) m/z calcd. for C₁₁H₂₂NSi [M+H]⁺ 196.1522, found 196.1519.

4-(3-(Trimethylsilyl)prop-2-yn-1-yl)morpholine (4c)

(Kashid and Balakrishna 2018): Colorless oil, yield 93%; ¹H NMR (300 MHz, CDCl₃): δ (ppm) 3.81–3.76 (m, 4H), 3.23 (s, 2H), 2.50–2.53 (m, 4H), 0.17 (s, 9H); ¹³C NMR (75 MHz, CDCl₃): δ (ppm) 85.7, 83.1, 59.8, 47.6, 36.3,

0.46; HRMS (ESI) m/z calcd. for $C_{10}H_{20}NOSi [M + H]^+$ 198.1314, found 198.1311.

1-Methyl-4-(3-(trimethylsilyl)prop-2-yn-1-yl)piperazine (4d)

(Kashid and Balakrishna 2018): Yellow oil, yield 90% ¹H NMR (300 MHz, CDCl₃): δ (ppm) 3.28 (s, 2H), 2.58–2.56 (m, 8H), 2.31 (s, 3H), 0.18 (s, 9H); ¹³C NMR (75 MHz, CDCl₃): δ (ppm) 107.9, 85.2, 59.4, 46.4, 36.3, 35.0, 0.45; HRMS (ESI) m/z calcd. for C₁₁H₂₃N₂Si [M+H]⁺ 211.1631, found 211.1628.

1-(3-(Trimethylsilyl)prop-2-yn-1-yl)pyrrolidine (4e)

Colorless oil, yield 95%; ¹H NMR (300 MHz, CDCl₃): δ (ppm) 3.23 (s, 2H), 2.80–2.62 (m, 4H), 1.95-1.76 (m, 4H), 0.13 (s, 9H); ¹³C NMR (75 MHz, CDCl₃): δ (ppm) 86.3, 84.2, 52.9, 43.6, 23.7, 0.42; HRMS (ESI) m/z calcd. for C₁₀H₂₀NSi [M+H]⁺ 182.1365, found 182.1358.

N-benzyl-*N*-methyl-3-(trimethylsilyl)prop-2-yn-1-amine (4f)

Colorless oil, yield 87%; ¹H NMR (300 MHz, CDCl₃): δ (ppm) 7.27–7.22 (m, 2H), 7.20–7.18 (m, 3H), 3.62 (s, 2H), 3.53 (s, 2H), 2.35 (s, 3H), 0.10 (s, 9H); ¹³C NMR (100 MHz, CDCl₃, 25 °C) δ 141.2, 128.9, 128.2, 126.6, 86.9, 83.6, 60.6, 45.0, 41.9, 0.47; HRMS (ESI) m/z calcd. for C₁₄H₂₂NSi [M+H]⁺ 232.1522, found 232.1518.

N,*N*-dimethyl-3-phenylprop-2-yn-1-amine (4 g)

(Xu et al. 2011): Colorless oil, yield 93%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 7.42–7.44 (m, 2H), 7.27–7.31 (m, 3H), 3.48 (s, 2H), 2.35 (s, 6H); ¹³C NMR (CDCl₃, 75 MHz): δ (ppm) 130.9, 128.6, 128.2, 122.7, 88.1, 83.6, 50.1, 44.3; HRMS (ESI) m/z calcd. for C₁₁H₁₄N [M+H]⁺ 160.1126, found 160.1121.

1-(3-Phenylprop-2-yn-1-yl)piperidine (4 h)

(Gao et al. 2012): Yellow oil, yield 86%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 7.43–7.40 (m, 2H), 7.31–7.28 (m, 3H),3.51 (s, 2H), 2.63–2.58 (m, 2H), 1.64 (dt, *J* = 10.9, 5.4 Hz, 4H), 1.47–1.44 (m, 4H); ¹³C NMR (CDCl₃, 75 MHz) δ 131.7, 128.3, 128.0, 123.2, 86.2, 83.1, 62.9, 59.4, 51.2, 26.3, 24.2; HRMS (ESI) m/z calcd. for C₁₄H₁₈N [M+H]⁺ 200.1439, found 200.1431.

