



Universidad Autónoma
de Madrid

Biblos-e Archivo
Repositorio Institucional UAM

Repositorio Institucional de la Universidad Autónoma de Madrid

<https://repositorio.uam.es>

Esta es la **versión de autor** del artículo publicado en:
This is an **author produced version** of a paper published in:

Green Chemistry 22 (2020): 6792-6797

DOI: <https://doi.org/10.1039/d0gc02618b>

Copyright: © 2020 The Royal Society of Chemistry

El acceso a la versión del editor puede requerir la suscripción del recurso
Access to the published version may require subscription

Metal-Free Visible Light-Promoted Synthesis of Isothiazoles: a Catalytic Approach for N–S Bond Formation from Iminyl Radicals under Batch and Flow Conditions

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

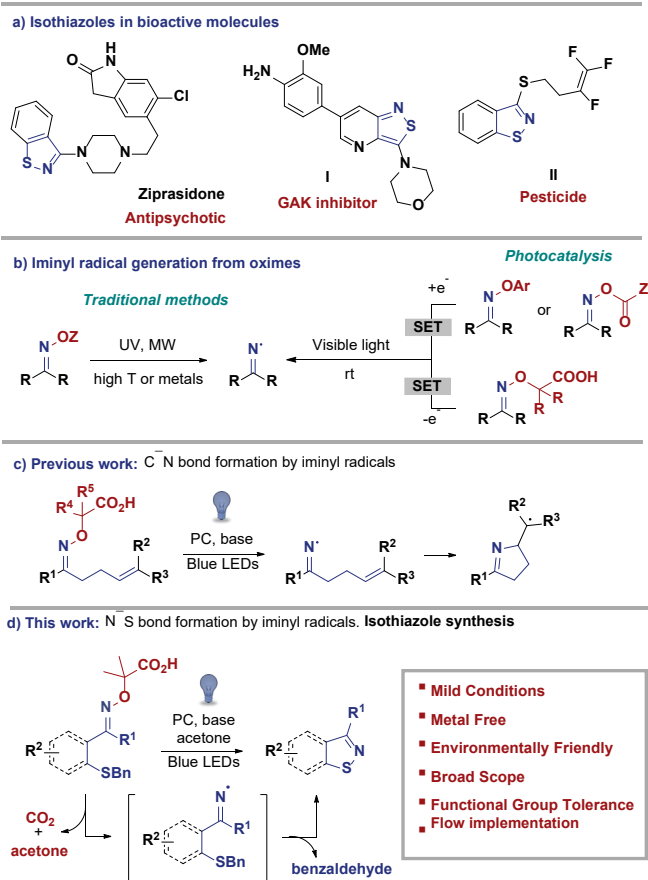
María Jesús Cabrera,^{†a} Sara Cembellín,^{†*a} Adhane Halima-Salem,^b Mateo Berton,^a Leyre Marzo,^a Abdellah Miloudi,^{b,c} M. Carmen Maestro,^{*a} and José Alemán^{*a,d}

A sustainable synthesis of isothiazoles has been developed using an α -amino-oxy acid auxiliary and applying photoredox catalysis. This simple strategy features mild conditions, broad scope and wide functional group tolerance representing a new environmentally friendly option to prepare these highly valuable heterocycles. Furthermore, the synthetic value of the method is highlighted by the preparation of a natural product derivative and the implementation of the reaction in a continuous flow setup.

Isothiazoles, which contain two electronegative heteroatoms (nitrogen and sulfur) in a 1,2-relationship, are important scaffolds in medicinal chemistry and agriculture industry.¹ This prominent moiety occurs in various antipsychotic drugs such as ziprasidone² and lurasidone,³ commonly used in the treatment of schizophrenia. Moreover, the isothiazole moiety is present in some inhibitors of biological targets such as compound I, a potent GAK (Cyclin G Associated Kinase) inhibitor,⁴ and in different pesticides such as the 3-substituted benzo[d]isothiazole II (Scheme 1a).⁵ Traditional methods for the preparation of these heterocycles often require high temperatures, harsh conditions or the use of transition metals.^{6,7} Therefore, a simple, direct and more sustainable approach towards the synthesis of isothiazoles would be of significant interest in synthetic chemistry.

Photoredox catalysis mediated by visible light has received much attention in the past decade.⁸ Its mild and green conditions have made it a suitable option to develop new efficient, economical and environmentally friendly transformations. In particular, iminyl radicals are versatile synthetic intermediates in the construction of more complex molecules.⁹ They have been successfully generated from oxime

radicals by single-electron oxidation of α -imino-oxy acids (Scheme 1c). Despite great progress in the area, the generation of iminyl radicals by oxidative single-electron transfer (SET) from oxime derivatives^{12–14} has been considerably overlooked when compared to its analogous reductive process.¹⁵ Indeed, all these strategies (Scheme 1b–c) involve the formation of C–N



Scheme 1. Importance of isothiazoles and iminyl radicals in photocatalysis.

bonds, but the formation of other attractive bonds such as N–S has never been explored under these photocatalytic conditions.

