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Functionalization of Quinones by Green Methods

Sarban Kumar Yadav[a], Bhawana Nagar[b], and Basab Bijayi Dhar*[a]

Abstract: Quinone motifs play a crucial role in a wide range of living organisms, including bacteria, fungi, higher plants, and some animals. They are also present in numerous natural pigments. This review summarizes recent advances in the direct functionalization of quinones using green methods. Green synthesis of quinones employs environmentally sustainable strategies such as solvent-free microwave-assisted techniques, photoredox catalysis, and electrochemical oxidation, *etc.* These approaches aim to minimize hazardous waste generation and energy consumption, offering a cleaner alternative to conventional synthetic methods.

Keywords: Photoredox catalysis · Quinones

1. Introduction

Quinones are widespread biological pigments found in a variety of organisms, including bacteria, fungi, higher plants, and some animals. Melanin, a quinone-based pigment,[1] for instance, gives color to human skin, hair, and eyes. Quinones also play a role in the coloring of flowers and fruits.[2] The basic structure of quinone contains two ketone groups on either side of a 6-membered aromatic ring. Quinones are typically yellow, orange, or red in color.[3] They are very reactive and can undergo a variety of chemical reactions, including oxidation, reduction, and polymerization.[4,5] Quinones are important electron carriers that take part in redox processes in biological systems.[6] They are capable of reversible oxidation-reduction reactions, which allow for the transfer of energy and electrons between various molecules.[5–8] Ubiquinone plays a crucial role in ATP (adenosine triphosphate) generation by acting as an electron carrier in the electron transport chain of cellular respiration.[7] Ubiquinol, the reduced form of ubiquinone acts as an antioxidant. Its antioxidant activity is independent of the effect of vitamin E.[8] As a cofactor, vitamin K is needed to synthesize Protein C, an anticoagulant that prevents excessive coagulation.[8]

Quinones can bind or interact with a variety of biological receptors and are a useful template for the design of new compounds of potential pharmacological activity. That is why they are considered a privileged structure in drug discovery. Mostly quinones are used as antitumor[9a], antibacterial[9b], antifungal[9c], antiviral[9d], anti-Alzheimer's disease (AD)[9e] and antimalarial drugs[9f] (Fig. 1).

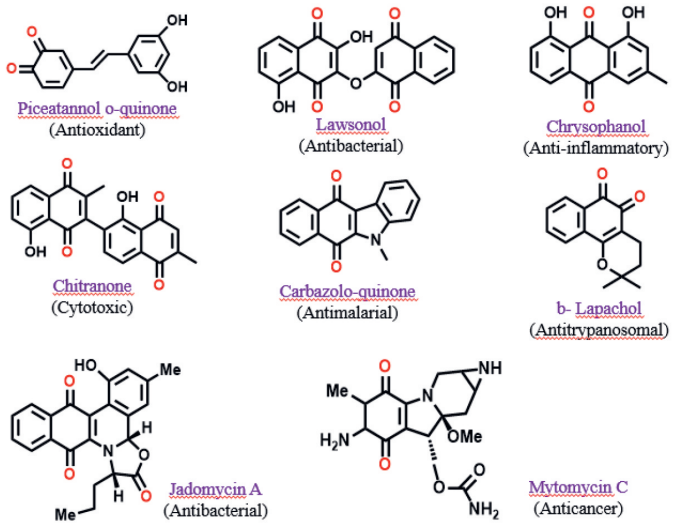


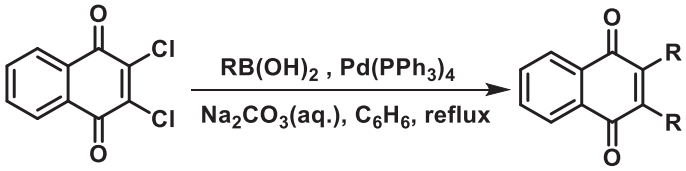
Fig. 1. Some quinone-based drug molecules.

2. Existing Synthetic Strategy for Substituted Quinone

2.1 *Arylation and Alkylation*

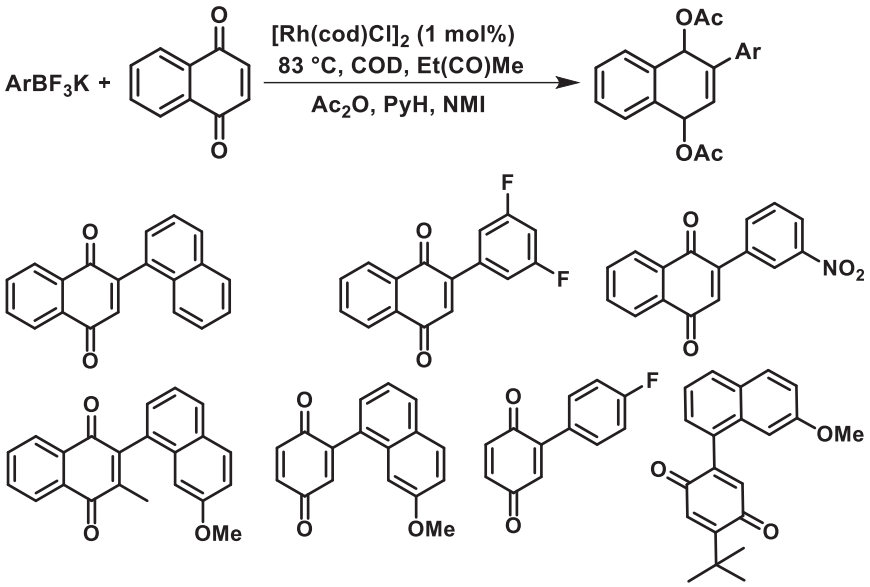
Conventional methods for forming C–C bonds on α,β-unsaturated carbonyl compounds often fail when applied to quinones due to their distinctive electronic properties. These approaches typically require a reoxidation step to restore the quinone's original oxidation state. To address these challenges, Winslande and coworkers (Scheme 1) developed a strategy involving the pre-halogenation of the quinone, followed by a palladium-catalyzed cross-coupling reaction.[10a]

Halogenated quinones are often difficult to synthesize due to challenges with chemo- and regioselectivity during halogenation. Furthermore, quinones can act as both ligands and oxidants towards palladium, complicating their use in cross-coupling reactions.[10b] An alternative approach - protecting halo-dihydroquinones followed by deprotection - is typically long and inefficient. As a result, there is a strong demand for cost-effective, efficient, and sustainable methods for quinone functionalization. In response



Scheme 1. Palladium-catalyzed cross-coupling of arylboronic acids with 2,3-dichloronaphthoquinone.

*Correspondence: Dr. B. B. Dhar, E-mail: basabbijayi@gmail.com
[a]Department of Chemistry, School of Natural Sciences, Shiv Nadar Institution of Eminence Deemed to be University, Delhi NCR, Gautam Buddha Nagar, Dadri, UP-201314, India; [b]Department of Applied Science, Jagannath Institute of Education, 48/4, Knowledge Park III, Greater Noida, UP-201303, India.



