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GRAPHICAL ABSTRACT:

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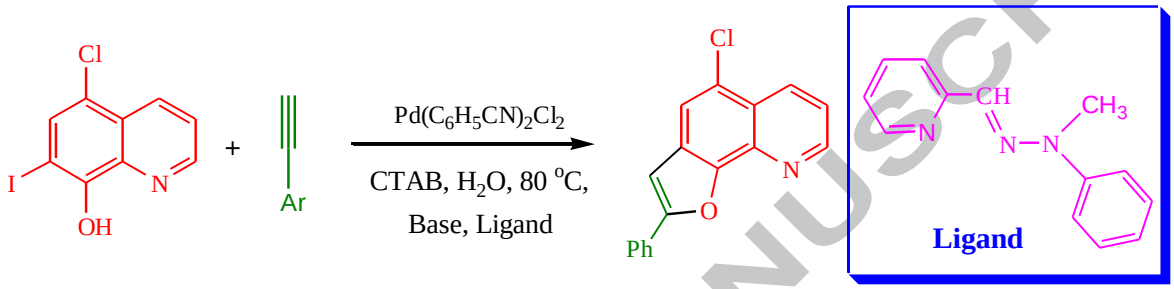

A green approach for highly regioselective syntheses of furo[3,2-*h*]quinolines in aqueous medium

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Abstract:

An environmentally benign, high yielding and operationally simple protocol has been developed for the regioselective synthesis of furo[3,2-*h*]quinolines in aqueous micellar medium involving Cu-free domino Sonogashira reaction followed by 5-endo-dig-cyclization of substituted 8-hydroxyquinolines and terminal alkyne by using $Pd(C_6H_5CN)Cl_2$ as catalyst and 2-pyridinecarboxaldehyde methylphenyl hydrazone as ligand under aerobic condition.

Keywords: Furo[3,2-*h*]quinolines; Micelle; Reaction in water; Cu-free Sonogashira; 5-Exo-dig cyclization; One-pot

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In recent years substantial interest has been perceived among the scientists to execute organic reactions in aqueous media[1] that leads to environmentally benign chemical processes.[2] But the hydrophobicity of maximum organic compounds is in fact a thwart for the execution of these reactions in aqueous environment. Introduction of aqueous surfactants, in the form of micelles, as the reaction medium endowed a way around this limitation.[3] In micellar catalysis, the surfactant micelles accumulate reacting molecules within its small volume. The high concentration of reactants with different orientations, often influence reaction mechanism and thus remarkable differences with respect to reaction rate and selectivity has been observed compared to homogeneous catalysis.[4]

Furoquinoline scaffold are present in many biologically and pharmacologically important molecules[5] and in the core structure of several natural products.[6] These varied biological profiles have attracted attentions of organic chemists for a long time and a number of synthetic

methodologies have been developed for this system.[7] However, most of the methods have drawbacks like involvement of multistep process, longer reaction time and use of hazardous chemicals/solvents etc. Moreover, 7-iodo-8-hydroxy-quinolines and terminal aryl acetylenes if employed as precursors under Pd/Cu catalysis, probability for the formation of acyclic Sonogashira-product cannot be neglected. The use of copper may also introduce Glaser-type homocoupling product.[8]

The Sonogashira reaction of terminal acetylenes with aryl or vinyl halides has been proved to be a powerful technique for C-C bond formation and has found wide applications in diverse areas such as natural product synthesis and material science.[9] A typical procedure requires utilization of catalytic palladium with another metal salt as co-catalyst and a base under inert condition.[10] Recently, palladium(II) salts, such as, $Pd(dba)_4$, $Pd(dtbpf)Cl_2$, $PdCl_2(PPh_3)_2$, having bidentate *N*,*N*- or *N*,*P*- ligands were used as efficient catalyst for this heteroannulation reaction but still required amines as solvents or as co-solvents with CuI as co-catalyst.[11] In general, palladium-mediated reactions are highly sensitive to moisture, but methods utilizing water as reaction medium have also been demonstrated.[12] However, these reactions require higher amount of palladium or elevated reaction temperature. Copper-free Sonogashira cross coupling reactions, using combination of at least one phosphine ligand or an amine with *tetra*-butyl ammonium salts as activators appears to be a suitable alternative.[13] Similar reactions have also been carried out both in organic solvents or in aqueous medium.[14]

