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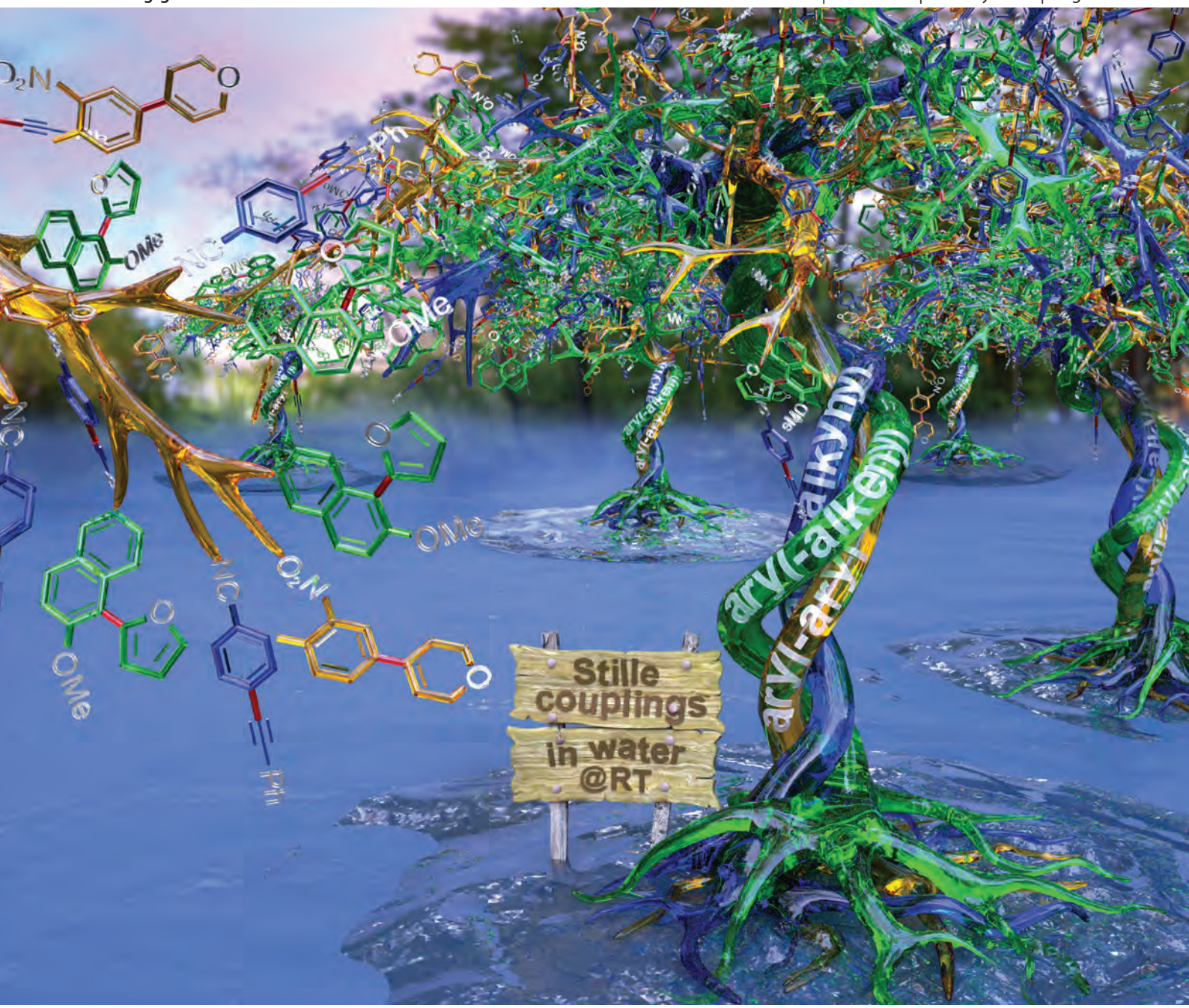

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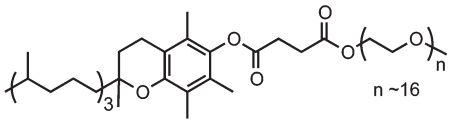
A nonionic amphiphile, TPGS-750-M, enables efficient Stille couplings between a wide range of substrates to be conducted in water as the only medium, in most cases at room temperature.

