



Photoinduced oxidative cyclization of dithienylarenes

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ABSTRACT

A photoinduced electrocyclization followed by aerobic oxidation of 1,2-dithienylarene derivatives is described as a greener alternative to direct aryl-aryl couplings. The formation of the naphthodithiophene type products was monitored by UV–vis spectroscopy. Naphthodithiophenes with different structural features and electronic characters were accessed. Oxidative cyclization using the combination of $\text{BF}_3 \cdot \text{Et}_2\text{O}$ and DDQ was a complementary approach to confirm the formation of the desired products. The method was also applicable to 2,3-dithienylbiphenylene having a backbone with antiaromatic character.

1. Introduction

Mallory-type reactions have been successfully used to convert diarylethene derivatives into multiring systems through a photochemical cyclization/oxidation (or elimination) sequence [1,2]. These steps have been extended by other (photo-)rearrangements and bond cleavages leading to a great diversity of highly functionalized (hetero)cyclic conjugated molecules that are relevant in medicinal or materials chemistry [3]. While the Mallory reaction has been described to a range of thiophene-containing diarylethene and terarylene derivatives [3], it has been explored much less among dithienylbenzenes. Dithienylbenzene **1-o** has been shown to undergo photochemical ring-closing through a 6π -electrocyclization reaction (Fig. 1) [4]. The stable aromatic product naphtho[2,1-*b*:3,4-*b'*]dithiophene (**1-ox**) that formed upon aerobic oxidation of the ring-closed structure **1-c** provided evidence for the photoreaction. Generally, however, **1-ox** type naphthodithiophenes have been prepared mainly through Scholl-type oxidative cyclizations [5–11] while the photochemical approach remained rarely reported [12]. The likely reason is that previously dithienylbenzene derivatives have been considered to be “resistant” to photocyclization due to their pronounced aromaticity [13] compared to the mostly studied dithienylheteroarenes. Notably, other photochemical transformations of thiophene derivatives leading to thienyl-(hetero)arenes have been reported [14–17]. Importantly, applying the Mallory conditions to the transformation of thienyl-substituted benzenoid aromatics could be a

greener alternative to access polycyclic heteroaryl structures that are widely studied as optoelectronic materials [18–23]. In this report we explore the photoinduced electrocyclization/aerobic oxidation sequence of some dithienylarene derivatives to demonstrate the accessibility of polycyclic heteroarenes through this approach.

2. Results and discussion

In the following we first describe the results of the photochemical irradiation of different dithienylarenes under aerobic conditions followed by UV–vis spectroscopy. The products are also accessed through the Scholl-reaction [24], which corroborated the formation of the polycyclic aromatic structures (Fig. 2). Next, complementary to aromatic dithienylbenzenes, the application of the biphenylene backbone with antiaromatic character is described.

First, we explored the behavior of dithienylbenzene derivative **1-o**, and regioisomeric bis(benzothienyl)benzene derivatives **2-o** and **3-o**, which were accessible through a twofold Suzuki–Miyaura coupling between 1,2-diiodobenzene and different thienylboronic acids (for synthetic details, see Supporting Information). These compounds were expected to work as one-way molecular switches that upon UV-irradiation under aerobic conditions can be converted to their ring-closed oxidized derivatives **1-ox**, **2-ox** and **3-ox**, respectively (Fig. 2). The initial step of this conversion is a light-induced 6π -electrocyclization that leads to the closed-isomer, which is followed by aerobic oxidation.

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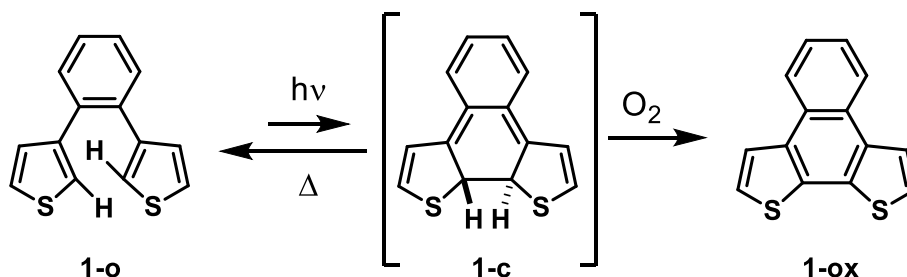


Fig. 1. Transformation of dithienylbenzene **1-o** to **1-ox** through a photoinduced electrocyclozation/aerobic oxidation sequence.