Scheme 2. Direct Rh-catalyzed coupling of quinones with arylboronic acid derivatives.

to this need, Demchuk and colleagues (Scheme 2) demonstrated that naphthoquinones can be functionalized with electron-rich aryltrifluoroborates using a rhodium catalyst at high tempera ture.[10c] Renaud and coworkers demonstrated two distinct pathways for the coupling of catecholboranes with quinones. In Pathway A, the coupling is followed by a reoxidation step to restore the quinone core. In Pathway B, an alternative sequence is employed, highlighting the versatility of this approach for quinone functionalization (Scheme 3).[10d]

In 2011, Baran and coworkers reported a C–H functionalization strategy for quinones using boronic acids in the presence of $AgNO_3$ as a catalyst at room temperature (rt). Their study included both mechanistic investigations and a broad substrate scope, demonstrating the versatility and efficiency of this approach for direct quinone functionalization (Scheme 4).[10e]

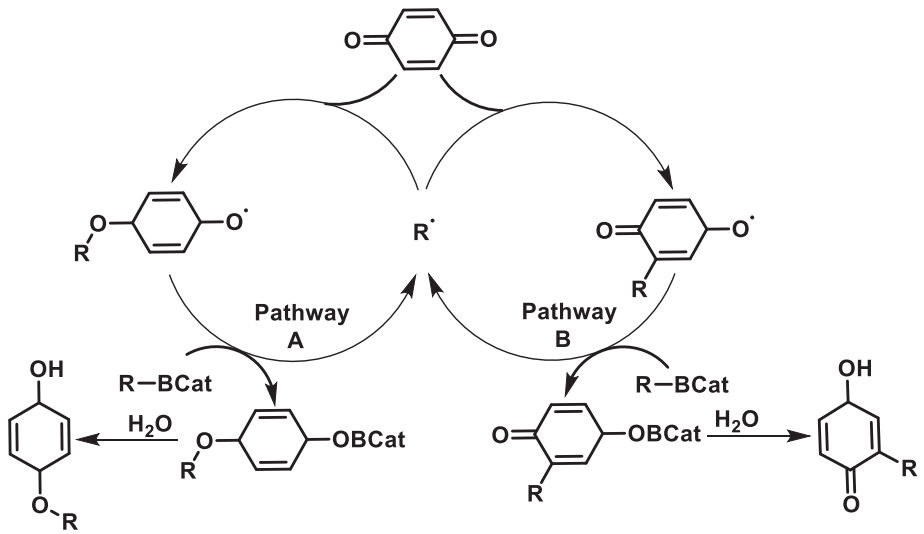
In 2013, Ilangovan and coworkers reported that β-keto radicals, generated *via* oxidative ring opening of cyclopropanols, could undergo addition to quinones, leading to the formation of γ-carbonyl-substituted quinones at rt. This strategy provided an efficient method for C–C bond formation at the quinone core through radical-mediated transformations (Scheme 5).[10f]

In 2016, Lee and coworkers developed a copper-catalyzed cross-dehydrogenative coupling (CDC) reaction employing cycloalkenes as alkylating agents. The transformation proceeded in the presence of *tert*-butyl hydroperoxide (TBHP) as the terminal oxidant, enabling direct C–C bond formation *via* C–H activation under oxidative conditions (Scheme 6).[10g]

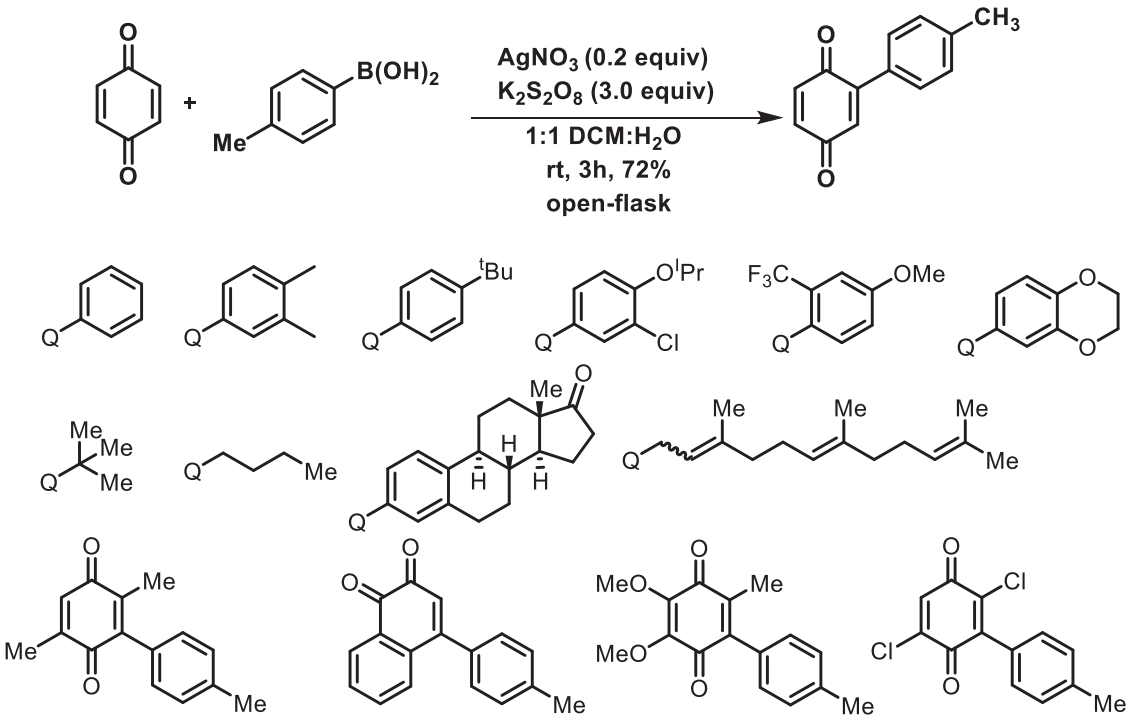
Maiti and coworkers developed a direct C–H arylation of quinones using arylboronic acids, catalyzed by the inexpensive and readily available iron salt $Fe(NO_3)_3$. This method offers a cost-effective and efficient approach for the functionalization of quinones under mild conditions (Scheme 7a).[10h] Gutiérrez-Bonet *et al.* demonstrated that under oxidative conditions, 1,4-dihydropyridines (DHPs) undergo homolytic cleavage to generate exclusively Csp^3-centered radicals. These radicals can then participate in the C–H alkylation of 1,4-quinones, providing a selective pathway for quinone functionalization (Scheme 7b).[10i]

2.2 *Thiolation*

In recent years, the synthesis of thioethers has attracted significant attention due to their wide range of applications. In 2015, Chou and colleagues developed a silver-catalyzed coupling meth-



Scheme 3. Mechanism for the addition of β-alkylcatecholborane to 1,4-benzoquinone.



Scheme 4. Coupling of alkyl- and arylboronic acids to 1,4-benzoquinone.