On this basis, and taking advantage of our previous experience in photocatalyzed sulfur chemistry,¹⁶ we envisioned that iminyl radicals generated by oxidative SET could be appropriate for the formation of N–S bonds, although to the best of our knowledge it has not been reported to date. Herein, we describe the efficient realization of this approach and we apply it to the development of a new synthesis of isothiazoles from α -imino-oxy acids under mild conditions and promoted by visible light (Scheme 1d). The green conditions of the protocol

^a Organic Chemistry Department, Módulo 1, Universidad Autónoma de Madrid, 28049 Madrid, Spain. E-mail: sara.cembellin@uam.es, carmen.maestro@uam.es, jose.aleman@uam.es.

^b Laboratoire de Chimie Fine, Département de Chimie, Faculté des Sciences Exactes et Appliquées, Université Oran-1, BP1524, El Mnaouer, 31100, Oran, Algeria.

^c Département des Classes Préparatoires en Sciences et Technologies, Ecole Nationale Polytechnique d'Oran e Maurice-Audin, BP1523, ElMnaouer, 31100, Oran, Algeria.

^d Institute for Advanced Research in Chemical Sciences (IAdChem), Universidad Autónoma de Madrid, 28049 Madrid, Spain.

[†] Both authors contribute equally.

Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

derivatives through a visible-light photoredox approach,¹⁰ avoiding the use of the UV irradiation or high temperatures, which had been previously required (Scheme 1b).¹¹

In 2017, the Studer¹² and Leonori¹³ groups simultaneously described for the first time the generation of these nitrogen

are highlighted not only by the reaction setup, at room temperature and without the necessity of transition metals or stoichiometric oxidants, but also by the formation of benign secondary products such as CO₂ gas, acetone and benzaldehyde.

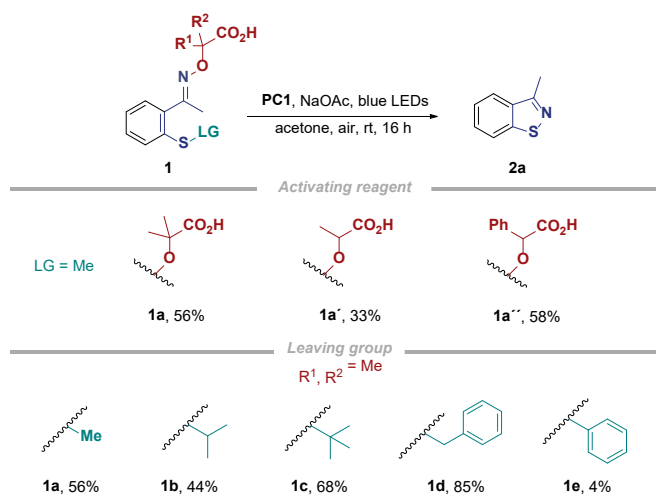
To probe the feasibility of our assumption, we selected the

Table 1. Reaction discovery and variation of standard conditions.

Chemical structures of photocatalysts PC1, PC2, PC3, PC4, and PC5 are shown below the reaction scheme.

Entry	Variation from standard conditions ^[a]	Yield [%] ^[b]
1	None	56
2	CsF instead of NaOAc	20
3	PC2 instead of PC1	35
4	PC3 instead of PC1	31
5	PC4 instead of PC1	32
6	PC5 instead of PC1	44
7	O ₂ instead of air	54
8	Ar instead of air	4
9	No base	0
10	No light	0
11	No photocatalyst	0

[a] Conditions: **1a** (0.05 mmol), photocatalyst PC (5 mol%) and NaOAc (0.05 mmol) in acetone (0.67 mL) under air and 450 nm single LED (380 mW). [b] Yields determined by ¹H-NMR spectroscopy using 1,3,5-trimethoxybenzene as internal standard.