We have developed a fast, efficient yet simple and green protocol which eliminates the use of copper salts, phosphine ligands and also do not require quaternary ammonium salts as activators. The method allows domino Sonogashira-cyclization of *o*-bromo or *o*-iodo-hydroxy-quinolines and terminal alkynes using 2-pyridinecarboxaldehyde methylphenyl hydrazone (**1i**) as ligand (Figure 1) in aqueous micellar medium under aerobic condition. Organic solvents are required only during column chromatography. Additionally, since copper salts are not involved in our protocol, copper-mediated oxidative homocoupling of acetylene can also be avoided. A library of furoquinolines could thus be synthesized in high yield and in short reaction time. The uniqueness of the methodology lies in its eco-friendly operation, short reaction time and excellent yield.

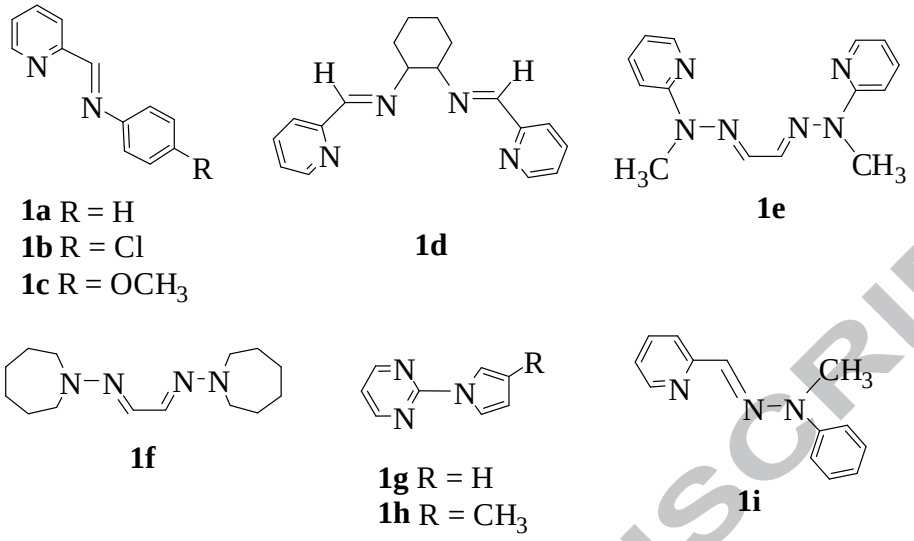
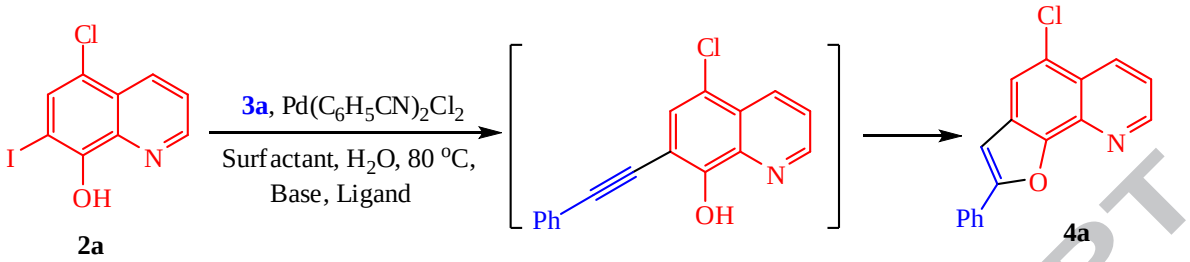


Figure 1. Ligands used in the study.

