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Visible-Light Palladium Catalysis for Alkylated and Difluoroalkylated Pyrazolones

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Anindya Das[a], Lennard Kloene,[b] Sneha Chandra,[a] Rene M. Koenigs*[b], and Sandip Murarka*[a]

We report a photoinduced palladium-catalyzed protocol for the synthesis of biologically relevant alkylated and difluoroalkylated pyrazolones via a radical cascade between *N'*-arylidene-*N*-acryloylphenylhydrazides and unactivated alkyl and difluoroalkyl halides. Mechanistic studies support a Pd-mediated radical generation and capture pathway, accommodating both electrophilic and nucleophilic carbon-centered radicals. The protocol exhibits broad substrate scope, good functional group tolerance, and applicability to complex drug and natural product-derived fragments, providing a practical platform for late-stage molecular diversification.

In the context of drug discovery, incorporating three-dimensional aliphatic frameworks into heterocyclic cores is highly desirable, as it often enhances molecular diversity and improves pharmacokinetic properties.[1] Given the pervasiveness of Csp^3-rich drug molecules in pharmaceutical research, the development of facile strategies for the efficient synthesis of alkylated molecular architectures is highly essential. Among them, radical cascades have attracted considerable attention as step-economic strategies for the construction of alkylated heterocycles. Although numerous alkylating surrogates have been reported in the literature,[2] most require preactivation or synthesis, generating substantial amounts of waste. Among alkyl sources, unactivated, commercially available alkyl halides are attractive precursors due to their abundance and structural versatility.[3] However, traditional transition-metal-catalyzed reactions with alkyl halides are often hindered by slow oxidative addition and competing β-hydride elimination pathways (Scheme 1A).[4] Recent advances in excited-state palladium catalysis have provided elegant solutions to these challenges. Visible-light-mediated palladium catalysis has emerged as a powerful and sustainable platform for enabling transformations that are challenging under conventional thermal conditions.[5] In such systems, the palladium catalyst serves a dual function, acting both as a photosensitizer that harvests photon energy and as a transition-metal catalyst that mediates bond-forming and bond-cleaving events, thereby eliminating the need for an exogenous photosensitizer. In such systems, oxidative addition proceeds via a single-electron transfer (SET) pathway, generating hybrid Pd–radical intermediates that enable various radical transformations under mild conditions.[6] Computational studies have further supported that these inner-sphere SET processes proceed with low activation barriers, highlighting their mechanistic efficiency (Scheme 1B).[7]

Meanwhile, 2-pyrazoline-5-one derivatives represent an important class of nitrogen-containing heterocycles with broad pharmacological significance, including analgesic, antipyretic, antitumor, antibacterial, and antidepressant activities. Beyond their biological importance, pyrazoline-5-ones serve as versatile building blocks for the synthesis of functionalized pyrazolones and pyrazoles (Scheme 1C).[8] Consequently, the development of efficient, modular synthetic routes for their structural diversification remains an active area of research. In 2024, our group reported a visible-light-driven radical cascade cyclization strategy that enabled the construction of functionalized pyrazolones via a novel *N'*-arylidene-*N*-acryloyltosylhydrazide scaffold.[9] Building on this concept, other groups have subsequently developed photo-induced radical annulation methods employing related frameworks.[10] Despite notable progress, most reported methods either depend on preactivated redox reagents bearing bulky leaving groups, which diminish atom economy and require additional preparation steps, or are restricted to electrophilic radical precursors, thereby limiting their overall practicality.

To address these limitations, we envisioned a cost-effective photoinduced Pd-catalyzed strategy employing readily available alkyl halides and *N'*-arylidene-*N*-acryloylphenylhydrazides for the direct synthesis of alkylated pyrazoline-5-ones. Furthermore, given the pharmacological relevance of *gem*-difluoroalkyl motifs as bioisosteres that can enhance lipophilicity, metabolic stability, and overall drug-like properties, we sought to extend this strategy to incorporate such groups.[11] As part of our program on photoinduced alkylative radical cascades[9a, 12] and palladium photocatalysis,[3, 6c, 13] herein, we report a visible-light-driven Pd-catalyzed (difluoro)alkylation/annulation involving *N'*-arylidene-*N*-acryloylphenylhydrazides, providing an efficient and versatile route to diversely functionalized pyrazolones.