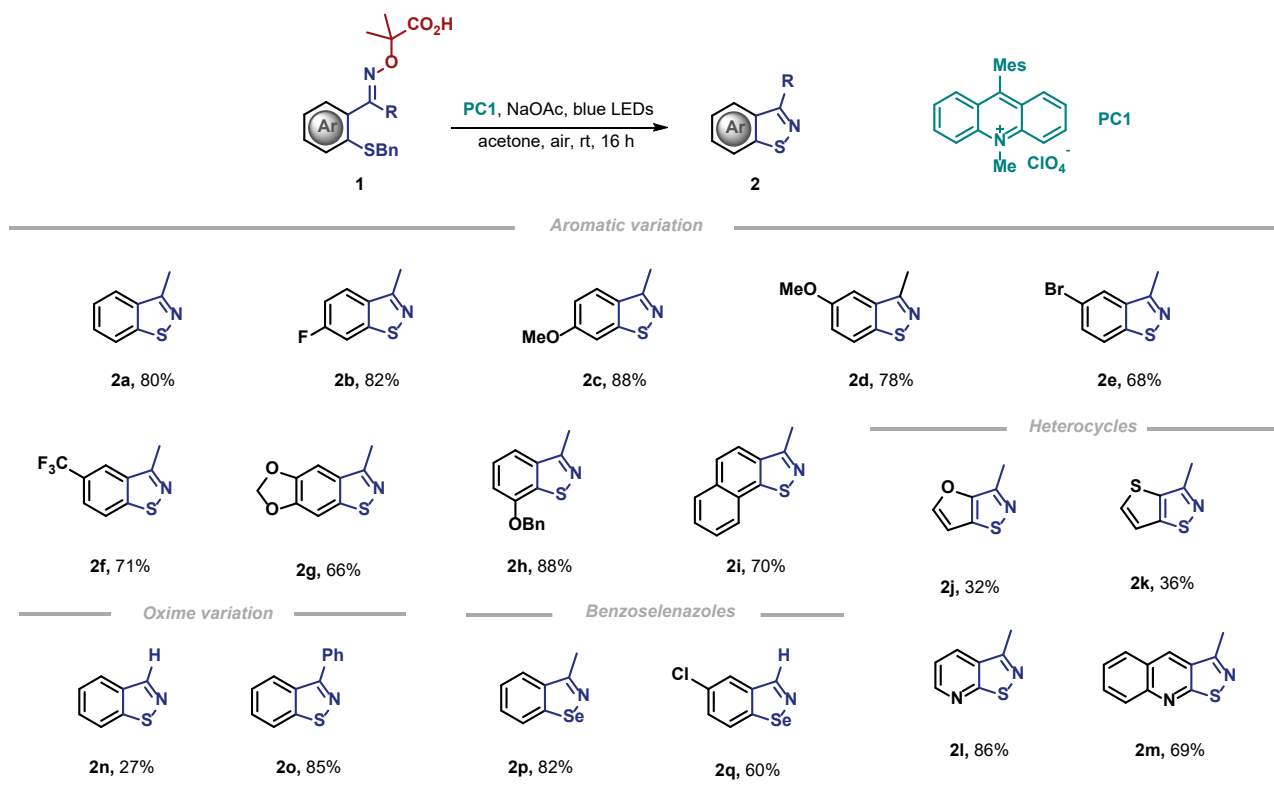


Scheme 2. Evaluation of the activating reagent and the leaving group (LG). Yields determined by ¹H-NMR spectroscopy using 1,3,5-trimethoxybenzene as internal standard

α -imino-oxy acid **1a** as model substrate, easily prepared from the corresponding ketone in one step (see ESI for details) and we studied its reactivity in the presence of various photocatalysts and bases. After extensive screening (see Table S1 in ESI for details), the desired benzo[d]isothiazole **2a** was obtained in 56% yield as a single product using the commercially available acridinium salt **PC1** as photocatalyst and NaOAc as a base in acetone under air and blue LED light irradiation (Table 1, Entry 1). The use of other bases frequently employed in the generation of iminyl radicals by oxidative SET of oximes, such as CsF (Table 1, Entry 2), or different solvents, provided worse results. A significant decrease in the yield was observed when other photoredox catalysts such as acridinium species **PC2** and **PC3**, Ir(dFCF₃ppy)₂(dtbbpy)PF₆ (**PC4**) and 4CzIPN dye (**PC5**) were used (Table 1, Entries 3–6). Moreover, when the reaction was carried out under oxygen atmosphere, the same result was obtained (Entry 7), while an argon atmosphere was found to have a detrimental effect on the transformation (Entry 8). These results show the necessity of the presence of oxygen in the reaction. Finally, control experiments verified that no product was formed in the absence of light, base or photocatalyst (Table 1, Entries 9–11).

Next, the nature of both the activating reagent for the carbonyl substrate and the leaving group (LG) were studied (Scheme 2). Under the previous optimized conditions, 2-imino-oxy propionic acid **1a'** afforded the desired benzoisothiazole **2a** in lower yield (33%), while the corresponding phenyl-substituted compound **1a''** displayed similar efficiency than our model substrate. Based on these results, we continued with the use of 2-(aminooxy)-2-methylpropanoic acid as the auxiliary of the reaction, due to the formation of acetone as secondary product which coincides with the solvent of our method.

Regarding the LG study, compounds **1b** and **1c** containing isopropyl and *tert*-butyl groups as LG gave the compound **2a** in 44% and 68% yield, respectively. In contrast, oxime **1e**, with a SPh moiety, was almost inactive in the reaction. Fortunately, α -imino-oxy acid **1d** led to the formation of the desired product



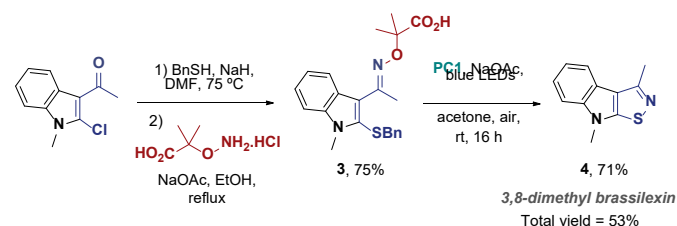
Scheme 3. Substrate scope of the synthesis of isothiazoles from α -imino-oxy acids.

in a very good yield (85%), which confirmed the benzyl group as the best LG for our transformation.

