JOC The Journal of Organic Chemistry

Article

Cross Dehydrogenative Coupling of Heterocyclic Scaffolds with Unfunctionalised Aroyl Surrogates by Palladium(II) Catalyzed C(sp2)-H Aroylation through Organocatalytic Dioxygen Activation

Bhavin Viththlbhai Pipaliya, and Asit K Chakraborti

J. Org. Chem., **Just Accepted Manuscript** • DOI: 10.1021/acs.joc.7b00226 • Publication Date (Web): 16 Mar 2017

ACS Publications

The Journal of Organic Chemistry is published by the American Chemical Society.
1155 Sixteenth Street N.W., Washington, DC 20036

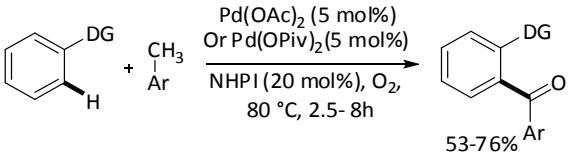
Cross Dehydrogenative Coupling of Heterocyclic Scaffolds with Unfunctionalised Aroyl Surrogates by Palladium(II) Catalyzed C(sp^2)-H Aroylation through Organocatalytic Dioxygen Activation

*Bhavin V. Pipaliya and Asit K. Chakraborti**

Department of Medicinal Chemistry, National Institute of Pharmaceutical Education and Research (NIPER), Sector 67, S. A. S. Nagar, Punjab 160 062, India.

CORRESPONDING AUTHOR FOOTNOTE Department of Medicinal Chemistry, National Institute of Pharmaceutical Education and Research (NIPER), Sector 67, S. A. S. Nagar 160 062, Punjab, India. Fax: 91-(0)-172 2214692; Tel: 91-(0)-172 2214683; E-mail: akchakraborti@niper.ac.in; akchakraborti@rediffmail.com

ABSTRACT.



Directing Group (DG): Benzothiazole, Benzoxazole, Pyridine, Pyrimidine, Quinoxaline, Azobenzene

Salient features: O_2 as oxidant, low catalyst loading, shorter time, versatile DGs, arylmethanes as aroyl surogates

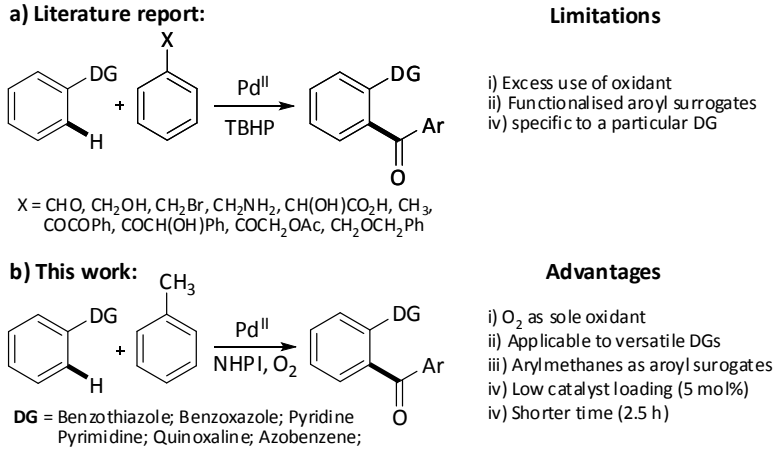
Cross dehydrogenative coupling of bio-relevant heterocyclic with arylmethanes for aroylation during the Pd(II)-catalysed C(sp^2)-H activation has been achieved through dioxygen activation by NHPI. Mass spectrometry and ^{1}H NMR based kinetic isotope effect studies revealed C-H bond activation as the rate determining step. Radical scavenging experiments indicated radical pathway. The ^{1}H NMR of an aliquot of reaction mixture and in situ trapping with 2-aminothiophenol revealed formation of aldehyde during aerobic oxidation of the arylmethanes. The reaction has broad scope for different variation of the aroyl source and the directing group that include benzothiazole, benzooxazole, pyridine, quinoxaline, pyrimidine, and azoarene. The benzylic methylene moiety was found to be the source of the aroyl carbon with the benzyl ether moiety being the most preferred followed by the carbonyl group of aryl aldehyde and the aryl methane. However, the ease of availability of aryl methanes makes them most attractive as aroyl source. A time dependent selective mono- and bis-aroylation can be acvhevde. The 1,3-diarylpyrimidines exhibited regioselective aroylation of the 2-phenyl moiety irrespective of the absence or presence of any substitutent (electron withdrawing or electron donating) in the 3-phenyl moiety. For unsymmetrical azoarenes, selective aroylation took place in the phenyl moiety bearing the substituent.

INTRODUCTION

Cross dehydrogenative coupling (CDC) is the most attractive strategy for C-C bond formation via C-H activation.[1] The recent progress on directing group (DG) assisted aroylation[2] represent a newer version of CDC. In this context we were fascinated to explore benzazoles as DGs due to their versatile therapeutic potential towards antitumor,[3a] antibiotic,[3a] anti-leishmanial,[3b] anti-inflammatory,[3c] anti-tubercular[3d] activities.

We observed that most of the reported procedures[2] used functionalised coupling partners as the aroyl surrogate e.g., aldehyde, benzyl alcohol, benzylic ether, mandelic acid, α-oxocarboxylic acids, benzylamine, benzyl bromide, etc. Although a few reports used non-functionalised coupling partner (e.g., arylmethanes),[2b] the use of bio-relevant DGs (e.g., benzazoles) are limited[4] which, however, involved the use of functionalized aroyl surrogates (e.g., aldehyde, benzyl alcohol, styrene, phenyl acetylene, and 2-acetoxy acetophenone) and only one report with aryl methanes.[4f] Most of these reported aroylation reactions use large amounts (1.5-10 equiv) of TBHP or 2 equiv of transition metal salt as the oxidising agent.

Scheme 1. The Pd-catalyzed aroylation of C(sp^2)-H bond.



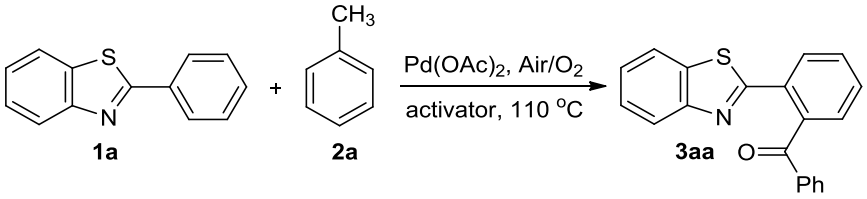
Molecular oxygen is the ideal oxidant and has gained popularity in various reactions.[5] The only report on aroylation with arylmethanes using molecular oxygen involves the use of pyridyl/*O*-methyl oxime as the DG at 100 °C for 24 h[6] but there is no report on CDC of bio-relevant benzazoles with arylmethanes using molecular oxygen as the oxidant. Herein we

report bio-relevant heterocyclic scaffolds directed C(sp^2)-H aroylation catalysed by Pd(II) compounds for CDC with arylmethanes through organo-catalytic non-hem model of dioxygen activation[7] (Scheme 1).

RESULTS AND DISCUSSION

To find the best operative reaction condition, the CDC of 2-phenylbenzo[*d*]thiazole (**1a**) with toluene (**2a**) was performed to form **3aa** under different variation of the reaction condition such as the use of varying amounts of different transition metal salts/complexes as catalyst, different oxidants, various dioxygen activators, varied reaction time and temperature etc (Table 1). These revealed the necessity to use 5 mol% of $Pd(OAc)_2$ and *N*-hydroxyphthalimide (NHPI) as the effective dioxygen activator required in 20 mol%. The reaction need to be performed under aerobic condition, however, use of oxygen is more effective than open air.

Table 1. The effect of oxidants and various dioxygen activators on the $Pd(OAc)_2$-catalysed CDC of **1a** with **2a** to form **3aa**.[a]



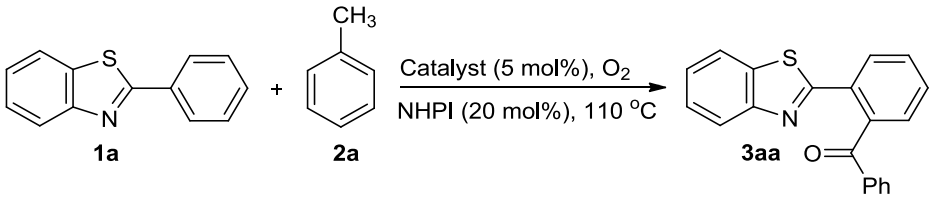
Entry	Catalyst (mol%)	Oxidant[b]	Activator (equiv)	Time (h)	Yield (%)[c]
1	$Pd(OAc)_2$ (10)	Air	NHPI (1)	12	62
2	$Pd(OAc)_2$ (20)	Air	NHPI (1)	12	64
3	$Pd(OAc)_2$ (10)	Air	NHSI (1)	12	0
4	$Pd(OAc)_2$ (10)	Air	HOBt (1)	12	0
5	$Pd(OAc)_2$ (10)	Air	NHQI (1)	12	0
6	$Pd(OAc)_2$ (10)	Air	NHPI (0.5)	12	64
7	$Pd(OAc)_2$ (10)	Air	NHPI (0.4)	12	63
8	$Pd(OAc)_2$ (10)	Air	NHPI (0.3)	12	64

9	$Pd(OAc)_2$ (10)	Air	NHPI (0.2)	12	64
10	$Pd(OAc)_2$ (10)	Air	BQ (0.2)	12	0
11	$Pd(OAc)_2$ (10)	Air	HQ (0.2)	12	0
12	$Pd(OAc)_2$ (10)	Air	AIBN (0.2)	12	0
13	$Pd(OAc)_2$ (10)	Air	BPO (0.2)	12	0
14	$Pd(OAc)_2$ (10)	O_2 balloon	NHPI (0.2)	12	75
15	$Pd(OAc)_2$ (5)	O_2 balloon	NHPI (0.2)	12	73
16	$Pd(OAc)_2$ (5)	Air	NHPI (0.2)	20	65
17	$Pd(OAc)_2$ (5)	O_2 balloon	NHPI (0.1)	12	44
18	$Pd(OAc)_2$ (2.5)	O_2 balloon	NHPI (0.2)	12	56

[a]Reaction conditions: 2-phenylbenzothiazole **1a** (1.0 mmol) was treated with toluene **2a** (2.0 mL) under different conditions at 110 °C for different time period. [b]Air: reaction was performed in open air; O_2 balloon: the reaction was performed under oxygen atmosphere using a balloon filled with oxygen. [c]Isolated yield of **3aa**. NHSI: *N*-Hydroxysuccinimide; HOBt: 1-Hydroxybenzotriazole; NHQI: 6-hydorxy-5*H*-pyrrolo[3,4-*b*]pyridine-5,7(6*H*)-dione; BQ: Benzoquinone; HQ: Hydroquinone; AIBN: Azobisisobutyronitrile; BPO: Benzoyl peroxide.

Among the various Pd(II) compounds used (Table 2, entries 1-9) the best result was obtained with $Pd(OAc)_2$ with $Pd(OPiv)_2$ as the next best catalyst. The other transition metal-based catalysts were ineffective (Table 2, entries 10-15).

Table 2. The effect of different Pd-compounds and other transition metal-derived salts/complexes for CDC of **1a** with **2a** to form **3aa** under oxygen (balloon) in the presence of NHPI (20 mol%).[a]



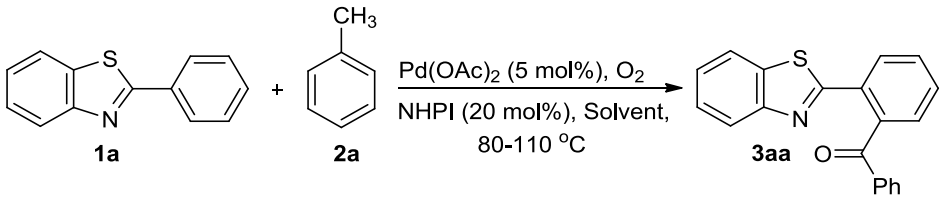
Entry	Catalyst	Yield (%)[b]
1	$Pd(OAc)_2$	73
2	$Pd(OPiv)_2$	70
3	$PdCl_2$	trace

4	$Pd_2(dba)_3$	trace
5	$Pd(dba)_2$	19
6	$Pd(PPh_3)_4$	0
7	Na_2PdCl_4	0
8	$Pd(OCOCF_3)_2$	0
9	$Pd(OH)_2/C$	0
10	$Cu(OAc)_2 \cdot H_2O$	0
11	$Co(OAc)_2 \cdot H_2O$	0
12	$Fe(OAc)_2 \cdot H_2O$	0
13	$[RuCl_2$ (*p*-cymene)$]_2$	0
14	$Ni(PCy_3)_2Cl_2$	0
15	$NiCl_2 \cdot 6H_2O$	0

[a]Reaction conditions: 2-phenylbenzothiazole **1a** (1.0 mmol) was treated with toluene **2a** (2.0 mL) in the presence of different transition metal-derived catalyst (5 mol%) and NHPI (20 mol%) at 110 ^{O}C for 12 h under oxygen atmosphere using a balloon filled with oxygen. [b]Isolated yield of **3aa**.

Further studies on passing oxygen gas into the reaction mixture (O_2 bubbling) instead of performing the reaction under oxygen atmosphere using a balloon filled with oxygen, using varying amounts of **2a** in various organic solvent rather than using **2a** as the solvent (Table 3) led to two reaction conditions: (**A**) treatment of the benzazole with the arylmethane (2 mL/mmol of benzazole) at 80 °C for 2.5 h under oxygen bubbling in the presence of NHPI (20 mol%) and $Pd(OAc)_2$ (5 mol%); (**B**) treatment of the benzazole with 5 molar equivalent of the arylmethane in PhCl (2 mL/mmol of benzazole) at 80 °C for 2.5 h under oxygen bubbling in the presence of NHPI (20 mol%) and $Pd(OAc)_2$ (5 mol%). Thus, passing (bubbling) oxygen gas into the reaction mixture rather than using oxygen gas under balloon provided advantages in reducing the reaction time from 12 h to 2.5 h as well as the reaction temperature from 110 °C to 80 °C.

