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Synthesis of peptide nanofibers decorated with palladium nanoparticles and its application as an efficient catalyst for the synthesis of sulfides *via* reaction of aryl halides with thiourea or 2-mercaptobenzothiazole

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In this work supported Pd nanoparticles on the peptide nanofiber (PdNP-PNF) has been prepared *via* fabrication of self-assembled woven nanofiberfrom peptide, subsequently immobilization of palladium nanoparticles on this nanostructural compound. To obtain self-assembled woven nanofiber, we designed and synthesized a peptide using arginine as building block. The C-terminus of amino acid was protected as ethylester. Coupling was mediated by dicyclohexylecarbodiimide-1-hydroxybenzotriazole (DCC-HOBT). TEM, SEM, XRD, ICP and FT-IR techniques were employed to characterize prepared nanofiber materials. In this work, the effect of phosphate buffer solutions (pH 8 and pH 11 (isoelectric point of arginine amino acid) on the structure of peptide nanofiber was investigated. Supported Pd nanoparticles on the peptide nanofiber (PdNP-PNF) were applied for the C–S coupling reaction using two different sulfur transfer reagents (thiourea and 2-mercaptobenzothiazole).

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1 Introduction

Production of nanofibers ranging from micron to nanometer scales have been studied due to their special properties such as up grading human artificial tissue including bone[1], cartilage[2], ligament[3], skeleton muscle[4], skin[5], vascular tissue engineering[6], neural[7], and as carriers for the controlled delivery[8], protines[9] and controlled DNA delivery.[10]Nanofiber can be produced in many different ways, for example self-assembly[11], drawing[12], electrospining[13], template synthesis[14]. Among these methods, electrospinning is a well-known technique to make a layer of nanofibers. In this layer, though, each nanofiber cannot be separated without their destruction and electrospinning needs larger electric fields, sensitivity to variability in solution conductivity and low production speed. Template synthesis is an efficacious route to produce nanofibers or nanotubes using a nanoporous membrane as a template. Yet, a disadvantage of this method is that it cannot make continuous nanofibers one by one. However, the template method is possible by controllingparameters such as melt time and temperature. Self-assembling is a procedure by which molecules organize and arrange themselves into patterns or structures through non-covalent forces such as hydrogen bonding, hydrophobic forces, and this technique shows good potential for designing novel scaffolds for tissue engineering applications. Several factors including, the concentration of peptide molecules, pH, solvent polarity, sonication, ionic strength and interaction with anions such as phosphate have been used to tune the peptide self-assembly process. Da-Wei.[15] indicated that the self-assembling process is enhanced at a low concentration of phosphate and the length of the fibrils is longer than that in pure water. Goldberger.[16] designed a series of PAs that can self-assemble into nanofibers when the solution pH is decreased from the normal physiological condition 7.4 to 6.6, Smith.[17] saw that the overall length of the nanofibers increased as the initial concentrationof insulin peptide increased. Prabhu[18] has shown that ultrasonication-induced fibril-formation by a bolaform peptide. Shen[19] demonstrated solventeffects for dissolved β-amyloid in different solvents of various concentrations, and found that the growth rate of the nanofibers was reduced. In the case of 100% dimethyl sulfoxide, no β-sheet content is visible, but in 10% dimethyl sulfoxide, nanofibers are seen to contain the rigid, hydrogen-bonded β-sheet structure. Therefore, nanofibers, are irrespective of their method ofsynthesis. Among different nanoparticles, self-assembling peptides are the best choice due to unique properties such as high surface area-to-volume and they are desirable in order to allow delivery of a high density of cells and tissue engineering. Among the applications of peptide nanofiber, their catalytic applications in organic reactions have attracted extensive attention; for example IndrajitMaity[20] reported the fabrication of peptide capped Pd nano particles, which enhanced the catalytic activity of C–C coupling reactions in aerobic conditions. Khalily [21] reported a supramolecular peptide nanofiber templated Pd nano catalyst for efficient Suzuki coupling reactions under aqueous conditions. Shao[22] reported coupling reactions of aromatic halides in the presence of palladium catalyst immobilized on poly (vinylalcohol) nanofiber. We demonstrate for the first time, the use of peptide nanofibers decorated with Pd nanoparticles with sizes ranging from 7.1 to 10.28 nm for the C–S coupling reactions using two different sulfur transfer reagents. Sulfides have shown widely applications as potent drugs for HIV[23], cancer[24], Alzheimer[25] and Parkinsons diseases.[26]They are useful compounds in chemistry due to their role as important intermediates in organic synthesis.[27] Therefore, there is still a great interest to find a new reagent or system to synthesis sulfides. Herein, we present for the first time the cross-coupling reactions of aryl/alkyl halides using 2-mercaptobenzothiazole or thioureaas efficient sulfur transfer reagent to afford symmetrical sulfides, which has been catalyzed by immobilized palladium nanoparticles on peptide nanofiber.

2 Results and discussion

In this work, to achieve an efficient and simple nanofiber support we performed the self-assembly of a peptide with arginine as building block. After converting of this peptide into nanofiber, palladium nanoparticles were immobilized on the surface of this nanostructural compound (Scheme 1).