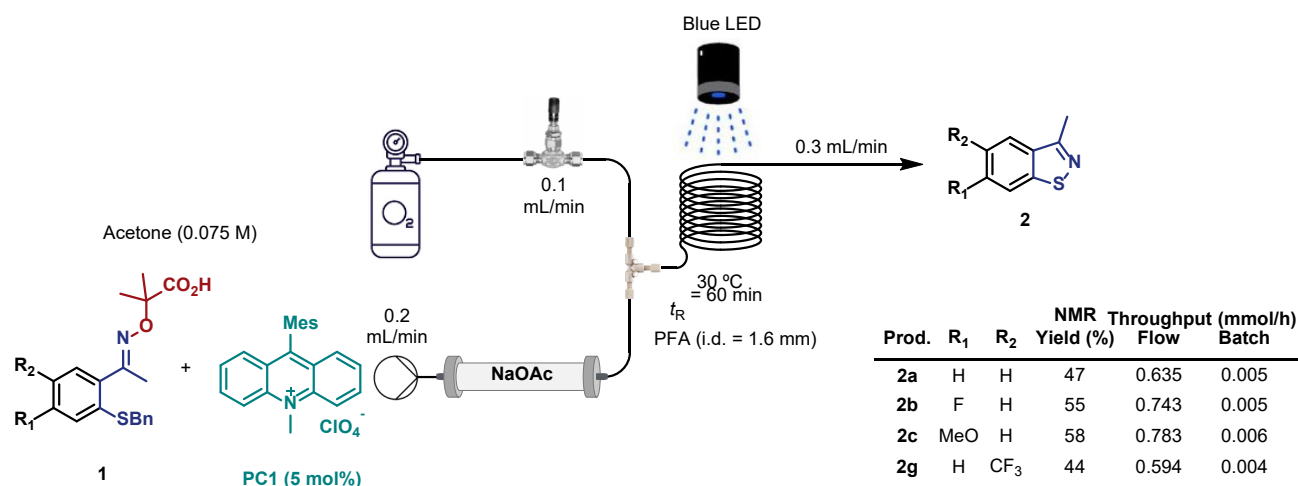
With the optimized reaction conditions in hand, we examined the scope of the reaction by first varying the moieties present in the aromatic ring of the substrate (Scheme 3). To our delight, a range of substituted aromatic oximes containing either electron-donating or electron-withdrawing groups such as MeO, Br, F and CF₃ could all be used to form the corresponding benzoisothiazoles **2a-h** in generally good to excellent yields. Halogen moieties, which could also enable the diversification of these scaffolds and may not be tolerated in other metal-catalyzed syntheses, remained unaltered after the reaction. Notably, not only distal positions of the aromatic ring, such as 4 and 5, but also the proximal one, 3, could be substituted in the starting materials affording the corresponding product **2h** in 88% yield. In addition, dioxolane and benzyloxy substituents, potentially sensitive groups under harsh conditions, were successfully preserved in the final benzoisothiazoles **2g** and **2h** respectively, which illustrates the mild conditions of our protocol. The synthetic value of this transformation was further demonstrated with its efficient application to oximes containing a naphthalene core and a variety of heterocycles present in biologically active molecules, such as furans, thiophenes, pyridines and quinolines.¹⁷ The desired isothiazoles **2j-k**, with two 5-membered rings in their structure, were successfully obtained in moderate yields (32% and 36% respectively), while the α -imino-oxy acids containing pyridine and quinoline scaffolds afforded the corresponding compounds **2l** and **2m** in 86% and 69% yield.

Encouraged by these results, we next examined the influence of the substitution on the oxime carbon. Pleasingly, aldoximes and diphenyloximes derivatives were also tested in this method, isolating products **2n** and **2o** in 27% and 85% yield, respectively. The low yield obtained in the formation of 1,2-benzoisothiazole **2n** was caused presumably due to its lower stability in comparison with the same heterocycles substituted in the 3-position of the ring and the formation of a secondary product, the 2-(benzylthio)-benzonitrile. Finally, having demonstrated the effectiveness of this approach, we sought to challenge this process for its application in the preparation of benzoselenazoles. Thus, the desired compounds **2p** and **2q** were successfully delivered when selenide derivatives were applied, delivering the corresponding products in excellent fashion (82% and 60% respectively).

To evaluate the applicability of this synthetic method, representative experiments were further conducted. First, the developed transformation was highly efficient in the synthesis of a derivative of the natural product brassilexin, a potent antifungal produced by several *Brassica* species.¹⁸ This valuable



Scheme 4. Synthesis of Brassilexin derivative **4**.