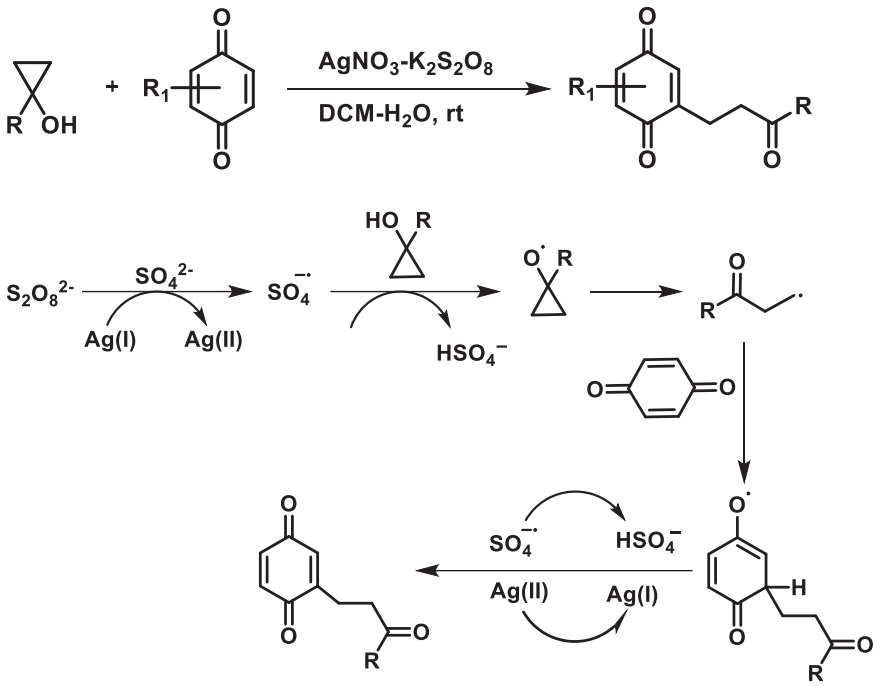
od that enables the formation of quinonyl aryl thioethers through the reaction of quinones with aryl disulfides. This transformation employs AgOAc as the catalyst, 1,3-bis(diphenylphosphino) propane (dppp) as the ligand, $(NH_4)_2S_2O_8$ as the oxidant, and Bu_4NBF_4 as an additive (Scheme 8).[11a]

Wang and coworkers described a copper-catalyzed sulfenylation of quinones with arylsulfonyl chlorides. In this method, arylsulfonyl chlorides were reduced to arylsulfenyl chlorides by triphenylphosphine, and then *in situ* generated arylsulfenyl chloride reacted with quinone in the presence of a base through the Baylis-Hillman process (Scheme 9).[11b]

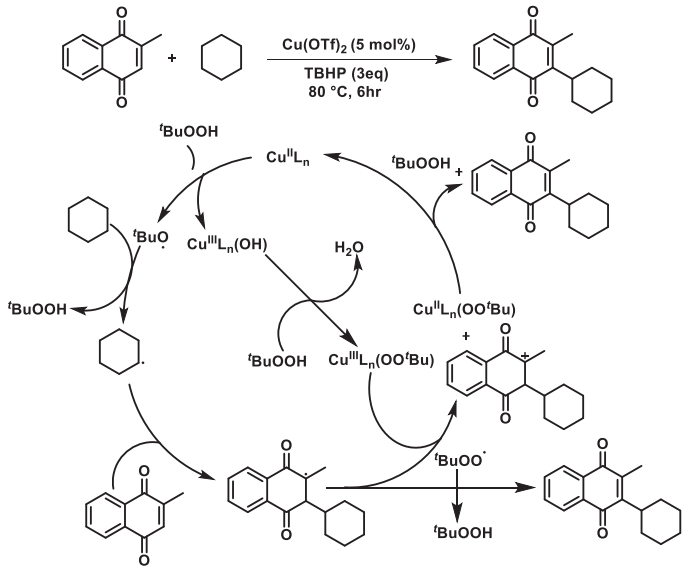
2.3 *Amination*

The reaction between primary or secondary amines and 1,4-naphthoquinone has been extensively investigated for nearly 150 years. Amination of quinones typically proceeds *via* two main pathways. One commonly observed route involves the nucleophilic 1,4-addition of the amine to the quinone, resulting in the formation of an amino-quinol intermediate. This intermediate is subsequently oxidized to yield the corresponding amino-quinone (Scheme 10).[12a]

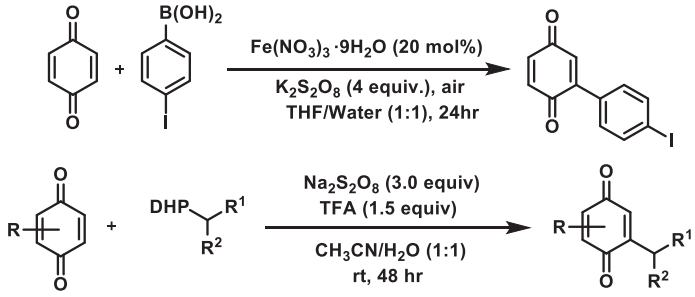
Alternatively, *via* nucleophilic substitution reactions of 2-halonaphthoquinones[12b] or 2-methoxynaphthoquinone derivatives[12c] amino-quinone can be synthesized (Scheme 11). In



Scheme 5. Synthesis of γ-carbonyl quinones by the addition of cyclopropanols and quinones.