(4-(Dimethylamino)but-2-yn-1-yl)isoindoline-1,3-dione (4i)

(Jeon et al. 2003): White solid, mp 95–97 °C, Lit. 94–96 °C. yield 91%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 7.82–7.85

(m, 2H), 7.76–7.73 (m, 2H), 4.48 (t, J=1.9 Hz, 2H), 3.24 (t, J=1.9 Hz, 2H), 2.36 (s, 6H); ¹³C NMR (CDCl₃, 75 MHz): δ (ppm) 166.4, 135.0, 132.6, 122.7, 85.4, 80.1, 49.8, 44.7, 28.2; HRMS (ESI) m/z calcd. for C₁₄H₁₅N₂O₂ [M+H]⁺ 242.1134, found 242.1120.

2-(4-(Piperidin-1-yl)but-2-yn-1-yl)isoindoline-1,3-dione (4j)

(Al-Qaisi et al. 2014): White solid, mp 87–88 °C, Lit. 83–84 °C, yield 90%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 7.86–7.82 (m, 2H), 7.75–7.71 (m, 2H), 4.47 (t, *J*=1.9 Hz, 2H), 3.21 (t, *J*=1.9 Hz, 2H), 2.51–2.47 (m, 4H), 1.59–1.42 (m, 4H), 1.02–0.75 (m, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ (ppm) 167.4, 134.7, 132.1, 128.6, 121.8, 86.5, 83.3, 62.6, 59.2, 26.4, 24.6; HRMS (ESI) m/z calcd. for C₁₇H₁₉N₂O₂ [M+H]⁺ 283.1447, found 283.1438.

N,*N*-dimethyl-4-phenoxybut-2-yn-1-amine (4 k) (Xu et al. 2011)

Colorless oil, yield 92%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 7.33–7.29 (m, 2H), 7.71–7.69 (m, 3H), 4.63 (s, 2H), 3.22 (s, 2H), 2.32 (s, 6H); ¹³C NMR (CDCl₃, 75 MHz): δ (ppm) 156.8, 129.1, 122.6, 114.7, 84.3, 82.0, 62.1, 49.0, 44.5; HRMS (ESI) m/z calcd. for C₁₂H₁₆NO [M+H]⁺ 190.1232, found 190.1227.

1-(4-Phenoxybut-2-yn-1-yl)piperidine (4 l)

(Jokubaityte et al. 1980): Colorless oil, yield 86%; ¹H NMR (CDCl₃, 300 MHz): δ (ppm) 7.78–7.76 (m, 3H), 7.56–7.51 (m, 2H), 4.48 (t, *J*=1.9 Hz, 2H), 3.25 (t, *J*=1.9 Hz, 2H), 2.57–2.54 (m, 4H), 1.57–1.54 (m, 4H), 1.45–1.42 (m, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ (ppm) 156.6, 129.5, 123.0, 113.6, 87.2, 84.3, 58.9, 49.3, 44.8; HRMS (ESI) m/z calcd. for C₁₅H₂₀NO [M+H]⁺ 230.1545, found 230.1539.

Results and discussion

Characterization of catalysts

Loading of TiO₂ samples by metal nanoparticles was carried out by a photodeposition technique (Bellardita et al. 2017). Platinum chloride and silver nitrate were used as precursors for Pt and Ag, respectively. The X-ray diffraction (XRD) peaks that are corresponding to bare TiO₂, Ag/TiO₂ and Pt/ TiO₂ photocatalysts are shown in (Fig. 2), confirmed on the formation of the as prepared nanocomposites with a single phase anatase structure without detecting any secondary phase.

The XRD spectra showed the main characteristic peaks of anatase phase at $2\theta = 25.28^{\circ}$, 37.80° , 48.05° , 53.89° , 55.06° ,



Fig. 2 XRD pattern of a bar $\rm TiO_2,~b~TiO_2$ doped with Ag, c $\rm TiO_2$ doped with Pt

 62.69° (Shi et al. 2014). The crystals phases of TiO₂ are slightly effected by the addition of metal dopants.

The surface structure, particle morphology, and crystallite sizes of the nanocatalysts were investigated by TEM and EDX (Fig. 3).