Scheme 5. Flow setup of the synthesis of the isothiazoles from α -imino-oxy acids.

molecule, the 3,8-dimethyl brassilexin, was obtained using our methodology in only three steps from 3-acetyl-2-chloro-1-methyl-1H-indole in 53% total yield (Scheme 4). In addition, and taking into account the limitation associated to the scale-up of photochemical transformations using conventional batch equipment,¹⁹ we implemented a continuous flow setup for the preparation of the isothiazoles. The main limitation arises from photon attenuation due to the fact that, as the Beer-Lambert law states, light intensity is distance dependent, which thwarts any classical dimension enlarging strategy. To overcome non-uniform light penetration, Booker-Milburn's approach was employed providing higher light flux and enhancing efficiency and reaction rates.²⁰ The reaction was performed in a coil ($V = 18$ mL) made of perfluoroalkoxy (PFA) tubing (i.d. = 1.6 mm) irradiated with a blue LED spot (40 W).

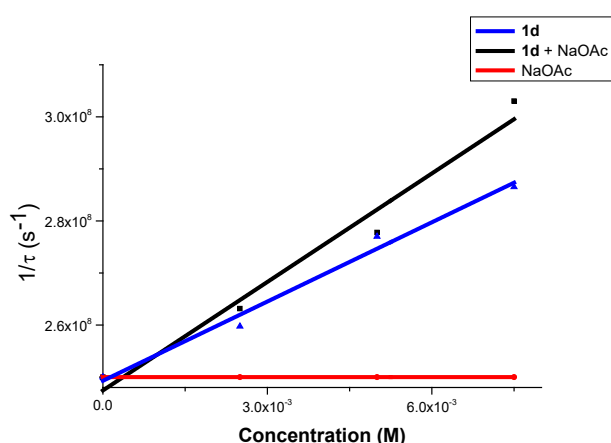
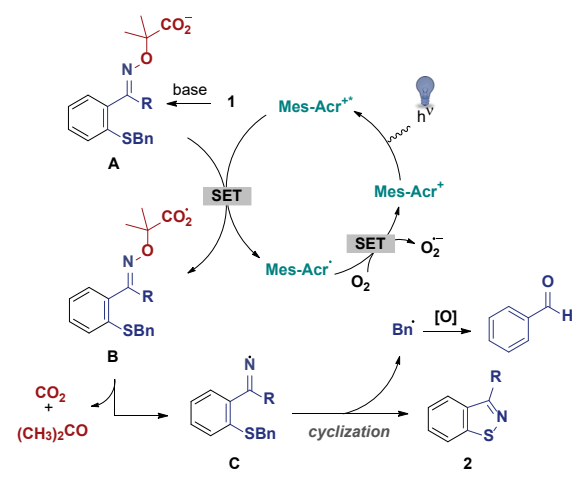
After screening of different conditions, standard compound **2a** was obtained in 47% yield, using **PC1** (5 mol%); oxygen gas at 1 bar of pressure and a residence time of 60 minutes (see Table S3 in ESI for details). To optimize the flow system, we decided to use O₂ gas in a segmented flow fashion, which provides efficient gas-liquid mixing due to the Taylor flow generated by gas slugs. Furthermore, we deprotonated the substrate by passing the starting material solution through a packed bed reactor filled with sodium acetate.

Finally, the optimized flow setup for **2a**, was utilized for the preparation of products **2b**, **2c** and **2g** in sequential manner. Gas/liquid segmented flow was generated by mixing both streams in a T-union and gas slugs (2 mm) were controlled using a micrometric valve. The three substrates were injected consecutively through the system separated by acetone (4 mL) to avoid product contamination from previous runs. In a total of 2 h, isothiazoles **2b**, **2c** and **2g** were obtained in respectively 55%, 58% and 44% yield. Even if the obtained values are lower than in batch, in all the transformations the throughput of the reaction is ≈ 140 times higher than in conventional conditions and around 15% of starting material is recovered in all the cases. Therefore, these results demonstrate the potential of the

developed chemistry in further large-scale preparation of benzo[d]isothiazole derivatives.

To gain insight into the reaction mechanism, we performed several experiments. Electrochemical analysis was realized in oximes **1** containing different activating reagents and leaving groups (Scheme 2). Oximes **1a**, **1a'** and **1a''**, with distinct moieties in the α position of the carboxylic acid, showed the same oxidation potential, while compounds **1a-e**, containing different leaving groups, displayed a relevant difference between their potential values. In both cases, the obtained data are not in accordance with the reactivity profile observed, revealing that the diverse reactivity of these oximes is dependent of the nature of each activating reagent or leaving group and not of the electrochemical properties of the substrates (see ESI for details). Furthermore, we carried out steady state and time resolved luminescence quenching studies of photocatalyst **PC1**. An efficient interaction of **1d** with the excited state of **PC1** was detected in the presence or absence of NaOAc, thus indicating that the oxidation of either the α -imino-oxy acid or the corresponding carboxylate is feasible. However more efficient quenching is observed with the carboxylate of oxime **1d** (Scheme 6, bottom, see ESI for details).

