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Decatungstate-Photocatalyzed Diastereoselective Dearomative Hydroalkylation of Indoles

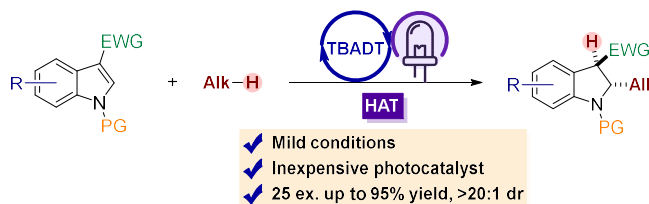
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Abstract: In this study, we present an efficient and straightforward dearomative hydroalkylation of indoles. By utilizing alkanes or ethers as alkyl radical sources and employing TBADT as a cost-effective photocatalyst for direct (HAT), we achieved successful conversion of these heterocyclic derivatives into 2-alkylindolines with good to excellent yields and high diastereoselectivity under mild reaction conditions.

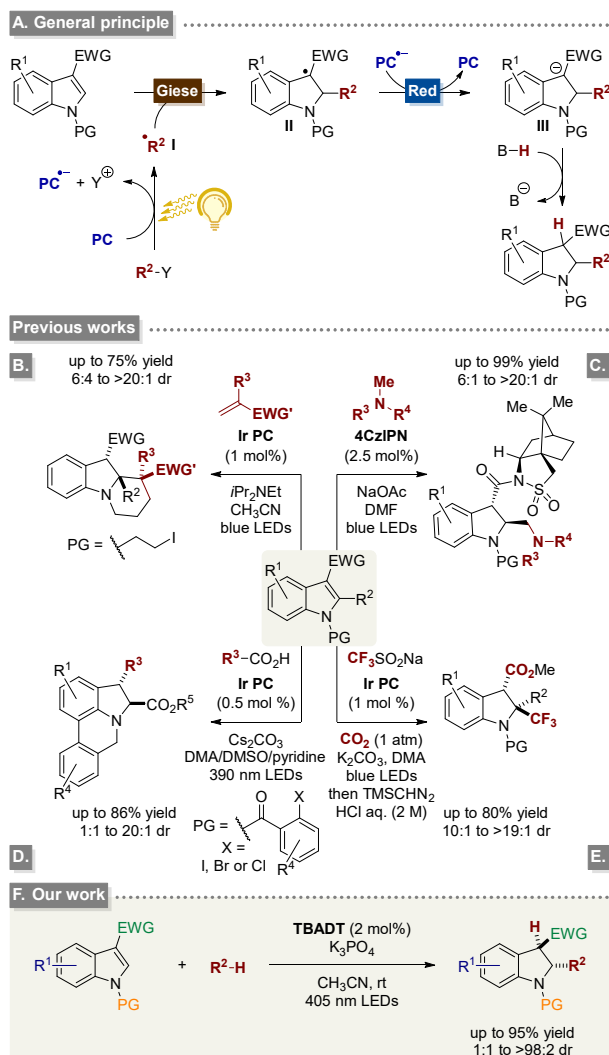


Introduction

Dearomatization of indoles^[1,2] is a valuable method for obtaining functionalized indolines which represent important and ubiquitous motifs in natural products, pharmaceuticals, and materials sciences.^[3,4] Notably, photocatalyzed Giese-type radical additions^[5,6] to electron-deficient indoles have emerged as an attractive route for synthesizing 2,3-disubstituted indolines under mild reaction conditions.^[7] In such strategies, photocatalytically-generated nucleophilic radical species **I** reacts with a substrate bearing an electron-withdrawing group at the C3 position (Scheme 1, A). Resulting intermediate **II** undergoes reduction to generate corresponding anion **III** which is finally protonated to yield a hydrofunctionalized product.