We envisaged 5-chloro-8-hydroxy-7-iodo-substituted quinolines and terminal alkynes to endow substituted aryl and alkyl acetylenes that could subsequently be used in a one-pot, two-step synthesis of furoquinoline (Scheme 1). We selected 7-iodo-8-hydroxyquinoline derivative (**2a**) and phenylethyne (**3a**) as model reactants for the synthesis of 2-phenylfuro[3,2-*h*]quinoline (**4a**) and evaluated the feasibility of a copper-free Sonogashira coupling-cycloisomerization domino strategy in aqueous micellar medium using $Pd(C_6H_5CN)_2Cl_2$ (2 mol%) under aerobic condition. The effect of different diimine, pyrazolyl-pyrimidine and hydrazone ligands[15] (Figure 1) was also investigated (Table 1). Diimine ligands, **1a-c**, yielded fused furoquinolines derivative **4a** in 64, 62 and 65% respectively, showing eventually no effect of electron donating or electron withdrawing groups on the benzene ring of the ligand. Use of ligand **1d** or **1e**, however, gave much less yield of 44% or 52% respectively. Similar observation was noted for bishydrazone ligand **1f** with seven-membered ring (found in repetitive experiments). Pyrazolyl-pyrimidine ligand **1g** or **1h** was not found to be very effective for the particular reaction whereas introduction of pyridine type hydrazone ligand **1i** led to excellent yield of 91%.



Scheme 1. Synthesis of **4a** in aqueous miceller medium.

Table 1. Effect of different ligands

Entry[a]	Ligands	Concentration (mol %)	**4a**[b] (Yield %)
1	1a	-	12
2	1a	2.5	64
3	1b	2.5	62
4	1c	2.5	65
5	1d	2.5	44
6	1e	2.5	52
7	1f	2.5	42
8	1g	2.5	51
9	1h	2.5	48
10	**1i**	**2.5**	**91**
11	1i	2.0	82
12	1i	3.0	91

[a]All reactions were performed using **2a** (1.0 equiv.) and **3a** (1.5 equiv.) in aqueous surfactant medium (CTAB, 80 mM) at 80 °C for 1 h under aerobic condition and (*i*-pr)$_2$EtN (2.0 equiv.); catalyst used Pd(C$_6$H$_5$CN)$_2$Cl$_2$ (2 mol%).
[b]Yield of isolated pure product; some loses during isolation is unavoidable in certain cases.

We also studied the outcomes of the reaction in aqueous solutions of various cationic, anionic and non-ionic surfactants to examine the role of surfactant solutions (Table 2). Reactions carried out in the absence of a surfactant remained ineffective even up to 12 h under aerobic condition. A drastic change in the reaction yield was observed when cetyltrimethylammonium bromide (CTAB, 50 mM, cmc 0.92 mM)[16] was introduced in the system. Carrying out the reaction in water at 80 °C for 1 h produced lower yield (32%; Table 2, entry 2) of **4a**. An increase in the reaction yield was noticed

when surfactant of higher concentration is used. The most prominent result (91%) was obtained when the reaction was performed using CTAB at 80 mM concentration (Table 2, entry 4); however, no considerable increase in the product was noticed beyond its 80 mM concentration (Table 2, entry 5). Use of other surfactants resulted in decrease in the product formation. Sodium dodecylsulfate (SDS: cmc 8.1 mM)[17] produced 70% (Table 2, entry 7) where as tetradecyltrimethylammonium bromide (TTAB: cmc 3.8 mM)[18] produced 76% product (Table 2, entry 6) both at 80 mM concentration. The use of a nonionic surface-active agent such as Triton X-114 (cmc 0.28 mM)[19] was found to be less effective compared to CTAB or TTAB (Table 2, entry 8).

The effect of different bases, *viz.* Et_3N, piperidine, tetramethyl piperidine, morpholine, DBU, DABCO, $(i\text{-pr})_2EtN$, DMAP, K_2CO_3 and Cs_2CO_3 was also investigated (Table 3). $(i\text{-pr})_2EtN$ appeared to be the most effective when employed in 2.0 molar equivalent affording the product in maximum yield (Table 3, entry 11). It is worth mentioning that other Pd-source [$PdCl_2$, $Pd(dba)_2$, $Pd(CH_3CN)_2Cl_2$, $Pd_2(dba)_3$, $Pd(PPh_3)_4$, Na_2PdCl_4, $Pd(dtbpf)Cl_2$] provided either very poor or no yield.