Introduction

In a recent review on Nobel Prize-winning Suzuki, Heck, and Negishi couplings by Colacot, Snieckus and co-workers,[1] data was presented indicative of the number of papers and patents associated with each of the commonly used cross-coupling reactions from the last decade. While Suzuki, Heck, and Sonogashira reactions ranked among the top three, fourth was Stille couplings with *ca.* 2000 citations. Thus, Pd-catalyzed Stille couplings of various organo- and pseudo-halides with organostannanes represent one of the most powerful tools for the formation of carbon–carbon bonds.[2] Their popularity is usually attributed to the stability and functional group tolerance of stannanes, as well as their chemoselectivity and broad scope in terms of reaction partners.[3] Traditionally, Stille couplings are carried out in organic solvents (*e.g.*, THF, DMF, NMP), and oftentimes at temperatures above ambient.[4] Although many attempts have been made to perform these reactions under thermally mild conditions,[5] use of (potentially toxic) organic solvents is always the norm, which by definition fails to meet the 12 Principles of Green Chemistry.[6]

Ideally, Stille couplings would be carried out at room temperature, in water as the only medium. Several nanometal catalysts have been designed to enable Stille couplings to be run under such conditions.[7] However, opportunities for variation in substrate type are limited. More commonly, high temperatures are required in the presence of various Pd catalysts.[8] Recently, we have reported that TPGS-750-M (polyethanol-α-tocopherylsuccinate; shown below) is an excellent commercially available "designer" surfactant that self-assembles in water to form nanomicelles within which several cross-couplings efficiently take place.[9] Herein, we describe a new protocol for conducting Stille couplings in an aqueous solution containing TPGS-750-M, in most cases at room temperature.

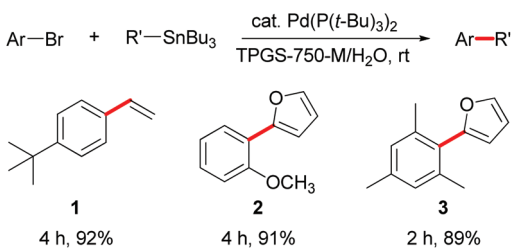


TPGS-750-M

Results and discussion

Scattered literature reports have mentioned that $Pd(P(t\text{-}Bu)_3)_2$ is an unusually reactive catalyst for Stille couplings of aryl bromides and chlorides.[4a,5c,10] Thus, three aryl bromides were initially coupled with vinyl- or 2-furyltributyltin using $Pd(P(t\text{-}Bu)_3)_2$ (2 mol%). Using 2 wt.% aqueous TPGS-750-M at room temperature (0.25 M), excellent yields of products **1–3** were obtained in two to four hours (Scheme 1).

Based on these initial results, both 3-chlorotoluene and 2-furyltributyltin were selected to investigate potential couplings between aryl chlorides, and to further optimize reaction conditions to be applied to couplings involving more challenging organotin partners (Table 1). Initially, several commonly used catalysts and additives were screened (entries 1–14). The combination of $Pd(P(t\text{-}Bu)_3)_2$ and DABCO[4c,11] emerged as the best choice. Remarkably, the limited conversion initially observed could be increased dramatically by adding one equivalent of NaCl (entries 15, 16), but not NaF (entry 17),



Scheme 1 Stille couplings with aryl bromides in water at room temperature.

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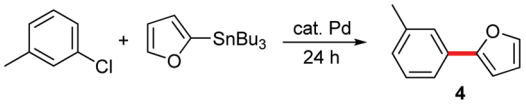
†Electronic supplementary information (ESI) available: More experimental details and characterization data of all products. See DOI: 10.1039/c2gc36042j

Table 1 Optimization of reaction conditions[a]



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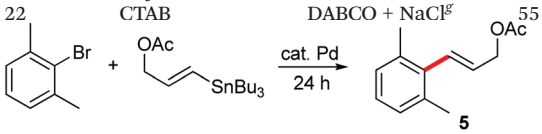
Entry	Surfactant	Additive	Conversion[b] (%)
1[c]	TPGS-750-M	/	NR
2[d]	TPGS-750-M	/	20
3[e]	TPGS-750-M	/	NR
4	TPGS-750-M	/	27
5	TPGS-750-M	CuI[f]	NR
6	TPGS-750-M	LiCl	14
7	TPGS-750-M	CsF	4
8	TPGS-750-M	Bu_4NF	17
9	TPGS-750-M	Net_3	30
10	TPGS-750-M	NaOH	7
11	TPGS-750-M	K_2CO_3	34
12	TPGS-750-M	K_2CO_3 + CuCl[f]	17
13	TPGS-750-M	K_2CO_3 + $ZnBr_2$[f]	12
14	TPGS-750-M	DABCO	37
15	TPGS-750-M	NaCl[g]	32
16	**TPGS-750-M**	**DABCO + NaCl[g]**	**50, 85[h,i]**
17	TPGS-750-M	DABCO + NaF[g]	35
18	None	DABCO + NaCl[g]	39
19	SDS	DABCO + NaCl[g]	50
20	Trition X-100	DABCO + NaCl[g]	40
21	Brij 30	DABCO + NaCl[g]	39
22	CTAB	DABCO + NaCl[g]	55