One of the seminal examples for this approach was disclosed by Brasholz *et al.* in 2015. They reported the synthesis of benzindolizidines via a photocatalyzed (4 + 2)-cyclization between *N*-(2-iodoethyl)-indoles and electron-poor olefins, involving a key dearomative 6-*exo-trig* step (Scheme 1, B).^[7a] Later, in 2021, Wang and co-workers achieved an intermolecular and asymmetric hydroalkylation^[8,9] of these azacycles, employing Oppolzer camphorsultam as a chiral auxiliary and tertiary amines as radical precursors, to produce diverse indolines in good yields with excellent diastereoselectivities (Scheme 1, C).^[7f] The same group successfully used aliphatic carboxylic acids as a convenient source of radicals in a subsequent publication.^[7g] Alternatively, when the indole bears an electron-depleting substituent at the C2 position, it is possible to perform a C3-alkylation. Hence, in 2022, Sharma *et al.* proposed an elegant cascade process involving such intermolecular dearomatization — with carboxylic acids as radical precursors — followed by an intramolecular cyclization resulting in the formation of 2,3-disubstituted pyrrolophenanthridone alkaloid derivatives (Scheme 1, D).^[7i] Furthermore, species **II** can recombine with a persistent radical^[7d] or add to a radical acceptor^[7c,j] allowing

for a double functionalization. In the same vein, anionic intermediate III can be trapped by an electrophile instead of being protonated.^[7e,k,l,n]



Scheme 1. Photocatalytic Giese-type dearomatization of indoles.

In this way, inspired by seminal works from the team of Yu,^[7e] Xi and coworkers devised a novel intermolecular dearomative trifluoromethylcarboxylation of indoles with CO₂ and Langlois reagent to synthesize a diverse array of fluoro-indoline-3-carboxylic acids (Scheme 1, E).^[7f] This strategy was further advanced by the group of Sun which used amines and α -amino acids as radical sources.^[7n] However, most of these transformations necessitate activated radical precursors such as carboxylic acids,^[7g,i] aryloxyamides^[7c,d] halides,^[7a,b,e,h,j,m] or silicates.^[7k] This is detrimental to atom-economy while requiring substrates pre-functionalization.

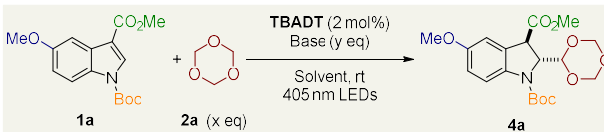
Therefore, developing new dearomatization approaches based on the direct generation of alkyl radicals from readily available alkanes or ethers remains desirable. Photocatalytic hydrogen atom transfers (HAT) are promising avenues to achieve this objective.^[10] In that respect, our group recently reported the catalytic hydroacylation of indoles leading to diverse *trans*-2-acylindolines with great yields and diastereoselectivities.^[11] We focused on tetrabutylammonium decatungstate (TBADT, **3**)^[12,13] — an easily available photoexcitable polyoxometalate (POM) based on Earth's crust abundant tungsten — to effectively promote the formation of acyl radicals from aldehydes through hydrogen abstractions.^[11] Building on this previous work and our long term interest in photocatalysis,^[14] our goal was to establish a novel C2-alkylation of indoles (Scheme 1, F).^[15,16]

Results and Discussion

Initially, we tested the addition of 1,3,5-trioxane (**2a**) onto substrate **1a** with TBADT (**3**) photocatalyst in CH₃CN under visible light (405 nm), drawing from our prior investigations. Pleasingly, these conditions led to the desired compound **4a** with a 70% NMR yield, albeit as a *cis/trans* mixture of diastereomers in 2.2:1 ratio (Table 1, entry 1). Interestingly, exclusive formation of *trans*-**4a** was observed when 3 equiv. of sodium carbonate (Na₂CO₃) were introduced into the reaction without any negative impact on the conversion rate (entry 2). This result suggests that the base facilitates the isomerization towards the thermodynamically favored product. However, at lower concentrations in CH₃CN (entry 3) or when using acetone as the solvent (entry 4), the NMR yield decreased. Other additives, including pyridine (entry 5) and tribasic potassium phosphate (entries 6-8), were explored with different ratios of both the base and **2a**. The optimal conditions were identified as using 5 equiv. of 1,3,5-trioxane and 3 equiv. of K₃PO₄ (entry 8) to afford 2-(1,3,5-trioxanyl)indoline **4a** with a 68% isolated yield and excellent diastereoselectivity (>20:1 dr).