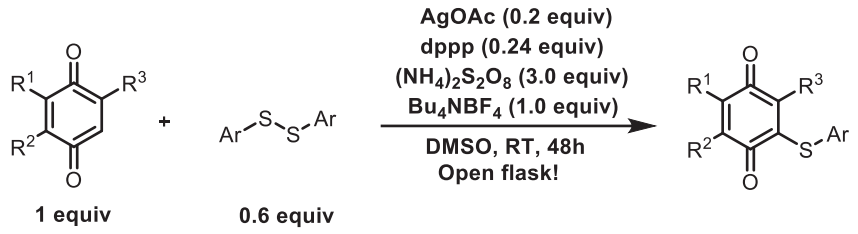


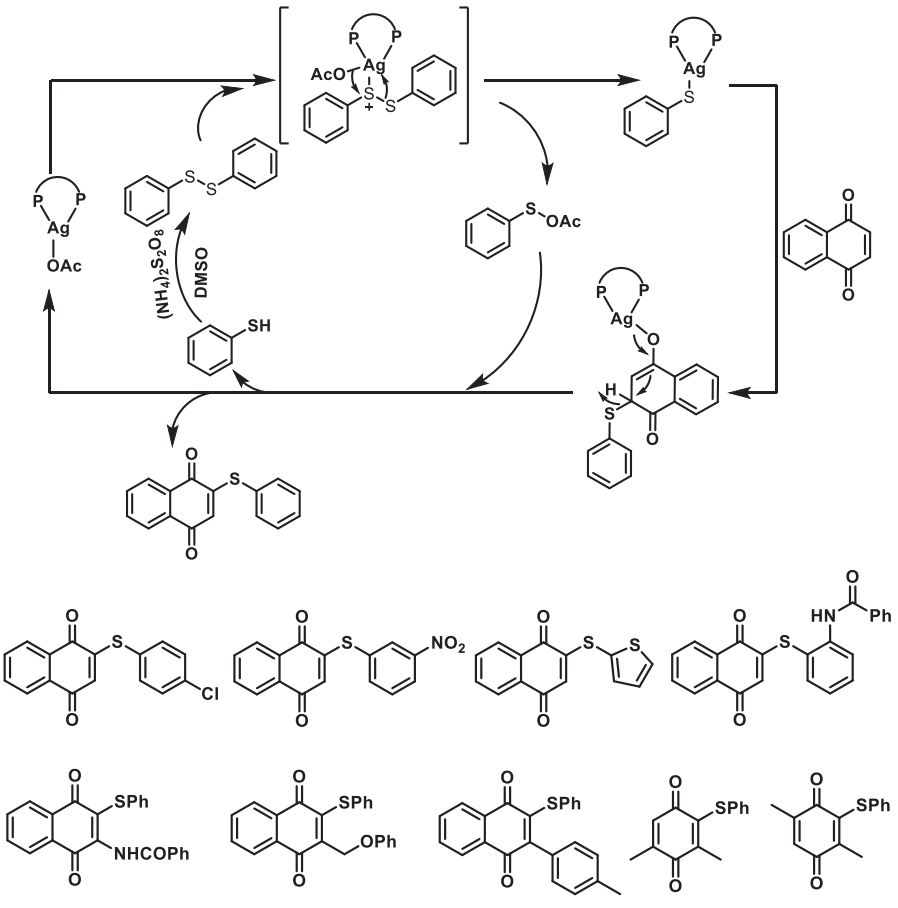
Scheme 6. Copper-catalyzed direct cross coupling reaction of quinones with cycloalkanes in the presence of TBHP.



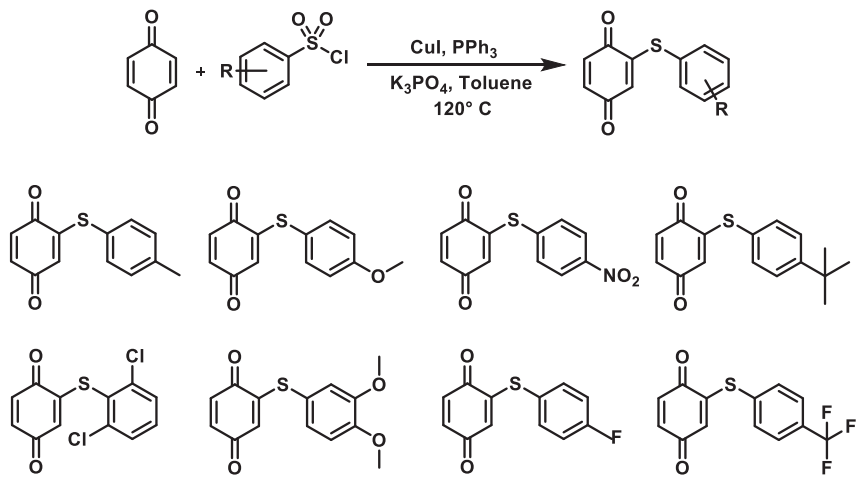
Scheme 7. (a) Iron-catalyzed direct C–H arylation of heterocycles and quinones with arylboronic acids. (b) C–H alkylation of heterocycles and 1,4-quinones *via* oxidative homolysis of 1,4-dihydropyridines.

2011, Garden and coworkers reported a copper(II)-catalyzed oxidative coupling method for the amination of 1,4-naphthoquinone using anilines as the amine source. In this study, hydrated copper(II) acetate was found to significantly shorten reaction times and minimize the formation of side products, affording a diverse range of 2-amino-1,4-naphthoquinones in excellent yields (Scheme 12).[12d]

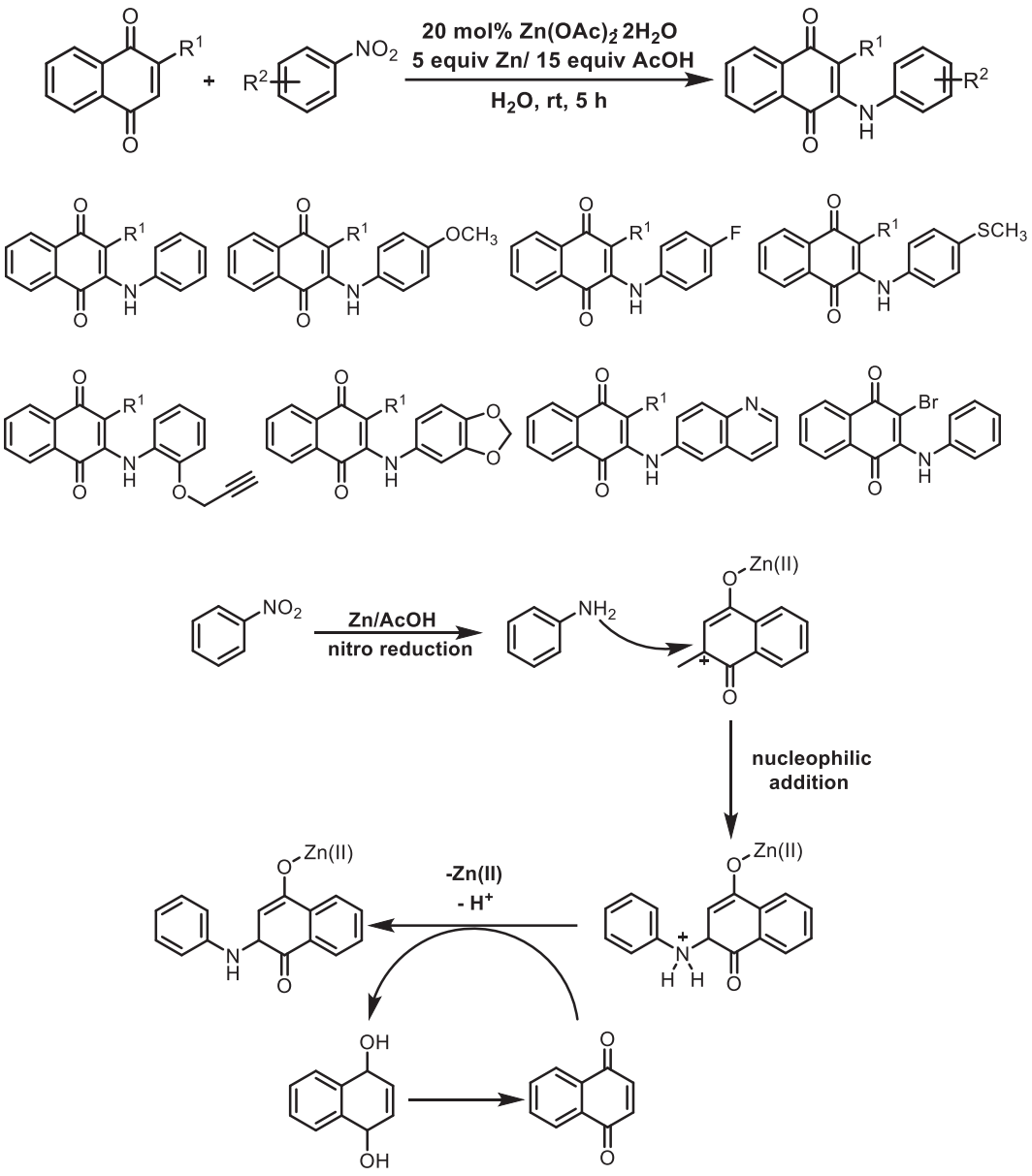




Scheme 8. Mechanism of silver-catalyzed direct thiolation of quinones by activation of aryl disulfides proposed by Chou and coworkers, and the substrate scope of this method.