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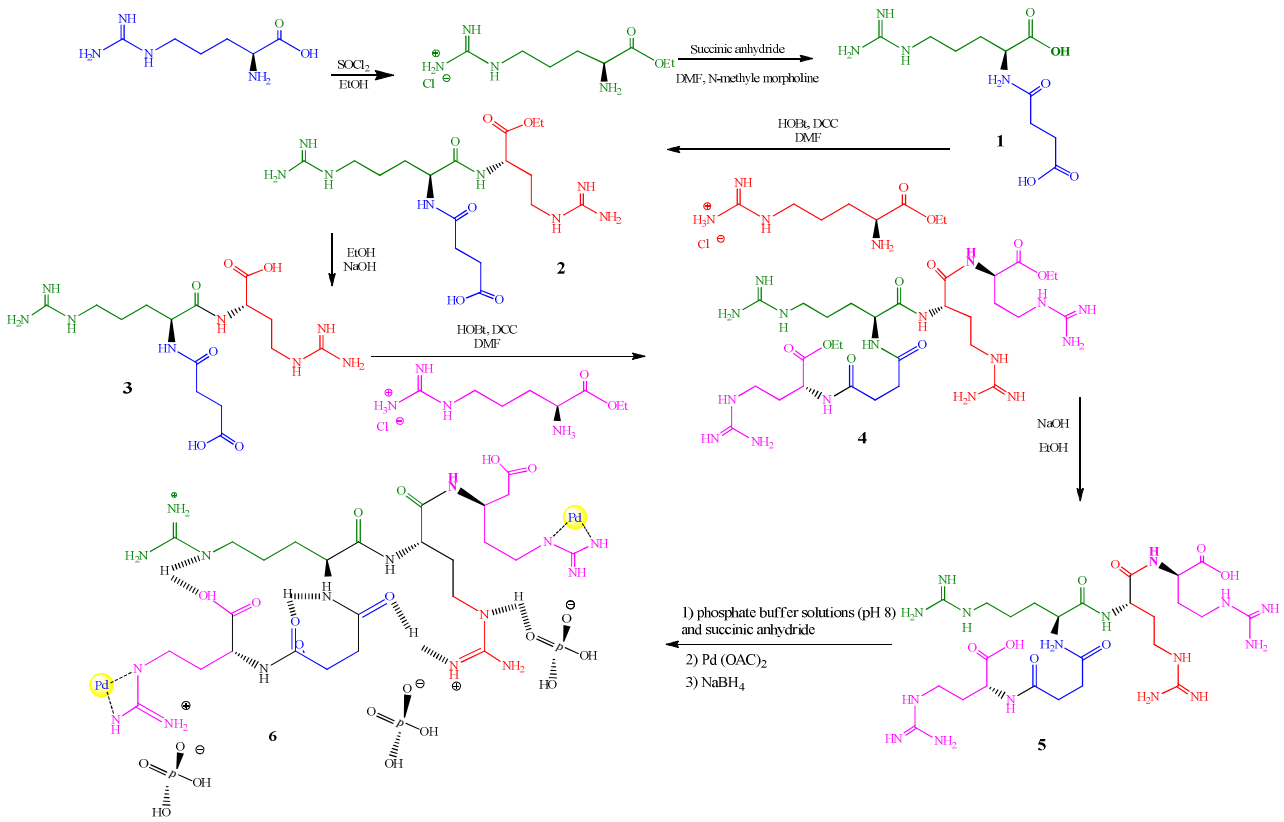

Scheme 1 Schematic synthesis of Pd nanoparticles supported on the peptide nanofiber.

We studied a simple, economic and environmentally friendly approach to the self-assembly of a peptide using phosphate buffer solutionin an aqueous media. Since one way to control the density and growth rate of nanofibers is through the use of the solvent that destabilize the peptide structure, so we decided to use water as self-assembling media because when we used peptide powder, no obvious self-assembly of nanofiber was observed in the SEM image (Fig. 1). Since the peptides formed various hydrogels depending on amino acids charges, therefore we investigate the effect of phosphate buffer solution at pH 8 and pH 11 (isoelectric point of arginine amino acid) on the structure of peptide nanofiber. The pH value was changed by adjusting the ratio of $[HPO_4^{2-}]/ H_2PO_4^-]$ while keeping the total concentration of phosphate constant. The effect of pH 11 solution was evaluated in two ways: i) when peptide solution was investigated at the pH 11 without adding succinic anhydride, colloidal solution was formed and no obvious self-assembly was observed in the scanning electron microscopy image (Fig. 2), ii) when succinic anhydride added to the peptide solution, the final pH of the solution was found to be 10 due to hydrolysis of succinic anhydride to succinic acid, microscopic images showed the formation of micro-crystals (Fig. 3). Surprisingly, at pH 8 by adding succinic anhydride to the peptide solution, which the final pH of the solution was found to be 7, the woven morphology of the nanofiber was observed in the SEM image (Fig. 4). The pH effect can be explained since a high pH environment dissociates H^+ of $HPO_4^{-2}/H_2PO_4^-$, it is known that one divalentanion have a charge of -2 and can effectively interact with two positively charged groups of the peptide molecule like a bridge. Since distance between two nearest arginine resides of the same peptide molecule is much larger than the size of HPO_4^{-2}, one divalent anion can hardly interact with two arginine residues simultaneously, which leads to form a short nanofibers aggregated before the peptide molecules self-assembled to grow longer nanofibers.

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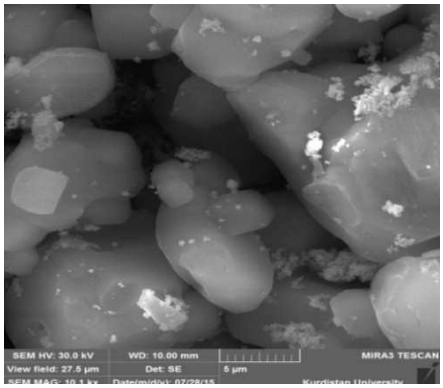


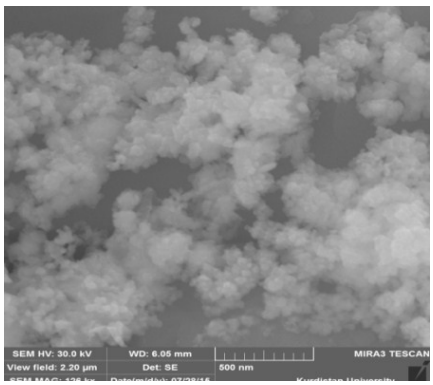
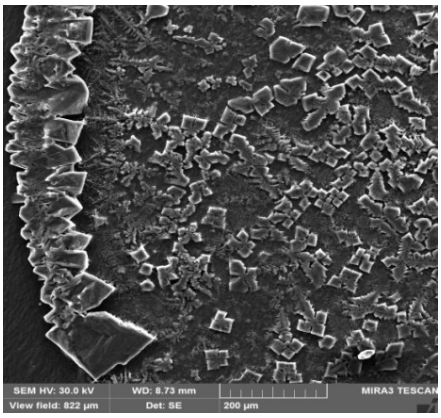