In both cases of the Ag- and Pt-doped nanocomposites, the TiO₂ particle sizes are quite uniform in a nearly spherical morphology which is in agreement with previous investigation by Yi et al. (Yi et al. 2014) who reported that metaldoped TiO₂ could be formed in homogeneous morphologies that may have impact in enhancement the catalytic efficiency. The representative TEM images had been performed for Ag/ TiO₂ and Pt/TiO₂ to show that Ag and Pt are doped into the TiO₂ framework (Fig. 3a, b). It was showed that the crystal sizes of Ag- and Pt-doped TiO₂ were ranging 16–25, 25–29 and 6–8 nm (Fig. 3a, b). In addition, EDX analysis showed the presence of (Ti, O and Ag) with (43.5 wt%, 21.42 wt% and 1.95 wt%) (Fig. 3c) and (Ti, O and Pt) with (43.64 wt%, 21.47 wt% and 4.75 wt%) (Fig. 3d), respectively.

Catalytic activity

To demonstrate the catalytic efficiency of TiO_2 , Ag/TiO_2 and Pt/TiO_2 nanocomposites as catalyst precursors for the well-known aldehyde–amine–alkyne coupling reaction (A³ coupling), a set of experiments were carried out. Trimethylsilylacetylene (1a), paraformaldehyde (2) and dimethylamine solution (40 wt% in water) (3a) were selected as model substrates to obtain propargylamine 4a (Scheme 1). The catalysts TiO₂, Ag/TiO₂ and Pt/TiO₂, respectively, were used in 0.1 mol % under thermal heating



Fig. 3 TEM images of a Ag/TiO₂, b Pt/TiO₂ and EDX pattern of c Ag/TiO₂, d Pt/TiO₂



using DMF, DMSO or THF, but no encouraging results were obtained. However, by carrying out the reaction by water as solvent under thermal condition at 100 °C, the adduct 4a was obtained in 67 and 54% isolated yields, respectively. Furthermore, it was found that using TiO₂ under thermal or microwave condition, the reaction was not performed and the starting materials were collected.

To achieve high catalytic performance of Ag/TiO₂ and Pt/ TiO₂ catalysts, microwave irradiation was used, yielding the corresponding propargylamine 4a, after 19 and 24 min with 82% and 75% isolated yields, respectively (Table 2).

From these results, it was observed that Pt/TiO₂ has a potential higher catalytic performance compared to Ag/ TiO₂.

reaction

Catalyst	Rx time (min)		Yield %	
	Thermal condition	MW condition	Thermal condition	MW condition
Pt/TiO ₂	3 h	19 min	67	82
Ag/TiO ₂	5 h	24 min	54	75
TiO ₂	48 h	120 min	n.d. ^a	n.d.

Table 2 The catalytic performance of Pt/TiO₂, Ag/TiO₂ and TiO₂ towards A^3 coupling reaction

^an.d. = not detected, it means no reaction was performed

Table 3 The effect of catalyst loading

Catalyst	Catalyst loading (mol %)	Rx time (min)	Yield %
Ag/TiO ₂	0.1	24	75
	0.15	20	80
	0.2	17	87
	0.25	9	92
Pt/TiO ₂	0.1	19	82
	0.15	13	89
	0.2	8	95
	0.25	6	98

Effect of catalyst loading

Scheme 2 Proposed reaction

mechanism

It is worth to note that when Ag/TiO_2 and Pt/TiO_2 nanocomposites were used in 0.1 mol %, the product was obtained in 82 and 75%, respectively, under microwave irradiation. Therefore, to achieve maximum yield for the A^3 coupling reaction, the loading of both catalysts was increased in parallel catalytic reactions. Interestingly, it was demonstrated that when the concentration of Ag/TiO_2 or Pt/TiO_2 nanocatalysts was increased, product **4a** was obtained after short time in high yield (Table 3).

It was observed from the abovementioned results, a further increase of Ag/TiO_2 or Pt/TiO_2 concentrations to 0.25 mol % leads to improvement in the reaction time and yields. From the results, it was worth noting that the Pt/TiO_2 catalyst showed superior catalytic activity than Ag/TiO_2 because it is hypnotized that the Pt/TiO_2 nanocatalyst could accelerate the process of formation of alkynide ion faster than Ag/TiO_2 . A possible mechanistic pathway has been suggested (Scheme 2).