Table 3. The effect of the varying amounts of **2a**, other organic solvents for the $Pd(OAc)_2$-catalysed CDC of **1a** with **2a** to form **3aa**.[a]

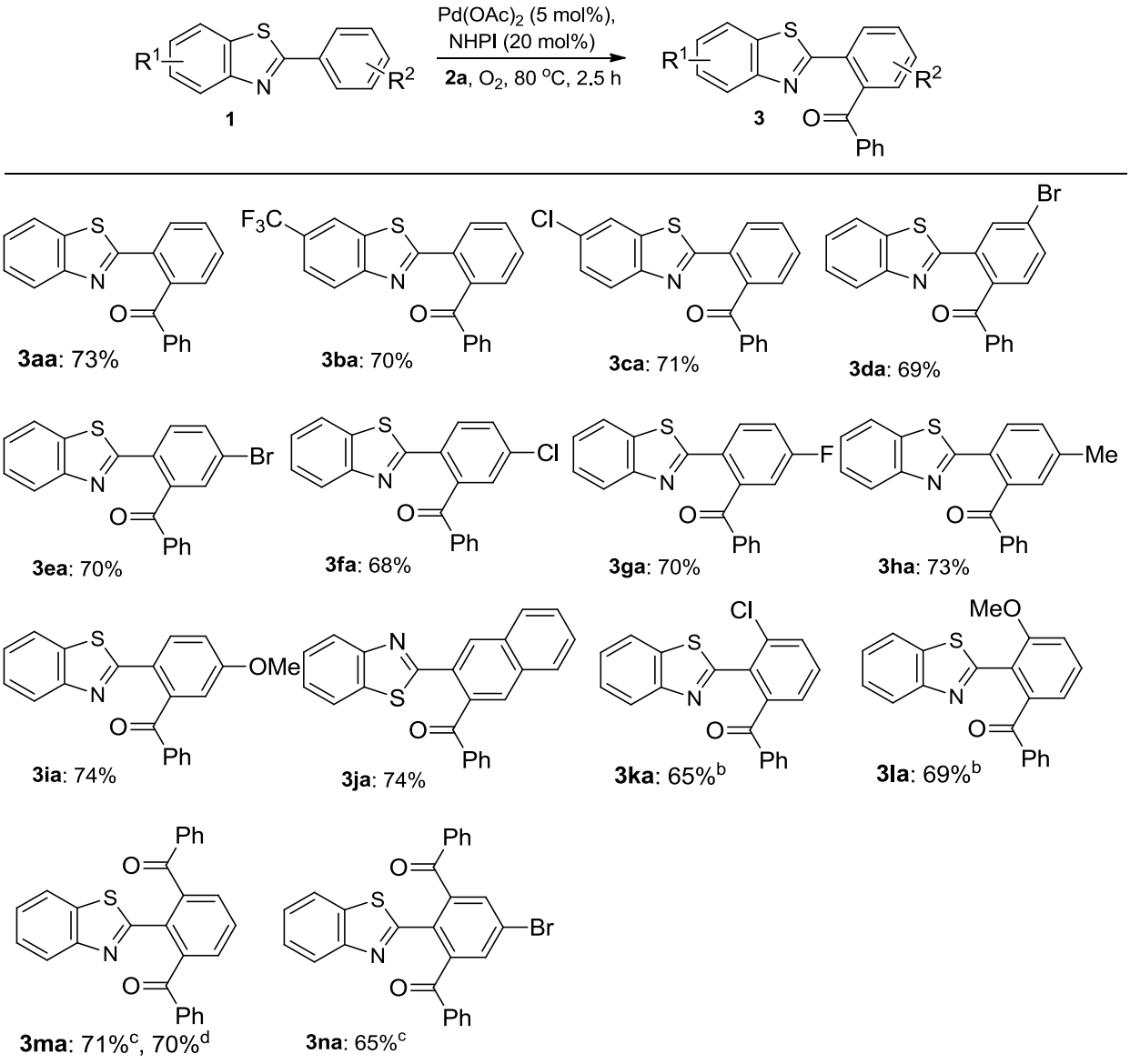


Entry	2a (amt)	Solvent	Temp (^{o}C)	Time (h)	Yield (%)[b]
1	As solvent	**2a**	110	2.5	76
2	As solvent	**2a**	110	2.5	59[c]
3	As solvent	**2a**	80	2.5	75
4	As solvent	**2a**	60	2.5	45
5	5.0 mmol	PhCl	80	2.5	70
6	2.5 mmol	PhCl	80	2.5	53
7	5.0 mmol	PhF	80	2.5	0
8	5.0 mmol	$PhCF_3$	80	2.5	Trace
9	5.0 mmol	DCE	80	2.5	29
10	5.0 mmol	1,4-Dioxane	80	2.5	0
11	5.0 mmol	MeCN	80	2.5	0
12	5.0 mmol	DMSO	80	2.5	0
13	10.0 mmol	None[d]	80	2.5	62
14	2.5 mmol	None[d]	80	2.5	49
15	5.0 mmol	None[d]	80	2.5	37

[a]Reaction conditions: 2-phenylbenzothiazole **1a** (1.0 mmol) was treated with toluene **2a** (5 mmol or as specified) in the presence of $Pd(OAc)_2$ (5 mol% except for entry 2), NHPI (20 mol%) various solvent at the specified temperature for different time period in open vessel while bubbling oxygen gas into the reaction mixture. [b]Isolated yield of **3aa**. [c]The reaction was carried out using 2.5 mol% of $Pd(OAc)_2$.[d]No solvent was used.

The scope of the C(sp^2)-H aroylation was next examined with respect to structurally diverse 2-arylbenzo[*d*]thiazoles[7] using **2a** as the aroyl source (Table 4).

Table 4. Scope with respect to structural variation of 2-arylbenzothiazole (**1**).[a]



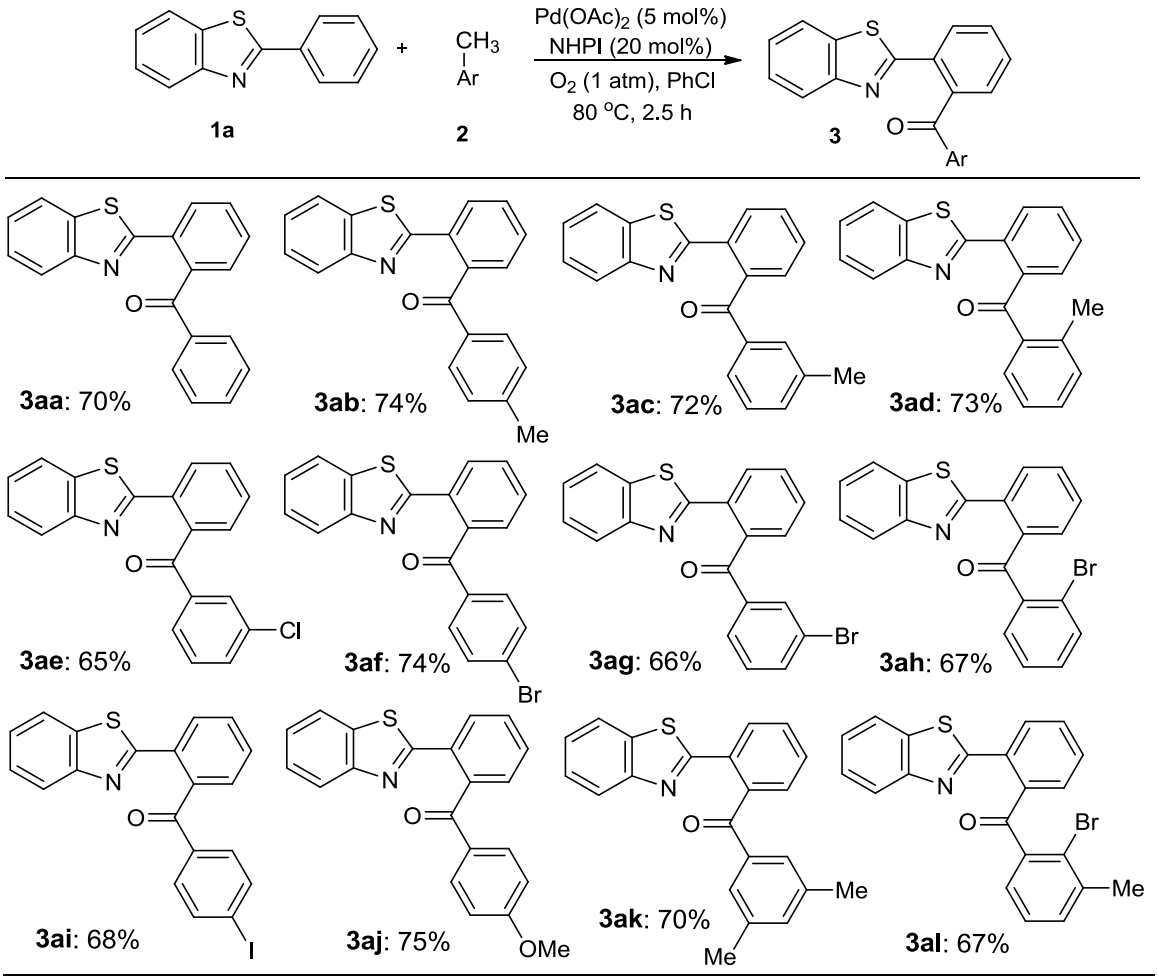
[a]Reaction condition A: **1** (1 mmol) was treated with **2a** (2 mL) in the presence of $Pd(OAc)_2$ (5 mol%) and NHPI (20 mol%) at 80 °C under O_2 bubbling for 2.5 h (yield of the isolated product given). [b]Reaction for 6 h. [c]Reaction for 8 h. [d]The yield obtained from the reaction of pre-formed **3aa** with **2a** for 3 h.

The 2-(3'-bromophenyl)benzothiazole exhibited excellent regioselectivity for aroylation at the less hindered *ortho*-position of the 2-aryl moiety to form **3da**. For 2-(2'-naphthyl)benzothiazoles, the *peri* hydrogen of the naphthyl group directs benzoylation at the 3'-position of the naphthyl moiety to form **3ja**. Benzothiazoles bearing halogen (Br, Cl, F) and electron donating (Me, OMe) substituents at the *para*-position of the 2-aryl group gave **3ea**, **3fa**, **3ga**, **3ha**, and **3ia** in 68-74% yields. There appears to be no influence on the regioselectivity and reaction time/yield of the electronic effect of the substituent present either

on the benzothiazole or on the 2-aryl moiety. However, the influence of the steric effect can be realised in regioselective formation of **3da** and **3ja**. The presence of Br at the *ortho*-position of the 2-aryl moiety is not compatible as the corresponding debrominated product **3aa** was formed in 68% yield. However, the corresponding *ortho*-chloro derivative gave the desired product **3ka** in 65%.[8] These results and the fact that the *meta* and *para* Br substituents remained unperturbed suggest chelation assisted oxidative addition of $Pd(OAc)_2$ to the *ortho* C-Br bond.[9] Substitution of OCH_3 at the *ortho*-position of the 2-aryl moiety provided **3la** in 69% yield but required longer reaction time (6 h) due to the steric effect. Excellent time-dependent selcectivity towards the formation of the mono- and bis-aroylated products was observed. In all cases the reaction of the 2-arylbenzothiazole **1** with the arylmethane **2** led to the exclusive formation of the corresponding mono-aroylated product in performing the reaction for 2.5 h. However, performing the reaction for longer period aforded the bis-aroylated products. Thus, the treatment of **1a** and **1e** with **2a** for 8 h afforded **3ma** and **3na** in 71 and 65 % yields, respectively. It was presumed that the bis-aroylated product **3ma** resulted from a sequential reaction pathway: formation of the mono-aroylated product **3aa** by the reaction of **1a** with **2a** followed by further reaction of the in situ generated **3aa** with **2a** to form the bis-aroylated product **3ma**. Thus, when pre-formed **3aa** was subjected to the reaction with **2a** for 3 h the bis-aroylated product **3ma** was obtained in 70% yield. Therefore, selective formation of the mono- and bis-aroylated products could be controlled by the reaction time.

The scope with various substituted arylmethanes was next evaluated (Table 5) under condition B. The aroylation is compatible with halogens irrespective of its nature and position. The reaction with ethyl benzene and isobutyl benzene gave **3aa** as the only product in 65 and 60% yields, respectively, suggesting the benzylic carbon as the preferred site to generate the carbonyl moiety.

Table 5. Scope with respect to structural variation of arylmethanes (**2**).[a]

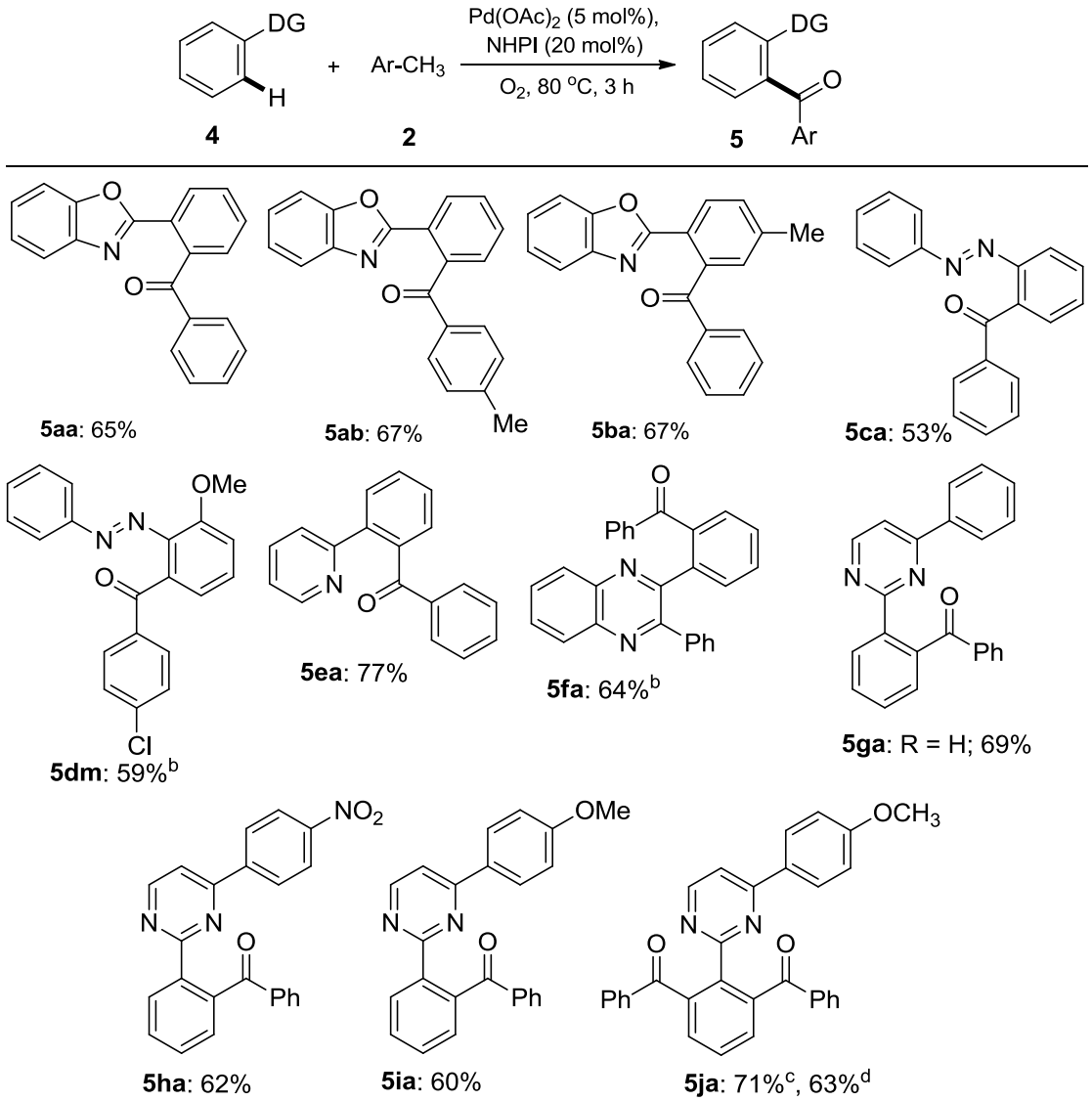


[a]Reaction condition B: **1a** (1 mmol) was treated with the arylmethane (5 mmol, 5 equiv) in PhCl (2.0 mL) in the presence of $Pd(OAc)_2$ (5 mol%), NHPI (20 mol%) at 80 °C under O_2 bubbling for 2.5 h. The yield of the isolated product mentioned against each example.