5

23	TPGS-750-M	/	12
24	TPGS-750-M	K_2CO_3	14
25	TPGS-750-M	DABCO	44
26	**TPGS-750-M**	**DABCO + NaCl[g]**	**76[i], 85[i,j]**
27	CTAB	DABCO + NaCl[g]	68[i]
28	None	DABCO + NaCl[g]	12

[a] Conditions: aryl halide (0.250 mmol), organotin reagent (0.275 mmol), $Pd(P(t\text{-}Bu)_3)_2$ (0.005 mmol for entries 1–22, 0.010 mmol for entries 23–28), solution of aqueous surfactant (2 wt.%, 1 mL), additive (0.750 mmol) rt, 24 h. [b] Conversion determined by GC. [c] The catalyst is $Pd(P(t\text{-}Bu)_2OH)_2Cl_2$ (2 mol%). [d] The catalyst is $Pd(OAc)_2$/2Xphos (2 mol%). [e] The catalyst is$Pd_2(dba)_3$/4P(*o*-Tol)$_3$ (1 mol%). [f] 20 mol%. [g] 1.0 equiv. [h] At 50 °C. [i] Isolated yield. [j] At 40 °C.

presumably due to the enlarged, reorganized micelles which offer increased surface area and thus, increased binding constants for substrates and catalysts.[9] Alternatively, the positive effects of chloride on the palladium center may be operative.[12] A good yield of product **4** (85%) could be achieved by slight heating to 50 °C. The corresponding coupling run "on water" (*i.e.*, in the absence of TPGS-750-M), led to lower conversion (entry 16 *vs.* entry 18).[13] Screening various surfactants indicated that both CTAB, an ionic surfactant (entry 22), and the neutral amphiphile TPGS-750-M were equally effective in this model reaction.

On the other hand, in the reaction between 2-bromo-1,3-dimethylbenzene and (*E*)-3-(tributylstannyl)allyl acetate, TPGS-750-M proved to be more effective than CTAB, run under otherwise identical conditions (entry 26 *vs.* 27). Very low conversion to the desired product **5** was observed when the reaction was conducted "on water" (entry 28), indicative of the vagaries associated with this type of approach to cross-couplings, as observed previously on many occasions.[13]

With optimized conditions in hand, several combinations of aryl halides and organotin reagents were investigated to ascertain the scope of the protocol (Table 2). In general, aryl bromides coupled smoothly at room temperature. Tributylphenyltin appeared to be a less active coupling partner than other organotin reagents. Although in the case of *p*-bromoanisole (entry 5), $P(P(t\text{-}Bu)_3)_2$ led to full conversion at 50 °C, a poor yield of desired product was obtained due to homocoupling of the bromide. Switching to $Pd_2(dba)_3$/P(*o*-Tol)$_3$ with increased catalyst loading (4 mol%) was found to enhance the yield at the expense of homocoupling.

The analogous reactions of aryl chlorides, not surprisingly, were more sluggish. However, in some cases, *e.g.*, 2-furyltributyltin and *p*-chlorobenzonitrile, the coupling was successful even at room temperature (entry 4). Generally, the couplings took place under the influence of mild heat, along with an increase in catalyst loading to 4 mol% (entries 9, 13–16). No product was formed, however, in the reaction of an electron-rich aryl chloride (*e.g.*, *o*-chloroanisole) with tributyl(phenylethynyl)-stannane (entry 11). It should be noted that the byproduct 4-butyl-2-nitrotoluene was formed when 4-chloro-2-nitrotoluene was coupled with either of two tributylstannanes (entries 13, 15). The by-product in the case of Bu_3SnPh could be avoided by switching to the trimethylstannyl analog (entry 14).

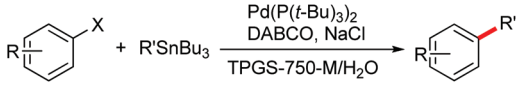
To compare and contrast these couplings, guided by the principles of green chemistry,[5] with traditional Stille coupling conditions, a direct comparison was performed between 3-bromobenzothiophene and 2-furyltributyltin (Scheme 2). Rather than an organic solvent (dioxane), additives (excess cesium fluoride), and heat (80 °C),[14] the "green" protocol afforded a considerably higher yield, done in water at room temperature, and in a shorter time frame.