In this reaction, when Pt-supported TiO_2 nanocomposite was irradiated by microwave irradiation, the generated electron could be transferred and trapped to the Pt nanoparticles due to the lower Fermi energy level of the noble metal (Schmickler and Santos 2010). The enriched electron density on Pt would favor the formation of iminium ion, while the abstraction of hydrogen from alkyne to furnish alkynide ion was performed over TiO₂ (Panagiotopoulou et al. 2013). The formed ions were reacted rapidly in fast step to form propargylamine.

Catalytic recyclability

Both catalysts Ag/TiO_2 and Pt/TiO_2 were separated and recovered by washing with water and $CHCl_3$. After drying, 0.25 mol % of each catalyst was loaded in the model reaction (see scheme 1) and the catalyst recovery process was performed up to four catalytic runs as shown in Figs. 4 and 5.

As seen above, it appears that the reaction in the presence of Pt/TiO_2 compared to Ag/TiO₂ can be readily recycled







Fig. 5 Catalytic recyclability of Pt/TiO₂ nanocomposite



Fig. 6 XRD pattern of the recycled Pt/TiO₂ nanocatalyst

and reused four times without any observable decrease in its activity which indicated on the reusability and stability of Pt/TiO₂ catalyst. To detect the crystal phase evolution of the Pt/TiO₂ nanocatalyst after the fourth catalytic cycle, XRD of the recycled catalyst was determined. The XRD pattern showed peaks at $2\theta = 25.26^{\circ}$, 37.85° , 48.07° , 53.88° , 55.06° , 62.66° (Fig. 6), which are assigned to Pt/TiO₂ with a single phase anatase. From this result, it was proved that the surface of the catalyst had not altered upon further use (see Fig. 2).

Evaluation of the catalytic activity of Pt/TiO₂ nanocomposite in a series of A³ coupling reactions

A variety of silyl-protected propargylamines were prepared from, trimethylsilylacetylene (1a), paraformaldehyde (2) and

Scheme 3 Pt/TiO₂ catalyzed A³ coupling for the synthesis of silyl-protected propargylamines



Table 4 Experimental results



amine **3b–f** that depicted in scheme 2. Propargylamine products **4b–f** were obtained in 87–95% yield (Scheme 3, Table 4). That provides a new efficient synthetic route for production of propargylamines. To achieve complete conversions of the starting materials to the products, the reactions were monitored by thin layer chromatography (TLC) analysis.

In another set of experiments, various A^3 coupling reactions were performed under the optimized condition (Scheme 4). The results are summarized in Table 5. The reactions of phenylacetylene (**1b**), *N*-phthalic anhydride–acetylene (**1c**) and phenoxyacetylene (**1d**) with paraformaldehyde and with secondary amine; dimethylamine solution (**3a**) or piperidine (**3b**) were carried out under microwave irradiation within 6–9 min to furnish the corresponding propargylamine **4 g–4 l** in high yields (86–93%) (Table 5).

From the aforementioned results, it was observed that different terminal alkynes and secondary amines were selected to be employed in the catalytic A³ coupling reactions catalyzed by Pt/TiO₂ nanocomposite which indicate that the catalyst is compatible for various types of substrates and it was demonstrated that Pt-supported TiO_2 nanoparticles is an efficient catalyst for the synthesis of different propargylamine derivatives.

Conclusion

In this report, we examined the catalytic performance of Ag/TiO_2 and Pt/TiO_2 under microwave irradiation in functionalized propargylamine. It was demonstrated that Pt/TiO_2 catalyst had higher catalytic activity than Ag/TiO_2 . An efficient route for the synthesis of propargylamine derivatives had been investigated with short reaction time, high yield and performing the reaction in water as solvent. In addition, the catalyst was easy to recover and reuse in another reaction cycle under the same reaction condition. The investigated procedure can open the access for designing multifunctional complex molecules via a green route due to its simplicity.

Scheme 4 Pt/TiO₂ catalyzed A³ coupling for the synthesis of diverse functionalized propargylamines



Table 5 Experimental results

Alkyne	Amine	Product	Rx time	Yield %
Ph 1b	Me HN Me 3a	Ph 4g Me	8	93
Ph—=== 1b	N H 3h	Ph 4h	7	86
O N Ic	Me HN Me 3a	O N Me Ai	7	91
	N H 3b		9	90
O Id	Me HN 3a	O N ^{, Me} Me 4k	6	92
O Id	N H 3b		8	86

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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