Fig. 1 SEM images of powder peptide



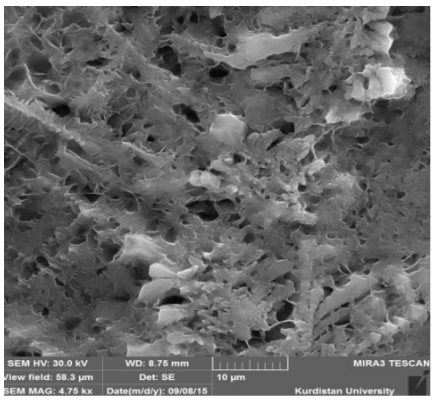
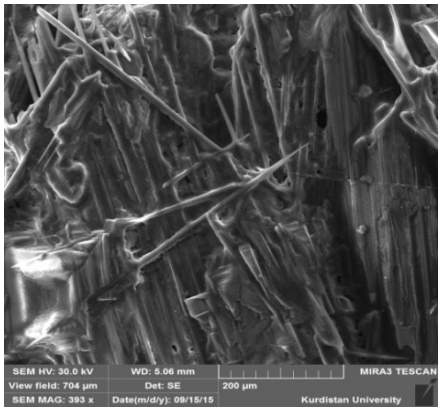


Fig. 2 SEM images of solution peptide at pH 11 without adding succinic anhydride.



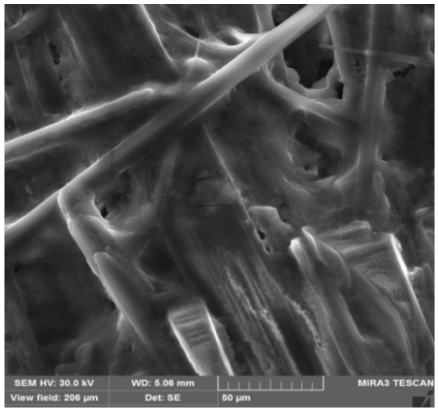


Fig. 3 SEM images of peptide solution at pH 11 in the presence of succinic anhydride

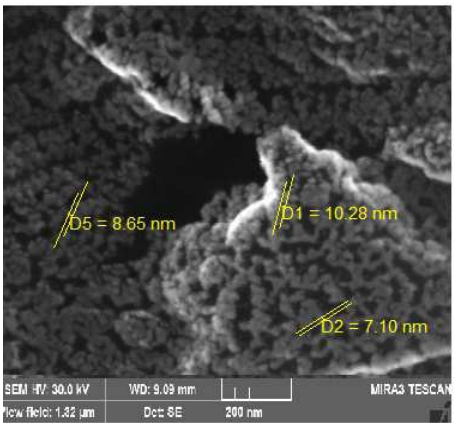


Fig. 4 SEM image of peptide solution at pH 8 In the presence of succinic anhydride

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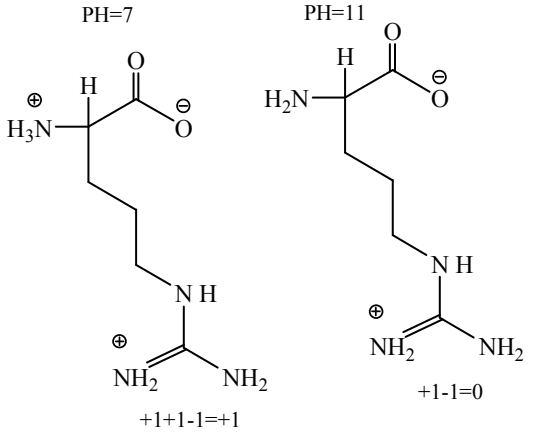
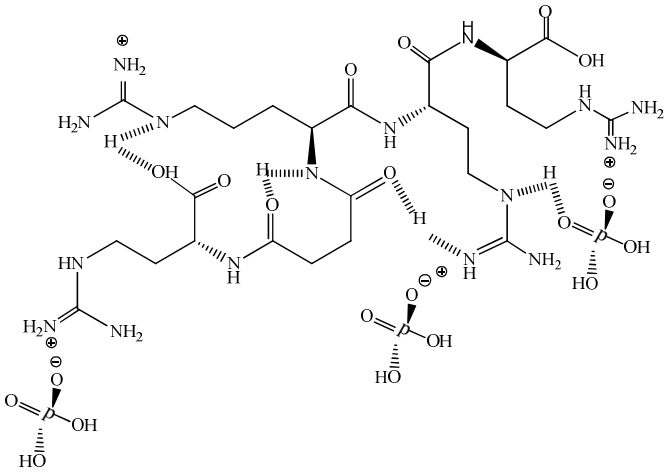
When the pH is raised to 11, it results in a negative deprotonated carboxylate of arginine and one positive protonated nitrogen atom (the arginine residue to be natural), thus, there is no electrostatic interaction between HPO_4^{-2} ion and arginine residues of the peptide molecule. But, when pH changes to 7, it results in a negative deprotonated carboxylate and two positive protonated nitrogen atoms (overall charge of +1) (Scheme 2). Since one monovalavet anion takes one negative charge and can interact with one positively charged groups of the peptide molecule therefore the monovalent ions can distribute the charges between the polar head groups to reduce electrostatic repulsion, which makes the more ordered nano-fibrils (Scheme 3). However increase of pH value results in the increase of $[HPO_4^{2-}]$, which makes conditions unfavorable for the formation of nanofiber network. But at pH 7 the concentration of the HPO_4^{-2} is lower than the concentration of the monovalent anion $H_2PO_4^-$; therefore the monovalent anions play a major role in the shielding of charges on the peptide molecules.



Scheme 2 Arginine.amino acid charge at the pH 7 and 11



Scheme 3 Schematic illustration of the proposed mechanism for the template-free formation of woven nanofiber in an aqueous solution

2.1Characterizationof peptide nanofiber

The self-assembly study of the peptide was investigated using various spectroscopic and microscopic techniques. FT-IR spectroscopy was used to study the structure of the nanofiber solution; a peak that appear at 1644cm^{-1}is correspondence to bending vibration of NH groups, while this peak for the peptide powder appear at 1629 cm^{-1}, the observed shift is probably due to signifies self-assembling and hydrogen bonding between phosphate and peptide. As a general rule, hydrogen bonding decreases the frequency of stretching vibrations, since it decreases the restoring force, but increases the frequency of bending vibrations since it produces an additional restoring force.[28] (Fig. 5). The SEM images show that the peptide molecules self-assembled into woven nanofiber[29] structures (Fig.4).