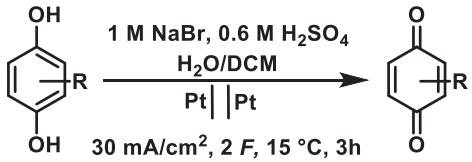
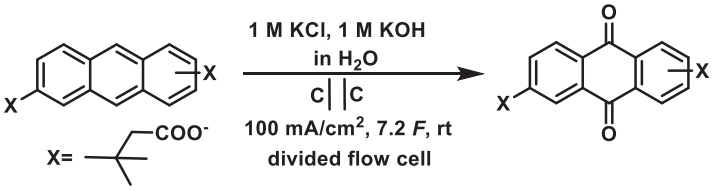
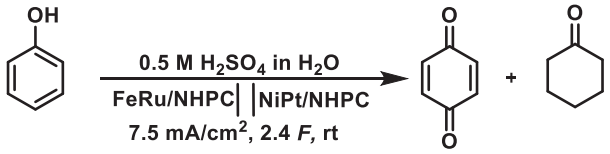
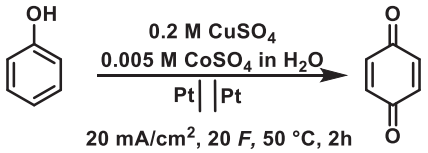
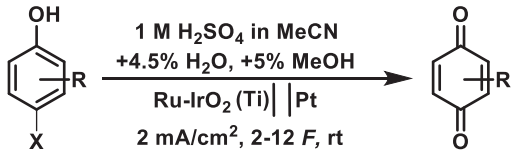
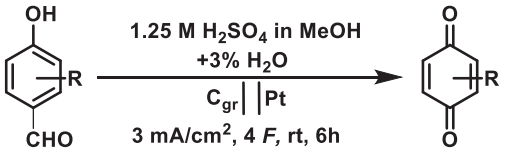


Scheme 9. Copper and triphenylphosphine-promoted sulfenylation of quinones with arylsulfonyl chlorides.



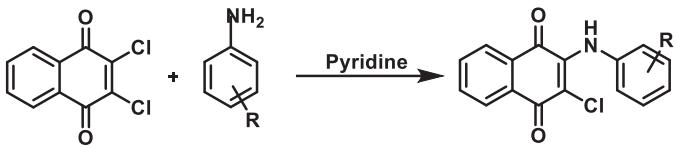
Scheme 10. Synthesis of 2-(*N*-substituted amino)-1,4-naphthoquinones with use of nitro compounds and 1,4-naphthoquinones in water.

Table 1. Electrochemical synthesis of quinones by various research groups.

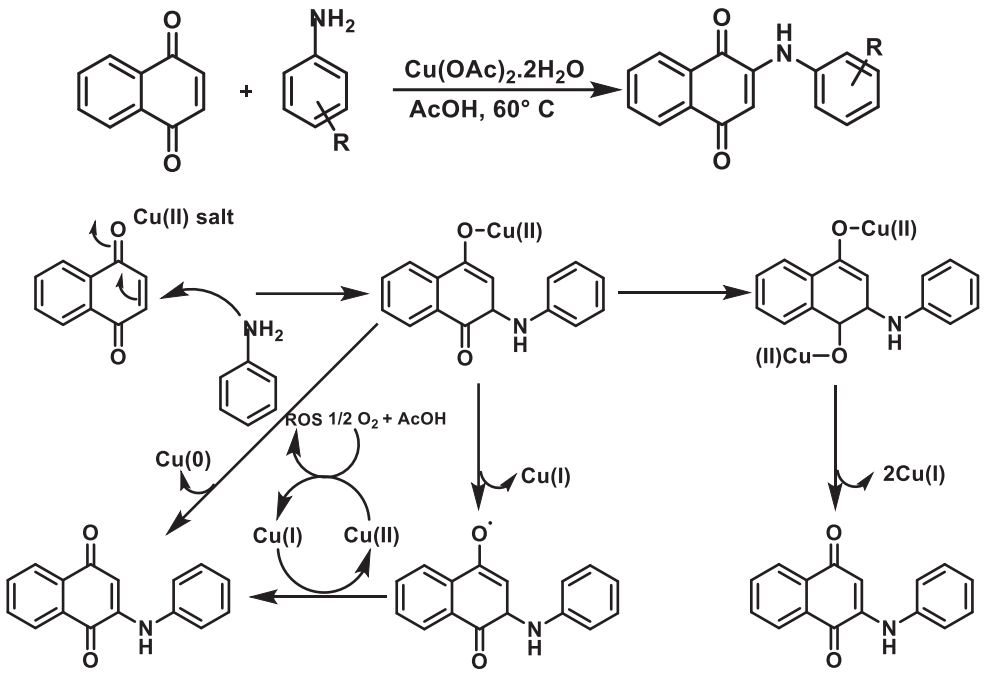
Year/ref.	Method Name	Scheme
Raja (2017)[23a]	Electrochemical synthesis of quinones from hydroquinones in a biphasic system	
Aziz (2020)[23b]	Flow-cell-based direct oxidation of DPivOHAC to DPivOHAQ for redox flow battery application	
Han (2022)[23c]	Simultaneous electrocatalytic synthesis of benzoquinone and cyclohexanone	
Zhang (2022)[23d]	Oxidation of phenol by homogeneous electrocatalysis	
Waldvogel (2022)[23e]	Electrosynthesis of para-benzoquinones by single pass flow electrolysis	
Waldvogel (2023)[23f]	Electrochemical benzoquinone synthesis from benzaldehydes	

3. Limitations in Present Synthetic Strategies

In general, second and third-row transition metal-catalysts are utilized for the functionalization of 1,4-benzoquinone or 1,4-naphthoquinone. These transition metal catalysts have some inherent disadvantages, such as restricted availability, being expensive, and toxicity. Therefore, transition metal-based catalysts need to be separated before being discarded. Recovering and recycling the transition metal catalyst from the reaction mixture requires additional steps, and it can be challenging.[13a] Additionally, transition metal catalysts often catalyze undesired side reactions, leading to lower overall yields and potentially complicating product separation. Some transition metal catalysts can be sensitive to harsh reaction conditions, leading to catalyst deactivation or decompo-



Scheme 11. Reaction of 2,3-dichloro-1,4-naphthoquinone with arylamines in pyridine.