Table 2. Effect of different surfactants

Entry[a]	Surfactant	Concentration (mM)	**4a**[b] (Yield %)
1	None	-	-
2	CTAB	60	32
3	CTAB	70	67
4	**CTAB**	**80**	**91**
5	CTAB	90	91
6	TTAB	80	76
7	SDS	80	70
8	Triton X-114	80	68

[a]All reactions were performed using **2a** (1.0 equiv.) and **3a** (1.5 equiv.) in water at 80 °C for 1 h under aerobic condition and $(i\text{-pr})_2EtN$ (2.0 equiv.); catalyst used $Pd(C_6H_5CN)_2Cl_2$ (2 mol%), ligand **1i** (2.5 mol%).

[b]Yield of isolated pure product; some loses during isolation is unavoidable in certain cases.

Table 3. Effect of different bases

Entry[a]	Base	Amount (mmol)	**4a**[b] (Yield %)
1	Et_3N	1.0	80
2	piperidine,	1.0	74
3	tetramethyl piperidine	1.0	75
4	morpholine	1.0	75
5	DBU	1.0	82
6	DABCO	1.0	78
7	DMAP	1.0	73
8	K_2CO_3	1.0	72
9	Cs_2CO_3	1.0	74
10	(*i*-pr)$_2$EtN	1.0	86
11	**(*i*-pr)$_2$EtN**	**2.0**	**91**
12	(*i*-pr)$_2$EtN	2.5	91

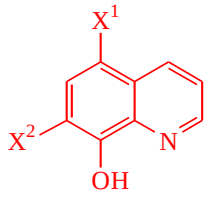
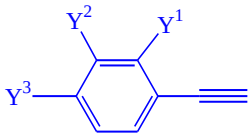
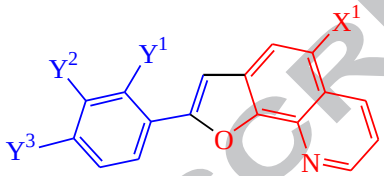
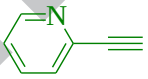
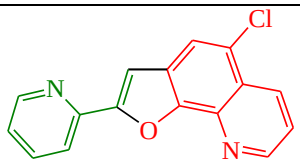
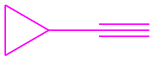
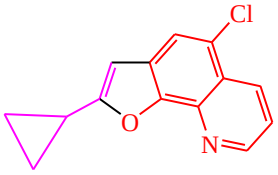
[a]Reactions performed using **2a** (1.0 equiv.) and **3a** (1.5 equiv.) in water at 80 °C for 1 h under aerobic condition in presence of CTAB (80 mM), $Pd(C_6H_5CN)_2Cl_2$ (2 mol%) and ligand **1i** (2.5 mol%).
[b]Yield of isolated pure product; some loses during isolation is unavoidable in certain cases.

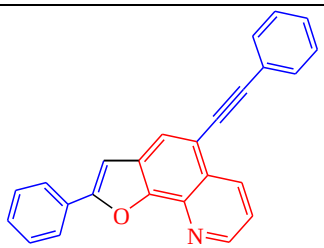
To establish the scope and applicability of this protocol, various aryl or heteroaryl alkynes was used in the study (Table 4). All reactions yielded only 5-endo-cyclized products and no acyclic Sonogashira product, or product due to 4-exo-dig cycloisomerization was noticed regardless of the electronic properties of the electrophilic substituents on both quinoline and acetylene compounds. Another major advantage of the procedure is that no dimerized product, which normally occurs during heteroannulation reaction, was observed. Moreover, corresponding bromides **2c**, which are less prone to participate in such reaction, gave equal yield in particular reaction condition (Table 4, entry 11).