The scope of this novel synthesis of 2-alkylindolines was then examined by varying the structure of the indole partner (Scheme 2). The transformation demonstrated full compatibility with substrates substituted with electron-withdrawing groups at the C5 position. Halogenated derivatives were effectively engaged, leading to alkylated products **4b** and **4c** with excellent yields and diastereoselectivity. Smooth reactions of 5-cyano-indole delivered the desired *trans*-product **4d** in a 61% isolated yield. Bromine at the C4, C5, C6, and C7 positions of the substrate resulted in the formation of corresponding products **4e-h** as single diastereomers. In particular, **4e** and **4f** were formed in high yield when the reaction was carried out in acetone due to better solubility of the starting indole. Electron-rich 5-methyl-indole was likely converted affording **4i** in moderate yield. Moreover, nitrile and sulfone were well-tolerated at the C3 position, providing **4j** and **4k** in 61% and 62% yields respectively. Additionally, the indole with a robust electron-withdrawing group (R= NO₂) was unreactive under the reaction conditions. Interestingly, when reacting a substrate functionalized by a C3-prenyl ester, we did not observe the generation of a C3-prenylated indoline — resulting from dearomative alkylation followed by Ireland–Claisen rearrangement — in contrast to an elegant transformation reported by Feng, Liu, and co-workers.^[17]

Table 1. Survey of reaction conditions for the photocatalyzed dearomative hydroalkylation of indoles.^[a]



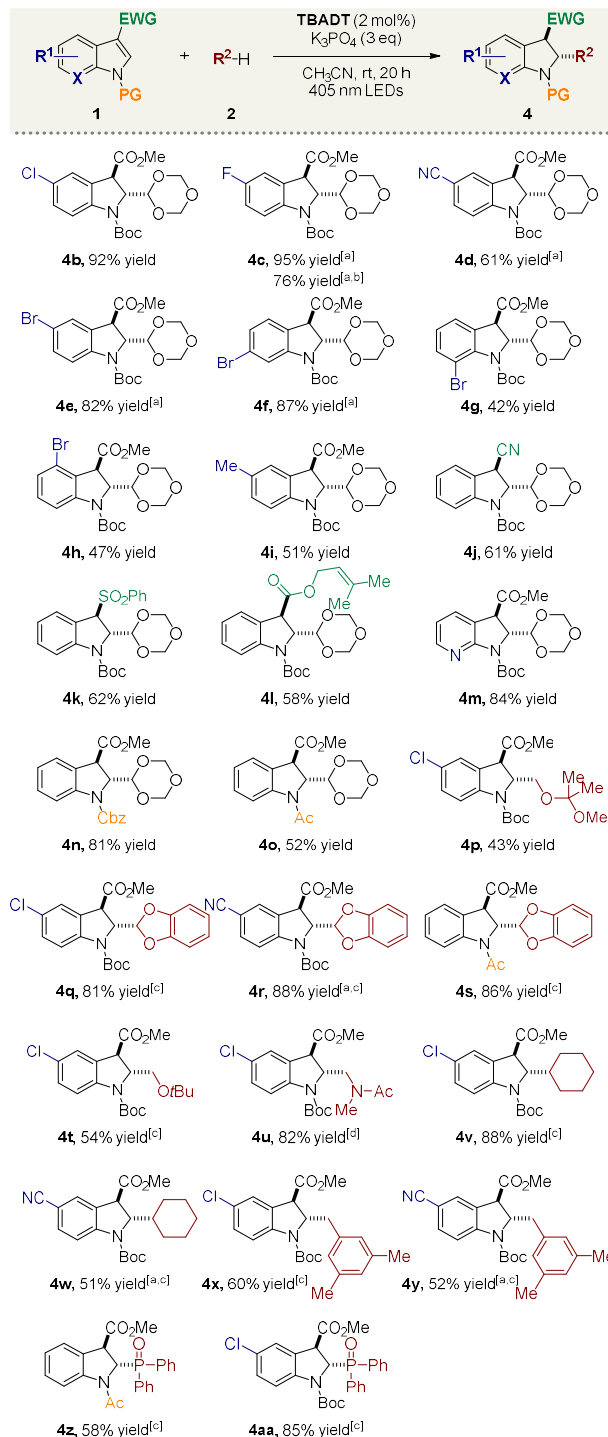
Entry	2a (x eq)	Base (y eq)	Solvent	4a Yield [%] ^[b] (Yield [%] ^[c])
1	3		CH ₃ CN	70 ^[d]
2	3	Na ₂ CO ₃ (3 eq)	CH ₃ CN	69 ^[e]
3 ^[f]	3	Na ₂ CO ₃ (3 eq)	CH ₃ CN	25 ^[e]
4	3	Na ₂ CO ₃ (3 eq)	acetone	45 ^[e]
5	3	Pyridine (2 eq)	CH ₃ CN	50 ^[e]
6	3	K ₃ PO ₄ (2 eq)	CH ₃ CN	60 ^[e]
7	3	K ₃ PO ₄ (3 eq)	CH ₃ CN	68 ^[e]
8	5	K ₃ PO ₄ (3 eq)	CH ₃ CN	76 ^[e] (68) ^[e]
9 ^[j]	5	K ₃ PO ₄ (3 eq)	CH ₃ CN	0
10 ^[k]	5	K ₃ PO ₄ (3 eq)	CH ₃ CN	0