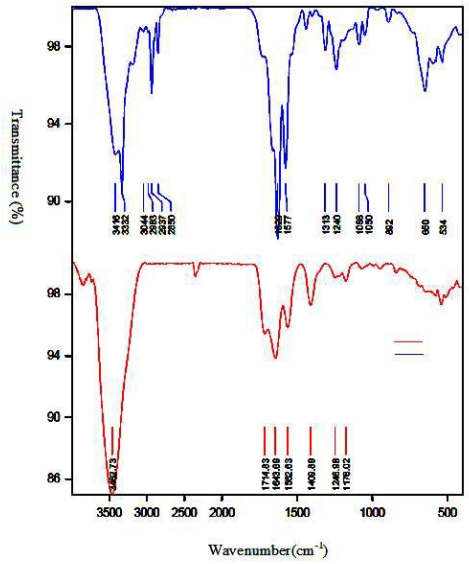


Fig. 5 FT-IR spectra of peptide powder (blue line); the peptide nanofiber (red line)

2.2 Characterization of supported Pd nanoparticles on the peptide nanofiber

The effect in the secondary structure of the peptide *via* the interaction between the metal nanoparticles and peptide was considered by FT-IR, SEM and TEM analysis. In the IR spectrum of supported Pd nanoparticles on the peptide nanofiber, the bending vibration of NH groups appeared at 1648 cm^{-1} (Fig. 6). The SEM and TEM images show that the Pd nanoparticles were regularly immobilized on the surface of woven peptide nanofibers (Fig. 7). The amount of Pd incorporated into the nanofiber found to be 250 ppm that determined by inductively coupled plasma optical emission spectrometry (ICP-OES). X-ray diffraction patterns of peptide nanofibers decorated with palladium is shown in (Fig. 8). The strong diffraction peaks about at 2Θ values of 41º, 47º, and 69º [30-31] is related to Pd (0)

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nanoparticles; also the other peaks related to peptide nanofiber structure.

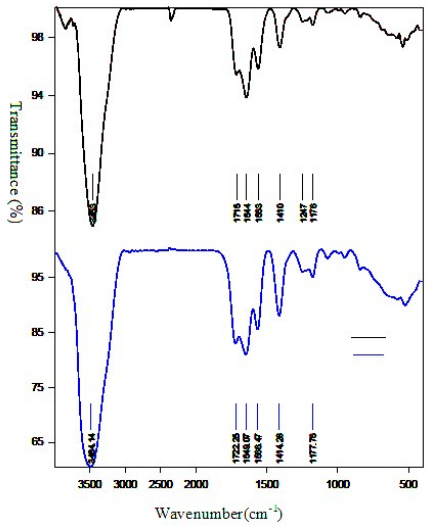
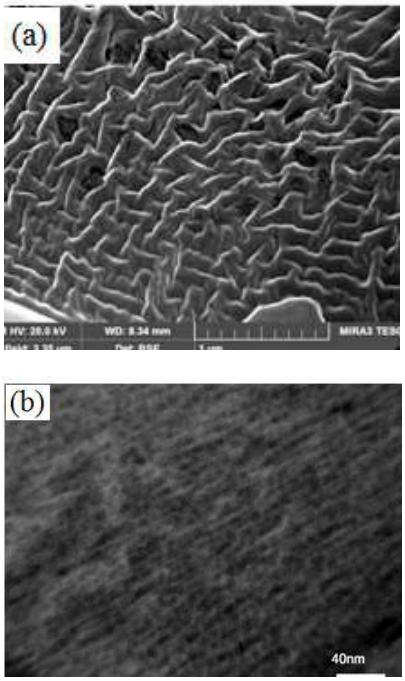


Fig. 6 FT-IR spectra of the peptide solution without Pd nanoparticles (black line), peptide nanofibers decorated with Pd nanoparticles (blue line).



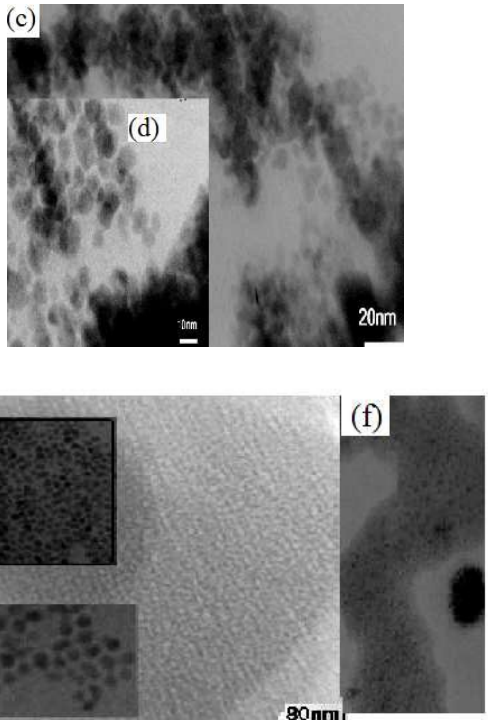


Fig. 7 (a) SEM image of immobilized Pd nanoparticles on the surface of the woven nanofibers; (b), (c), (d) (e) and (f) TEM surface of the woven nanofibers at pH 8.