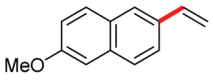
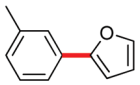
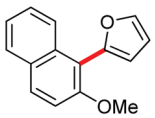
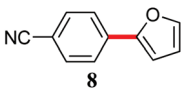
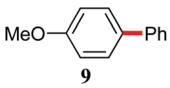
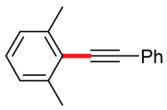
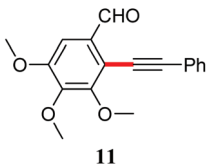
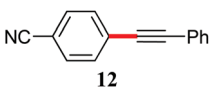
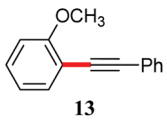
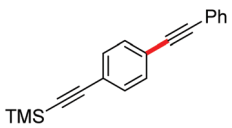
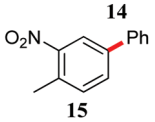
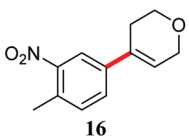
Likewise, Stille couplings with alkenyl halides could also be effected under otherwise identical conditions (Table 3). Both alkenyl iodides and bromides readily participate at room temperature to afford products **18–21** (entries 1–4). In the case of (*Z*)-β-bromostyrene, significant undesired *Z*-to-*E* isomerization,[15] as well as homocoupling, took place (entry 5). However, switching catalysts from $Pd(P(t\text{-}Bu)_3)_2$ to $Pd_2(dba)_3$/P(*o*-Tol)$_3$ led to retention of stereochemistry giving *Z*-**22** in high yield, while avoiding homocoupling (entry 6).

Interestingly, while the literature illustrates a traditional coupling between *Z*-alkenyl triflate **23** and tributyl-4-methoxyphenylstannane in NMP leading to *isomerized E*-product **24**,[16] the desired *Z*-**24** is formed under micellar conditions (Scheme 3). To further demonstrate the potential of this methodology, dienoate **25**, a crucial intermediate en route to mammalian V-ATPase inhibitor **26**,[17] was smoothly generated by reaction between (*E*)-ethyl 3-iodoacrylate and (*E*)-3-(tributylstannyl)-prop-2-en-1-ol, yielding the unprotected alcohol **25** in water at room temperature (Scheme 4).

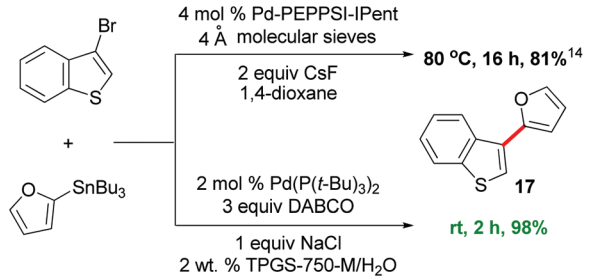
Finally, the prospects for recycling aqueous solutions of TPGS-750-M used in Stille couplings were studied (Table 4).

Table 2 Stille couplings with aryl halides in aqueous TPGS-750-M[a]



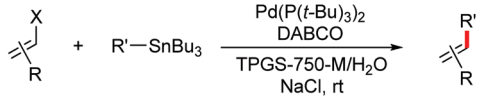
Entry	X	Time (h)	T (°C)	Product	Yield[b] (%)
1	Br	24	rt	 **6**	93
2	Br	4	rt	 **4**	88
3	Br	4	rt	 **7**	94
4	Cl	24	rt	 **8**	94
5	Br	24	50	 **9**	39, 80[c]
6	Br	4	rt	 **10**	91
7	Br	5	rt	 **11**	92
8	Br	1	rt	 **12**	95
9	Cl	24	50		75[d]
10	Br	4	rt	 **13**	97
11	Cl	24	50		NR[d]
12	Br	5	rt	 **14**	97
13	Cl	24	60	 **15**	78[d,e]
14	Cl	24	60		92[d,f]
15	Cl	24	50	 **16**	45[d]
16	Cl	24	60		73[d]

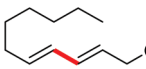
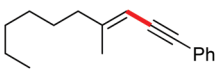
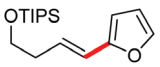
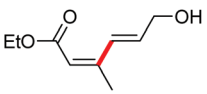
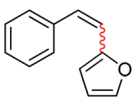
[a] Conditions: aryl halide (0.250 mmol), organotin reagent (0.275 mmol), Pd(P(t-Bu)$_3$)$_2$ (0.005 mmol), aqueous TPGS-750-M solution (2 wt.%, 1 mL), DABCO (0.750 mmol), NaCl (0.250 mmol). [b] Isolated yield. [c] 2 mol% $Pd_2(dba)_3$ and 8 mol % P(o-Tol)$_3$ are used as catalyst. [d] 4 mol% Pd(P(t-Bu)$_3$)$_2$ is used. [e] A mixture of **15** and 4-butyl-2-nitrotoluene (3 : 1) determined by ^{1}H NMR. [f] Trimethylphenyltin (1.1 equiv) used.