The protocol was also found to be equally good for aliphatic alkynes. Compound **4j** was formed in good yield when cyclopropyl acetylene **3j** was reacted with quinoline **2a** under the same condition (Table 4, entry 10). It is interesting to note that the same reaction yielded furoquinoline **5**[20] (Scheme 2) when performed with trimethylsilyl acetylene **3k** in presence of *tetra*-butylammonium fluoride (50 mol%). This may be due to the presence of fluoride ion in the immediate vicinity of the cationic

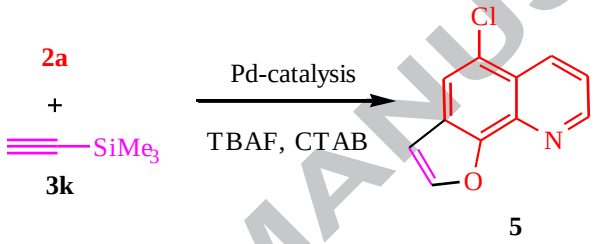
surfactant and thus acted as desilylating agent.

Table 4. Reactions of 7-halo-8-hydroxyquinolines (**2a-c**) with terminal alkynes (**3a-j**) leading to furoquinolines (**4a-k**) in aqueous micellar medium

Entry	Quinoline	Acetylene	Product[a]	Yield[b](%)	Ref
					
1	**2a:** X^1=Cl, X^2=I	**3a:** Y^1=Y^2=Y^3=H	**4a:** X^1=Cl, Y^1=Y^2=Y^3=H	91	7a
2	**2a**	**3b:** Y^1=Y^2=H, Y^3=OMe	**4b:** X^1= Cl, Y^1=Y^2=H, Y^3=OMe	89	-
3	**2a**	**3c:** Y^1=Y^2=H, Y^3=OPh	**4c:** X^1=Cl, Y^1=Y^2=H, Y^3=OPh	87	-
4	**2a**	**3d:** Y^1=Y^2=H, Y^3=n-pentyl	**4d:** X^1=Cl, Y^1=Y^2=H, Y^3=n-pentyl	90	-
5	**2a**	**3e:** Y^1=F, Y^2=Y^3=H	**4e:** X^1=Cl, Y^1=F, Y^2=Y^3=H	91	7a
6	**2a**	**3f:** Y^2=Cl, Y^1=Y^3=H	**4f:** X^1=Cl, Y^2=Cl, Y^1=Y^3=H	88	7a
7	**2a**	**3g:** Y^1=Y^2=H, Y^3=NO_2	**4g:** X^1=Cl, Y^1=Y^2=H, Y^3=NO_2	92	-
8	**2b:** X^1=NO_2, X^2=I	**3h:** Y^1=Y^2=Y^3=H	**4h:** X^1=NO_2, Y^1=Y^2=Y^3=H	87	7a
9	**2a**	 **3i**	 **4i**	83	7a
10	**2a**	 **3j**	 **4j**	52	-

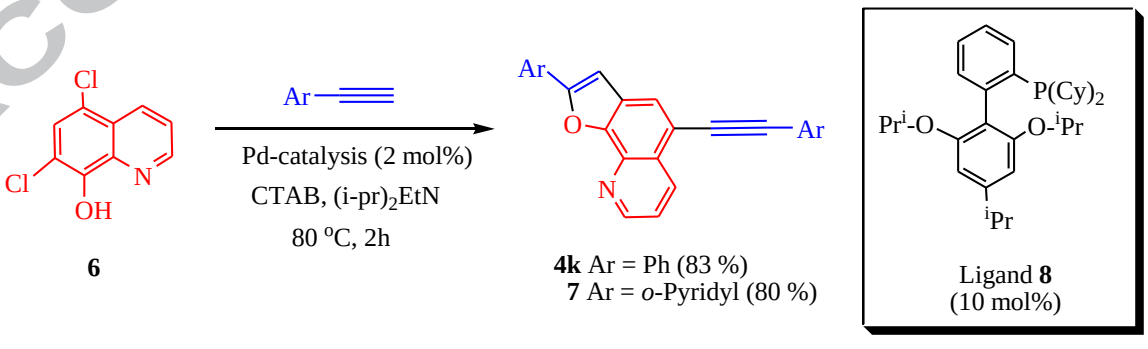
11	**2c:** X^1=Br, X^2=Br	**3a**	 **4k**	89	7a

[a] Reactions were performed using **2a-c** (10 mmol), alkyne (15 mmol), $Pd(C_6H_5CN)_2Cl_2$ (2 mol%), ligand **1i** (2.5 mol%), (*i*-pr)$_2$EtN (20 mmol) in water at 80 °C for 1 h under aerobic condition in presence of CTAB. Products were characterized by spectroscopic and analytical data.
[b] Isolated yield; some loses during isolation is unavoidable in certain cases.