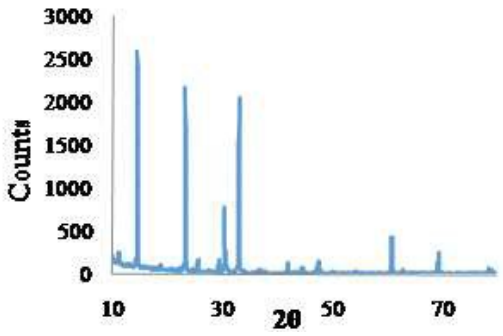


Fig. 8 The X-ray diffraction pattern of Pd immobilized on peptide nanofibers

2.3 Catalytic studies

After preparation and characterization of Pd nanoparticle supported on the peptide nanofiber catalytic activity of this compound was investigated for C-S coupling reaction. A variety of symmetrical aryl/alkyl sulfides can beobtained in moderate to excellent yields (up to 90%). In this work thiourea and 2-mercaptobenzothiazole(as a new heterocyclic sulfur donor) has been utilized for the direct synthesis of organic sulfides from aryl/alkyl halides in the presence of a peptide nanofibers decorated with Pd nanoparticles (PdNP-PNF) that effectively led to the

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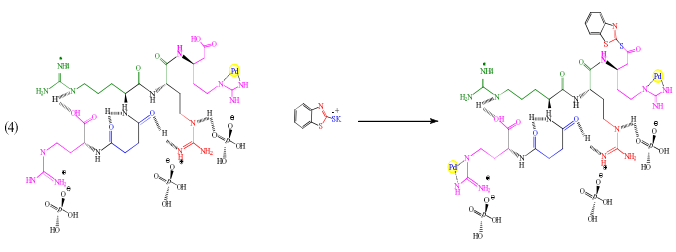
production of sulfides in high yield. In order to optimize the reaction conditions, the reaction of iodobenzene with 2-mercaptobeczothiazole in the presence of PdNP-PNF has been selected as model reaction and different parameters including the type of base, solvent and temperature has been studied (Table 1). It was found that the base and solvent significantly influenced the outcome of C-S coupling reaction. Also, the reaction rate was increased by rising reaction temperature. With optimal conditions in hand, a variety of symmetrical diaryl/alkyl sulfides were synthesized using 1.3 equivalents of 2-mercaptobenzothiazole at 130 °C with high purity (Table 2). Also, resulting optimized generally, the C-S coupling reactions of aryl halides with electron with drawing groups preceded more rapidly and high yields of products have been obtained. However, the C-S coupling reaction including aryl chlorides showed less reactivity than that of aryl iodides and bromides.Suggested mechanism for these transformations has been illustrated in Schemes 4 and 5. Iinitially aryl halide reacts with Pd by oxidative addition to form intermediate (***a***), then the intermediate (***a***) reacts with 2-mercaptobeczothiazole to produce intermediate (***b***), which is transformed into thiol anion in the presence of KOH. Then thiol anion reacts with intermediate (***a***) *via* reductive elimination reaction to afford sulfide and releases palladium nanoparticle. It should be noted that Gracia-Espono et al reported when thiolated substrates are used, such as S-rGOx, the Pd nanoparticles exhibit smaller sizes, improved spatial distribution, and poor or null agglomeration because of the stronger interaction with the thiolated graphene surface.[32] The thiol bridges play an active role in the adsorption mechanism of the Pd cluster, which would increase the reactivity. During the theoretical studies Gracia-Espono et al observed the following chemical reactions:

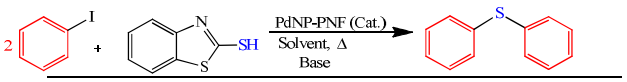
(1) $C_7H_7SH + rGOx\text{-}Vc \rightarrow rGOx{-}H{-}S{-}C_7H_7$

(2) $C_7H_7SH + rGOx{-}OH \rightarrow rGOx{-}S{-}C_7H_7 + H_2O$

(3) $C_7H_7SH + rGOx{-}NH_2 \rightarrow rGOx{-}S{-}C_7H_7 + NH_3$

The chemical reaction shown in eq 1 was observed during the first adsorption event, while the chemical reactions in eqs 2 and 3 were not observed until Pd_{13} adsorption[30]. Thus, according to results we can conclude that thiol anion is more willing to react with palladium. Because otherwise if that reacts with functional groups on the surface of peptide, no disulfide could be synthesized in eq 4.





Entry	Solvent	Temp. (ºC)	Base	Time (h)	Yield (%)[b]
1	DMSO	130	KOH	2	90
2	DMF	130	KOH	2	N.R
3	PEG	130	KOH	2	N.R
4	CH_3CN	130	KOH	2	N.R
5	H_2O	130	KOH	2	N.R
6	EtOH	130	KOH	2	N.R
7	DMSO	130	NaOH	2	43
8	DMSO	130	K_2CO_3	2	N.R
9	DMSO	130	Na_2CO_3	2	N.R
10	DMSO	130	Et_3N	2	N.R
11	DMSO	130	NaOEt	2	N.R
12	DMSO	100	KOH	2	63
13	DMSO	80	KOH	2	trace

[a] Reaction conditions: iodobenzene 1 mmol, 2-mercaptobenzothiazole 1.3 mmol, PdNP-PNF (200µL), base .1 gr, [b] Isolated yield.

Table 1 Optimization of the reaction conditions for the C-S coupling using 2-mercaptobenzothothiazol as sulfur transfer agent.[a]

Finally, the recoverability and reusability of the Pd nanoparticle supported on the peptide nanofiber in the synthesis of sulfides *via* reaction of iodobenzene with thiourea over four successive runs, was investigated. Reaction was performed in DMSO at 130 °C, using 1 mmol iodobenzene, 1 .3 mmol thiourea and 1 gr KOH in the presence of PdNP-PNF (200µl), upon completion of the reaction, the mixture was cooled to room temperature. 20 mL of ethyl acetate was added to the reaction mixture, which led to the precipitation of PdNP-PNF. The resulting precipitate was washed twice with ethyl acetate (2 x 10 mL), dried and applied for the next run. It was found that Pd NP-PNF could be reused at least four times without a significant loss of its catalytic activity.

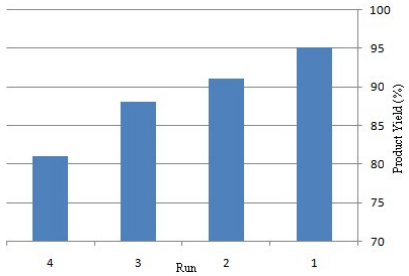


Fig. 8 Reusability of the Pd immobilized on peptide nanofiber

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for the synthesis of symmetrical sulfides *via* reaction of thiourea with iodobenzene

In order to evaluate the catalytic activity of peptide nanofibers decorated with palladium nanoparticles, we compared the results for the synthesis of diphenyl sulfide in the presence of described catalyst with previously reported methods in the literature (Table 4). This catalyst leads to good reaction time and higher yield than the other catalysts. More importantly, compared with other catalysts, PdNP-PNF is easily prepared and can be reused at least four times without any significant loss of its catalytic activity.

s.