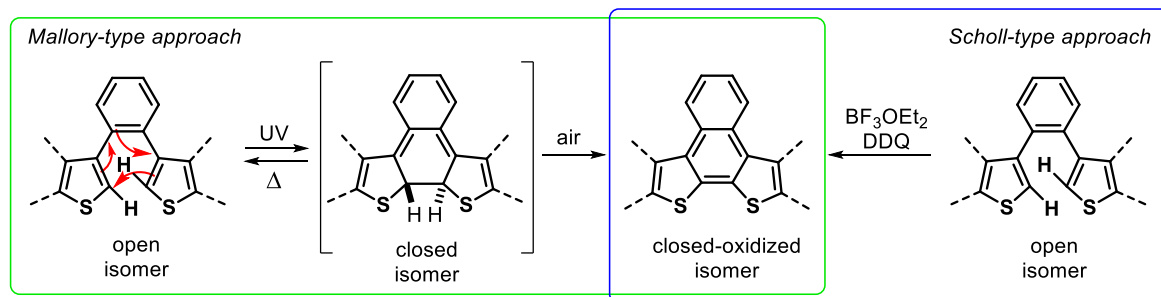


Fig. 2. Strategies to access the aryl-fused closed-oxidized isomer.

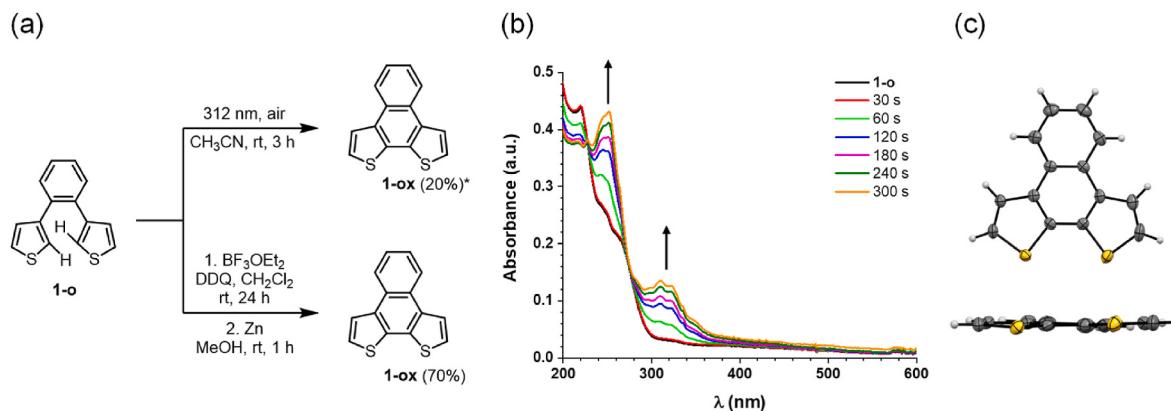


Fig. 3. (a) Conversion of **1-o** to **1-ox** by photochemical and chemical pathways; (b) changes in the UV-vis spectrum of **1-o** by time upon irradiation with 254 nm light in CH_3CN under aerobic conditions; (c) X-ray crystallographic structure of **1-ox** (ORTEP style representation is drawn at the 50 % probability level). (*Yield is based on ^1H NMR spectroscopy.)