The applicability of the aroylation protocol was extended to other DGs (Table 6). The 2-arylbenzoxazoles[10] **4a** and **4b** underwent CDC with **2a** and *p*-xylene (**2b**) to afford **5aa**, **5ab**, and **5ba** in 65, 67, and 67% yields, respectively. The treatment of the azobenzene **4c**, 2-phenylpyridine **4e** and the 2,3-diphenyl quinoxaline **4f**[11] with **2a** afforded **5ca**, **5ea**, and **5fa** in 53, 77, and 64% yields, respectively. The selective monoaroylation mark the specific advantage of the present work. Thus, although the benzoylation of **4e** has been reported[6] to form **5ea** (80%) along with the corresponding bis-benzoylated product in 5% yield, repetition on our hand afforded **5ea** (30%) and the bis-benzoylated product (46%). In case of **4c** and **4f** only one of the two phenyl groups underwent benzoylation. For the unsymmetrical azobenzene **4d** the selective aroylation with 4-chlorotoluene (**2m**) was observed in the

electron rich phenyl ring to afford **5dm**. The pyrimidine **4f** contains two phenyl groups and represents a perfect example of regioselectivity. Selective aroylation took place at the 2-phenyl ring of 2,4-diphenylpyridine **4g** giving **5ga** as the only product in 69% yield. Increase or decrease of electron density at the 4-phenyl ring did not have any effect on the regioselective outcome as the reaction of 4-(4'-nitrophenyl)-2-phenylpyrimidine **4h** and 4-(4'-methoxyphenyl)-2-phenylpyrimidine **4i** afforded **5ha** and **5ia** in 62 and 60% yields, respectively, indicating selective activation of the C(sp^2)-H bond of the 2-phenyl ring.

Table 6. Scope of other directing groups.[a]



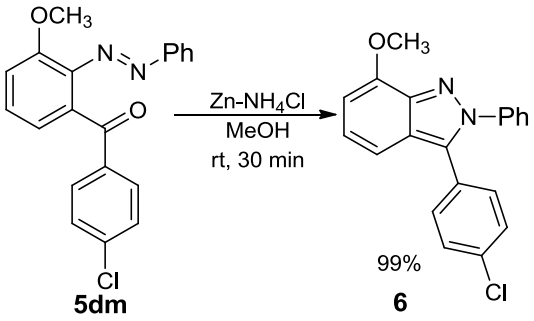
[a]**4** (1 mmol) was treated with **2** (2 mL) in the presence of $Pd(OAc)_2$ (5 mol%) and NHPI (20 mol%) at 80 °C under O_2 bubbling for 3 h (yield of the isolated product given). [b]Reaction with 5 mmol of **2a**/**2m** in PhCl (2 mL). [c]Yield obtained from the

reaction of **5ia** with **2a** for 3 h. [d]Yield obtained from the reaction of **4i** with **2a** for 8 h.

The influence of differential electronic effect of the substituent present in the 2-phenyl and 4-phenyl ring in reversing the regioselectivity towards the 4-phenyl ring was investigated. The pyrimidine derivative **5ia** bearing electron rich 4-phenyl and electron deficient 2-phenyl moieties on aroylation with **2a** gave **5ja** in 71% yield indicating the ability of the pyrimidine moiety in directing aroylation at the 2-phenyl ring. However, **5ja** was obtained in 63% yield when the reaction of **4i** with **2a** was performed for 8 h. This further demonstrated that a time dependent selective mono- and bis-aroylation can be achieved.

The aroylation product **5dm** on reductive cyclisation afforded a liver(X) receptor agonist[12] (Scheme 2) with distinct advantages over existing reports[13] in avoiding use of excessive oxidant, additional ligand, and base in minimizing generation of wastes.

Scheme 2. Synthesis of liver(X) receptor agonist (**6**)

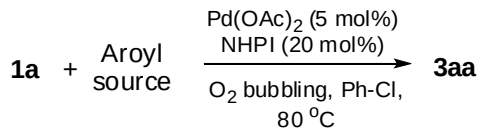


To demonstrate good scale-up capability, a gram scale reaction was carried out during the treatment of **1a** (1.47g, 7 mmol) with **2a** that afforded the desired product **3aa** in 70 and 68% yields under reaction conditions A and B, respectively.

The applicability of other aroyl surrogates was examined under the condition B (Table 7). The treatment of **1a** with 5 molar equiv of each of benzaldehyde[14] and benzyl alcohol in PhCl at 80 °C under O_2 bubbling for 2.5 h afforded **3aa** in 67 and 61% yields, respectively. The best result (84% yield in 2.5 h) was obtained using dibenzyl ether. Others such as benzyl amine, mandelic acid, benzil, and benzoyl acetone gave **3aa** in inferior yields (25-51%). The

use of 4-phenyl-2-butanone formed **3aa** as the only product (32% yield) and further indicated the benzylic carbon as the preferred source of the aroyl carbonyl.

Table 7. Scope of aroyl surrogates.[a]



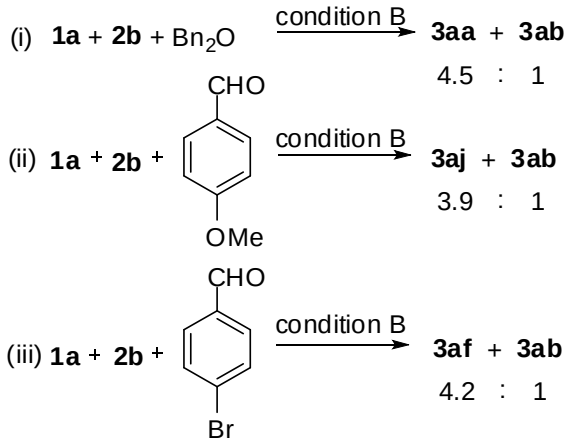
Entry	Aroyl source	Equiv	Time (h)	Yield (%)[b]
1	$PhCH_3$	**5.0**	**2.5**	**70**
2		5.0	1.5	41
3		2.5	2.5	51
4	PhCHO	**5.0**	**2.5**	**67**
5		5.0	1.5	45
6		2.5	2.5	56
7	Bn_2O	5.0	2.5	86
8		5.0	1.5	86
9		**2.5**	**2.5**	**84**
10	$PhCH_2OH$	5.0	2.5	61
11	$PhCH_2NH_2$	5.0	2.5	26
12	$PhCH_2Cl$	5.0	2.5	0
13	PhCH(OH)COOH	5.0	2.5	29
14	PhCOCOPh	5.0	2.5	0
15	PhCOCH(OH)Ph	5.0	2.5	51
16	$PhCOCH_2COCH_3$	5.0	2.5	25
17	$Ph(CH_2)_2COCH_3$	5.0	2.5	32
18	PhCN	5.0	2.5	0

[a]Reaction conditions: **1a** (0.5 mmol), aroyl source, $Pd(OAc)_2$ (5 mol%), NHPI (20 mol%), chlorobenzene (1.0 mL), O_2 bubbling at 80 °C. [b]Isolated yield of **3aa**.

The above results reflect that aroylation is more facile using dibenzyl ether is used as the aroyl source. However, no major difference (in terms of product yield and reaction time) could be observed for aroylation using toluene and benzaldehyde as the aroyl source. Thus, to assess the distinct difference on the ease of aroylation using benzyl ether, aryl aldehyde, and aryl methane as the aroyl source the following inter- and intra-molecular competition studies (Schemes 3 and 4) were performed.

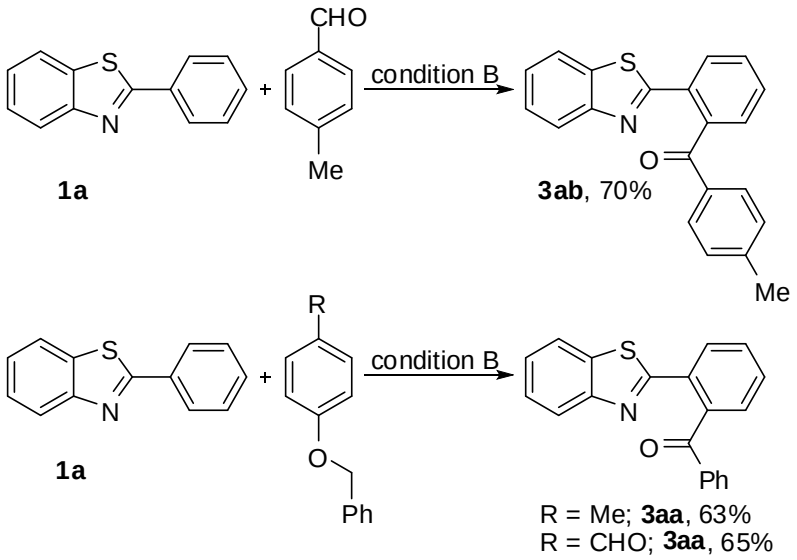
During the intermolecular competitions **1a** was treated with (i) 5 equiv of each of *p*-xylene (**2b**) and dibenzyl ether; (ii) 5 equiv of each of **2b** and 4-methoxybenzaldehyde; and (iii) 5 equiv of each of **2b** and 4-bromobenzaldehyde (Scheme 3). In all of these cases a mixture of aroylated products corresponding to the respective aroyl source were formed and could not be isolated in pure form. Therefore, a quantitative estimation of the corresponding aroylated product was obtained mass spectrometrically[15] by subjecting an aliquot portion of the reaction mixture to ESI/MS analysis and determining the ion current[16] of the mass peak of the corresponding sodium adduct ($M+Na^+$). The ratio of the ion current provided the relative amount of formation of the corresponding product. The results reflected that the dibenzyl ether and aldehyde are more effective/reactive aroyl source compared to arylmethanes.

Scheme 3. Intermolecular competition during aroylation of **1a** with dibenzyl ether, arylmethane, and aryl aldehydes as the aroyl surrogates.



For intramolecular competition studies (Scheme 4) **1a** was treated with (i) of *p*-tolualdehyde, (ii) 4-benzyloxy toluene, (iii) 4-benzyloxybenzaldehyde under reaction condition B that would represent competitive aroylation involving aryl methane vs aryl aldehyde, aryl methane vs benzyl ether, and aryl aldehyde vs benzyl ether, respectively. In each case the corresponding product was isolated and characterised. The results obtained suggest aryl aldehyde as the preferred aroyl source over the aryl methane but benzyl ether is the most preferred aroyl source compared to both aryl methane and aryl aldehyde. However, the readily availability of arylmethanes make them a preferred choice as the aroyl surrogate.

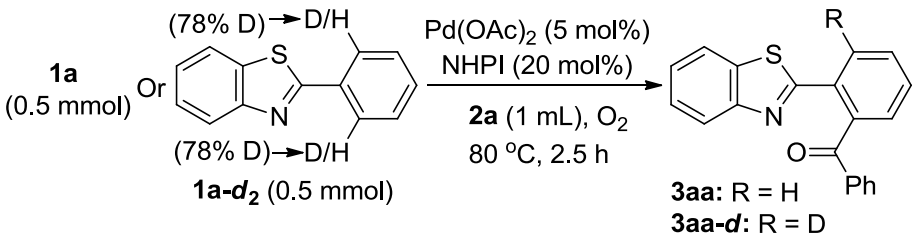
Scheme 4. Intramolecular competition during aroylation of **1a** with 4-methylbenzaldehyde, 4-benzyloxytolune, and 4-benzyloxybenzaldehyde as the aroyl surrogates.



Anticipating that the aroylation proceeds through C-H activation, kinetic isotope effect (KIE) studies were carried out. In two separate experiments **1a** and **1a-d$_2$** were treated with **2a** in the presence of $Pd(OAc)_2$ (5 mol%) at 80 °C under O_2 bubbling. A quantitative estimation of the corresponding aroylated product **3aa**/**3aa-d** was made by determination of ion current[17] of the mass peak of the corresponding sodium adduct ($M+Na^+$) by subjecting an aliquot portion of the reaction mixture, withdrawn after specified time interval to ESI/MS analysis

(Table 8). The ratio of the ion current provided the k_H/k_D values that reflected the kinetic isotope effect and provided evidence for C-H activation.

Table 8. Determination of k_H/k_D by ESI/MS.[a]

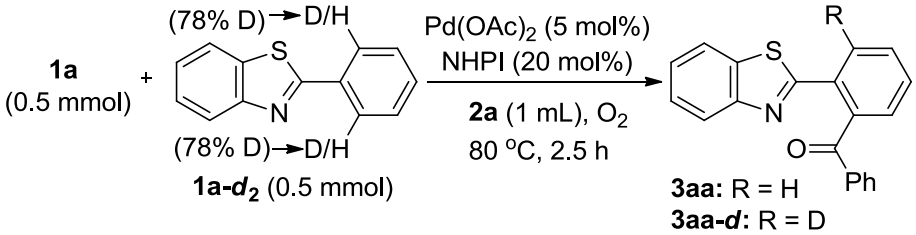


entry	time (h)	ion current of [M+Na$^+$] peak		k_H/k_D[c]
		3aa (X)[b]	3aa-*d* (Y)[b]	
1	0.5	2.25×10^7	0.65×10^7	2.11
2	1.0	1.17×10^7	0.40×10^7	1.87
3	1.5	0.77×10^7	0.22×10^7	2.24
4	2.0	1.45×10^7	0.57×10^7	1.62

[a]**1a** (0.5 mmol) and **1a-*d*$_2$** (0.5 mmol) were separately treated with **2a** (1 mL) and after the specific time 10 µL of the reaction mixture was subjected to ESI-MS analysis. [b]The area of the ion peak of the sodium adduct of the benzoylated product. [c]The k_H/k_D is represented by the ratio X/Y.