Scheme 12. C–H functionalization of 1,4-naphthoquinone by oxidative coupling with anilines in the presence of a catalytic quantity of copper(II) acetate.

sition over time.[13b] The use of a large excess of sacrificial oxidant is required in a few processes. In several cases, long reaction times (more than 48 hrs) are also a major disadvantage. Furthermore, quinones possess distinct electronic properties that enable them to function both as ligands and as oxidants in chemical transformations. These dual roles can interfere with catalytic cycles, making the effective application of quinones in transition-metal-catalyzed reactions particularly challenging.[14]

4. Green Synthesis of Quinones

The green synthesis of quinones employs environmentally sustainable strategies such as solvent-free microwave-assisted techniques, photoredox catalysis, and electrochemical oxidation *etc.* (Table 1). These approaches aim to minimize hazardous waste generation and energy consumption, offering a cleaner alternative to conventional synthetic methods. The resulting quinone derivatives hold significant promise for applications in areas such as energy storage, pharmaceuticals, and materials science.

4.1 *Microwave Assisted Techniques*

Microwave-assisted synthesis has emerged as an efficient and environmentally friendly method for the preparation of quinones. By utilizing microwave irradiation, reactions can be significantly accelerated due to rapid and uniform heating, often leading to improved yields, shorter reaction times, and reduced energy consumption compared to conventional heating methods. Ravichandiran *et al.* reported a solvent free microwave assisted synthesis using a mixture of 2,3-dichloro-1,4-naphthaquinone (0.227 g, 0.01 mol.) and dapsone (0.248 g, 0.01 mol.).[15] The reaction mixture was irradiated in a domestic microwave oven for 10 seconds per cycle (1350 W). The duration of irradiation varied depending on the degree of reaction completion (40–110 s), as confirmed by thin-layer chromatography.

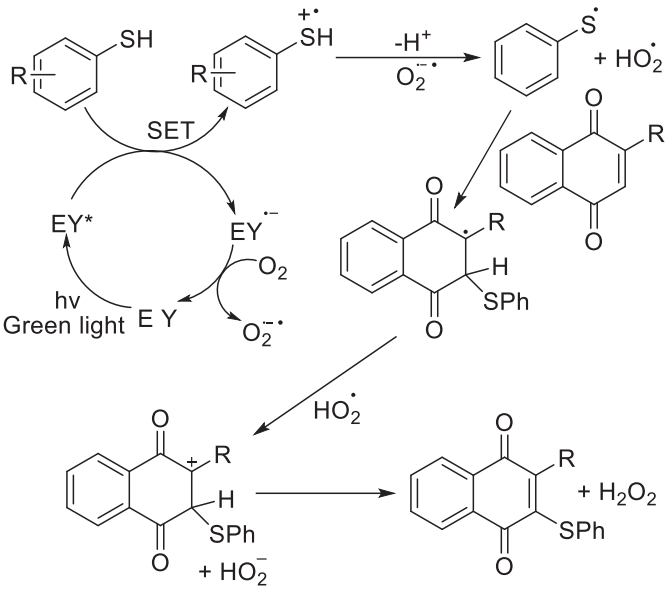
4.2 *Functionalization of Quinones Through Photoredox Catalysis*

The presence of conjugated carbonyl groups in quinones reduces the electron density on the quinoidal carbon atoms within the diene fragment, significantly enhancing their oxidative character. In addition, quinone moieties are highly sensitive to light irradiation. As a result, radical-based C–H functionalization through photocatalytic pathways under oxidative conditions presents a promising approach for the direct functionalization of *para*-quinones. Shah and coworkers have investigated a light-driven, photosensitizer-free alkylation of 1,4-naphthoquinones using cyclic ethers in the presence of potassium persulfate ($K_2S_2O_8$).[16] The proposed mechanism involves the initial formation of an electron donor–acceptor (EDA) complex between the quinone and the persulfate anion. Upon irradiation with light, this EDA complex is photoexcited, resulting in the generation of a naphthoquinone radical and a sulfate radical anion ($SO_4^{\bullet-}$). The sulfate radical then initiates a hydrogen atom transfer (HAT) from the C–H bond of the cyclic ether, producing an α-oxyalkyl radical. This radical subsequently couples with the naphthoquinone to form a radical intermediate. Finally, another $SO_4^{\bullet-}$ species oxidizes the resulting quinoyl radical *via* a second HAT step, completing the transformation.

Building on these findings, Wang and coworkers developed a blue light-mediated Minisci-type C–H alkylation of *N*-heteroarenes using 4-alkyl-1,4-dihydropyridines as the alkyl radical precursor.[17] The reaction proceeds at room temperature in the presence of an Ir(III)-based photocatalyst and employs molecular oxygen as a green oxidant. This method enables the efficient functionalization of a broad range of *N*-heteroarenes with various cyclic and acyclic primary, secondary, and tertiary alkyl groups, and is easily scalable to gram-scale synthesis.

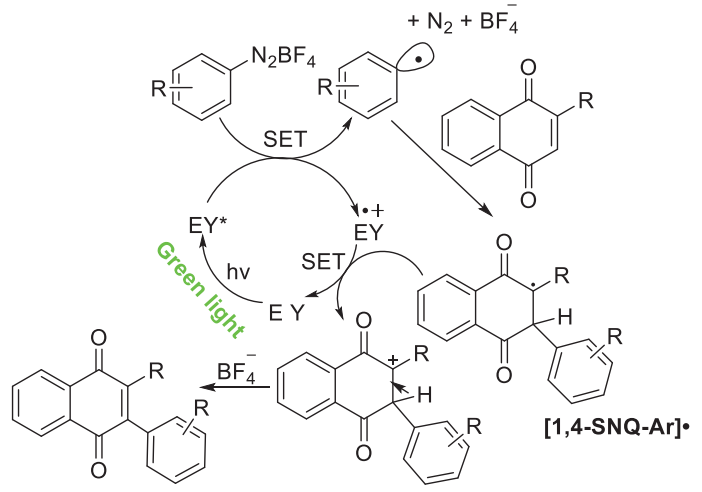
In 2021, Ilangovan and coworkers reported a photoredox-catalyzed mono- and dialkylamidation of naphthoquinones using Eosin Y (EY) as a visible-light photocatalyst.[18] Jha *et al.* reported a site-selective C–H alkylation of naphthoquinones using unactivated alkanes, catalyzed by $Mn_2(CO)_{10}$ under blue-light irradiation (457 nm). Notably, the reaction proceeds without the need for an external base or oxidant, offering a mild and efficient approach to quinone functionalization.[19] Recently, our group reported a series of visible light-mediated transformations of substituted 1,4-naphthoquinones (1,4-SNQ), including thiolation, arylation, and thio-amination, using EY as a photoredox catalyst at room temperature.[20–22]

A sustainable and efficient one-step thiolation protocol (isolated yield ≥ 75%) was developed employing various aromatic and aliphatic thiols under visible light irradiation with EY. The



Scheme 13. Formation of thiolated derivatives of 1,4-SNQ in the presence of EY and green LED.