4 Conclusions

In summary, we demonstrate an effective route to fabricate peptide nanofiber in an aqueous solution using phosphate buffer solutions with pH 8. This peptide nanofiber was used as nano support to immobilized palladium nanoparticles. PdNP-PNF with special properties such as large specific surface area and with sizes ranging from 7.1 to 10.28 nm was use as catalyst for the synthesis of alkyl/aryl sulfides. We describe for the first time the reactivity of 2-mercaptobenzothiazoleas a new heterocyclic sulfur transfer agent for direct synthesis of symmetric sulfides with aryl/alkyl halides in the presence of this peptide nanofiber decorated with Pd nanoparticles

5 Experimental

5.1 Preparation of arginine ethyl ester hydrochloride

Thionyl chloride (6.0 mL, 82.1 mmol) was added *via* dropping funnel to a stirred suspension of arginine (9.03 g, 54.7 mmol) in Ethanol (100 mL) at0 °C. The mixture wasstirred for 24 h at room temperature, and then solvent was removed. The crude product was recrystallized from EtOAc /EtOH (95:5) to give a white solid of the title compound melting point- 46-48°C[33], FT-IR (KBr) ν_{max}/cm^{-1}: 3428, 3190, 2876, 2940, 2874, 1735, 1658, 1735**.**

5.2 Synthesis of compound 1

0.5 g (5 mmol) Succinic anhydride in 3 mL of DMF were cooled in an ice-water bath and in another round bottom flask, 1.235 g (5 mmol) of arginine ethyl ester hydrochloride was neutralized in ethyl acetate (10 mL), which was then added to the reaction mixture, and 0.5 g (5 mmol) *N*-methyl morpholine was added to this mixture. The reaction mixture was stirred for overnight. After completion, ethyl acetate (50 mL) was added to the reaction mixture. Solvent was removed under reduced pressure to yield compound **1** as a white solid. FT-IR (KBr) ν_{max}/cm^{-1}: 3608, 3566, 1718, 1648.

Synthesis of compound 2

0.917 g (3.5 mmol) of compound **1** in 3 mL of DMF was cooled in an ice-water bath then arginine ethyl ester in ethyl acetate (10 mL) was added to this mixture, which was isolated from 1.72 g (7 mmol) of arginine ethyl ester hydrochloride *via* neutralization. Then 0.68 g (3.85 mmol) DCC and 0.520 g (3.85 mmol) of HOBt was added to this mixture. The reaction mixture was stirred for overnight. Then ethyl acetate (50 mL) was added and the DCU was filtered off. The filtrate was washed with sodium carbonate solution to yield compound **2** as a white solid. FT-IR (KBr) ν_{max}/cm^{-1}: 3336, 3173, 2931, 2855, 1735, 1660, 1526, 1460, 1380, 1303, 1223, 1174, 1104, 1025.

5.3 Synthesis of compound 3

To the 1.31 g (2.7 mmol) of compound **2**,in 6 mL EtOH in a round bottom flask, 2M NaOH (2mL) was added drop wise. The reaction mixture was stirred for overnight. Then 5 mL of distilled water was added to the reaction mixture and EtOH was removed under vacuum. The residue was washed with diethyl ether (2 x 30 mL). Then it was cooled down under ice-water bath for 10 minute and then pH was adjusted to 1 by drop wise addition of 1 M HCl. Then ethyl acetate (50 mL) was added and filtered off. The filtrate was washed with sodium carbonate solution to yield compound **3** as a white solid. FT-IR (KBr) ν_{max}/cm^{-1}: 3440, 3288, 3176, 2978, 1706, 1641, 1571, 1453, 1413, 1339, 1053, 1021.

5.4 Preparation of peptide nanofiber (PNF)

In our experiment 30.14 mg (0.04 mmol) of peptide was dissolved in 0.2 mL of doubly distilled water and 0.8 mL phosphate buffer solution (pH 8). Then 32 mg (0.31 mmol) of succinic anhydride were added to the peptide solution. The mixture sonicated for a few minutes, and then heated at 80°C overnight to form nanofiber solution.

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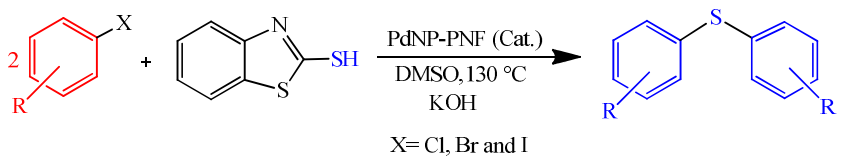
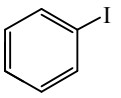
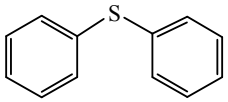
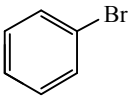
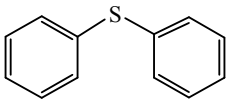
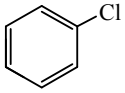
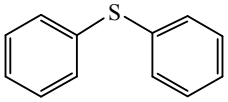
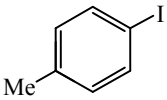
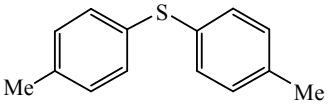
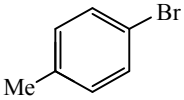
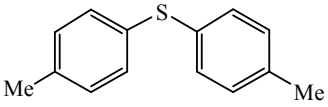
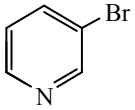
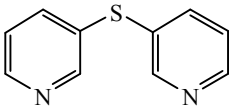
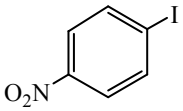
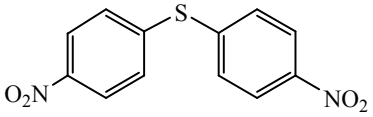
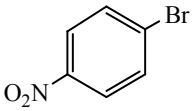
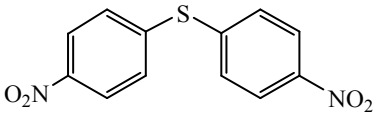
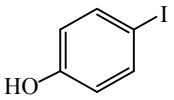
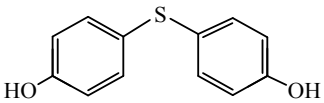
Table 2 Synthesis of symmetrical sulfides *via* reaction of 2-mercaptobenzothiazole and aryl/alkyl halides catalyzed by peptide nanofibers decorated with Pd nanoparticles (PdNP-PNF) in DMSO.[a]