Intermolecular competition experiments, monitored through ^{1}H NMR reflected more pronounced KIE (k_H/k_D 2.91-3.62) (Table 9).

Table 9. Determination of k_H/k_D by NMR.[a]



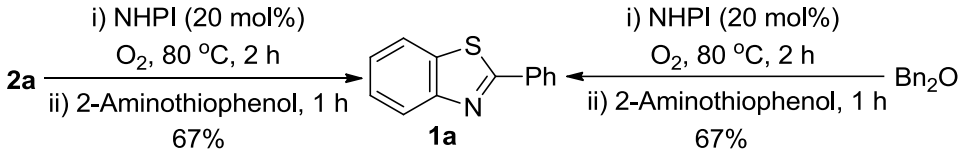
Entry	Time (h)	3aa (X)[b]	3aa-*d* (Y)[b]	k_H/k_D[c]
1	0.75	85	15	3.62
2	1.0	84	16	3.36
3	1.5	82	18	2.91

[a]The mixture of **1a** (0.5 mmol) and **1a-d$_2$** (0.5 mmol) was treated with **2a** (1 mL) in the presence of $Pd(OAc)_2$ (5 mol%) and NHPI (20 mol%) at 80

°C under O_2 bubbling (1 atm). [b]The ratio of the product was determined by NMR. [c]The relative rate (k_H/k_D) is represented by the ratio X/Y

In order to get further mechanistic insight, the mixture of **2a**/Bn_2O and NHPI (20 mol%) was heated at 80 °C under O_2 (bubbling) for 2 h in the absence of any Pd catalyst followed by treatment of the reaction mixture with 2-aminothiophenol for further 1 h to furnish **1a** in 67 and 79% yields, respectively, (Scheme 5). In situ formation of benzaldehyde from **2a** was also confirmed by subjecting an aliquot of the crude reaction mixture of **2a** and NHPI (20 mol%) under O_2 bubbling after 2 h to ^{1}H NMR analysis after distilling off the excess of **2a**. The remaining reaction mixture was diluted with EtOAc (5 mL), washed with water (2 X 5 mL), dried with Na_2SO_4, and concentrated under vacuum. The resultant crude product in toluene (2 mL) on being treated with 2-aminothiophenol afforded **1a** in 65%. This indicates *in situ* formation of benzaldehyde as aldehydes are known to form benzothiazoles on reaction with 2-aminothiophenols.[7]

Scheme 5. Evidence for in situ formation of aldehyde.



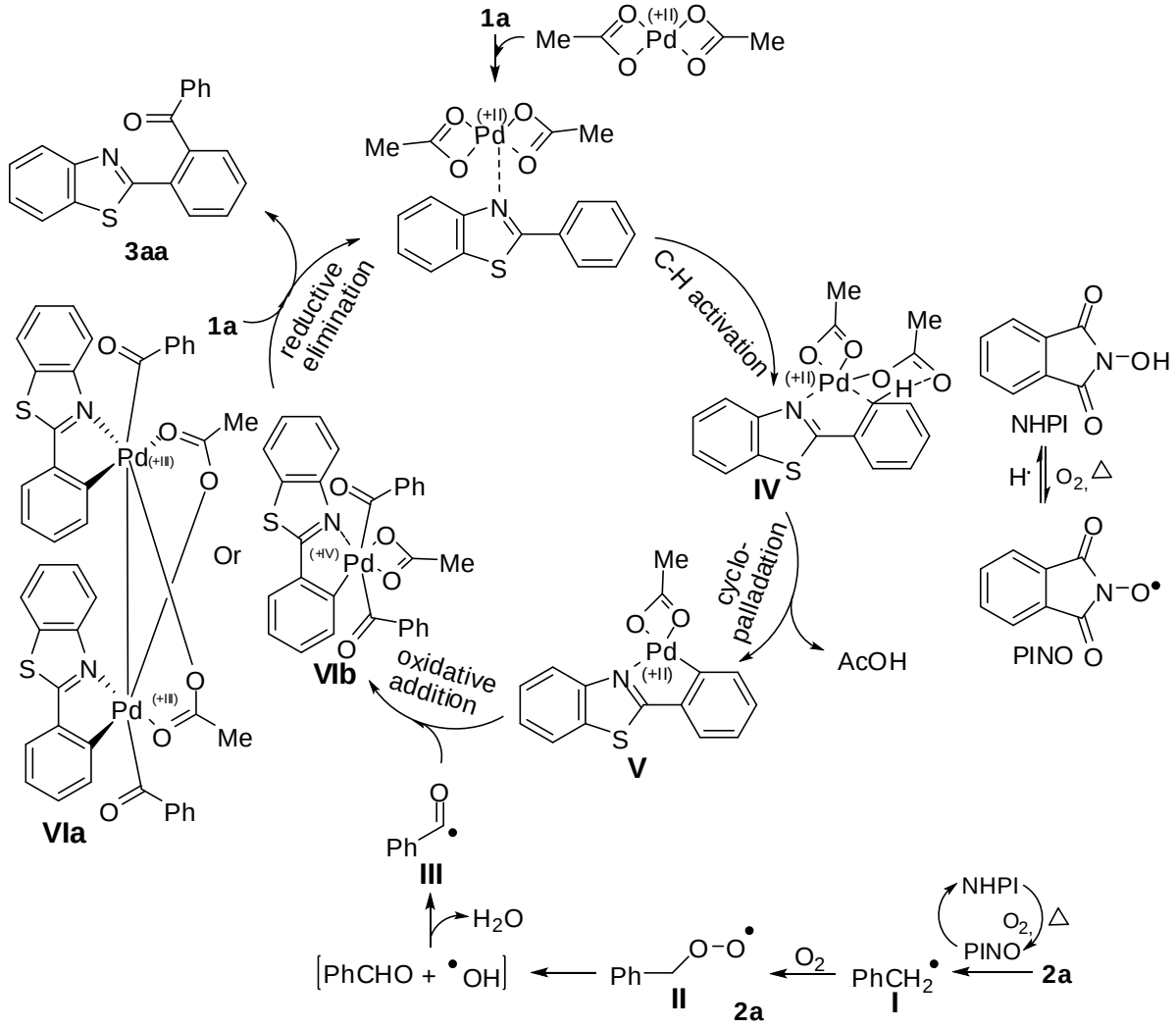
The addition of TEMPO (1.5 equiv) to the $Pd(OAc)_2$ (5 mol%) catalysed reaction of **1a** with **2a** in the presence of NHPI (20 mol%) at 80 °C under O_2 (bubbling) for 2.5 h did not produce any significant amount of **3aa**. This suggests the involvement of radical pathway for the aroylation.

The $Pd(OAc)_2$ (5 mol%) catalysed reaction of **1a** with **2a** in the presence of NHPI (20 mol%) at 80 °C under N_2 (balloon) for 12 h did not produce any significant amount of **3aa** indicating the essentiality of molecular oxygen for this oxidative coupling reaction.

Based on these studies and precedent literature reports[6,17] a plausible mechanistic pathway is proposed (Scheme 6). The first step involves the generation of the phthalimide-*N*-oxyl (PINO) radical from NHPI and dioxygen. The *in situ* generated PINO radical abstracts hydrogen

radical from the arylmethane to form the benzylic radical **I** which subsequently reacts with dioxygen to form the benzyl peroxyradical **II** (Scheme 6)[17b] which disproportionates to the aldehyde and hydroxyl radical. The generated hydroxyl/PINO radical would abstract the hydrogen radical from the aldehyde group to form the acyl radical **III**.[18,14] The in situ formed aldehyde may also undergo acyl radical formation in the presence of molecular oxygen.[19] The $Pd(OAc)_2$ coordinates with the benzazole through the nitrogen atom and activates the *ortho* C-H bond of the 2-aryl moiety. The chelation-directed C-H bond activation is followed by the (acetate) ligand-assisted proton abstraction[20] through a six-membered chair-like transition state in **IV** to the cyclo-palladated complex **V**. The lack of catalytic efficiency of $PdCl_2$ as well as Na_2PdCl_2 could be due to the poor basicity (and hence H-B formation ability) of the chloride anion. In case of $Pd(dba)_3$ and $Pd(dba)_2$ as the ligand attains psuedoaromatic character involving the *d* orbital of the Pd(II) it is unable to form the chair-like transition state to abstract the *ortho* aryl proton. On similar reason $Pd(PPh_3)_4$ is also ineffective. On the other hand, in $Pd(OPiv)_2$ the pivalate anion can take part in forming the chair-like transition state to abstract the *ortho* arylproton due to its basicity (hydrogen bond acceptor ability) and hence exhibited catalytic efficiency comparable to that of $Pd(OAc)_2$. The inability of $Pd(OCOCF_3)_2$ to promote the reaction is supportive of the proposal on ligand-assisted abstraction of the *ortho*-aryl proton as the trifluoroacetate anion is less basic. The poor H-B accepting ability of the carbonyl oxygen of the trifluoroacetate anion is not conducive for formation of the six-membered chair-like transition state leading to the analogous complex **IV** (Scheme 6).

Scheme 6. Proposed mechanism for $C(sp^2)$-H aroylation.



To demonstrate that the deprotonation of the *ortho* aryl proton in **IV** does not take place by external base a few additional experiments were performed. Thus, the $PdCl_2$-catalysed reaction of **1a** with **2a** that did not afford any significant amount of **3aa** under method A was performed separately by adding KOAc (5 mol%) alone as well as along with 5 mol% of 18-C-6. Thus, external base is not involved in the abstraction of the *ortho* proton of the 2-aryl moiety. The complex **V** undergoes oxidative addition to **III** to form the intermediate Pd(III)/Pd(IV)[21] species **VIa**/**VIb** which on reductive elimination by new C-C bond formation is converted to the aroylated product and the Pd(II) catalyst is regenerated and re-enters into the catalytic cycle.

In conclusions, cross dehydrogenative coupling of arylmethanes with bio-relevant heterocycles has been achieved for Pd(II)-catalysed C(sp^2)-H aroylation through organocatalytic dioxygen activation. Mass and NMR spectrometry based kinetic isotope effect studies revealed C-H bond activation as the rate-determining step and radical scavenging experiment established radical pathway to generate aroyl radical as the actual aroylation species formed by aerial oxidation of the arylmethanes through organocatalytic activation of molecular oxygen. Excellent selectivity was observed in forming the mono- and the bis-aroylated produtcs through a time dependent reaction. The exclusive formation of the mono-aroylated product took place for a shorter reaction period (2.5 – 3 h) while performing the reaction for longer period (~ 8 h) gave the bis-aroylated product which, however, can also be obtained by further aroylation of the corresponding pre-formed mono-aroylated compound. A representative application of this newly developed synthetic methodology on C(sp^2)-H aroylation via organocatalytic dioxygen activation has been demonstrated through the preparation of liver(X) receptor agonist. The use of molecular oxygen as the oxidant, arylmethanes as unfunctionalised aroyl surrogates, lesser catalyst loading, and the applicability with diverse directing groups mark the distinct advancements in catalytic C(sp^2)-H aroylation.

EXPERIMENTAL SECTION

General: ^{1}H and ^{13}C NMR spectra were recorded on a 400 MHz NMR spectrometer in $CDCl_3$ with a residual undeuterated solvent ($CHCl_3$ at 7.26/77.0) using TMS as an internal standard. Chemical shifts (δ) are given in ppm and *J* values are given in Hz. ^{13}C NMR spectra were fully decoupled and were referenced to the middle peak of the solvent $CDCl_3$ at 77.00 ppm. Splitting patterns were designated as s, singlet; d, doublet; dd, doublet of doublet; dt, doublet of triplet; td, triplet of doublet; t, triplet; m, multiplet. The IR spectra were recorded either on KBr pellets (for solids) or neat (for liquids) on a FTIR spectrometer. High resolution mass spectra (HRMS) were obtained using the electron spray ionization (ESI) technique and

TOF mass analyzer. Melting points were measured using a melting point apparatus and were uncorrected. ESI/MS spectra were recorded on advance mass spectrometer with ion trap mass analyzer. Open column chromatography and thin layer chromatography (TLC) were performed on silica gel (60-120 mesh and fluorescent silica gels, respectively). Evaporation of solvents was performed under reduced pressure, using a rotary vacuum evaporator.

All the commercially available chemicals were used without further purification. Starting material **1b**-**1j**,[7] **4a**-**4b**,[10] **4d**,[22] and **4f**,[11] were synthesized according to literature protocol. Liver receptor agonist (**6**) from **5dm** was synthesized using reported methodology.[23]

General procedure for the $Pd(OAc)_2$ catalyzed Cross-dehydrogenative coupling of 2-arylbenzo[*d*]thiazole (1) with arylmethane (2) (reaction of 1a with 2a to form 3aa) (Condition A):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (211 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%) and NHPI (33 mg, 20 mol%) in toluene (**2a**) (2.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (50 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to afford 2-(benzo[*d*]thiazol-2-yl)phenyl)(phenyl)methanone **3aa** (236 mg,75%) as yellowish solid; mp: 82-83 ^oC; IR (KBr) ν_{max}: 3059, 2923, 1608, 1596, 1508, 1448, 1432, 1314, 1263, 1151, 1072, 967, 927, 759, 703 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.97-7.95 (m, 1H), 7.81-7.78 (m, 4H), 7.66-7.61 (m, 2H), 7.58-7.56 (m, 1H), 7.43-7.38 (m, 2H), 7.32 (t, J = 7.8 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.6, 165.3, 153.5, 139.7, 137.8, 135.3, 132.7, 132.1, 130.3, 130.2, 129.6, 129.2, 128.9, 128.2, 126.1, 125.3, 123.4, 121.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{13}NOSNa$ 338.0616; found 338.0630. Identical with those of an authentic sample.[4d]

Phenyl(2-(5-(trifluoromethyl)benzo[*d*]thiazol-2-yl)phenyl)methanone (3ba): Yellowish solid (268 mg, 70%); mp: 127-128 ^{o}C; IR (KBr) ν_{max}: 3062, 2926, 1673, 1596, 1511, 1452, 1422, 1329, 1267, 1149, 1124, 1076, 1055, 965, 931, 840, 767, 708, 671, 637 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.01 (s, 1H), 7.98-7.92 (m, 2H), 7.81 (d, J = 7.6 Hz, 2H), 7.70-7.64 (m, 2H), 7.58-7.55 (m, 2H), 7.46 (t, J = 7.3 Hz, 1H), 7.38-7.34 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.2, 167.6, 153.0, 139.9, 138.7, 137.5, 133.0, 131.5, 130.8, 130.3, 129.9, 129.4, 129.0, 128.7, 128.4, 122.1, 121.7 (J = 3.0 Hz), 120.5 (J = 4.0 Hz); HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{12}F_3NOSNa$ 406.0489; found 406.0496.