[a] *Department of Chemistry, Indian Institute of Technology Jodhpur, Karwar-342037, Rajasthan, India.*
[b] *University of Bayreuth, D-52074 Bayreuth, Germany*
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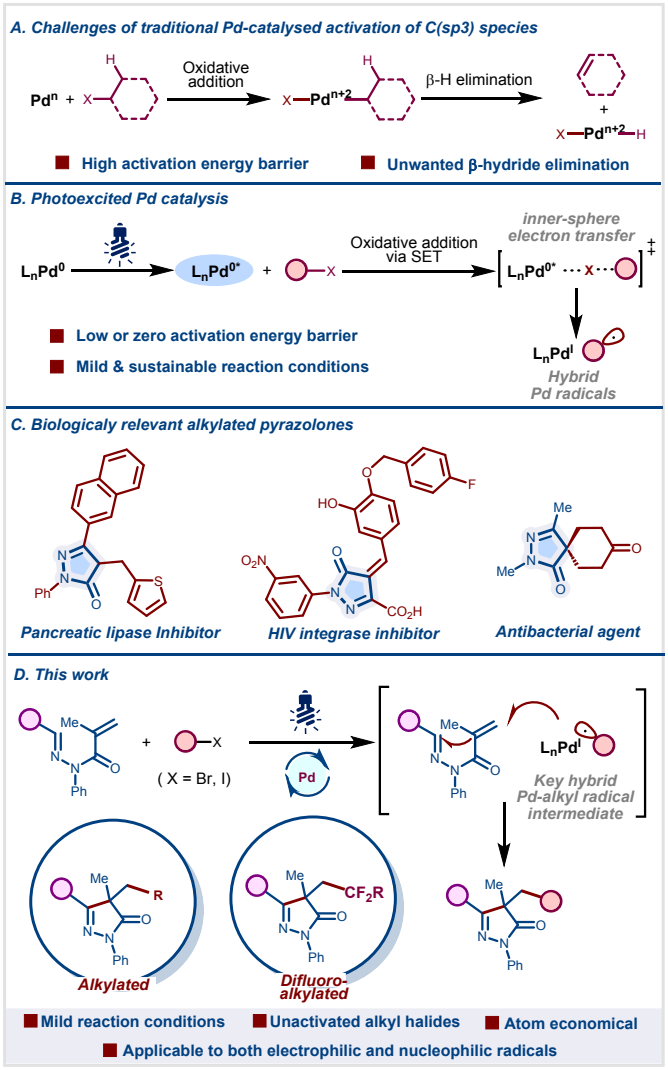
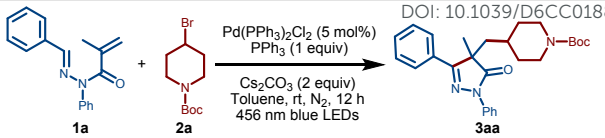


Scheme 1 (A) Challenges of Traditional Pd-Catalyzed activation of C(sp^3) species. (B) Photoexcited Pd Catalysis. (C) Biologically Relevant Alkylated Pyrazolones. (D) This Work: Pd Photocatalysis to Synthesize Functionalized Pyrazolones.

To realize the feasibility of the conceived approach, (*E*)-*N*′-benzylidene-*N*-phenylmethacrylohydrazide (**1a**) and 1-Boc-4-bromopiperidine (**2a**) were taken as model substrates and optimization studies were carried out (Table 1, see Table S1 in SI for complete optimization studies). We were pleased to observe that the reaction between **1a** (1.0 equiv.), **2a** (1.5 equiv.), in the presence of $Pd(PPh_3)_2Cl_2$ (5.0 mol%) as a catalyst, PPh_3 (1.0 equiv.) as a ligand and Cs_2CO_3 (2.0 equiv.) as a base in toluene (1 mL) provided **3aa** in 78% yield after irradiation with blue LEDs (456 nm) for 12 h (Table 1, entry 1). Screening of various Pd catalysts did not improve the yield (entry 2). Altering the ligand loading (6 mol%) or replacing PPh_3 with other ligands (6 mol%) such as Xantphos, and RuPhos proved ineffective (entry 3). Evaluation of other bases, both organic and inorganic (Et_3N, K_3PO_4, Na_2CO_3), resulted in diminished yields (entry 4). Changing the solvent either reduced the yield or completely suppressed product formation (entry 5). Replacing the alkyl bromide with its iodide congener did not improve reaction efficiency (entry 6). Control experiments confirmed that the catalyst, base, and visible light are all essential for the transformation (entry 7).