X= Cl, Br and I

Entry	Ar-X	Product	Time (h)	Yield[b] (%)
1			5	92
2			6	87
3			12	43
4			8.5	63
5			10	57
6			1	83
7			25 min	55
8			50 min	41
9			7	61

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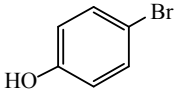
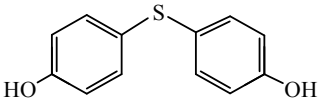
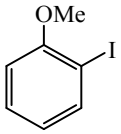
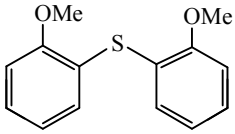
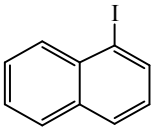
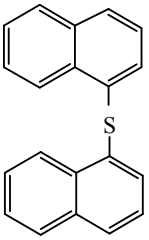
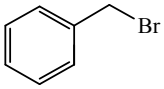
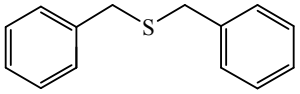
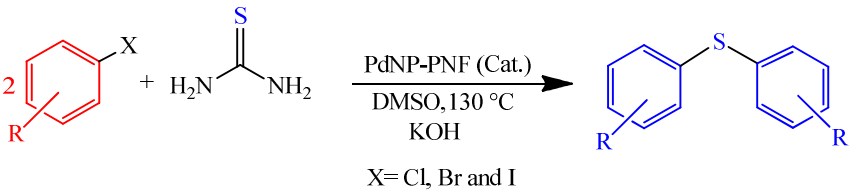
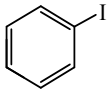
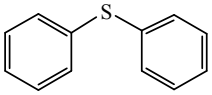
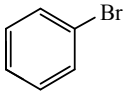
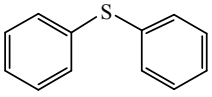
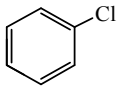
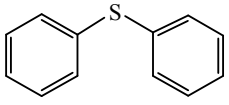
	10			9	53
	11			2	92
	12			10	70
[a] Reaction	13			1	83

conditions: aryl halides (1 mmol), 2-mercaptobenzothiazole (1.3 mmol), PdNP-PNF (200µL), base (1 gr) and DMSO (2 mL).[b]Isolated yield.

Table 3 Synthesis of symmetrical sulfides *via* reaction of thiourea and aryl/alkyl halides catalyzed by peptide nanofibers decorated with Pd nanoparticles (PdNP-PNF) in DMSO.[a]



Entry	Ar-X	Product	Time (h)	Yield[b] (%)
1			2	95
2			3	88
3			10	47

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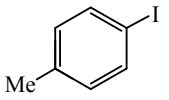
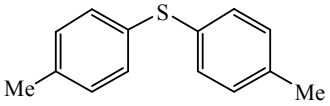
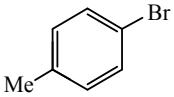
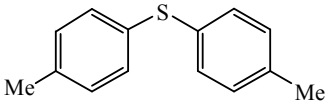
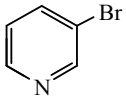
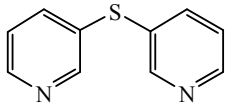
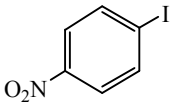
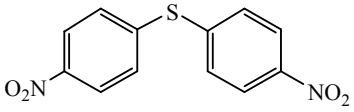
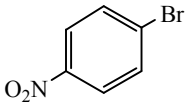
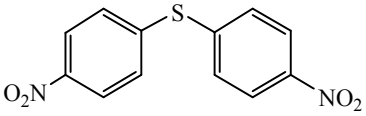
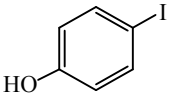
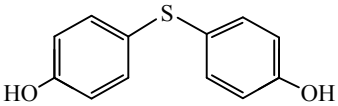
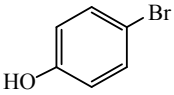
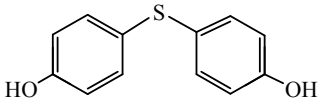
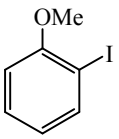
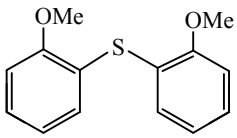
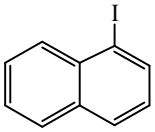
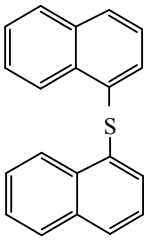
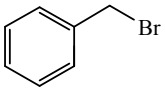
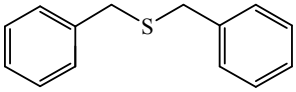
4			7	65
5			9	55
6			30 min	87
7			10 min	55
8			40 min	50
9			6	67
10			9	53
11			2	92
12			10	70
13			1	83

[a] Reaction conditions: aryl halides (1 mmol), 2-mercaptobenzothiazole (1.3 mmol), PdNP-PNF (200µL), base (1 gr) and DMSO (2 mL). [b] Isolated yield.