(2-(5-Chlorobenzo[*d*]thiazol-2-yl)phenyl)(phenyl)methanone (3ca): Yellowish solid (247 mg, 71%); mp: 107-108 ^{o}C; IR (KBr) ν_{max}: 3059, 2926, 1671, 1596, 1509, 1450, 1432, 1286, 1267, 1151, 1074, 965, 929, 902, 794, 768, 704, 676, 637 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.60 (m, 1H), 7.80-7.78 (m, 3H), 7.71 (d, J = 8.5 Hz, 1H), 7.68-7.62 (m, 2H), 7.57-7.55 (m, 1H), 7.47-7.43 (m, 1H), 7.37-7.33 (m, 2H), 7.29 (dd, J = 8.5, 2.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.3, 167.3, 154.2, 139.8, 137.6, 133.5, 132.8, 132.2, 131.7, 130.6, 130.2, 129.7, 129.3, 128.9, 128.3, 125.9, 123.1, 122.1; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}ClNOSNa$ 372.0226; found 372.0233.

(2-(Benzo[*d*]thiazol-2-yl)-4-bromophenyl)(phenyl)methanone (3da): Off white solid (272 mg, 69%); mp: 104-105 ^{o}C; IR (KBr) ν_{max}: 3061, 2925, 1670, 1596, 1581, 1449, 1434, 1378, 1313, 1278, 1260, 1151, 977, 925, 829, 760, 703, 672, 654 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.08 (d, J = 1.8 Hz, 1H), 7.78 (t, J = 7.8 Hz, 2H), 7.74-7.71 (m, 3H), 7.40 (d, J = 8.2 Hz, 1H), 7.37 (d, J = 7.9 Hz, 1H), 7.34 (d, J = 8.9 Hz, 1H), 7.31-7.27 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.6, 163.5, 153.3, 138.4, 137.4, 135.4, 134.0, 133.2, 132.9, 132.4, 130.4, 129.2, 128.3, 126.4, 125.7, 124.2, 123.6, 121.5; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}BrNOSNa$ 415.9721; found 415.9717.

(2-(Benzo[*d*]thiazol-2-yl)-5-bromophenyl)(phenyl)methanone (3ea): Yellowish solid (276 mg, 70%); mp: 123-124 ^{o}C; IR (KBr) ν_{max}: 2924, 1769, 1596, 1501, 1448, 1383, 1258, 1108,

1052, 749 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.84 (d, J = 8.3 Hz, 1H), 7.82-7.77 (m, 5H), 7.68 (d, J = 1.9 Hz, 1H), 7.46-7.38 (m, 2H), 7.36-7.31 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 195.8, 164.0, 153.4, 141.2, 137.2, 135.2, 133.2, 133.0, 131.7, 130.9, 129.2, 128.4, 126.3, 125.6, 124.9, 123.5, 121.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}BrNOSNa$ 415.9708; found 415.9721.

(2-(Benzo[*d*]thiazol-2-yl)-5-chlorophenyl)(phenyl)methanone (3fa): Yellowish solid (273 mg, 68%); mp: 135-136 ^oC; IR (KBr) ν_{max}: 3057, 2924, 1672, 1596, 1522, 1449, 1346, 1314, 1275, 1260, 1157, 1093, 967, 750, 705, 645 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.90 (d, J = 8.4 Hz, 1H), 7.81-7.78 (m, 4H), 7.62 (dd, J = 8.3, 2.2 Hz, 1H), 7.53 (d, J = 2.1 Hz, 1H), 7.45-7.38 (m, 2H), 7.37-7.30 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 195.9, 164.0, 153.4, 141.1, 137.2, 136.7, 135.2, 133.0, 130.8, 130.5, 130.2, 129.2, 128.9, 128.4, 126.3, 125.5, 123.5, 121.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}ClNOSNa$ 372.0226; found 372.0236.

(2-(Benzo[*d*]thiazol-2-yl)-5-fluorophenyl)(phenyl)methanone (3ga): Yellowish gummy (233 mg, 70%); IR (neat) ν_{max}: 3060, 2918, 1672, 1596, 1581, 1482, 1449, 1404, 1314, 1276, 1261, 1209, 1098, 980, 860, 841, 759, 709 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.93 (dd, J = 8.6, 5.5 Hz, 1H), 7.78-7.75 (m, 4H), 7.42-7.23 (m, 7H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 195.9, 164.8-162.2 (J_{FC} = 253 Hz), 164.1, 153.4, 142.0 (J_{FC} = 7.0 Hz), 137.2, 135.2, 133.0, 131.8 (J_{FC} = 9.0 Hz), 129.2, 128.4, 126.2, 125.4, 123.4, 121.4, 117.2 (J_{FC} = 22 Hz), 116.2 (J_{FC} = 23.0 Hz); HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}FNOSNa$ 356.0521; found 356.0533.[4f]

(2-(Benzo[*d*]thiazol-2-yl)-5-methylphenyl)(phenyl)methanone (3ha): Off white solid (240 mg, 73%); mp: 103-104 ^oC; IR (KBr) ν_{max}: 3066, 2922, 1670, 1592, 1578, 1515, 1486, 1452, 1433, 1314, 1267, 1209, 1176, 976, 817, 753, 705, 645, 620 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.82 (d, J = 8.0 Hz, 1H), 7.70-7.74 (m, 4H), 7.41 (d, J = 7.9 Hz, 1H), 7.37-7.31 (m, 3H), 7.30-7.25 (m, 3H), 2.47 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.8,

165.4, 153.5, 140.9, 139.7, 137.9, 135.2, 132.6, 130.8, 129.5, 129.4, 129.4, 129.2, 128.2, 126.0, 125.1, 123.3, 121.3, 21.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NOSNa$ 352.0772; found 352.0787.[4d]

(2-(Benzo[*d*]thiazol-2-yl)-5-methoxyphenyl)(phenyl)methanone (3ia): Yellowish solid (255 mg, 74%); mp: 88-89 ^oC; IR (KBr) ν_{max}: 3048, 2923, 1668, 1598, 1484, 1399, 1311, 1218, 1100, 1030, 964, 938, 761, 709, 620 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.90 (d, J = 8.6 Hz, 1H), 7.81-7.75 (m, 4H), 7.41 (t, J = 7.3 Hz, 1H), 7.37-7.26 (m, 4H), 7.15 (dd, J = 8.6, 2.6 Hz, 1H), 7.06 (d, J = 2.6 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.3, 165.0, 161.2, 153.5, 141.3, 137.6, 135.0, 132.7, 131.2, 129.2, 128.2, 126.0, 125.0, 124.6, 123.1, 121.3, 115.9, 113.9, 55.7; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NO_2SNa$ 368.0721; found 368.0728.[4f]

(3-(Benzo[*d*]thiazol-2-yl)naphthalen-2-yl)(phenyl)methanone (3ja): Yellowish solid (270 mg, 74%); mp: 119-120 ^oC; IR (KBr) ν_{max}: 3060, 2925, 1664, 1596, 1497, 1430, 1381, 1260, 1105, 956, 884, 754, 747, 728, 701 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.44 (s, 1H), 8.06 (s, 1H), 8.06-8.03 (m, 1H), 7.97-7.95 (m, 1H), 7.85-7.82 (m, 4H), 7.70-7.64 (m, 2H), 7.44-7.36 (m, 3H), 7.36-7.31 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.2, 165.6, 153.6, 138.2, 137.0, 135.2, 133.4, 133.2, 132.6, 130.1, 129.9, 129.4, 129.3, 128.5, 128.5, 128.4, 128.3, 128.2, 126.1, 125.3, 123.4, 121.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{24}H_{15}NOSNa$ 388.0772; found: 388.0786.

(2-(Benzo[*d*]thiazol-2-yl)-3-chlorophenyl)(phenyl)methanone (3ka): Off white solid (227 mg, 65%); IR (KBr) ν_{max}: 1732, 1668, 1448, 1314, 1280, 1235, 1134, 966, 760, 701 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.87 (d, J = 7.9 Hz, 1H), 7.82 (m, 1H), 7.69 (dd, J = 7.8, 1.5 Hz, 1H), 7.66-7.63 (m, 2H), 7.55-7.52 (m, 1H), 7.49 (dd, J = 7.6, 1.5 Hz, 1H), 7.41-7.31 (m, 3H), 7.27-7.23 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 195.7, 152.2, 142.9, 137.0, 136.0, 134.4, 134.1, 132.8, 132.0, 130.6, 129.9, 129.4, 128.1, 127.4, 126.0, 125.6,

123.6, 121.3; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}ClNOSNa$ 372.0226; found 372.0221.[4f]

(2-(Benzo[*d*]thiazol-2-yl)-3-methoxyphenyl)(phenyl)methanone (3la): White solid (238 mg, 69%); mp: 148-149 ^oC; IR (KBr) ν_{max}: 2934, 1668, 1575, 1449, 1316, 1288, 1160, 1066, 974, 760, 701 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.80 (d, J = 7.4 Hz, 1H), 7.76-7.71 (m, 3H), 7.58 (t, J = 7.9 Hz, 1H), 7.35-7.21 (m, 6H), 7.16 (dd, J = 7.6, 1.0 Hz), 4.08 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.2, 160.4, 157.1, 151.4, 142.3, 138.2, 135.9, 132.0, 131.3, 128.7, 128.0, 125.6, 124.9, 122.9, 121.1, 120.9, 120.8, 112.7, 56.1; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NO_2SNa$ 368.0721; found 368.0721.[4d]

(2-(Benzo[*d*]thiazol-2-yl)-1,3-phenylene)bis(phenylmethanone) (3ma): Off white solid (353 mg, 71%); mp: 129-130 ^oC; IR (KBr) ν_{max}: 3050, 1669, 1593, 1445, 1312, 1287, 1260, 1158, 1007, 788, 761, 712 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.78-7.71 (m, 8H), 7.58 (d, J = 7.9 Hz, 1H), 7.38 (t, J = 7.4 Hz, 2H), 7.32-7.25 (m, 5H), 7.21 (t, J = 7.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.8, 162.9, 152.6, 141.0, 136.8, 136.4, 133.2, 131.3, 130.4, 129.7, 129.6, 128.3, 126.0, 125.3, 123.4, 121.2; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{27}H_{17}NO_2SNa$ 442.0878; found 442.0872.

(2-(Benzo[*d*]thiazol-2-yl)-5-bromo-1,3-phenylene)bis(phenylmethanone) (3na): Yellowish solid (324 mg, 65%); mp: 124-125 ^oC; IR (KBr) ν_{max}: 3060, 2924, 1732, 1596, 1451, 1380, 1283, 1174, 1001, 758, 708 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.22 (d, J = 7.4 Hz, 2H), 7.96-7.94 (m, 2H), 7.87-7.82 (m, 3H), 7.75-7.71 (m, 3H), 7.58-7.54 (m, 3H), 7.42-7.38 (m, 1H), 7.32-7.27 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 195.1, 162.8, 162.1, 142.5, 136.3, 134.9, 134.8, 133.5, 132.9, 130.7, 129.6, 129.0, 128.9, 128.4, 126.1, 125.5, 125.3, 124.3, 124.0, 123.4, 121.2; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{27}H_{16}BrNO_2SNa$ 519.9983; found 519.9978.

General procedure for the $Pd(OAc)_2$ catalyzed cross-dehydrogenative coupling of 1 with arylmethanes (2) via C(sp^2)-H bond activation (reaction of 1a with 2a to form to 3aa): (Condition B):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (211 mg, 1.0 mmol), **2a** (531 µL, 5 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%) and NHPI (33 mg, 20 mol%) in PhCl (2.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (50 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to afford 2-(benzo[*d*]thiazol-2-yl)phenyl)(phenyl)methanone **3aa** (225 mg, 70%) as yellowish solid that was identical (spectral data) with the authentic sample.

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(*p*-tolyl)methanone (3ab): Off white solid (243 mg, 74%); mp: 103-104 ^oC; IR (KBr) ν_{max}: 3066, 2922, 1670, 1592, 1578, 1515, 1486, 1452, 1433, 1314, 1267, 1209, 1176, 976, 817, 753, 705, 645, 620 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.82 (d, J = 8.0 Hz, 1H), 7.70-7.74 (m, 4H), 7.41 (d, J = 7.9 Hz, 1H), 7.37-7.31 (m, 3H), 7.30-7.25 (m, 3H), 2.47 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.8, 165.4, 153.5, 140.9, 139.7, 137.9, 135.2, 132.6, 130.8, 129.5, 129.4, 129.4, 129.2, 128.2, 126.0, 125.1, 123.3, 121.3, 21.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NOSNa$ 352.0772; found 352.0787.[4d]

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(*m*-tolyl)methanone (3ac): Yellowish oil (237 mg, 72%); IR (neat) ν_{max}: 2923, 1670, 1432, 1276, 1207, 967, 762, 729 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.86 (d, J = 7.4 Hz, 1H), 7.74-7.69 (m, 2H), 7.57-7.50 (m, 3H), 7.46-7.44 (m, 2H), 7.30-7.27 (m, 1H), 7.24-7.18 (m, 1H), 7.13-7.07 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.8, 165.4, 153.5, 139.9, 138.0, 137.7, 135.4, 133.6, 132.2, 130.2, 130.1, 129.7,

129.7, 128.9, 128.1, 126.8, 126.1, 125.3, 123.4, 121.4, 21.2; HRMS (ESI-TOF) m/z: [M + Na]$^+$ Calcd for $C_{21}H_{15}NOSNa$ 352.0772; found 352.0761.[4f]

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(*o*-tolyl)methanone (3ad): White solid (240 mg, 73%); mp: 105-106 ^{o}C; IR (KBr) ν_{max}: 3058, 2925, 1664, 1593, 1500, 1456, 1378, 1254, 1160, 1122, 967, 924, 853, 754, 737, 662, 638 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.89 (d, J = 8.2 Hz, 1H), 7.87-7.84 (m, 1H), 7.79 (d, J = 7.8 Hz, 1H), 7.67-7.63 (m, 3H), 7.42 (td, J = 7.7, 1.2 Hz, 1H), 7.34-7.30 (m, 1H), 7.18-7.14 (m, 2H), 7.09 (d, J = 7.5 Hz, 1H), 6.95 (t, J = 7.5 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 199.04, 165.7, 153.5, 141.0, 139.8, 137.6, 135.4, 132.5, 131.4, 131.2, 130.4, 130.3, 130.1, 129.9, 129.6, 126.1, 125.2, 124.9, 123.4, 121.4, 21.4; HRMS (ESI-TOF) m/z: [M + Na]$^+$ Calcd for $C_{21}H_{15}NOSNa$ 352.0772; found 352.0784.