Scheme 2. Synthesis of disilylated furoquinoline **5**.

Sonogashira coupling reaction is generally inefficient when aryl chlorides are used as coupling partners. The catalytic systems that can perform domino Sonogashira-cyclization more efficiently with aryl chlorides in short time is still in high demand. We applied our protocol to dichloro derivative **6** (Scheme 3). Compound **4k** and **7**[7a] was formed in good yield. However, 10 mol% of ligand (**8**) was required to perform these reactions. Increase in the amount of the ligand/catalyst beyond 10 mol% lead to dechlorination of **6**, and thus desired product was obtained in low yield.



Scheme 3. Synthesis of disubstituted furoquinolines

In summary, an efficient, economical and environmentally benign process[21,22] for the synthesis of furoquinolines scaffold in aqueous miceller medium has been demonstrated under aerobic condition. We established that, 2-pyridinecarboxaldehyde methylphenyl hydrazone was useful as phosphine-free ligand for this protocol. Future work will be focused on probing the role and reaction mechanism of the ligands used in this study for Sonogashira reaction in aqueous micellar medium.

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Supplementary data

Supplementary data (^{1}H and ^{13}C NMR spectra of all new compounds) associated with this article can be found in the online version, at doi…..

Notes and references:

1. (a) Manabe, K. S.; Iimura, S.; Sun, X. -M.; Kobayashi, S. *J. Am. Chem. Soc*. **2002**, *124*, 11971; (b) Li, C. J.; Chan, T. H. *Organic Reactions in Aqueous Media*, John Wiley, New York, 1997; (c) Shiri, M.; Zolfigol, M. A. *Tetrahedron* **2009**, *65*, 587.
2. (a) Anastas, P.; Warner, J. C. *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 1998; (b) Polshettiwar, V.; Varma, R. S. *J. Org. Chem.* **2007**, *72*, 7420.
3. Dwars, T.; Paetzold, E.; Oehme, G. *Angew. Chem. Int. Ed*. **2005**, *44*, 7174.
4. Fendler, J. H.; Fendler, E. J. *Catalysis in Micellar and Macromolecular Systems*, Academic Press, New York, 1975.
5. (a) Chamberlain, T. R.; Grundon, M. F. *J. Chem. Soc. C* **1971**, 910; (b) Grundon, M. F.; McCorkindale, N. J. *J. Chem. Soc*. **1957**, 2177.
6. (a) Svoboda, G. H.; Poore, G. H.; Simpson, P. J.; Boder, G. B. *J. Pharm. Sci.* **1966**, *55*, 758; (b) Petit-Pali, G.; Rideau, M.; Chenieux, J. C. *Planta Med. Phytother.* **1982**, *16*, 55; (c) Basco, L. K.; Mitaku, S.; Skaltsounis, A. L.; Ravelomanantsoa, N.; Tillequin, F.; Koch, M.; Le Bras, J. *Antimicrob. Agents Chemother*. **1994**, *38*, 1169; (d) Wolters, B.; Eilert, U. *Planta Med.* **1981**,

42, 137.