Table 1 Optimization of the reaction conditions[a]



entry	deviation from standard condition	yield (%)[b]
1	none	78
2	Pd-Cat: $Pd(PPh_3)_4$, $Pd(OAc)_2$, $Pd(Ptol_3)_2Cl_2$	67, 65, N.D.
3	Ligand (6 mol%): Xanthphos, RuPhos, PPh_3	36, N.D., 31
4	Base: K_3PO_4, Na_2CO_3, Et_3N	34, 21, N.D.
5	Solvent: ACN, DMF, Benzene	41, 28, 71
6	Alkyl iodide instead of alkyl bromide	58
7	No Pd-Cat, No Base, No Irradiation	N.D., N.D., N.D.

[a]Reaction conditions: **1a** (0.1 mmol, 1 equiv), **2a** (1.5 equiv), $Pd(PPh_3)_2Cl_2$ (5 mol%), PPh_3 (1.0 equiv) and Cs_2CO_3 (2 equiv) in toluene (1 mL), irradiated at 456 nm blue LEDs at room temperature under N_2 atmosphere for 12 h. [b]Isolated yields. N.D. = Not Detected.

With the optimized reaction conditions in hand, we next explored the substrate scope of the cascade manifold by reacting a series of *N*-acryloyl aldehyde hydrazones (**1**) with alkyl bromide **2a** (Scheme 2A). A diverse range of aryl aldehyde-derived *N*-methacryloyl hydrazones bearing electron-donating (Me, NMe_2, OMe, OAllyl, OBn) and electron-withdrawing (CF_3, Cl) substituents at the *para*-position of the aromatic ring participated smoothly in the reaction, affording the corresponding alkylated pyrazolones (**3ba-3ha**) in moderate to good yields (57-79%). Substituents at the *meta*- and sterically demanding *ortho*-positions were also well tolerated, furnishing products **3ia** and **3ja** in 72% and 56% yields, respectively. The methodology further accommodated hydrazones derived from structurally diverse aliphatic aldehydes, including pivaldehyde, cyclopentane- and cyclohexanecarbaldehyde, delivering the corresponding products (**3ka-3ma**) in 61-65% yields. Moreover, heteroaromatic substrates such as pyridine and thiophene were well tolerated, affording **3na** and **3oa** in 70% and 64% yields, respectively. Notably, polycyclic aromatic substrates, such as naphthyl derivatives, were also compatible, delivering the corresponding yielding **3pa** in 65% yield. Next, the generality of the protocol with respect to alkyl halides (**2**) was examined by reacting with **1a** under the optimized conditions (Scheme 2B). Primary alkyl bromides bearing long alkyl chains or functional groups, such as nitriles and alkenes, were compatible, affording desired products (**3ab-3af**) in appreciable yields (48-69%). Furthermore, both cyclic and acyclic secondary alkyl halides underwent smooth transformation, delivering respective products (**3ag-3al**) in good to excellent yields (58-81%). Notably, heterocyclic secondary alkyl bromides provided the best results, further underscoring the broad applicability and efficiency of the method. A range of tertiary such as *tert*-butyl, 1-adamantyl, and methyl 2-bromo-2-methylpropanoate, readily participated in the reaction to furnish the corresponding products (**3am-3ao**) in 45-80% yields, demonstrating that the reactive ester functionality was well tolerated. Furthermore, the reaction was successfully extended to densely functionalized *N*-methacryloyl aldehyde hydrazones derived from complex molecules, such as stearic acid, affording **3qa** in 63% yield. Likewise, alkyl halides functionalized with valproic acid, gemfibrozil, cholesterol, palmitic acid, naproxen and ibuprofen moieties underwent smooth transformation to furnish products **3ap-3au** in 64-71% yields (Scheme 2C).