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(3-chlorophenyl)methanone (3ae): Yellowish oil (227 mg, 65%); IR (neat) ν_{max}: 3063, 2924, 1674, 1570, 1432, 1255, 1154, 967, 760 cm^{-1}; mp: 88-89 ^{o}C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.96 (m, 1H), 7.82 (d, J = 7.6 Hz, 1H), 7.79 (d, J = 7.6 Hz, 1H), 7.77 (t, J = 1.8 Hz, 1H), 7.70-7.60 (m, 3H), 7.57-7.55 (m, 1H), 7.42-7.37 (m, 1H), 7.36-7.31 (m, 2H), 7.22 (t, J = 7.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.2, 165.0, 153.4, 139.6, 139.0, 135.2, 134.4, 132.4, 132.0, 130.6, 130.5, 129.6, 129.5, 128.9, 128.9, 127.2, 126.3, 125.5, 123.4, 121.5; HRMS (ESI-TOF) m/z: [M + Na]$^+$ Calcd for $C_{20}H_{12}ClNOSNa$ 372.0226; found 372.0225.[4d]

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(4-bromophenyl)methanone (3af): Yellowish solid (216 mg, 74%); mp: 131-132 ^{o}C; IR (KBr) ν_{max}: 3055, 2928, 1669, 1585, 1482, 1397, 1365, 1265, 1068, 1010, 967, 922, 841, 752, 726, 699 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.97-7.95 (m, 1H), 7.84-7.82 (m, 1H), 7.79-7.77 (m, 1H), 7.67-7.61 (m, 4H), 7.54-7.52 (m, 1H), 7.46-7.44 (m, 2H), 7.42-7.34 (m, 2H);^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.6, 153.4, 139.1, 136.7, 131.9, 131.7, 131.6, 130.6, 130.5, 130.5, 130.4, 129.6, 128.8, 127.8, 126.3, 125.5, 123.4, 121.5; HRMS (ESI-TOF) m/z: [M + Na]$^+$ Calcd for $C_{20}H_{12}BrNOSNa$ 415.9703; found 415.9721.[4f]

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(3-bromophenyl)methanone (3ag): Yellowish gummy (193 mg, 66%); IR (neat) ν_{max}: 3059, 2925, 1673, 1567, 1432, 1281, 1259, 1151, 1068, 968, 760, 728, 697, 673 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.95-7.92 (m, 2H), 7.81 (t, J = 8.3 Hz, 2H), 7.69-7.62 (m, 3H), 7.28-7.55 (m, 1H), 7.49 (d, J = 7.9 Hz, 1H), 7.42-7.31 (m, 2H), 7.15 (t, J = 7.9 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.1, 165.0, 153.4, 139.8, 138.9, 135.3, 135.2, 132.0, 131.8, 130.6, 130.5, 129.8, 129.6, 128.9, 127.6, 126.3, 125.5, 123.4, 122.5, 121.5; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}BrNOSNa$ 415.9718; found 415.9721.

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(2-bromophenyl)methanone (3ah): Yellowish solid (195 mg, 67%); mp: 124-125 ^oC; IR (KBr) ν_{max}: 3060, 1672, 1581, 1430, 1294, 1252, 1025, 967, 929, 759, 729 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.03 (d, J = 8.2 Hz, 1H), 7.80-7.70 (m, 3H), 7.66-7.59 (m, 2H), 7.43-7.39 (m, 2H), 7.33-7.29 (m, 2H), 7.06-6.98 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 195.9, 165.4, 153.5, 139.3, 138.9, 135.5, 134.1, 133.2, 131.8, 131.2, 131.1, 130.6, 130.3, 130.0, 126.5, 126.1, 125.3, 123.8, 121.5, 121.3; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}BrNOSNa$ 415.9721; found 415.9708.

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(4-iodophenyl)methanone (3ai): White solid (300 mg, 68%); mp: 107-108 ^oC; IR (KBr) ν_{max}: 3060, 2924, 1671, 1580, 1456, 1431, 1390, 1276, 1261, 1151, 1055, 1007, 967, 761, 697, 669, 644 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.95 (m, 1H), 7.83 (d, J = 7.5 Hz, 1H), 7.79 (d, J = 7.8 Hz, 1H), 7.70-7.61 (m, 4H), 7.54-7.52 (m, 1H), 7.51-7.48 (m, 2H), 7.42-7.32 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.8, 165.0, 153.4, 139.1, 137.6, 137.3, 135.2, 131.9, 130.5, 130.4, 130.4, 129.6, 128.7, 126.3, 125.5, 123.4, 121.5, 100.6; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{12}INOSNa$ 463.9582; found 463.9590.

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(4-methoxyphenyl)methanone (3aj): White solid (258 mg, 75%); mp: 128-129 ^oC; IR (KBr) ν_{max}: 1652, 1599, 1509, 1418, 1260, 1150, 1029, 970, 928, 764, 608 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.98 (d, J = 7.4 Hz, 1H), 7.86 (d, J = 8.1

Hz, 1H), 7.82-7.77 (m, 3H), 7.65-7.58 (m, 2H), 7.52-7.50 (m, 1H), 7.39 (t, *J* = 7.6 Hz, 1H), 7.32 (t, *J* = 7.5 Hz, 1H), 6.81 (d, *J* = 8.9 Hz, 2H), 3.79 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.2, 165.4, 163.3, 153.5, 140.1, 135.5, 132.0, 131.8, 130.7, 130.2, 129.9, 129.8, 128.6, 126.1, 125.2, 123.5, 121.4, 113.6, 55.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NO_2SNa$ 368.0721; found 368.0733.[4d]

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(3,5-dimethylphenyl)methanone (3ak): Yellowish oil (240 mg, 70%); IR (neat) ν_{max}: 3060, 2922, 1668, 1605, 1456, 1433, 1379, 1311, 1224, 1136, 1023, 967, 863, 814, 763, 698, 674 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.98-7.97 (m, 1H), 7.85 (d, *J* = 8.1 Hz, 1H), 7.81 (d, *J* = 8.3 Hz, 1H), 7.67-7.59 (m, 2H), 7.55-7.53 (m, 1H), 7.42-7.38 (m, 3H), 7.33 (td, *J* = 7.6, 1.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.9, 165.5, 153.5, 140.1, 137.8, 137.7, 135.5, 134.5, 132.2, 130.1, 130.1, 129.7, 128.8, 127.3, 126.1, 125.2, 123.4, 121.4, 21.1; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{22}H_{17}NOSNa$ 366.0929; found 366.0931.[4i]

(2-(Benzo[*d*]thiazol-2-yl)phenyl)(2-bromo-3-methylphenyl)methanone (3al): Yellowish oil (273 mg, 67%); IR (neat) ν_{max}: 3061, 2927, 1676, 1432, 1291, 1238, 1026, 968, 761, 728, 668, 643 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.06 (d, *J* = 8.1 Hz, 1H), 7.81-7.76 (m, 3H), 7.67-7.62 (m, 2H), 7.45 (t, *J* = 7.7 Hz, 1H), 7.35 (t, *J* = 8.0 Hz, 1H), 7.12 (d, *J* = 7.5 Hz, 1H), 7.08 (d, *J* = 7.4 Hz, 1H), 6.98 (t, *J* = 7.5 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.3, 165.8, 153.4, 139.9, 139.5, 139.3, 133.5, 132.7, 131.4, 130.9, 130.3, 130.2, 128.4, 126.2, 126.0, 125.2, 123.8, 126.6, 121.3; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{14}BrNOSNa$ 429.9877; found 429.9893.

General procedure for the synthesis of starting material 2,4-diphenylpyrimidine (4g):

To the magnetically stirred mixture of acetophenone (2.5 mmol, 450 mg) and DMF-DMA (357 mg, 3.0 mmol, 0.39 mL, 1.2 equiv) at 100 °C under N_2 was added 1-methylimidazole (MeIm) (2.5 mmol, 0.19 mL, 1 equiv) and the mixture was stirred until acetophenone was completely consumed for 3 h; The mixture was subjected to rotary evaporation in vacuum to

remove the volatile components (excess DMF-DMA and the liberated MeOH). The crude (*E*)-3-(dimethylamino)-1-phenylprop-2-en-1-one[24] was directly treated with benzamidine hydrochloride (0.300 g, 2.5 mmol, 1.0 equiv) and $LiOH{\cdot}H_2O$ (126.0 mg, 1.2 equiv) in ethanol (15.0 mL) at 80 ^oC and stirred magnetically for 6.0 h. After the completion of reaction ethanol distilled off in rotary evaporator and the residue was diluted with EtOAc (20 mL). The organic later was washed with H_2O (3 × 10 mL), brine (3 × 10 mL) dried (anh Na_2SO_4) and purified by column chromatography using 5% EtOAc in hexane as solvent system to afford the 2,4-diphenylpyrimidine (**4g**) as white solid (644 mg, 74%), mp: 88-90 ^oC; IR (KBr) ν_{max}: 3076, 1549, 1524, 1347, 1107, 742 cm-1;^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.86 (d, J = 5.3 Hz, 1H), 8.65-8.6 (m, 2H), 8.27-8.25 (m, 2H), 7.62-7.55 (7H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 164.6, 163.9, 157.9, 137.9, 137.0, 131.0, 130.7, 129.0, 128.6, 128.3, 127.2, 114.5; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{16}H_{12}N_2Na$ 255.0898; found 255.0900.

4-(4-Nitrophenyl)-2-phenylpyrimidine (4h): White solid (443 mg, 64%); mp: 122-124 ^oC; IR (KBr) ν_{max}: 3070, 1543, 1524, 1356, 1103, 746 cm^{-1}; 1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.93 (d, J = 5.2 Hz, 1H), 8.59-8.56 (m, 2H), 8.39 (s, 4H), 7.65 (d, J = 5.2 Hz, 1H), 7.55-7.53 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 165.0, 161.5, 158.6, 149.3, 142.9, 137.3, 131.2, 128.7, 128.4, 128.2, 124.1, 115.1; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{16}H_{11}N_3O_2Na$ 300.0749; found 300.0753.

4-(4-Methoxyphenyl)-2-phenylpyrimidine (**4i**): White solid (459 mg, 70%); mp: 92-94 ^oC; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.77 (d, J = 5.3 Hz, 1H), 8.58-8.57 (m, 2H), 8.20 (d, J = 7.4 Hz, 2H), 7.54-7.49 (m, 4H), 7.03 (d, J = 9.5 Hz, 2H), 3.88 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 164.4, 163.4, 162.1, 157.5, 138.0, 130.6, 129.4, 128.8, 128.5, 128.3, 114.3, 113.7, 55.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{17}H_{14}N_2ONa$ 285.1004; found 285.1009.

General procedure for $Pd(OAc)_2$ catalyzed cross-dehydrogenative coupling of 2-arylbenzoxazoles with arylmethanes (2) via C(sp^2)-H bond activation (4a to 5aa):

The magnetically stirred mixture of 2-phenylbenzoxazole (**4a**) (195 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%) and NHPI (33 mg, 20 mol%) in toluene (**2a**) (2.0 mL) was heated at 80 ^oC (oil bath temp) for 3 h (TLC) while O_2 gas was bubbled (passed) into (O_2 cylinder outlet pressure 10 psi) the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (50 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation under. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 2% EtOAc in hexane as eluent to afford (2-(benzo[*d*]oxazol-2-yl)phenyl)(phenyl)methanone (**5aa**) as yellowish solid (194 mg, 65%); mp: 54-56 ^oC; IR (KBr) ν_{max}: 3062, 2924, 1671, 1596, 1450, 1314, 1280, 1151, 1032, 433, 812, 761, 745, 712 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.24-8.21 (m, 1H), 7.73-7.71 (m, 2H), 7.62-7.57 (m, 2H), 7.56-7.52 (m, 1H), 7.47-7.45 (m, 1H), 7.37-7.34 (m, 1H), 7.29-7.24 (m, 3H), 7.19-7.16 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.1, 161.3, 150.6, 141.6, 140.1, 137.3, 133.0, 131.1, 130.1, 129.5, 129.2, 128.6, 128.4, 125.4, 125.3, 124.5, 120.3, 110.5; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{13}NO_2Na$ 322.0844; found 322.0852.[4f]

(2-(Benzo[*d*]oxazol-2-yl)phenyl)(*p*-tolyl)methanone (5ab) (Using method B): Off white solid (210 mg, 67%); mp: 99-100 ^oC; IR (KBr) ν_{max}: 3059, 2923, 1669, 1605, 1452, 1278, 1033, 932, 746, 711 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.34-8.32 (m, 1H), 7.73 (d, *J* = 8.2 Hz, 2H), 7.68-7.64 (m, 3H), 7.54-7.52 (m, 1H), 7.39-7.37 (m, 1H), 7.29-7.26 (m, 2H), 7.18 (d, *J* = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.8, 161.4, 150.6, 144.0, 141.7, 140.4, 134.9, 131.0, 129.9, 129.7, 129.3, 129.1, 128.4, 125.3, 125.2, 124.4, 120.3, 110.5, 21.6; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NO_2Na$ 336.1000; found 336.1015.[4f]

(2-(Benzo[*d*]oxazol-2-yl)-5-methylphenyl)(phenyl)methanone (5ba) (Using method A): White solid (210 mg, 67%); mp: 126-127 ^oC; IR (KBr) ν_{max}: 3060, 2927, 1690, 1603, 1500, 1453, 1422, 1323, 1299, 1243, 1178, 1127, 1070, 1026, 934, 811, 746, 709, 667 cm^{-1}; ^1H

NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.22 (d, J = 8.0 Hz, 1H), 7.82 (d, J = 8.0 Hz, 2H), 7.63-7.60 (m, 1H), 7.51-7.44 (m, 2H), 7.38-7.34 (m, 4H), 7.26-7.24 (m, 2H), 2.51 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.4, 161.5, 150.5, 141.9, 141.7, 140.0, 137.4, 133.0, 130.9, 129.4, 129.2, 129.1, 128.4, 125.0, 124.4, 122.6, 120.1, 110.4, 21.6; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{21}H_{15}NO_2$ 336.1000; found 336.1009.