rate-determining step involves the formation of a thiyl radical, which was confirmed *via* high-resolution mass spectrometry (HRMS) (Scheme 13).[20] In a separate study, we demonstrated a visible light-induced C–H arylation of substituted 1,4-SNQs using diazonium salts in the presence of EY, also achieving isolated yields of ≥ 75%. The key intermediate, an aryl radical, was detected and characterized by HRMS (Scheme 14).[21] Furthermore, we developed a visible light-driven synthesis of substituted phenothiazines *via* a three-component coupling of substituted 2-aminothiophenols, diazonium salts, and 1,4-naphthoquinones. The reaction proceeded efficiently under green LED light (525 nm, 44 W) for 8 hours at room temperature, affording isolated yields of 68–90%. Fluorescence quenching experiments and density functional theory (DFT) calculations revealed that the triplet excited state of EY (EY*; τT = 320 ± 10 ns) undergoes oxidative quenching by the diazonium salt (ArN_2^+), generating $EY^{+\bullet}$ ($E° = -1.11$ V *vs*. SCE). Both thoyl and aryl radicals were captured as TEMPO (2,2,6,6-tetramethylpiperidine 1-oxyl) adducts and confirmed *via* HRMS. Additionally, the reaction was not inhibited by the singlet oxygen scavenger 1,4-diazabicyclo[2.2.2]octane (DABCO), indicating that singlet oxygen is not involved in the mechanism.



Scheme 14. Arylated derivatives of 1,4-SNQ in the presence of EY and green LED.

4.3 *Electrochemical Synthesis of Quinones*

In 2017, Raja and coworkers developed an electrochemical method for oxidizing hydroquinones to benzoquinones using a batch-type cell with biphasic media.[23a] The oxidation was performed in an aqueous sulfuric acid/sodium bromide electrolyte, while the resulting non-polar quinones partitioned into a dichloromethane layer. In 2020, Aziz reported a method for the *in situ* generation of anthraquinone directly from anthracene, providing a streamlined approach to quinone synthesis from polycyclic aromatic hydrocarbons.[23b] Attempts to directly oxidize phenol electrochemically were hindered by anodic surface passivation, as revealed by cyclic voltammetry studies. In 2022, Han and coworkers developed an innovative electrochemical method enabling the simultaneous conversion of phenol into two valuable products: benzoquinone and cyclohexane.[23c] This dual transformation was achieved using a nitrogen-doped hierarchically porous carbon (NHPC) framework, with a NiPt catalyst at the cathode and a FeRu catalyst at the anode. Zhang and coworkers investigated the electrochemical oxidation of phenol to benzoquinone using a different approach from that of Han.[23d] Instead of employing heterogeneous electrodes, they developed a homogeneous electrocatalytic system, utilizing $CoSO_4$ and $CuSO_4$ as co-catalytic redox mediators to facilitate the transformation. Waldvogel and coworkers developed a single-pass flow electrolysis method for the efficient conversion of phenols, 4-hydroxyanisoles, and related substrates into *para*-benzoquinones[23e] and in 2023 he also devised electrochemical benzoquinone synthesis from benzaldehydes.[23f] This continuous-flow electrochemical approach offers improved efficiency and scalability compared to traditional batch processes.

5. Conclusion

Quinones possess unique electronic properties that enable them to function as both ligands and oxidants in chemical reactions. However, these same characteristics can complicate their effective use in transition-metal-catalyzed transformations. To address this challenge, direct functionalization of quinones has largely been achieved through radical pathways facilitated by photoinitiators. This review highlights recent progress in the direct functionalization of quinones using microwave-assisted techniques, photoredox catalysis, and electrochemical oxidation.

Acknowledgements

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Conflicts of Interest

There are no conflicts to declare.

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[1] J. V. Paulin, C. F. O. Graeff, *J. Mater. Chem. C*, **2021**, *9*, 14514, https://doi.org/10.1039/D1TC03029A.
[2] B. Dulo, K. Phan, J. Githaiga, K. Raes, S. De Meester, Waste Biomass Valor. **2021**, *12*, 6339, https://doi.org/10.1007/s12649-021-01443-9.
[3] S. S. Devi, H. M. Mehendale, Encyclopedia of Toxicology **2014**, *3*, 26, https://doi.org/10.1016/B978-0-12-386454-3.00350-X.
[4] C. F. S. Lima, F. P. Pauli, D. C. S. Costa, A. S. Souza, L. S. M. Forezi, V. F. Ferreira, F. C. Fernando Silva, *Eur. J. Org. Chem.* **2020**, *18*, 2650, https://doi.org/10.1002/ejoc.201901796.
[5] E. R. Lopat'eva, I. B. Krylov, D. A. Lapshin, A. O. Terent'ev, *J. Org. Chem.* **2022**, *18*, 1672, https://doi.org/10.3762/bjoc.18.179.
[6] S. D. Minteer, F. Giroud, R. D. Milton, B. Tan, Electrochem. Soc. Meeting Abstracts **2015**, *227*, 2307, https://doi.org/10.1149/MA2015-01/45/2307.
[7] J. D. Hernández-Camacho, M. Bernier, G. López-Lluch, P. Navas, *Front. Physiol.* **2018**, *9*, https://doi.org/10.3389/fphys.2018.00044.
[8] B. Dahlbäck, B. O. Villoutreix, *Arterioscler. Thromb.* **2005**, *25*, 1311, https://doi.org/10.1161/01.ATV.0000168421.13467.82.

[9] (a) D. J. B. Lima, R. G. Almeida, G. A. M. Jardim, B. P. A Barbosa, A. C. C. Santos, W. O. Valença, M. R. Scheide, C. C. Gatto, G. G. C. de Carvalho, P. M. S. Costa, C. Pessoa, C. L. M. Pereira, C. Jacob, A. L. Braga, E. N. da Silva Júnior, *RSC Med. Chem*. **2021**, *12*, 1709, https://doi.org/10.1039/D1MD00168J. (b) P. M. S. Sahoo, S. Behera, R. Behura, A. Acharya, D. Biswal, S. K. Suna, R. Sahoo, R. C. Soren, B. R. Jali, *Biointerface Res. Appl. Chem.* **2021**, *12*, 3247, https://doi.org/10.33263/BRIAC123.32473258. (c) G. Meazza, F. E. Dayan, D. E. Wedge, *Agric. Food Chem*. **2003**, *51*, 3824, https://doi.org/10.1021/jf0343229. (d) G. Krishnamoorthy, S. P. Webb, T. Nguyen, P. K. Chowdhury, M. Halder, N. J. Wills, S. Carpenter, G. A. Kraus, M. S. Gordon, J. W. Petrich, *Photochem. Photobiol*. **2005**, *81*, 924, https://doi.org/10.1562/2004-11-23-RA-378R1.1 (e) D. Chena, H. Gaoa, C. Penga, S. Peia, A. Daia, X. Yua, P. Zhoua, Y. Wanga, B. Caia, *J. Pharm. Pharmacol*. **2020**, *72*, 1481, https://doi.org/10.1111/jphp.13332. (f) O. P. S. Patel, R. M. Beteck, L. J. Legoabe, *Eur. J. Med. Chem*. **2021**, *210*, 113084, https://doi.org/10.1016/j.ejmech.2020.113084.