7. (a) Saha, P.; Naskar, S.; Paira, R.; Mondal, S.; Maity, A.; Sahu, K. B.; Paira, P.; Hazra, A.; Bhattacharya, D.; Banerjee, S.; Mondal, N. B. *Synthesis* **2010**, 486; (b) Cironi, P.; Tulla-Puche, J.; Barany, G.; Albericio, F.; Álvarez, M. *Org. Lett.* **2004**, *6*, 1405; (c) Yavari, I.; Anary-Abbasinejad, M.; Alizadeh, A. *Tetrahedron Lett.* **2002**, *43*, 4503; (d) Beugelmans, R.; Bois-Choussy, M. *Heterocycles* **1987**, *26*, 1863.
8. (a) Eglington, G.; Galbraith, R. *J. Chem. Soc*., **1959**, 889; (b) Hay, A. S. *J. Org. Chem*. **1960**, *25*, 1275; (c) Meng, X.; Li, C. B.; Han, B. C.; Wang, T. S.; Chen B. H. *Tetrahedron* **2010**, *66*, 4029; (d) Yang, F.; Cui, X.; Li, Y.; Zhang, J.; Ren, G.; Wu, Y. *Tetrahedron* **2007**, *63*, 1963; (e) Yan, J.; Lin, F.; Yang, Z. *Synthesis* **2007**, 1301; (f) Li, J. H.; Liang, Y.; Zhang, X. D. *Tetrahedron* **2005**, *61*, 1903; (g) Chassaing, S.; Alix, A.; Boningari T.; Sido, K. S. S.; Keller, M.; Kuhn P.; Louis, B.; Sommer, J.; Pale, P. *Synthesis* **2010**, 1557.
9. (a) Sonogashira, K. In *Metal-Catalyzed Cross-Coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: New York, 1998; Chapter 5; (b) Brandsma, L.; Vasilevsky, S. F.; Verkruijsse, H. D. *Application of Transition Metal Catalysts in Organic Synthesis*; Springer-Verlag: Berlin, 1998; Chapter 10; (c) Sonogashira, K. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon: New York, 1991; Vol. 3, Chapter 2.4.
10. (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467; (b) Graham, A. E.; McKerrecher, D.; Davies, D. H.; Taylor, R. J. K. *Tetrahedron Lett.* **1996**, *37*, 7445; (c) Nicolaou, K. C.; Ladduwahetty, T.; Taffer, I. M.; Zipkin, R. E. *Synthesis* **1986**, 344; (d) Shiga, F.; Yasuhara, A.; Uchigawa, D.; Kondo, Y.; Sakamotot, T.; Yamanaka, H. *Synthesis* **1992**, 746. (e) Miller, M. W.; Johnson, C. R. *J. Org. Chem.* **1997**, *62*, 1582.
11. (a) Kundu, N. G.; Khan, M. W. *Tetrahedron* **2000**, *56*, 4777; (b) Kundu, N. G.; Khan, M. W.; Mukhopadhyay, R. *Tetrahedron* **1999**, *55*, 12361; (c) Komáromi, A.; Tolnai, G. L.; Novák, Z. *Tetrahedron Lett.* **2008**, *49*, 7294; (d) Arques, A.; Auñon, D.; Molina, P. *Tetrahedron Lett.* **2004**, *45*, 4337.
12. (a) Peng, Z. -Y.; Wang, J. -P.; Cheng, J.; Xie, X.; Zhang, Z. *Tetrahedron* **2010**, *66*, 8238; (b) Bhattacharya, S.; Sengupta, S. *Tetrahedron Lett.* **2004**, *45*, 8733; (c) Nishimura, M.; Ueda, M.; Miyaura, N. *Tetrahedron* **2002**, *58*, 5779; (d) Iranpoor, N.; Firouzabadi, H.; Tarassoli, A.; Fereidoonnezhad, M. *Tetrahedron* **2010**, *66*, 2415; (e) Yang, S. -C.; Hsu, Y. -C.; Gan, K. -H. *Tetrahedron* **2006**, *62*, 3949; (f) Gan, K. -H.; Jhong, C. -J.; Yang, S. -C. *Tetrahedron* **2008**, *64*,

1204; (g) Prabakaran, K.; Khan, F. N.; Jin, J. S. *Tetrahedron Lett.* **2011**, *52*, 2566.