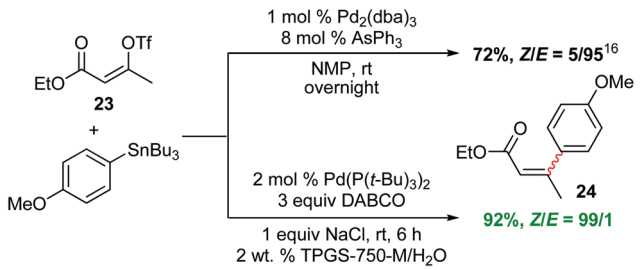
Scheme 2 The reaction of 3-bromobenzothiophene with 2-furyltributyltin.

Table 3 Stille couplings of alkenyl halides under aqueous micellar conditions[a]



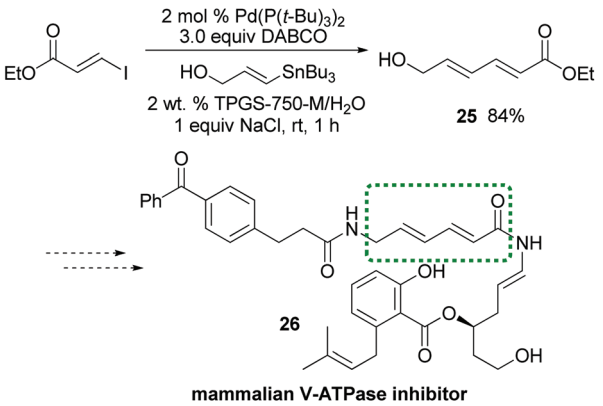
Entry	X	Time (h)	Product		Yield[b] (%)
1	I	6		**18**	88
2	I	4		**19**	91
3	Br	24		**20**	89
4	I	2		**21**	94 (Z/E = 99/1)
5[c]	Br	24		**22**	50 (Z/E = 90/10)[d]
6[c]	Br	24			90 (Z/E = 96/4)[d,e]

[a] Conditions: alkenyl halide (0.250 mmol), organotin reagent (0.275 mmol), Pd(P(t-Bu)$_3$)$_2$ (0.005 mmol), aqueous TPGS-750-M solution (2 wt.%, 1.0 mL), DABCO (0.750 mmol), NaCl (0.250 mmol), rt. [b] Isolated yield. [c] The Z/E ratio of β-bromostyrene is 96/4. [d] Z/E ratio of product is determined by GC on the crude products. [e] 1 mol% $Pd_2(dba)_3$ and 4 mol% P(o-Tol)$_3$ are used as catalyst.



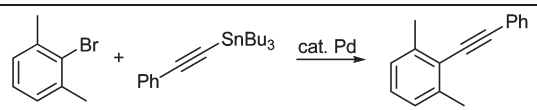
Scheme 3 Stille couplings with a Z-alkenyl triflate.

After the successful coupling of 2-bromo-1,3-dimethylbenzene and tributyl(phenylethynyl)stannane under optimized conditions (entry 1), in-flask extractions with minimal amounts of hexane led to facile product isolation. The extraction also removed much of the Pd catalyst, accounting for the reduced



Scheme 4 A potential application of Stille couplings to total synthesis.

Table 4 The recycling of the aqueous solution of TPGS-750-M[a]



Entry	Run	Time (h)	Yield[b] (%)
1	1	4	91
2[c]	2	4	80[d] (22)[e]
3[c]	3	6	92
4[c]	4	6	89
5[c]	5	6	88

[a] Conditions: 2,6-dimethylbromobenzene (0.250 mmol), tributyl phenylethynyltin (0.275 mmol), $Pd(P(t\text{-}Bu)_3)_2$ (0.005 mmol), aqueous TPGS-750-M solution (2 wt.%, 1.0 mL), DABCO (0.750 mmol), NaCl (0.250 mmol), rt. [b] Isolated yield. [c] Additional 2 mol% $Pd(P(t\text{-}Bu)_3)_2$ is used. [d] Yield after 4 h with additional 2 mol% $Pd(P(t\text{-}Bu)_3)_2$. [e] No additional $Pd(P(t\text{-}Bu)_3)_2$ added; conversion determined by GC.

yield (22%; entry 2). The addition of fresh catalyst to each recycle increased the level of conversion and the resulting yields returned to that seen in the initial experiment (entries 3–5).