General procedure for $Pd(OAc)_2$ catalyzed cross-dehydrogenative coupling of azobenzene (4c) with toluene (2a) via C(sp^2)-H bond activation (4c to 5ca):

The magnetically stirred mixture of azobenzene (**4c**) (182 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%) and NHPI (33 mg, 20 mol%) in toluene (**2a**) (2.0 mL) was heated at 80 ^{o}C (oil bath temp) for 3 h (TLC) while O_2 gas was bubbled (passed) into (O_2 cylinder outlet pressure 10 psi) the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (50 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation under. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 2% EtOAc in hexane as eluent to afford (*E*)-phenyl(2-(phenyldiazenyl)phenyl)methanone (**5ca)** (152 mg, 53%) as red liquid; IR (neat) ν_{max}: 3060, 2926, 1667, 1595, 1448, 1314, 1288, 1148, 1071, 929, 774, 700 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.98 (d, J = 7.9 Hz, 1H), 7.80 (d, J = 7.5 Hz, 2H), 7.69-7.66 (m, 1H), 7.61 (d, J = 4.2 Hz, 2H), 7.52-7.46 (m, 3H), 7.41-7.33 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.2, 152.0, 150.2, 138.4, 136.9, 132.8, 131.4, 130.9, 130.8, 129.4, 128.9, 128.8, 128.4, 122.9, 120.1; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{19}H_{14}N_2ONa$ 309.1004; found 309.0997.[25]

(*E*)-(4-Chlorophenyl)(3-methoxy-2-(phenyldiazenyl)phenyl)methanone (5dm) (Using method B): Yellowish solid (186 mg, 59%); ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 7.61-7.59 (m, 2H), 7.55-7.52 (m, 1H), 7.47-7.45 (m, 2H), 7.36-7.32 (m, 3H), 7.26-7.22 (m, 3H), 6.99 (dd, J = 7.5, 1.0 Hz, 1H), 4.08 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 194.6, 156.6,

151.5, 140.7, 138.6, 135.9, 132.0, 131.4, 129.9, 128.9, 128.6, 122.5, 120.7, 114.1, 56.7; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{20}H_{15}ClN_2O_2Na$ 373.0720; found 373.0719.[25]

Phenyl(2-(pyridin-2-yl)phenyl)methanone (5ea): White solid (199 mg, 77%); mp: 108-109 ^oC; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.39 (d, J = 4.6 Hz, 1H), 7.89 (d, J = 7.5 Hz, 1H), 7.70 (d, J = 7.6 Hz, 2H), 7.63-7.49 (m, 5H), 7.40 (t, J = 6.7 Hz, 1H), 7.30-7.26 (m, 2H), 7.045-7.032 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 198.2, 156.8, 149.0, 139.6, 139.5, 137.9, 136.3, 132.3, 130.2, 129.5, 129.1, 128.8, 128.5, 128.0, 122.8, 121.9; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{18}H_{13}NONa$ 282.0895; found 282.0889.[6]

(2-(Pyridin-2-yl)-1,3-phenylene)bis(phenylmethanone) (5ea'): Colourless liquid; IR (neat) ν_{max}: 3063, 2922, 1663, 1589, 1274, 1243, 935, 760 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.13, (d, J = 4.1 Hz, 1H), 7.65-7.55 (m, 7H), 7.30 (t, J = 7.4 Hz, 2H), 7.19-7.09 (m, 6H), 6.71-6.69 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.70, 149.1, 140.3, 137.1, 135.6, 132.8, 130.6, 129.9, 129.8, 128.3, 128.2, 128.1, 125.4, 122.0; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{25}H_{17}NONa$ $[M + Na]^+$ 386.1157; found 386.1150.

Typical procedure for the $Pd(OAc)_2$ catalyzed cross-dehydrogenative coupling of 2,3-diphenylquinoxaline (4f) with toluene (2a) via C(sp^2)-H bond activation (4f to 5fa):

The magnetically stirred mixture of 2,3-diphenylquinoxaline (**4f**, 282 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%), NHPI (33 mg, 20 mol%), toluene (**2a**, 0.530 mg, 5.0 mmol) in chlorobenzene (2.0 mL) was heated at 80 ^oC (oil bath temp) for 3 h (TLC) while O_2 gas was bubbled (passed) into (O_2 cylinder outlet pressure 10 psi) the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (50 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation under. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 5% EtOAc in hexane as eluent to afford phenyl(2-(3-phenylquinoxalin-2-yl)phenyl)methanone (**5fa**) as gummy liquid (198 mg, 64%); IR (neat) ν_{max}: 3061, 2924, 1660,

1597, 1447, 1344, 1271, 1026, 978, 763, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.15 (d, J = 7.5 Hz, 1H), 8.03 (d, J = 8.5 Hz, 1H), 7.7-7.71 (m, 2H), 7.67 (d, J = 7.4 Hz, 1H), 7.63-7.58 (m, 1H), 7.49-7.37 (m, 7H), 7.33-7.25 (m, 3H), 7.20-7.15 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 196.5, 153.7, 153.3, 141.3, 141.0, 140.8, 138.7, 138.4, 137.0, 132.5, 131.5, 131.2, 130.2, 130.2, 130.0, 129.9, 129.7, 129.2, 129.1, 128.7, 128.2, 127.9, 127.0; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{27}H_{18}N_2ONa$ 409.1317; found 409.1312.[26]

Typical procedure for the $Pd(OAc)_2$ catalyzed cross-dehydrogenative coupling of 2,4-diphenylpyrimidine scaffolds with toluene (2a) via C(sp^2)-H bond activation (4g to 5ga):

The magnetically stirred mixture of 2,4-diphenylpyrimidine (**4g**, 232 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%), NHPI (33 mg, 20 mol%), toluene (**2a**, 2.0 mL) was heated at 80 ^oC (oil bath temp) for 3 h (TLC) while O_2 gas was bubbled (passed) into (O_2 cylinder outlet pressure 10 psi) the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (50 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation under. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 8% EtOAc in hexane as eluent to afford phenyl(2-(4-phenylpyrimidin-2-yl)phenyl)methanone (**5ga**) as yellowish solid (234 mg, 69%); mp: 106-107 ^oC; IR (KBr) ν_{max}: 3060, 2928, 1660, 1562, 1543, 1423, 1380, 1282, 931, 768, 747 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.68 (d, J = 5.3 Hz, 1H), 8.49 (d, J = 9.7 Hz, 1H), 7.86-7.84 (m, 2H), 7.75-7.72 (m, 2H), 7.68 (td, J = 7.5, 1.4 Hz, 1H), 7.63 (td, J = 7.4, 1.5 Hz, 1H), 7.56-7.54 (m, 1H), 7.48-7.47 (m, 1H), 7.46-7.36 (m, 4H), 7.26-7.22 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 198.0, 163.8, 163.4, 157.6, 140.6, 137.9, 137.4, 135.9, 134.3, 132.3, 131.0, 130.2, 129.8, 129.6, 129.3, 128.8, 128.4, 128.0, 127.2, 123.6, 114.0; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{16}N_2ONa$ 359.1160; found 359.1153.

(2-(4-(4-Nitrophenyl)pyrimidin-2-yl)phenyl)(phenyl)methanone (5ha): Yellowish solid (236 mg, 62%); mp: 175-176 ^oC; IR (KBr) ν_{max}: 3081, 2922, 1603, 1549, 1518, 1449, 1426, 1409, 13789, 1347, 1249, 1071, 931, 836, 769, 747, 715 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ

(ppm): 8.82 (d, *J* = 5.2 Hz, 1H), 8.51 (d, *J* = 7.7 Hz, 1H), 8.21 (d, *J* = 8.9 Hz, 2H), 7.94 (d, *J* = 8.9 Hz, 2H), 7.77 (d, *J* = 8.1 Hz, 2H), 7.70-7.65 (m, 2H), 7.70-7.65 (m, 2H), 7.53 (d, *J* = 7.4 Hz, 1H), 7.50 (d, *J* = 5.2 Hz, 1H) 7.46 (t, *J* = 7.4 Hz, 1H), 7.31 (t, *J* = 7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.8, 164.3, 161.0, 158.5, 149.2, 141.8, 140.8, 137.7, 136.6, 132.7, 130.6, 129.4, 129.8, 129.4, 128.3, 128.3, 128.2, 123.9, 114.8; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{23}H_{15}N_3O_3Na$ 404.1011; found 404.1012.

(2-(4-(4-Methoxyphenyl)pyrimidin-2-yl)phenyl)(phenyl)methanone (5ia): Yellowish solid (220 mg, 60%); mp: 102-103 ^{o}C; IR (KBr) ν_{max}: 1672, 1581, 1541, 1429, 1287, 1255, 1174, 1024, 928, 827, 708, 581 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.60 (d, *J* = 5.4 Hz, 1H), 8.46 (d, *J* = 7.7 Hz, 1H), 7.82 (dd, *J* = 7.0, 1.9 Hz, 2H), 7.72 (d, *J* = 7.2 Hz, 2H), 7.68-7.62 (m, 2H), 7.55 (d, *J* = 7.4 Hz, 1H), 7.37-7.35 (m, 1H), 7.32 (d, *J* = 5.4 Hz, 1H), 7.25-7.22 (m, 2H), 6.91 (dd, *J* = 7.0, 1.8 Hz, 2H), 3.88 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 198.0, 163.7, 162.9, 162.0, 157.3, 140.6, 137.9, 137.6, 132.3, 130.1, 129.8, 129.5, 129.2, 128.9, 128.4, 128.4, 128.0, 114.0, 113.0, 55.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for Calcd for $C_{24}H_{18}N_2O_2Na$ 389.1266; found 389.1274.

(2-(4-(4-Methoxyphenyl)pyrimidin-2-yl)-1,3-phenylene)bis(phenylmethanone) (5ja): White solid (334 mg, 71%); mp: 195-196 ^{o}C; IR (KBr) ν_{max}: 1662, 1579, 1542, 1416, 1319, 1273, 1178, 1007, 833, 713 cm^{-1};^{1}H NMR ($CDCl_3$, 400 MHz) δ (ppm): 8.21 (d, *J* = 5.4 Hz, 1H), 7.34-7.64 (m, 9H), 7.36 (d, *J* = 7.3 Hz, 2H), 7.25-7.21 (m, 4H), 7.03 (d, *J* = 5.4 Hz, 1H), 6.87 (d, *J* = 8.8 Hz, 2H), 3.87 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ (ppm): 197.3, 162.8, 162.5, 162.1, 156.5, 141.0, 137.5, 137.3, 132.5, 130.1, 129.6, 129.2, 128.8, 128.1, 128.0, 114.0, 112.6, 55.4; HRMS (ESI-TOF) m/z: $[M + Na]^+$ Calcd for $C_{31}H_{22}N_2O_3$ 493.1528; found 493.1540.

Typical procedure for the gram scale reaction of $Pd(OAc)_2$ catalyzed Cross-dehydrogenative coupling of 2-phenylbenzo[*d*]thiazole (1a) with toluene (2a) to form 3aa (Condition A):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (1.48 g, 7.0 mmol), $Pd(OAc)_2$ (78 mg, 5 mol%) and NHPI (228 mg, 20 mol%) in toluene (**2a**) (14.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (100 mL), washed with brine (3 × 20 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to afford 2-(benzo[*d*]thiazol-2-yl)phenyl)(phenyl)methanone **3aa** (1.54 g, 70%) as yellowish solid that was identical (spectral data) with the authentic sample.

Typical procedure for the gram scale reaction of $Pd(OAc)_2$ catalyzed Cross-dehydrogenative coupling of 2-phenylbenzo[*d*]thiazole (1a) with toluene (2a) to form 3aa (Condition B):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (1.48 mg, 7.0 mmol), **2a** (3.72 mL, 35 mmol), $Pd(OAc)_2$ (78 mg, 5 mol%) and NHPI (228 mg, 20 mol%) in PhCl (14 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (100 mL), washed with brine (3 × 20 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to afford 2-(benzo[*d*]thiazol-2-yl)phenyl)(phenyl)methanone **3aa** (1.50 g, 68 %) as yellowish solid that was identical (spectral data) with the authentic sample.

Typical procedure for the intermolecular competition between dibenzyl ether and *p*-xylene during aroylation of 1a (Condition B): The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (106 mg, 0.5 mmol), **2b** (308 µl, 5 mmol), dibenzyl ether (475 µl, 5 mmol), $Pd(OAc)_2$ (6 mg, 5 mol%) and NHPI (17 mg, 20 mol%) in PhCl (1.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas was bubbled (passed) into the

reaction mixture. Aliquot (10 µL) portion of the reaction mixture was withdrawn after 2.0 h, diluted with MeOH (1 mL), 50 µL of the resultant solution was subjected to (+ve) ESI/MS, and the ion current of the mass peak at *m*/*z* 338 corresponding to the Na^+ adduct of **3aa** (MW: 315) and mass peak at *m*/*z* 352 corresponding to the Na^+ adduct of **3ab** (MW: 329) was estimated. The ratio of the ion current of the **3aa/3ab** was found to be 4.5.

Typical procedure for the intermolecular competition between 4-methoxybenzaldehyde and *p*-xylene during aroylation of 1a (Condition B): The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (106 mg, 0.5 mmol), **2b** (308 µl, 5 mmol), 4-methoxybenzaldehyde (304 µl, 5 mmol), $Pd(OAc)_2$ (6 mg, 5 mol%) and NHPI (17 mg, 20 mol%) in PhCl (1.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas was bubbled (passed) into the reaction mixture. Aliquot (10 µL) portion of the reaction mixture was withdrawn after 2.0 h, diluted with MeOH (1 mL), 50 µL of the resultant solution was subjected to (+ve) ESI/MS, and the ion current of the mass peak at *m*/*z* 368 corresponding to the Na^+ adduct of **3aj** (MW: 345) and mass peak at *m*/*z* 352 corresponding to the Na^+ adduct of **3ab** (MW: 329) was estimated. The ratio of the ion current of the **3aj/3ab** was found to be 3.9.

Typical procedure for the intermolecular competition between 4-bromobenzaldehyde and *p*-xylene during aroylation of 1a (Condition B):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) (106 mg, 0.5 mmol), **2b** (308 µl, 5 mmol), 4-bromobenzaldehyde (462 mg, 5 mmol), $Pd(OAc)_2$ (6 mg, 5 mol%) and NHPI (17 mg, 20 mol%) in PhCl (1.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas was bubbled (passed) into the reaction mixture. Aliquot (10 µL) portion of the reaction mixture was withdrawn after 2.0 h, diluted with MeOH (1 mL), 50 µL of the resultant solution was subjected to (+ve) ESI/MS, and the ion current of the mass peak at *m*/*z* 417 corresponding to the Na^+ adduct of **3af** (MW: 394) and mass peak at *m*/*z* 352 corresponding to

the Na^+ adduct of **3ab** (MW: 329) was estimated. The ratio of the ion current of the **3af/3ab** was found to be 4.2.

Typical experimental procedure for intramolecular competition during aroylation of 1a with 4-methylbenzaldehyde as the aroyl surrogates (Condition B):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) 106 mg, 0.5 mmol), 4-methylbenzaldehyde (294 µL, 2.5 mmol), $Pd(OAc)_2$ (6 mg, 5 mol%) and NHPI (17 mg, 20 mol%) in PhCl (1.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (25 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to afford **3ab** (115 mg, 70%).

Typical experimental procedure for intramolecular competition during aroylation of 1a with 1-(benzyloxy)-4-methylbenzene as the aroyl surrogates (Condition B):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) 106 mg, 0.5 mmol), 1-(benzyloxy)-4-methylbenzene (495 mg, 2.5 mmol), $Pd(OAc)_2$ (6 mg, 5 mol%) and NHPI (17 mg, 20 mol%) in PhCl (1.0 mL) was heated at 80 ^oC (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (25 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to **3aa** (99 mg, 63%).