[10] (a) W. M. Best, C. G. Sims, M. Winslade, *Aust. J. Chem*. **2001**, *54*, 401, https://doi.org/10.1071/CH01024. (b) J. M. Wood, R. L. de Carvalho, E. N. Silva Júnior, *Chem. Rec*. **2021**, *21*, 2604, https://doi.org/10.1002/tcr.202000163. (c) O. M. Demchuk, K. M. Pietrusiewicz, *Synlett* **2009**, *7*, 1149, https://doi.org/10.1055/s-0028-1088118. (d) E. Kumli, F. Montermini, P. Renaud, *Org. Lett.* **2006**, *8*, 5861, https://doi.org/10.1021/ol0624629. (e) Y. Fujiwara, V. Domingo, I. B. Seiple, R. Gianatassio, M. Del Bel, P. S. Baran, *J. Am. Chem. Soc*. **2011**, *133*, 3292, https://doi.org/10.1021/ja111152z. (f) A. Ilangovan, K. S. Saravana, S. Malayappasamy, *Org. Lett*. **2013**, *15*, 4968, https://doi.org/10.1021/ol402229m. (g) E. R. Baral, S. H. Kim, Y. R. Lee, *Asian J. Org. Chem*. **2016**, *5*, 1134, https://doi.org/10.1002/ajoc.201600219. (h) A. Deb, S. Manna, A. Maji, U. Dutta, D. Maiti, *Eur. J. Org. Chem*. **2013**, *24*, 5251, https://doi.org/10.1002/ejoc.201300743. (i) A. Gutiérrez-Bonet, C. Remeur, J. K. Matsui, G. A. Molander, *J. Am. Chem. Soc*. **2017**, *139*, 12251, https://doi.org/10.1021/jacs.7b05899.

[11] (a) C. Zhang, J. McClure, C. J. Chou, *J. Org. Chem*. **2015**, *80*, 4919, (b) X. Yu, Q. Wu, H. Wan, Z. Xu, X. Xu, D. Wang, *RSC Adv*. **2016**, *6*, 62298, https://doi.org/10.1039/C6RA11301J.

[12] (a) X.-L. Chen, Y. Dong, R. Zhang, H. Zhang, L. Tang, X. Zhang, J. Wang, *Synlett*. **2019**, *30*, 615, https://doi.org/10.1055/s-0037-1610689. (b) L. N. Agarwal, W. Schaefer, *J. Org. Chem*. **1980**, *45*, 5139, https://doi.org/10.1021/jo01313a023. (c) A. I. Francisco, M. D. Vargas, J. W. d. M. Carneiro, M. Lanznaster, J. C. Torres, C. A. Camara, A. C. Pinto, *J. Mol. Struct*. **2008**, *891*, 228, (d) C. S. Lisboa, V. G. Santos, B. G. Vaz, N. C. Lucas, M. N. Eberlin, S. J. Garden, *J. Org. Chem*. **2011**, *76*, 5264, https://doi.org/10.1021/jo200354u.

[13] (a) J. R. Carney, B. R. Dillon, S. P. Thomas, *Eur. J. Org. Chem*. **2016**, *23*, 3912, https://doi.org/10.1002/ejoc.201600018. (b) S. Hübner, J. G. de Vries, V. Farina, *Adv. Synth. Catal*. **2016**, *358*, 3, https://doi.org/10.1002/adsc.201500846.

[14] (a) P. Saravanan, P. Anbarasan, *Org. Lett*. **2014**, *16*, 848, https://doi.org/10.1021/ol4036209. (b) R. Xu, J.-P. Wan, H. Mao, Y. Pan, *J. Am. Chem. Soc*. **2010**, *132*, 15531, https://doi.org/10.1021/ja107758d. (c) S. D. Timpa, C. J. Pell, O. V. A. Ozerov, *J. Am. Chem. Soc*. **2014**, *136*, 14772, https://doi.org/10.1021/ja505576g.

[15] P. Ravichandiran, R. Kannan, A. Ramasubbu, S. Muthusubramanian, V. K. Samuel, *J. Saudi Chem. Soc*. **2016**, *20*, S93, https://doi.org/10.1016/j.jscs.2012.09.011.

[16] S. Devari, B. A. Shah, *Chem. Commun*. **2016**, *52*, 1490, https://doi.org/10.1039/C5CC08817H.

[17] J. Dong, F. Yue, W. Xu, H. Song, Y. Liu, Q. Wang, *Green Chem*. **2020**, *22*, 5599, https://doi.org/10.1039/D0GC02111C.

[18] P. Sakthivel, T. P. A. Krishna, A. Ilangovan, *ChemistrySelect* **2021**, *6*, 2094, https://doi.org/10.1002/slct.202100054.

[19] R. K. Jha, K. Rohilla, S. Jain, D. Parganiha, S. Kumar, *Chem. Eur. J.* **2024**, *30*, e202303537, https://doi.org/10.1002/chem.202303537.

[20] B. Nagar, B. B. Dhar, *J. Org. Chem*. **2022**, *87*, 3195, https://doi.org/10.1021/acs.joc.1c02924.

[21] B. Nagar, B. B. Dhar, *ACS Omega* **2022**, *7*, 32615, https://doi.org/10.1021/acsomega.2c04289.

[22] B. Nagar, S. K. Yadav, N. Karmodak, B. B. Dhar, Y. Eosin, *ACS Omega* **2024**, *9*, 35458, https://doi.org/10.1021/acsomega.4c02167.

[23] (a) V. M. Shanmugam, K. Kulangiappar, M. Ramaprakash, D. Vasudevan, R. Senthil Kumar, D. Velayutham, T. Raju, *Tetrahedron Lett*. **2017**, *58*, 2294, https://doi.org/10.1016/j.tetlet.2017.04.099. (b) Y. Jing, M. Wu, A. A. Wong, E. M. Fell, S. Jin, D. A. Pollack, E. F. Kerr, R. G. Gordon, M. J. Aziz, *Green Chem*. **2020**, *22*, 6084, https://doi.org/10.1039/D0GC02236E. (c) R. Wu, Q. Meng, J. Yan, H. Liu, Q. Zhu, L. Zheng, J. Zhang, B. Han, *J. Am. Chem. Soc*. **2022**, *144* , 1556, https://doi.org/10.1021/jacs.1c09021. (d) W. Xu, Y. Sun, N. Li, W. Liu, Z. C. Zhang, *ChemElectroChem*. **2023**, *10*, e202300187, https://doi.org/10.1002/celc.202300187. (e) F. Sprang, J. D. Herszman, S. R. Waldvogel, *Green Chem*. **2022**, *24*, 5116, https://doi.org/10.1039/D2GC01296K. (f) F. Sprang, J. Klein, S. R. Waldvogel, *ACS Sustainable Chem. Eng*. **2023**, *11*, 7755, https://doi.org/10.1021/acssuschemeng.3c00257.

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