Conclusions

In summary, Stille couplings can be performed in water typically at room temperature by employing nanoreactors formed from the nonionic designer surfactant TPGS-750-M. The catalyst system $Pd(P(t\text{-}Bu)_3)_2$/DABCO leads, in many cases, to a wide range of couplings between various organostannanes and both aryl and alkenyl halides. The newly developed procedures are environmentally friendly in that no organic solvent is required in these couplings, limited amounts of water are invested, and workup entails only an in-flask extraction with a minimal amount of a single, recoverable organic solvent. These reactions take place in high yields and stereoselectivity, thereby offering considerable potential for applications to complex targets in organic synthesis.

Experimental

General procedure for Stille couplings in water

The palladium catalyst (0.005 mmol), organohalides (0.250 mmol), DABCO (0.750 mmol) and NaCl (0.250 mmol) were weighed into a microwave vial at room temperature, and the organotin reagent (0.275 mmol) and 2 wt.% aqueous TPGS-750-M solution (1.0 mL) were then added by syringe. (The liquid organohaildes were also added by syringe.) The resulting solution was allowed to stir at room temperature (slight heating was required in some cases) and monitored by GC or TLC. Upon completion, the reaction mixture was then diluted with NEt_3 (0.3 mL) and EtOAc (4.0 mL), filtered through a bed of silica gel layered over Celite. The volatiles were removed *in vacuo* to afford the crude product. The extent of conversion and *Z*/*E* ratios were determined by GC. Further column chromatography on silica gel afforded the pure desired product.

Procedure for recycling aqueous solutions of TPGS-750-M

After completion of the reaction, the mixture was extracted by hexane (4 × 1 mL). The organic layer was separated from the aqueous layer by syringe. The remaining hexane in the micellar solution was removed *in vacuo*. For the second run, fresh starting materials and $Pd(P(t\text{-}Bu)_3)_2$ (2 mol%) were added to the aqueous solution, and the reaction was conducted as described for the initial run.

Characterization data of new compounds

(*E*)-3-(2,6-Dimethylphenyl)allyl acetate (5). ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.11 (s, 3H), 2.29 (s, 6H), 4.75–4.76 (dd, J = 6.5, 1.5 Hz, 2H), 5.77–5.87 (dt, J = 16.0, 6.3 Hz, 1H), 6.63–6.66 (d, J = 16.5 Hz, 1H), 7.02–7.08 (m, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.8, 21.0, 65.2, 126.9, 127.7, 128.6, 131.9, 135.9, 170.8. HRMS(EI) Calcd for $C_{13}H_{16}O_2$ 204.1150, found 204.1142.

2-(2-Methoxynaphthalen-1-yl)furan (7). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.93 (s, 3H), 6.30 (d, J = 1.5 Hz, 2H), 7.34–7.46 (m, 3H), 7.66–7.67 (t, J = 1.5 Hz, 1H), 7.81–7.91 (m, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 56.8, 110.8, 111.3, 113.5, 114.5, 123.8, 125.1, 126.9, 128.0, 129.0, 130.7, 133.7, 142.2, 148.8, 155.6. HRMS(EI) Calcd for $C_{15}H_{12}O_2$ 224.0837, found 224.0839.

3,4,5-Trimethoxy-2-(phenylethynyl)benzaldehyde (11). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.94 (s, 3H), 3.99 (s, 3H), 4.04 (s, 3H), 7.28 (s, 1H), 7.37–7.38 (m, 3H), 7.55–7.57 (m, 2H), 10.53 (s, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 56.2, 61.2, 61.5, 80.6, 99.2, 105.3, 115.9, 122.7, 128.5, 128.8, 131.5, 131.8, 147.6, 154.0, 154.6, 190.6. HRMS(ESI) Calcd for $C_{18}H_{16}O_4$ 296.1049, found $(M + Na)^+$ 319.0933.