[a] Reaction conditions: **1a** (0.1 mmol), **2** (x × 0.1 mmol), TBADT (**3**) (0.02 mmol, 2 mol%) and bases (y × 0.1 mmol) in 1.0 mL of CH₃CN under argon and 405 nm irradiation, for 20 h. [b] ¹H NMR yield to isomer **4** determined using C₂H₂Cl₄ as an external standard. [c] Yields refer to chromatographically pure *trans*-isomer **4**. [d] Mixture of diastereomers: 2.2:1 *cis/trans* determined by crude ¹H NMR analysis. [e] *Trans*-isomer **4a** with a >98:2 dr determined by ¹H NMR analysis. *Trans*-relative configuration was assigned by X-ray single crystal structure analysis of **4c** (see Supporting Information). [f] With 2.0 mL of solvent. [j] Without light irradiation. [k] Without TDADT (**3**).

Instead, compound **4l** was exclusively formed. Besides, 7-azaindole was compatible, furnishing **4m** with high yield and complete diastereoselectivity. Ultimately, satisfactory outcomes were achieved when varying the protecting group on the nitrogen including benzyloxycarbonyl or acetate which provided **4n**, **4o**, **4s**, and **4z** in moderate to good yields.

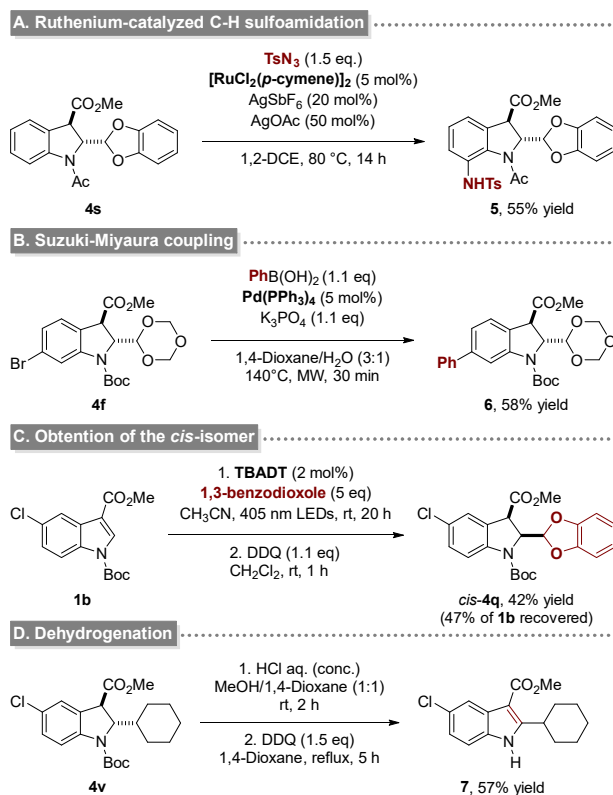
Continuing our investigations, we tried other radical precursors in the hydroalkylation. The reaction involving dimethoxymethane yielded a complex mixture of products, indicative of non-selective HAT. Pleasingly, utilization of 2,2-dimethoxypropane resulted in the exclusive formation of product, **4p**, suggesting site-selective from the OMe moiety,

affording **4p** with moderate yield. However, when testing 1,3-benzodioxole, only trace amounts of product **4q** were detected. We reoptimized the conditions and noted that conducting the reaction without base allowed for the formation of the desired indoline in high conversion, albeit as a diastereomeric mixture (2.3:1 dr) with *cis*-isomer as the major product. Further studies revealed that the addition of K_3PO_4 (3 equiv.) at the end of the process led to the exclusive formation of *trans*-**4q** in 81% yield.^[18] The generality of this adapted procedure was exemplified with other indoles enabling the efficient and selective formation of *trans*-products **4r** and **4s**. The reaction with methyl *tert*-butyl ether delivered indoline **4t** in moderate yield.