Based on the aforementioned results and previous reports,¹²⁻¹⁴ a plausible mechanism was proposed (Scheme 6, top). The reaction starts with the photoexcitation of Mes-Acr⁺ (**PC1**) by visible light to form the excited Mes-Acr⁺⁺ complex. This species ($E_{\text{red}} = 2.06$ V vs. SCE)²¹ oxidizes by single electron transfer the carboxylate **A** (E_{ox} [for **1d**] = 1.62 V vs. SCE), formed by reaction of α -imino-oxy acid **1d** and base. Subsequently, fragmentation of the obtained intermediate **B** generates the iminiyl radical **C**, with loss of CO₂ and acetone, which is followed by a cyclization to deliver isothiazole **2**. The photoredox catalytic cycle is closed with SET reduction of oxygen by the reduced photocatalyst Mes-Acr^{*} and the benzyl radical, which is transformed to benzaldehyde.²²



Scheme 6. Proposed mechanism based on time resolved fluorescence quenching studies

In summary, we have developed an efficient and scalable method to synthesize isothiazoles using readily accessible oximes derivatives and visible light. The described protocol involves an organo-photoredox generation of iminyl radicals by oxidative SET followed by a cyclization, which represents an effective approach to create N–S bonds under mild conditions. Moreover, the preparation of a valuable molecule and the implementation of the reaction in a flow setup highlighted the broad applicability of the strategy.

Conflicts of interest

There are no conflicts to declare.

Acknowledgments

We acknowledge the financial support by the Spanish Government (RTI2018-095038-B-I00) and ERC (ERC-CG, 647550). S.C. thanks the Ministerio de Ciencia e Innovación for a Juan de la Cierva contract. M. J. C. thanks the Comunidad Autónoma de Madrid for a postdoctoral contract (PEJD-2018-POST/AMB-8938). L. M. thanks the Comunidad Autónoma de Madrid for a postdoctoral contract (PEJD-2018-POST/AMB-8938), and for an Atracción de Talento Investigador contract (2017-T2/AMB-5037). The authors also wish to thank the Comunidad

de Madrid and European Structural Funds for their financial support to FotoArt-CM project (S2018/NMT-4367).