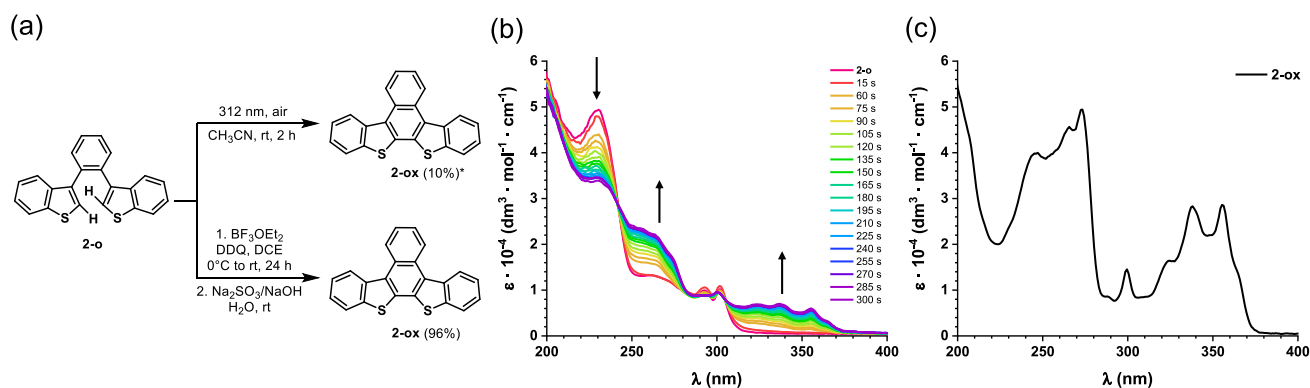


Fig. 4. (a) Conversion of **2-o** to **2-ox** by photochemical and chemical pathways; (b) changes in the UV-vis spectrum of **2-o** by time upon irradiation with 254 nm light in CH_3CN under aerobic conditions; (c) UV-vis spectrum of **2-ox** (CH_3CN , rt). (*Yield is based on ^1H NMR spectroscopy.)

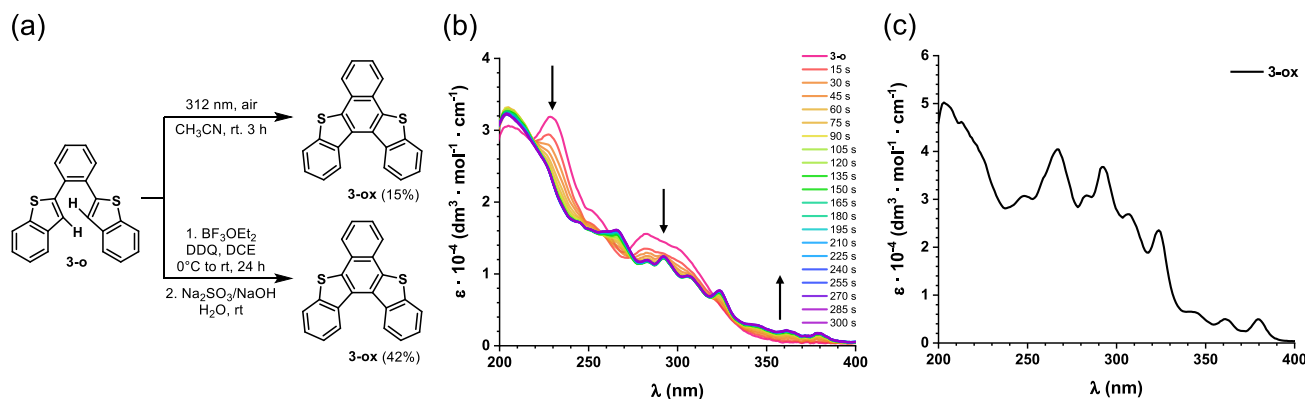


Fig. 5. (a) Conversion of **3-o** to **3-ox** by photochemical and chemical pathways; (b) changes in the UV-vis spectrum of **3-o** by time upon irradiation with 254 nm light in CH₃CN under aerobic conditions; (c) UV-vis spectrum of **3-ox** (CH₃CN, rt).

Alternatively, the ring-closed oxidized species could be accessed by a Scholl-type intramolecular oxidative coupling of the open isomers. For this, we used the combination of BF₃·Et₂O and DDQ, which was found to be an efficient method [24].

Compound **1-o** has been described previously as a photochemical one-way switch that under aerobic conditions forms compound **1-ox** (Fig. 3a) [4]. The irreversible changes in its UV-vis spectrum upon irradiation with 254 nm light indicated the formation of the stable aromatic product (Fig. 3b). Using the BF₃·Et₂O/DDQ system **1-o** could be converted to **1-ox** in good yield (Fig. 3a). Single crystals of **1-ox** suitable for X-ray crystallographic measurement could be obtained from a hexane solution upon slow evaporation of the solvent. Crystallographic analysis revealed that the polycyclic product is a planar structure (Fig. 3c).

Both the photochemical and the chemical approach were successful in the conversion of **2-o** to **2-ox** (Fig. 4a) and of regioisomeric **3-o** to **3-ox** (Fig. 5a). Upon irradiation of **2-o** with 254 nm light major changes that appeared in its spectrum included a decrease in intensity at 230 nm and an increase both at around 260 nm and in the region of 310–370 nm (Fig. 4b).

Compared to **2-o**, somewhat different changes occurred in the spectrum of **3-o** upon irradiation (254 nm). In this case, a decrease in absorption intensity was observed at 230 nm as well; however, a slight decrease in the region of 270–320 nm occurred, while the increment above 330 nm was smaller compared to that of compound **2-o** (Fig. 5b). These changes in the absorptions could be explained by the different conjugation modes of the two isomers, while the planarity of **2-ox** [6]

and the helical structure of **3-ox** [9] could also play a role. Comparison of the UV-vis spectra of the photogenerated **2-ox** and **3-ox** products with the spectra of the isolated compounds from the Scholl-type approach (Figs. 4c and 5c, respectively) showed good agreement. Notably, the chemical transformation of **3-o** yielded **3-ox** in only moderate yield (42 %) compared to that obtained in the synthesis of **2-ox** (96 %).