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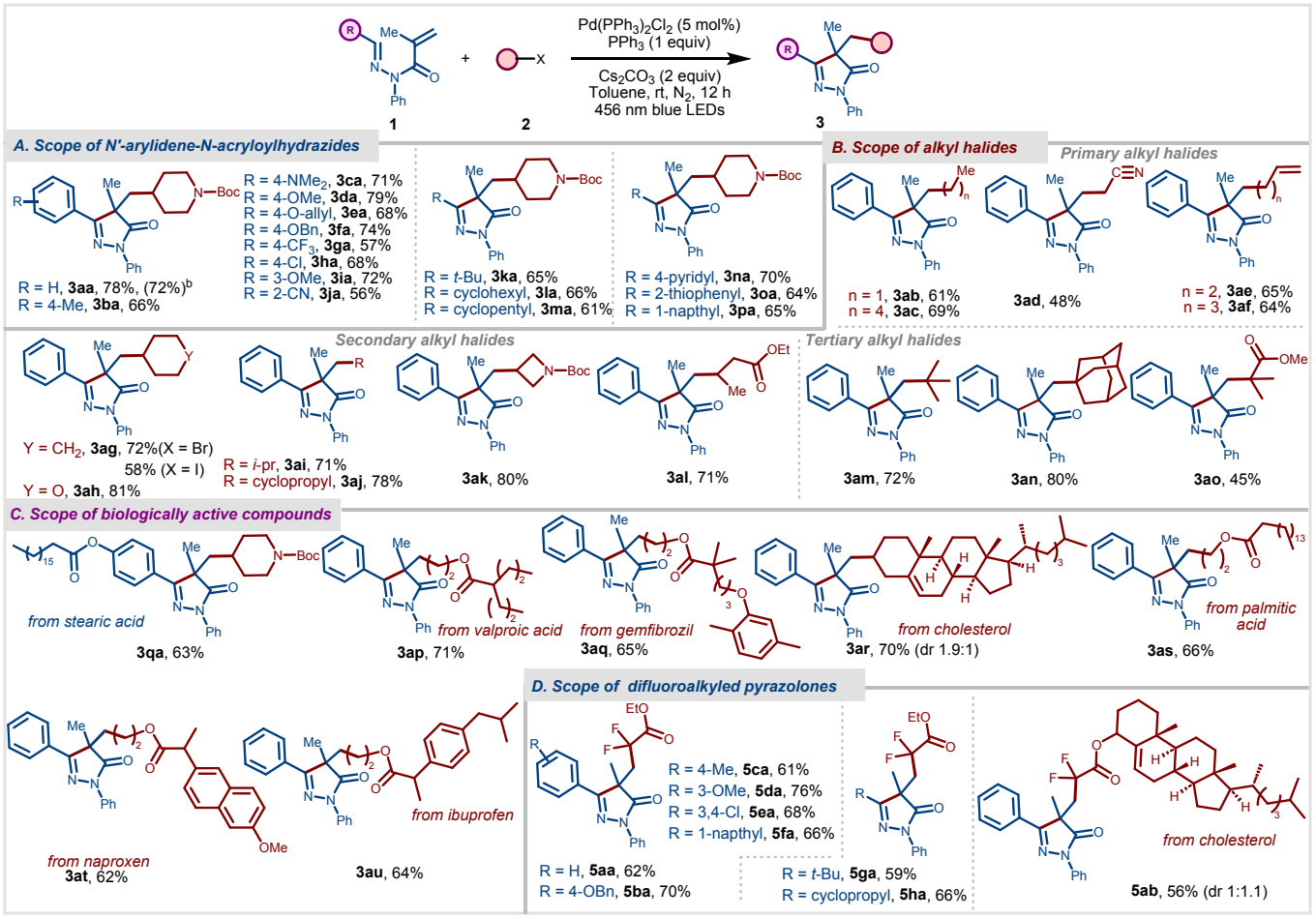


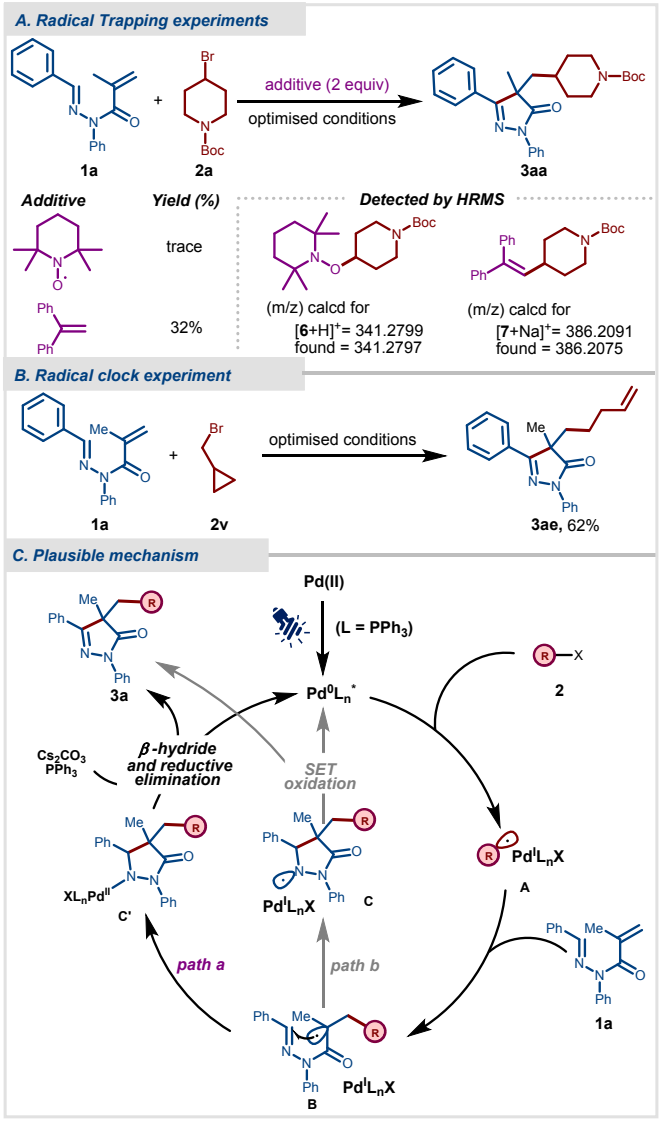
Scheme 2. Reaction conditions: [a]**1a** (0.25 mmol, 1 equiv), **2a** (1.5 equiv), $Pd(PPh_3)_2Cl_2$ (5 mol%), PPh_3 (1 equiv), and toluene (2.5 mL) under nitrogen atmosphere using blue LEDs (456 nm) for 12h. [b]Gram-scale synthesis using optimized conditions.