4-(4-Methyl-3-nitrophenyl)-3,6-dihydro-2*H*-pyran (16). ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.50–2.53 (m, 2H), 2.59 (s, 3H), 3.94–3.96 (t, J = 5.5 Hz, 2H), 4.33–4.35 (q, J = 3.0 Hz, 2H), 6.22–6.24 (m, 1H), 7.30 (d, J = 8.0 Hz, 1H), 7.51–7.53 (dd, J = 8.0, 2.0 Hz, 1H), 7.98 (d, J = 1.5 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.1, 26.9, 64.2, 65.7, 120.7, 124.3, 128.9, 132.1, 132.2,

132.8, 139.3, 149.3 HRMS(ESI) Calcd for $C_{12}H_{13}NO_3$ 219.0895, found $(M + Na)^+$ 242.0781.

(2*E*,4*E*)-Undeca-2,4-dien-1-ol (18). ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.87–0.90 (t, J = 7.0 Hz, 3H), 1.26–1.39 (m, 8H), 2.06–2.10 (q, J = 7.0 Hz, 2H), 4.15–4.17 (t, J = 5.8 Hz, 2H), 5.68–5.75 (m, 2H), 6.02–6.07 (dd, J = 15.0, 10.0 Hz, 1H), 6.19–6.24 (dd, J = 15.5, 10.5 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.1, 22.6, 28.9, 29.2, 31.7, 32.6, 63.6, 129.3, 132.2, 135.9. HRMS(EI) Calcd for $C_{11}H_{20}O$ 168.1514, found 168.1513.

(*E*)-(4-Methyldec-3-en-1-ynyl)benzene (19). ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.88–0.91 (t, J = 7.0 Hz, 3H) 1.26–1.33 (m, 6H), 1.43–1.54 (m, 2H), 1.97 (s, 3H), 2.21–2.15 (t, J = 7.5 Hz, 2H), 5.49 (s, 1H), 7.26–7.32 (m, 3H), 7.42–7.44 (dd, J = 7.5, 1.5 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.1, 19.4, 22.6, 27.6, 28.9, 31.7, 38.8, 87.8, 91.7, 104.6, 124.1, 127.6, 128.2, 131.2, 153.0. HRMS(EI) Calcd for $C_{17}H_{22}$ 226.1722, found 226.1728.

(*E*)-(4-(Furan-2-yl)but-3-enyloxy)triisopropylsilane (20). ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.07 (s, 18H), 2.41–2.45 (m, 3H), 3.69–3.83 (m, 4H), 6.14–6.39 (m, 5H), 7.03 (d, J = 2.0 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 12.0, 18.0, 36.6, 63.1, 106.2, 111.0, 120.2, 126.2, 141.3, 153.2. HRMS(EI) Calcd for $C_{17}H_{30}O_2Si$ 294.2015, found 294.1991.

(2*Z*,4*E*)-Ethyl 6-hydroxy-3-methylhexa-2,4-dienoate (21). ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.26–1.29 (t, J = 7.3 Hz, 3H), 2.01 (d, J = 1.0 Hz, 3H), 4.14–4.18 (q, J = 7.0 Hz, 2H), 4.32 (br, 2H), 5.70 (s, 1H), 6.20–6.25 (dt, J = 16.0, 5.5 Hz, 1H), 7.72–7.76 (dd, J = 16.0, 1.0 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.3, 21.0, 59.8, 63.6, 117.9, 127.8, 135.9, 150.0, 166.2. HRMS(EI) Calcd for $C_9H_{14}O_3$ 170.0943, found 170.0950.

Notes and references

1 C. C. Carin, J. Seechurn, M. O. Kitching, T. J. Colacot and V. Snieckus, *Angew. Chem., Int. Ed.*, 2012, **51**, 5062.

2 (*a*) M. Kosugi, K. Sasazawa, Y. Shimizu and T. Migita, *Chem. Lett.*, 1977, 301; (*b*) D. Milstein and J. K. Stille, *J. Am. Chem. Soc.*, 1978, **100**, 3636; (*c*) M. Kosugi and K. Fugami, *J. Organomet. Chem.*, 2002, **653**, 50. For an updated review, see: .Y. Pengand W.-D. Z. Li, *Eur. J. Org. Chem.*, 2010, **6703**, and references therein.

3 (*a*) M. D. Shair, T. Y. Yoon, K. K. Mosny, T. C. Chou and S. J. Danishefsky, *J. Am. Chem. Soc.*, 1996, **118**, 9509; (*b*) P. Espinet and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2004, **43**, 4704; (*c*) H. Fuwa, N. Kainuma, K. Tachibana and M. Sasaki, *J. Am. Chem. Soc.*, 2002, **124**, 14983; (*d*) J. H. Chang, H.-U. Kang, I.-H. Jung and C.-G. Cho, *Org. Lett.*, 2010, **12**, 2016.