Typical experimental procedure for intramolecular competition during aroylation of 1a with 4-(benzyloxy)benzaldehyde as the aroyl surrogates (Condition B):

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**) 106 mg, 0.5 mmol), 4-(benzyloxy)benzaldehyde (538 mg, 2.5 mmol), $Pd(OAc)_2$ (6 mg, 5 mol%) and NHPI (17 mg,

20 mol%) in PhCl (1.0 mL) was heated at 80 ^{o}C (oil bath temp) for 2.5 h (TLC) while O_2 gas (cylinder outlet pressure 10 psi) was bubbled (passed) into the reaction mixture. The reaction mixture was cooled to rt and diluted with EtOAc (25 mL), washed with brine (3 × 5 mL), dried (anh Na_2SO_4), filtered, and concentrated under rotary vacuum evaporation. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 4% EtOAc in hexane as eluent to afford **3aa** (102 mg, 65%).

Typical procedure for the synthesis of 2-phenylbenzo[*d*]thiazole-d_2 (1a-d_2):

The starting material 2-(2,6-dibromophenyl)benzo[*d*]thiazole for the synthesis of **1a-d_2** was synthesized as per literature report.[27] *n*-BuLi (1.6 M in hexane, 2.5 equiv, 2.5 mmol) was added drop wise to the magnetically stirred mixture of 2-(2,6-dibromophenyl)benzo[*d*]thiazole (369 mg, 1 mmol) in dry THF at -40^{o}C under N_2 atmosphere. The reaction mixture was stirred for the 30 min and quenched with 4.0 mL of deuterium oxide (D_2O) at the same temperature. The temperature of the reaction mixture was slowly raised to rt for 30 min. The solution was then diluted with ethyl acetate (50 mL), washed with brine (3 x 5 mL), dried over anhydrous Na_2SO_4, filtered, and evaporated under vaccum. The crude reaction mixture was purified by column chromatography on silica gel (60-120 mesh size) using 2% hexane/EtOAc as eluent to afford 2-phenylbenzo[*d*]thiazole-d_2 (**1a**-d_2) in 59% yield (130 mg). The percent of deutarium content in **1a**-d_2 was determined by comparing with the corresponding *ortho* proton peak of C-2 phenyl ring of **1a**.

Typical experimental procedure for determination of k_H/k_D through the estimation of the ion current of the Na^+ adducts of the corresponding aroylated product using (+ve) ESI/MS:

Reaction of 1a with 2a: To the magnetically stirred mixture of **1a** (105.5 mg, 0.5 mmol), $Pd(OAc)_2$ (5.6 mg, 5 mol%), and NHPI (33 mg, 20 mol%) in toluene (**2a**) (2.0 mL) at 80 ºC (oil bath) oxygen gas was bubbled into (O_2 cylinder outlet pressure 10 psi). Aliquot (10 µL) portion of the reaction mixture was withdrawnafter0.5 h, 1.0 h, 1.5 h and 2.0 h. On each case

the withdrawn sample was diluted with MeOH (1 mL) and 50 µL of the resultant solution was subjected to (+ve) ESI/MS and on each occasion the ion current of the mass peak at *m*/*z* 338 corresponding to the Na^+ adduct of **3aa** (MW: 315) was estimated (Table 8).

Reaction of 1a-d_2 with 2a: To the magnetically stirred mixture of **1a-*d_2*** (106.5 mg, 0.5 mmol), $Pd(OAc)_2$ (5.6 mg, 5 mol%), and NHPI (33 mg, 20 mol%) in toluene (**2a**) (2.0 mL) at 80 ºC (oil bath) oxygen as was bubbled into (O_2 cylinder outlet pressure 10 psi). Aliquot (10 µL) portion of the reaction mixture was withdrawn after 0.5 h, 1.0 h, 1.5 h and 2.0 h. On each case the withdrawn sample was diluted with MeOH (1 mL) and 50 µL of the resultant solution was subjected to (+ve) ESI/MS and on each occasion the ion current of the mass peak at *m*/*z* 339 corresponding to the Na^+ adduct of **3aa-*d_2*** (MW: 316) was estimated (Table 8).

The total ion current corresponding to the peak area of the potassium adduct $(M + Na)^+$ of the **3aa** (m/z = 338) formed from **1a** was compared with that of the **3aa-*d*** (m/z = 339) formed from **1a-*d_2***. In all the cases, ion current corresponding to **3aa** was found to be much greater in comparison to the ion current of the corresponding **3aa-*d***. These provided direct evidences of the k_H/k_D (Table 8).

Typical experimental procedure for kinetic isotope effect study for the determination of k_H/k_D by intermolecular competition experiment:

To the magnetically stirred mixture of **1a** (105.5 mg, 0.5 mmol), **1a-*d_2*** (106.5 mg, 0.5 mmol), $Pd(OAc)_2$ (5.6 mg, 5 mol%), and NHPI (33 mg, 20 mol%) in toluene (**2a**) (2.0 mL) at 80 ºC (oil bath) oxygen gas was bubbled into (O_2 cylinder outlet pressure 10 psi).The product mixture of **3aa** and **3aa-*d*** was isolated at different time interval of 0.75 h, 1.0 h and 1.5 h and subjected for ^{1}H-NMR analysis.

Evidence for *in situ* formation of aldehyde from 2 during the treatment with molecular oxygen in the presence of NHPI (reaction of 2a to form 1a via in situ generation of benzaldehyde:

The magnetically stirred mixture of **2a** and NHPI (20 mol%) was heated at 80 °C under O_2 (bubbling) for 2h in the absence of any Pd catalyst followed by treatment of the reaction mixture with 2-aminothiophenol for further 1 h to furnish **1a** in 67% yield. This result indicates *in situ* formation of aldehyde.[7]

Evidence for the involvement of radical pathway during the Pd-catalysed CDC of 1a with 2a through organo catalytic dioxygen activation by NHPI:

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**, 211 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%), NHPI (33 mg, 20 mol%), TEMPO (234 mg, 1.5 mmol) in toluene (**2a**, 2.0 mL) was heated at 80 °C under O_2 bubbling for 2.5 h did not produce any significant amount of **3aa** suggesting the involvement of radical pathway for aroylation.

Evidence for requirement of molecular oxygen for aroylation:

The magnetically stirred mixture of 2-phenylbenzo[*d*]thiazole (**1a**, 211 mg, 1.0 mmol), $Pd(OAc)_2$ (11.2 mg, 5 mol%), NHPI (33 mg, 20 mol%) in toluene (**2a**, 2.0 mL) was heated at 80 °C under N_2 atmosphere for 12 h resulting in complete recovery of **1a** indicating the essentiality of molecular oxygen for aroylation reaction.

ASSOCIATED CONTENT

Supporting Information

Spectral data, scanned spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

*E-mail: akchakraborti@niper.ac.in; akchakraborti@rediffmail.com

Note

The authors declare no competing financial interest.

ACKNOWLEDHEMENT

BVP thanks Department of Science and Technology, New Delhi for INSPIRE senior research fellowship.

REFERENCES

(1) Recent reviews: (a) Girard, S.; Knauber, A. T.; Li, C. J. *Angew. Chem. Int. Ed.* **2014**, *53*, 74–100. (b) Liu, C.; Yuan, J.; Gao, M.; Tang, S.; Li, W.; Shi, R.; Lei, A. *Chem. Rev*. **2015**, *115*, 12138-12204. (c) Chen, Z.; Wang, B.; Zhang, J.; Yu, W.; Liu, Z.; Zhang, Y. *Org. Chem. Front*. **2015**, *2*, 1107-1295.

(2) (a) Yuan, Y.; Chen, D.; Wang, X. *Adv. Synth. Catal*. **2011**, *353*, 3373-3379. (b) Wu, X. F. *Chem. Eur. J.* **2015**, *21*, 12252-12265 and the references therein.

(3) Antitumor and antibiotic: (a) Sommer, P. S. M.; Almeida, R. C.; Schneider, K.; Beil, W.; Süssmuth, R. D.; Fiedler, H. P. *J. Antibiot.* **2008**, *61*, 683-686. Anti-leishmanial: (b) Tipparaju, S. K.; Joyasawal, S.; Pieroni, M.; Kaiser, M.; Brun, R.; Kozikowski, A. P. *J. Med. Chem*. **2008**, *51*, 7344-7347. Anti-inflammatory: (c) Seth, K.; Garg, S. K.; Kumar, R.; Purohit, P.; Meena, V. S.; Goyal, R.; Banerjee, U. C.; Chakraborti, A. K. *ACS Med. Chem. Lett.* **2014**, *5*, 512-516. Anti-tubercular: (d) Pancholia, S.; Dhameliya, T. M.; Shah, P.; Jadhavar, P. S.; Sridevi, J. P.; Yogeshwari, P.; Sriram, D.; Chakraborti, A. K. *Eur. J. Med. Chem*. **2016**, *116*, 187-199.

(4) (a) Zhang, Q.; Li, C.; Yang, F.; Li, J.; Wu, Y. *Tetrahedron* **2013**, *69*, 320–326. (b) Zhang, Q.; Yang, F.; Wu, Y. *Tetrahedron* **2013**, *69*, 4908-4914. (c) Ding, Q.; Ji, H.; Ye, C.; Wang, J.; Wang, J.; Zhou, L.; Peng, Y. *Tetrahedron* **2013**, *69*, 8661-8667. (d) Banerjee, A.; Santra, S. K.; Guin, S.; Rout, S. K.; Patel, B. K. *Eur. J. Org. Chem*. **2013**, 1367-1376. (e) Khatun, N.; Banerjee, A.; Santra, S. K.; Behera, A; Patel, B. K.

RSC Adv. **2014**, *3*, 54532-54538. (f) Zheng, Y.; Song, W. -B.; Zhang, S. -W.; Xuan, L. -J. *Tetrahedron* **2015**, *71*, 1574–1580. (g) Santra, S. K.; Banerjee, A.; Mohanta, P. R.; Patel, B. K. *J. Org. Chem*. **2016**, *81*, 6066-6064.

(5) Gulzar, N.; Schweitzer-Chaput, B.; Klussmann, M. *Catal. Sci. Technol.* **2014**, *4*, 2778-2796.

(6) Liang, Y. -F.; Li, X.; Wang, X.; Yan, Y.; Feng, P.; Jiao, N. *ACS Catal.* **2015**, *5*, 1956–1963.

(7) Transition metal free non-hem dioxygen activation: Parikh, N.; Kumar, D.; Roy, S. R.; Chakraborti, A. K. *Chem. Commun*. **2011**, *47*, 1797–1799.

(8) Oxidative debromination of C-Br bond is due to the differential bond dissociation energies for aryl halides (Ph-X: Cl 96 kcal/mol; Br 81 kcal/mol) [McMilan, D. M.; Golden, D. M. *Annu. Rev. Phys. Chem.* **1982**, *33*, 493-532].

(9) Seth, K.; Purohit, P.; Chakraborti, A. K. *Org. Lett*. **2014**, *16*, 2334-2337.

(10) Kumar, D.; Rudrawar, S.; Chakraborti, A. K. *Aust. J. Chem*. **2008**, *61*, 881-887.

(11) Kumar, D.; Seth, K.; Kommi, D. N.; Bhagat, S.; Chakraborti, A. K. *RSC Adv.* **2013**, *3*, 15157-15168.

(12) Steffan, R. J.; Matelan, E. M.; Bowen, S. M.; Ullrich, J. W.; Wrobel, J. E.; Zamaratski, E.; Kruger, L.; Olsen Hedemyr, A. L.; Cheng, A.; Hansson, T.; Unwalla, R. J.; Miller, C. P.; Rhonnstad, P. P. U.S. Pat. Appl. Publ. US 2006030612 A1 20060209, 2006; *Chem. Abstr*. **2006**, *144*, 212770.

(13) Ohnmacht, S. A.; Culshaw, A. J.; Greaney, M. F. *Org. Lett.* **2010**, *12*, 224–226.

(14) Liang, Y. F.; Wang, X.; Tang, C.; Shen, T.; Liu, J.; Jiao, N. *Chem. Commun*. **2016**, *52*, 1416-1419.

(15) (a) Santos, L. S. *Eur. J. Org. Chem*. **2008**, 235-253. (b) Chakraborti, A. K.; Raha Roy, S. *J. Am. Chem. Soc*. **2009**, *131*, 6902-6903.

(16) (a) Raha Roy, S.; Chakraborti, A. K. *Org. Lett*. **2010**, *12*, 3866-3869. (b) Seth, K.; Raha Roy, S.; Chakraborti, A. K. *Chem. Commun*. **2016**, *52*, 922-925.

(17) (a) Ishii, Y.; Iwahama, T.; Sakaguchi, S.; Nakayama, K; Nishiyama, Y. *J. Org. Chem.* **1996**, *61*, 4520–4526. (b) Yan, Y.; Feng, P.; Zheng, Q. -Z.; Liang, Y. -F.; Lu, J. -F.; Cui, Y.; Jiao, N. *Angew. Chem. Int. Ed.* **2013**, *52*, 5827–5831.

(18) Aldehydes are known to form acyl radical in the presence of other radical species [(a) Chatgilialoglu, C.; Crich, D.; Komatsu, M.; Ryu, I. *Chem. Rev*. **1999**, *99*, 1991-2070. (b) Vandenberk, S.; Peeters, J. *J. Photochem. Photobiol. A: Chem*. **2003**, *157*, 269-274].

(19) McNesby, J. R.; Heller, C. A. Jr. *Chem. Rev*. **1954**, *54*, 325-346.

(20) Seth, K.; Nautiyal, M.; Purohit, P.; Parikh, N.; Chakraborti A. K., *Chem. Commun.* **2015**, *51*, 191–194.

(21) (a) Powers, D. C.; Geibel, M. A. L.; Klein, J. E. M. N.; Ritter, T. *J. Am. Chem. Soc*. **2009**, *131*, 17050-17051. (b) Deprez, N. R.; Sanford, M. S. *J. Am. Chem. Soc*. **2009**, *131*, 11234-11241.

(22) Yin, Z.; Jiang X.; Sun, P. *J. Org. Chem.* **2013**, *78*, 10002-10007.

(23) Majhi, B.; Ahammed, S.; Kundu, D.; Ranu, B. *Asian J. Org. Chem.* **2015**, *4*, 154–163.

(24) Guirado, A.; Alarcón, E.; Vicente, Y.; Andreu, R. *Tetrahedron Lett.* **2013**, *54*, 5115–5117.

(25) Xiong, F.; Qian, C.; Lin, D.; Zeng, W.; Lu, X. *Org. Lett.* **2013**, *15*, 5444–5447.

(26) Santra, S. K.; Banerjee, A.; Patel, B. K. *Tetrahedron* **2014**, *70*, 2422–2430.

(27) Santra, S. K.; Banerjee, A.; Khatun, N.; Samanta, A.; Patel, B. K. *RSC Adv*. **2015**, *5*, 11960-11965.