Notes and references

- (a) F. Zani and P. Vicini, *Arch. Pharm. Pharm. Med. Chem.*, 1998, **331**, 219; (b) P. Vicini, A. Geronikaki, M. Incerti, B. Busonera, G. Poni, C. A. Cabras and P. La Colla, *Bioorg. Med. Chem.*, 2003, **11**, 4785; (c) G. Morini, E. Poli, M. Comini, A. Menozzi and C. Pozzoli, *Arch. Pharm. Res.*, 2005, **28**, 1317; (d) A. Geronikaki, P. Eleftheriou, P. Vicini, I. Alam, A. Dixit and A. K. Saxena, *J. Med. Chem.*, 2008, **51**, 5221.
- (a) T. F. Seeger, P. A. Seymour, A. W. Schmidt, S. H. Zorn, D. W. Schulz, L. A. Lebel, S. McLean, V. Guanowsky, H. R. Howard, J. A. Lowe III and J. Heym, *J. Pharmacol. Exp. Ther.*, 1995, **275**, 101; (b) C. Prakash, A. Kamel, D. Cui, *Drug Metab. Dispos.*, 1997, **25**, 897.
- (a) M. George, R. Amrutheshwar, R.P. Rajkumar, S. Kattimani and S. A. Dkhar, *Eur. J. Clin. Pharmacol.*, 2013, **69**, 1497; (b) M. Sanford and S. Dhillon, *CNS Drugs*, 2015, **29**, 253.
- S. Kovackova, L. Chang, E. Bekerman, G. Neveu, R. Barouch-Bentov, A. Chaikvad, C. Heroven, M. Šála, S. De Jonghe, S. Knapp, S. Einav and Piet Herdewijn, *J. Med. Chem.*, 2015, **58**, 3393.
- De. Pat.*, DE3837578A1, 1990.
- For selected reviews on synthesis of isothiazoles, see: (a) D. W. Brown and M. Sainsbury, in *Science of Synthesis*, ed. E. Schaumann, Thieme, Stuttgart, 2002, vol. 11, pp. 573-623; (b) R. V. Kabardin and V. I. Potkin, *Russ. Chem. Rev.*, 2002, **71**, 673; (c) A.-S. S. Hamad Elgawzy, *Tetrahedron*, 2003, **59**, 7445; (d) A. De Oliveira Silva, J. McQuade and M. Szostak, *Adv. Synth. Catal.*, 2019, **361**, 3050; (e) A. V. Kletskev, N. A. Bumagin, F. I. Zubkov, D. G. Grudin and V. I. Potkin, *Synthesis*, 2020, **52**, 159.
- For selected references on the synthesis of benzoisothiazoles, see: (a) R. Leardini, H. McNab, M. Minozzi and D. Nanni, *J. Chem. Soc., Perkin Trans. 1*, 2001, 1072; (b) T. Creed, R. Leardini, H. McNab, D. Nanni, I. S. Nicolson and D. Reed, *J. Chem. Soc., Perkin Trans. 1*, 2001, 1079; (c) N. O. Devarie-Baez and M. Xian, *Org. Lett.*, 2010, **12**, 752; (d) Y. Chen and M. C. Willis, *Org. Lett.*, 2015, **17**, 4786; (e) F. Xu, Y. Chen, E. Fan and Z. Sun, *Org. Lett.*, 2016, **18**, 2777; (f) H. Xie, G. Li, F. Zhang, F. Xiao and G.-J. Deng, *Green Chem.*, 2018, **20**, 827; (g) R. Zhu, Z. Liu, J. Chen, X. Xiong, Y. Wang, L. Huang, J. Bai, Y. Dang and J. Huang, *Org. Lett.*, 2018, **20**, 3161; (h) H. Yuan and Z. Sun, *Synlett*, 2019, **30**, 1904.
- For selected reviews, see: (a) J. M. R. Narayanam and C. R. J. Stephenson, *Chem. Soc. Rev.*, 2011, **40**, 102. (b) C. K. Prier, D. A. Rankic and D. W. C. MacMillan, *Chem. Rev.*, 2013, **113**, 5322; (c) K. L. Skubi, T. R. Blum and T. P. Yoon, *Chem. Rev.*, 2016, **116**, 10035; (d) N. A. Romero and D. A. Nicewicz, *Chem. Rev.*, 2016, **116**, 10075; (e) *Visible Light Photocatalysis in Organic Chemistry*, ed. C. R. J. Stephenson, T. P. Yoon and D. W. C. MacMillan, Wiley-VCH, Weinheim, 2018; (f) L. Marzo, S. K. Pagire, O. Reiser and B. König, *Angew. Chem. Int. Ed.*, 2018, **57**, 10034; (g) R. C. McAtee, E. J. McClain and C. R. J. Stephenson, *Trends Chem.*, 2019, **1**, 111; (h) A. F. Garrido-Castro, M. C. Maestro and J. Alemán, *Tetrahedron Lett.*, 2018, **59**, 1286; (i) A. F. Garrido-Castro, M. C. Maestro and J. Alemán, *Catalysts*, 2020, **10**, 562.
- For reviews on iminyl radicals, see: (a) S. Z. Zard, *Synlett*, 1996, **12**, 1148; (b) J. C. Walton, *Molecules*, 2016, **21**, 1690; (c) M. M. Jackman, Y. Cai and S. L. Castle, *Synthesis*, 2017, **49**, 1785; (d) J. Lei, D. Li and Q. Zhu, *Top. Heterocycl. Chem.*, 2018, **54**, 285; (e) W. Yin and X. Wang, *New J. Chem.*, 2019, **43**, 3254. (f) S. P. Morcillo, *Angew. Chem. Int. Ed.*, 2019, **58**, 14044.