4 (*a*) A. F. Littke and G. C. Fu, *Angew. Chem., Int. Ed.*, 1999, **38**, 2411; (*b*) S. P. H. Mee, V. Lee and J. E. Baldwin, *Chem.–Eur. J.*, 2005, **11**, 3294; (*c*) J.-H. Li, Y. Liang, D.-P. Wang, W.-J. Liu, Y.-X. Xie and D.-L. Yin, *J. Org. Chem.*, 2005, **70**, 2832.

5 (*a*) J. K. Stille and B. L. Groh, *J. Am. Chem. Soc.*, 1987, **109**, 813; (*b*) J. K. Stille and J. H. Simpson, *J. Am. Chem. Soc.*, 1987, **109**, 2138; (*c*) A. F. Littke, L. Schwarz and G. C. Fu, *J. Am. Chem. Soc.*, 2002, **124**, 6343; (*d*) D.-H. Lee, A. Taher, W.-S. Ahn and M.-J. Jin, *Chem. Commun.*, 2010, **46**, 478; (*e*) W. Su, S. Urgaonkar, P. A. McLaughlin and J. G. Verkade, *J. Am. Chem. Soc.*, 2004, **126**, 16433.

6 (*a*) P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, UK, 1998; (*b*) P. T. Anastas and T. Williamson, *Green Chemistry, Frontiers in Benign Chemical Synthesis and Process*, Oxford University of Press, Oxford, UK, 1998; (*c*) C. Capello, U. Fischer and K. Hungerbuhler, *Green Chem.*, 2007, **9**, 927.

7 (*a*) J. C. Garcia-Martinez, R. Lezutekong and R. M. Crooks, *J. Am. Chem. Soc.*, 2005, **127**, 5097; (*b*) M. A. Bernechea, M. E. de Jesús, C. López-Mardomingo and P. Terreros, *Inorg. Chem.*, 2009, **48**, 4491; (*c*) L. Wu, X. Zhang and Z. Tao, *Catal. Sci. Technol.*, 2012, **2**, 707.

8 C. Wolf and R. Lerebours, *J. Org. Chem.*, 2003, **68**, 7551.

9 (*a*) B. H. Lipshutz, S. Ghorai, A. R. Abela, R. Moser, T. Nishikata, C. Duplais, A. Krasovskiy, R. D. Gaston and R. C. Gadwood, *J. Org. Chem.*, 2011, **76**, 4379; (*b*) B. H. Lipshutz, B. R. Taft and A. R. Abela, *Platin. Met. Rev.*, 2012, **56**, 62; (*c*) B. H. Lipshutz and S. Ghorai, *Aldrichimica Acta*, 2008, **41**, 59; (*d*) B. H. Lipshutz and S. Ghorai, *Aldrichimica Acta*, 2012, **45**, 3.

10 C. G. Fu, *Acc. Chem. Res.*, 2008, **41**, 1555.

11 J.-H. Li, X.-C. Hu, Y. Liang and Y.-X. Xie, *Tetrahedron*, 2006, **62**, 31.

12 (*a*) B. H. Lipshutz, S. Ghorai, W. W. Y. Leong, B. R. Taft and D. V. Krogstad, *J. Org. Chem.*, 2011, **76**, 5061; (*b*) T. Kobayashi, M. Nakashima, T. Hakogi, K. Tanaka and S. Katsumura, *Org. Lett.*, 2006, **8**, 3809.

13 (*a*) J. E. Klijn and J. B. Engberts, *Nature*, 2005, **435**, 746; (*b*) S. Narayan, J. Muldoon, M. G. Finn, V. V. Fokin, H. C. Kolb and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2005, **44**, 3275; (*c*) B. H. Lipshutz and B. R. Taft, *Org. Lett.*, 2008, **10**, 1329; (*d*) B. H. Lipshutz, D. W. Chung and B. Rich, *Org. Lett.*, 2008, **10**, 3793; (*e*) T. Nishikata and B. H. Lipshutz, *Org. Lett.*, 2009, **11**, 2377.

14 M. Dowlut, D. Mallik and M. G. Organ, *Chem.–Eur. J.*, 2010, **16**, 4279.

15 (*a*) A. Krasovskiy and B. H. Lipshutz, *Org. Lett.*, 2011, **13**, 3818; (*b*) G. P. Lu, K. R. Voigtritter, C. Cai and B. H. Lipshutz, *J. Org. Chem.*, 2012, **77**, 3700.

16 V. Farina and G. P. Roth, *Tetrahedron Lett.*, 1991, **32**, 4243.

17 R. Shen, T. Inoue, M. Forgac and J. A. Porco, *J. Org. Chem.*, 2005, **70**, 3686.