These results further highlight the robustness, scalability, and excellent functional group tolerance of the developed methodology. Encouraged by the success of the alkylation process, we sought to further expand the synthetic utility of the developed protocol. Considering the beneficial role of *gem*-difluoroalkyl groups in enhancing the physicochemical and pharmacokinetic profiles of bioactive molecules, we envisioned a divergent extension of this strategy toward the synthesis of *gem*-difluoroalkylated 2-pyrazoline-5-ones. Gratifyingly, the optimized reaction conditions could be directly applied to achieve this transformation, affording a diverse array of *gem*-difluoroalkylated pyrazolones with substitution either at the aldehyde or alkyl halide terminus of the scaffold (**5aa–5ha** and **5ab**) (scheme 2D). In these reactions, the corresponding difluoroalkyl bromides (**4**) served efficiently as radical precursors, delivering the desired products in good yields (56-76%). The practicality of the method was demonstrated on a 1 g scale, where **1a** reacted with **2a** to afford **3aa** in 72% yield (Scheme 2A). These findings highlight the broad adaptability, scalability and versatility of the method.

Radical-trapping experiments revealed that the reaction was completely or partially suppressed in the presence of TEMPO (trace) and 1,1-diphenylethylene (32% yield), and corresponding adducts (**6** and **7**) were detected by HRMS (Scheme 3A). Additionally, a radical-clock experiment using **2r** yielded the ring-opened product **3ae** in 62%, supporting a radical-mediated pathway (Scheme 3B). The light-dark experiment, combined with quantum yield (Φ = 0.212) measurements, indicated the necessity of continuous irradiation and ruled out the possibility of a radical chain mechanism (See SI, fig. S2).

Based on control experiments and documented literature,[6c-e] a plausible mechanism involving an alkyl radical palladium hybrid species is shown in (Scheme 3C).[6b, 6d] Initially Single electron reduction of alkyl-X (X = Br, I) by excited-state Pd(0) affords alkyl-Pd(I)-X radical hybrid species **A** under visible light irradiation. The addition of the nucleophilic alkyl radical to the activated double bond of the *N*-acryloyl hydrazone **1a** delivers the carbon-centred radical intermediate **B**, which subsequently undergoes regioselective intramolecular *5-endo-trig* cyclization,[14] leading to intermediate **C** or

C'. Intermediate **C** furnishes the product via β-hydride elimination followed by reductive elimination (*path a*), while intermediate **C'** undergoes single-electron oxidation followed by base-assisted deprotonation to furnish **3** (*path b*). In both pathways, the reduced Pd(0) species is regenerated, thereby completing the photoredox catalytic cycle. Notably, PPh_3 serves a dual role in the catalytic cycle, both as a ligand as well as a reductant to regenerate the active Pd species from Pd(II).[6k]



Scheme 3 (A) Radical trapping experiments. (B) Radical clock experiment. (C) Plausible mechanism.

In summary, we have disclosed a visible-light-mediated, excited-state palladium-catalyzed radical cascade enabling the synthesis of alkylated and difluoroalkylated 2-pyrazoline-5-ones from unactivated alkyl halides and *N*-acryloyl aldehyde hydrazones in good to excellent yields. The reaction accommodates a broad array of diverse hydrazones and primary, secondary, tertiary, and sterically hindered alkyl halides as reacting partners under mild conditions, demonstrating high tolerance to various functional groups. This method is robust, scalable, and compatible with densely functionalized substrates derived from natural products and pharmaceuticals. Detailed mechanistic studies support a hybrid alkyl-Pd radical pathway and confirm the proposed mechanism.

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Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the Supplementary Information.

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