13. (a) Yi, C.; Hua, R. *J. Org. Chem*. **2006**, *71*, 2535; (b) Liang, B.; Dai, M.; Chen, J.; Yang, Z. *J. Org. Chem*. **2005**, *70*, 391; (c) Mino, T.; Shirae, Y.; Saito, T.; Sakamoto, M.; Fujita, T. *J. Org. Chem*. **2006**, *71*, 9499; (d) Dang, D.; Zheng, Y.; Bai, Y.; Guo, X.; Ma, P.; Niu, J. *Cryst. Growth Des*. **2012**, *12*, 3856.
14. (a) Marziale, A. N.; Schlüter, J.; Eppinger, J. *Tetrahedron Lett.* **2011**, *52*, 6355; (b) Li, N.; Lim, R. K. V.; Edwardraja, S.; Lin, Q. *J. Am. Chem. Soc*. **2011**, *133*, 15316; (c) Guan, J. T.; Weng, T. Q.; Yu, G. -A.; Liu, S. H. *Tetrahedron Lett.* **2007**, *48*, 7129.
15. (a) Mino, T.; Shirae, Y.; Saito, T.; Sakamoto, M.; Fujita, T. *J. Org. Chem*. **2006**, *71*, 9499; (b) Song, J.; Shen, Q.; Fan Xu, F.; Lu, X. *Tetrahedron* **2007**, *63*, 5148; (c) Pelagatti, P.; Carcelli, M.; Costa, M.; Ianelli, S.; Pelizzi, C.; Rogolino, D. *Journal of Molecular Catalysis A: Chemical* **2005**, *226*, 107; (d) Civicos, J. F.; Alonso, D. A.; Najera, C. *Adv. Synth. Catal*. **2013**, *355*, 203.
16. Kalyanasundaram, K. *Photochemistry in Microheterogeneous Systems,* Academic Press, San Diego, 1987.
17. Israelachvili, J., *Intermolecular and Surface Forces,* Academic Press, San Diego, 1997.
18. Evans, D. F.; Allen, M.; Ninham, B. W.; Fouda, A. *J. Solution Chem.* **1984,** *13*, 87.
19. McCarroll, M.; Toerne, K.; Wandruszka, R. V. *Langmuir* **1998,** *14*, 2965.
20. Satoh, M.; Miyaura, N.; Suzuki, A. *Synthesis* **1987**, 373.
21. *General reaction procedure for the synthesis of furo[3,2-h]quinolines (**4a-4k**)*: In an open round-bottomed flask filled with 50 mL of water, hydroxy quinolines (**2a-c**, 1.0 equiv.), alkyne (**3a-j**, 1.5 equiv.), $Pd(C_6H_5CN)_2Cl_2$ (0.02 equiv.), ligand **1i** (0.025 equiv.), $(i\text{-pr})_2EtN$ (2.0 equiv.) was stirred vigorously for 1 h at 80 °C with CTAB (4 mmol). When TLC indicated completion of the reaction, the mixture was extracted with ethyl acetate (4 x 30 mL) and the organic layer was washed thoroughly with water. The crude mass was purified by column chromatography using silica gel and petroleum ether: ethyl acetate (4:1) as eluent.
22. *Spectral data of 5-Chloro-2-(4-methoxyphenyl)furo[3,2-h]quinoline (**4b**)*: White solid (yield: 89%); ^{1}H NMR (DMSO-d_6, 600 MHz): δ = 3.84 (s, 3H, OCH_3), 7.12 (d, *J* = 8.7 Hz, 1H), 7.48 (s, 1H), 7.71 (dd, *J* = 4.3, 8.5 Hz, 1H), 7.96-7.97 (m, 2H), 8.10 (s, 1H), 8.64 (d, *J* = 8.5 Hz, 1H), 9.04-9.05 (m, 1H); ^{13}C NMR (DMSO-d_6, 150 MHz): δ = 55.79, 101.63, 115.13, 121.02, 121.95, 122.38, 123.17, 125.46, 126.96, 129.01, 133.74, 136.48, 147.77, 151.57, 157.52,

160.57; HRMS (ESI): m/z calcd for $C_{18}H_{12}O_2NCl$ $[M+H]^+$310.0635; found: 310.0622.