- 10 For reviews on these visible-light mediated processes, see: (a) J. Davies, S. P. Morcillo, J. J. Douglas and D. Leonori, *Chem. Eur. J.*, 2018, **24**, 12154; (b) H. Jiang and A. Studer, *CCS Chem.*, 2019, **1**, 38; (c) X.-Y. Yu, Q.-Q. Zhao, J. Chen, W.-J. Xiao and J.-R. Chen, *Acc. Chem. Res.*, 2020, **53**, 1066.
- 11 For selected reviews, see: (a) J. C. Walton, *Molecules*, 2016, **21**, 63; (b) J. C. Walton, *Acc. Chem. Res.*, 2014, **47**, 1406; (c) M. Kitamura and K. Narasaka, *Bull. Chem. Soc. Jpn.*, 2008, **81**, 539; (d) K. Narasaka and M. Kitamura, *Eur. J. Org. Chem.*, 2005, 4505.
- 12 H. Jiang and A. Studer, *Angew. Chem. Int. Ed.*, 2017, **56**, 12273.
- 13 J. Davies, N. S. Sheikh and D. Leonori, *Angew. Chem. Int. Ed.*, 2017, **56**, 13361.
- 14 For photocatalytic generation of iminyl radicals by oxidative SET of oximes, see: (a) E. M. Dauncey, S. P. Morcillo, J. J. Douglas, N. S. Sheikh and D. Leonori, *Angew. Chem. Int. Ed.*, 2018, **57**, 744; (b) H. Jiang and A. Studer, *Angew. Chem. Int. Ed.*, 2018, **57**, 1692; (c) F. Le Vaillant, M. Garreau, S. Nicolai, G. Gryn'ova, C. Corminboeuf and J. Waser, *Chem. Sci.*, 2018, **9**, 5883; (d) E. M. Dauncey, S. U. Dighe, J. J. Douglas and D. Leonori, *Chem. Sci.*, 2019, **10**, 7728; (e) J.-L. Tu, J.-L. Liu, W. Tang, M. Su and F. Liu, *Org. Lett.*, 2020, **22**, 1222.
- 15 For selected examples of photocatalytic generation of iminyl radicals by reductive SET of oximes, see: (a) H. Jiang, X. An, K. Tong, T. Zheng, Y. Zhang and S. Yu, *Angew. Chem. Int. Ed.*, 2015, **54**, 4055; (b) J. Davies, S. G. Booth, S. Essafi, R. A. W. Dryfe and D. Leonori, *Angew. Chem. Int. Ed.*, 2015, **54**, 14017; (c) S.-H. Cai, J.-H. Xie, S. Song, L. Ye, C. Feng and T.-P. Loh, *ACS Catal.*, 2016, **6**, 5571; (d) W. Shu and C. Nevado, *Angew. Chem. Int. Ed.*, 2017, **56**, 1881; (e) X.-Y. Yu, J.-R. Chen, P.-Z. Wang, M.-N. Yang, D. Liang and W.-J. Xiao, *Angew. Chem. Int. Ed.*, 2018, **57**, 738; (f) X.-Y. Yu, Q.-Q. Zhao, J. Chen, J.-R. Chen and W.-J. Xiao, *Angew. Chem. Int. Ed.*, 2018, **57**, 15505; (g) H. Li, A. Bunrit, J. Lu, Z. Gao, N. Luo, H. Liu and F. Wang, *ACS Catal.*, 2019, **9**, 8843; (h) T. Wang, Y.-N. Wang, R. Wang, B.-C. Zhang, C. Yang, Y.-L. Li and X.-S. Wang, *Nat. Commun.*, 2019, **10**, 5373; (i) B. Zhao, Y. Wu, Y. Yuan and Z. Shi, *Chem. Commun.*, 2020, **56**, 4676; (j) L. Feng, L. Guo, C. Yang, J. Zhou and W. Xia, *Org. Lett.*, 2020, **22**, 3964.
- 16 (a) A. Casado-Sánchez, R. Gómez-Ballesteros, F. Tato, F. J. Soriano, G. Pascual-Coca, S. Cabrera and J. Alemán, *Chem. Commun.*, 2016, **52**, 9137; (b) A. F. Garrido-Castro, H. Choubane, M. Daaou, M. C. Maestro and J. Alemán, *Chem. Commun.*, 2017, **53**, 7764; (c) A. Guerrero-Corella, A. M. Martínez-Gualda, F. Ahmadi, E. Ming, A. Fraile and J. Alemán, *Chem. Commun.*, 2017, **53**, 10463; (d) A. F. Garrido-Castro, N. Salaverri, M. C. Maestro and J. Alemán, *Org. Lett.*, 2019, **21**, 5295; (e) A. Jiménez-Almarza, A. López-Magano, L. Marzo, S. Cabrera, R. Mas-Ballesté and J. Alemán, *ChemCatChem*, 2019, **11**, 4916; (f) A. López-Magano, A. E. Platero-Prats, S. Cabrera, R. Mas-Ballesté, J. Alemán *Appl. Catal., B*, 2020, **272**, 119027.
- 17 *Heterocycles in Natural Product Synthesis*, ed. K. C. Majumdar and S. K. Chattopadhyay, Wiley-VCH, Weinheim, 2011.
- 18 (a) M. S. C. Pedras and M. Jha, *J. Org. Chem.*, 2005, **70**, 1828; (b) M. S. C. Pedras and M. Hossain, *Org. Biomol. Chem.*, 2006, **4**, 2581; (c) M. S. C. Pedras and Z. Minic, *Bioorg. Med. Chem.*, 2014, **22**, 459.
- 19 (a) A. E. Cassano, C. A. Martin, R. J. Brandi and O. M. Alfano, *Ind. Eng. Chem. Res.*, 1995, **34**, 2155; (b) J. Colina-Marquez, F. Machuca-Martinez and G. L. Puma, *Environ. Sci. Technol.*, 2010, **44**, 5112.
- 20 B. D. A. Hook, W. Dohle, P. R. Hirst, M. Pickworth, M. B. Berry and K. I. Booker-Milburn, *J. Org. Chem.*, 2005, **70**, 7558.
- 21 (a) S. Fukuzumi and K. Ohkubo, *Chem. Sci.*, 2013, **4**, 561; (b) S. Fukuzumi and K. Ohkubo, *Org. Biomol. Chem.*, 2014, **12**, 6059.
- 22 K. Ohkubo, K. Mizushima, R. Iwata, K. Souma, N. Suzuki and S. Fukuzumi, *Chem. Commun.*, 2010, **46**, 601.

GRAPHICAL ABSTRACT