Scheme 2. Scope of the synthesis of 2-alkylindolines **4**. Reaction conditions: **1** (0.1 mmol), **2** (0.5 mmol), TBADT (**3**) (2 mol%), and K_3PO_4 (0.3 mmol) in 1.0 mL of CH_3CN under argon and 405 nm irradiation for 20 h. Yields refer to chromatographically pure products obtained as single diastereomers unless stated otherwise. [a] In acetone. [b] On 1.0 mmol scale. [c] Reaction performed without K_3PO_4 for 16 h and followed by the addition of K_3PO_4 (0.3 mmol) for 2 h without irradiation. [d] Mixture of diastereomers: 4:1 dr determined by crude 1H NMR analysis.

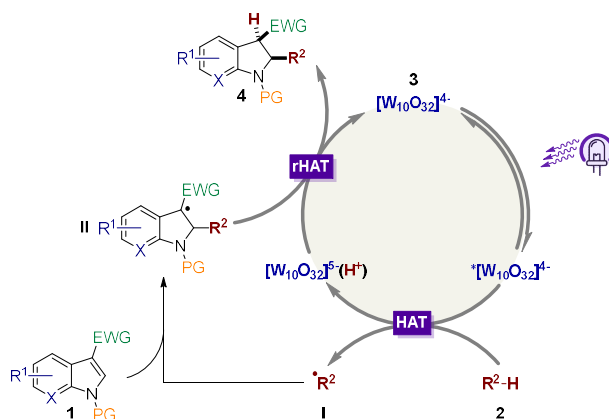
Similarly, DMA could be used to synthesize **4u** in satisfactory yield.^[19] Pleasingly, excited TBADT is reactive enough to abstract hydrogen atoms directly on cyclohexane or mesitylene despite the absence of a stabilizing oxygen at the α position of the resulting alkyl radicals. Hence, they served as competent alkylation partners, producing the desired products **4v-y** in decent yields. Finally, diphenylphosphine oxide also acted as a successful radical precursor, furnishing the corresponding indolines **4z** and **4aa** in excellent yields



Scheme 3. Synthetic transformations of indolines **4**.

To demonstrate the applicability of our methodology, the transformation was conducted on 1.0 mmol scale under standard conditions. Indoline **4c** was obtained with only a slight erosion of the yield (Scheme 2). Furthermore, we illustrated the synthetic potential of the obtained derivatives through post-functionalizations. For example, ruthenium-catalyzed direct C–H sulfonamidation at the C7 position of product **4s** was performed with a 55% yield (Scheme 3, A).^[20] In addition, a Suzuki cross-coupling between bromide **4f** and phenyl boronic acid, under microwave conditions, furnished **6** in 58% yield (Scheme 3, B).^[11] With the aim of oxidizing the indoline product to access to a 2-alkylindole, we replaced the addition of K_3PO_4 by a one-pot treatment with DDQ, in the hydroalkylative dearomatization of **1b** with 1,3-benzodioxole. Surprisingly, it selectively led to *cis*-**4q** in 42% yield (Scheme 3, C). Interestingly, pure *trans*-**4q** was found to stable to DDQ, even after prolonged reaction times, resulting in the exclusive recovery of *trans*-**4q**. However, indole **1b** formation was rapidly observed when *trans*-**4q** and DDQ were reacted in presence of benzodioxole thereby reflecting the “one pot” condition. This result suggested that an elimination of the C2-ether substituent occurred in the *trans*-product, though the intervention a possible quinoid radical^[21] providing the kinetic isomer. Nevertheless, we managed to perform such dehydrogenation on deprotected indoline **4v**, affording compound **7** in convenient yield (Scheme 3, D).