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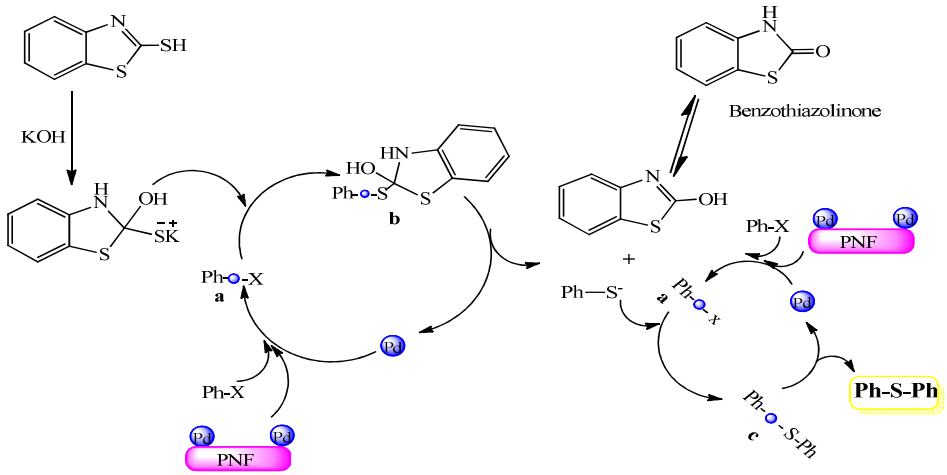
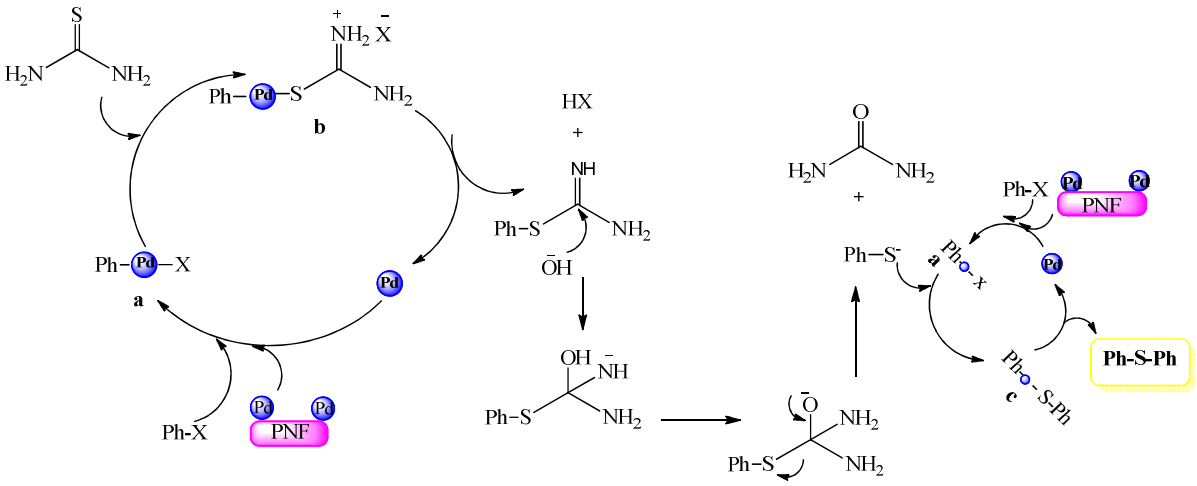


Scheme 4. Proposed mechanism for the synthesis of sulfides through cross- coupling reactions of aryl halides with 2-mercaptobenzothiazole catalyzed by peptide nanofibers decorated with Pd nanoparticles.



Scheme 5 Proposed mechanism for the synthesis of aryl sulfides through cross-coupling reactions of aryl halides with thiourea catalyzed by peptide nanofibers decorated with Pd nanoparticle.

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Table 4. Comparison of PdNP-PNF for the synthesis of diphenyl sulfide with previously reported procedures

Entry	Catalyst	Yield (%)[a]	Time (h)	Ref.
1	MCM-41-2N-CuI	Trace	48	37
2	CuO nanoparticles	70	15	38
3	Nano copper oxide	63	20	39
4	CuI	N.R	21	40
5	$Pd_2(dba)_3$/Xantphos	85	15	41
6	PdNP-PNF	88	3	This work

[a] Isolated yield

5.5 Synthesis of Pd nanoparticle supported on the peptide nanofiber (PdNP-PNF)
Peptide 30.14 mg (0.04 mmol) was dissolved in 0.2 mL in doubly distilled water and 0.8 mL phosphate buffer solution (pH 8) was added. Then solution was sonicated for a few minutes. This mixture was stirred overnight at 80 °C. In the next step $Pd(OAc)_2$ (2.5 mg, 0.01 mmol) was added to reaction mixture and stirred for 12 hour at 80 °C, then $NaBH_4$ (6 mg, 0.15 mmol) was added and the mixture kept under stirring for 2h to obtain PdNP-PNF quantitatively.

5.6 General procedure for the sulfides synthesis
A round bottom flask was charged with of 1.3 mmol of thiourea or 2-mercaptobenzothiazole, 1mmol aryl/alkyl halide, 1 g KOH, 200µL of the solution containing Pd nanoparticle decorated on nanofibers and DMSO (2mL). Then reaction mixture was stirred at 130°C. The progress of reaction was monitored by TLC. After reaction completion, the mixture was extracted with dichloromethane (2×20 mL). The organic extract was washed twice with water and dried with anhydrous Na_2SO_4, then filtered and the solvent was evaporated to achieve corresponding sulfide. In order to obtain high pure sulfide, the crude product purified by preparative TLC.

5.6 Selected spectral data
Bis-(3-pyridyl) sulfide[34]
Colorless oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ(ppm)= 7.29-7.32 (m, 2H), 7.56-7.57 (m, 2H), 8.56-8.57 (m, 2H), 8.58 (s, 2H);^{13}C NMR ($CDCl_3$, 100 MHz), δ(ppm)= 124.1, 132.1, 139.2, 148.1, 151.0.

2,2'-Dimethoxy diphenyl sulfide[35]
Yellow liquid; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm)= 6.88-7.30 (m, 8H), 3.87 (s, 6H);^{13}C NMR ($CDCl_3$, 100 MHz), δ (ppm)= 157.7, 132.5, 128.4, 122.3, 121.3, 110.8, 55.8.

Bis-(1-naphthyl) sulfide[36] White solid, m.p. 156-158 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm)= 7.47-8.49 (m, 2H), 7.37-7.94 (m, 12H);^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm)=134.2, 132.7, 132.6, 130.0, 128.7, 128.0, 126.5, 126.3, 126.0, 125.1.

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Synthesis of peptide nanofibers decorated with palladium nanoparticles and its application as an efficient catalyst for the synthesis of sulfides *via* reaction of aryl halides with thiourea or 2-mercaptobenzothiazole

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