Control experiments were conducted to gain mechanistic insights. The reaction did not take place without irradiation or TBADT (Table 1, entries 9 and 10). Moreover, the use of 2,2,6,6-tetramethylpiperidin-1-yl)oxy (TEMPO), as a radical scavenger, impeded the formation of **4a**. HRMS analyses revealed the presence of a TEMPO adduct resulting from the trapping of the trioxanyl radical (see the Supporting information). This provides support for a radical process in the dearomative alkylation reaction. Based on these results, along with our previous work^[11] and other reports,^[10,12] we propose a plausible mechanism depicted in Scheme 4. Initially, visible light excites decatungstate anion ($[W_{10}O_{32}]^{4-}$), producing a triplet state ($^*[W_{10}O_{32}]^{4-}$). This activation initiates a HAT from alkane **2**, resulting in the formation of $[W_{10}O_{32}]^{5-}(H^+)$ and alkyl radical **I**. Its subsequent regioselective Giese addition to the electron-deficient indole **1** generates intermediate **II**. Eventually, a sequence comprising a mono-electronic reduction of the latter species and a proton transfer^[22] or a retro-HAT step closes the catalytic cycle regenerating TBADT and delivering indoline **4**.



Scheme 4. Mechanistic hypothesis.

Conclusion

In summary, we have established a mild and photocatalyzed dearomative hydroalkylation of indoles leading to 2-alkylindolines in convenient to excellent yields. This method relied on a direct hydrogen atom transfer process mediated by TBADT. This cost-effective polyoxometalate enabled the use of readily accessible alkanes and ethers as radical sources. Our reaction demonstrated a high diastereoselectivity, a wide functional tolerance, and an exciting versatility as it could be extended to hydrophosphorylations. Moreover, the obtained products could undergo further transformations, highlighting their potential for valuable synthetic applications in the future.

Experimental Section

General procedure for the photocatalytic dearomative hydroalkylation of indoles: Indole derivative **1** (1.0 equiv., 0.1 mmol), radical precursor **2** (5.0 equiv., 0.5 mmol), dry potassium phosphate tribasic (3.0 equiv., 0.3 mmol) and TBADT (**3**), (2.0 mol%, 0.002 mmol) were charged in a flame-dried tube. The vessel was purged under vacuum and backfilled with argon before adding CH₃CN or acetone (1.0 mL, 0.1 M). The reaction mixture was irradiated at 405 nm under a vigorous stirring at room temperature for 20 h. It quickly took a strong dark blue color indicating the formation of excited TBADT species. The reaction was quenched by adding brine, diluted with CH₂Cl₂ and extracted. Combined organic layers were dried with Na₂SO₄, filtered, and concentrated under reduced pressure. The crude residue was purified by flash column chromatography using a gradient of petroleum ether and AcOEt to afford pure indoline **4**.

Compound **4a**: White solid. (26.9 mg, 68%), **¹H NMR** (500 MHz, CD₃CN at 25 °C) δ 7.50 (*br. s*, 1H), 6.95 (d, *J* = 2.1 Hz, 1H), 6.78 (dd, *J* = 8.8, 2.5 Hz, 1H), 5.44 (s, 1H), 5.16 (s, 2H), 5.08 (d, *J* = 6.2 Hz, 1H), 5.01 (d, *J* = 6.3 Hz, 1H), 4.79 (s, 1H), 4.38 (s, 1H), 3.75 (s, 3H), 3.72 (s, 3H), 1.55 (s, 9H). **¹³C NMR** (126 MHz, CD₃CN at 25 °C) δ 172.4, 156.7, 152.8, 137.2, 130.3, 116.4, 114.5, 112.1, 99.9, 93.9, 93.7, 82.3, 64.3, 56.2, 53.4, 46.8, 28.5 (3C). **IR** (neat) ν (cm⁻¹): 2976, 2870, 1738, 1693, 1615, 1600, 1491, 1455, 1436, 1393, 1369, 1342, 1321, 1269, 1254, 1231, 1165, 1149, 1133, 1064, 1044, 1025, 988, 951, 858, 813, 762, 739. **HRMS** (ESI+, *m/z*): calculated for C₂₁H₂₈N₂O₈Na [M+CH₃CN+Na]⁺: 459.1743, found 459.1735.

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Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: Visible-Light • Photocatalysis • Dearomatization • Hydroalkylation • Decatungstate

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