We also attempted the preparative scale photochemical transformation of **1-o**, **2-o** and **3-o** to their respective closed-oxidized isomers. Compound **2-o** was chosen as benchmark for the optimization of the reaction conditions, due to the low solubility of product **2-ox** in common organic solvents. We expected that its precipitation would limit the absorbance of the already formed product under continuous irradiation, thus improving the efficiency of the reaction. Furthermore, the workup of the reaction would only consist of a simple filtration. While at the low concentration of the UV-vis experiment the 254 nm irradiation led to the desired transformation, the larger scale experiment deemed more challenging. Using a 13 W 254 nm light-source (LightTech GH0436T51/4, 48 W; Arc Length 360 mm, 13 W for the 254 nm light) [25], irradiation of a solution of **2-o** (100 mg in acetonitrile) in a quartz reactor in the presence of bubbling air, rapid transformation of the starting material along with the rapid degradation of **2-ox** were observed (for further details see Supporting Information). The results could be improved by using a 312 nm light-source and acetonitrile/H₂O (4 : 1) as solvent that facilitated the precipitation of the product **2-ox**. In this way a yield of 10 % could be obtained as determined by ¹H NMR spectroscopy (for further details on quantitative ¹H NMR measurements, see Supporting Information). This approach (312 nm light,

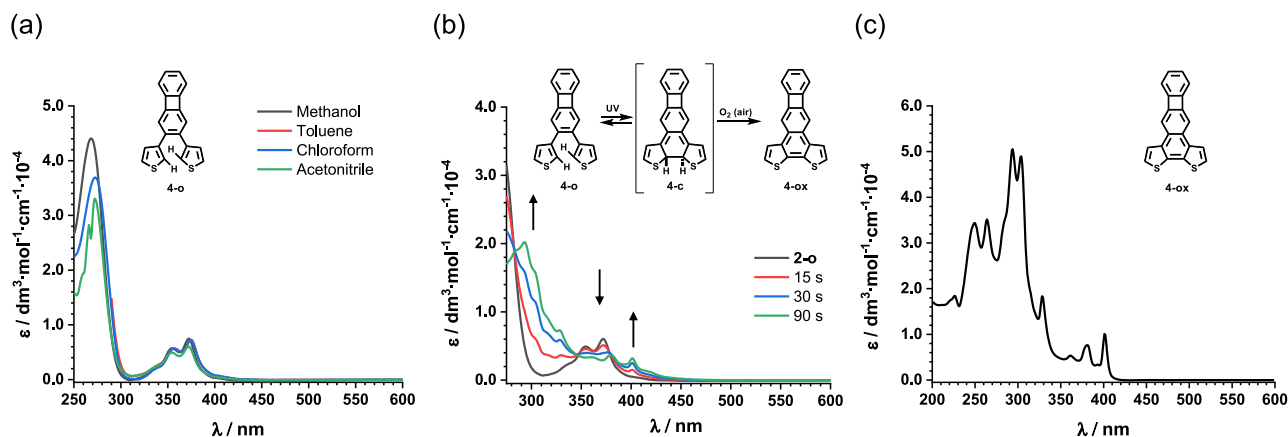


Fig. 6. (a) UV-Vis absorption spectra of compound **4-o** in different solvents; (b) changes in the UV-vis spectrum of **4-o** by time upon irradiation with 365 nm light in CH₃CN under aerobic conditions; (c) UV-vis spectrum of **4-ox** (CH₃CN, rt).

acetonitrile/H₂O (4 : 1)) was extended to the transformation of compounds **1-o** and **3-o**. While a yield (based on ¹H NMR spectroscopy) of about 20 % could be reached for **1-ox**, **3-ox** was isolated in 15 % yield. Notably, the conversion of compound **1-o** was relatively low (<25 %) after 3 h irradiation (for further details, see Supporting Information).

It is important to note that performing the Mallory oxidation on a preparative scale would prove to be a greener alternative to the currently employed direct aryl-aryl coupling methods for obtaining the ring fused compounds. Not only is the atom economy improved, since no other reagents than the precursor are needed, but the workup is also significantly more straightforward, potentially only consisting of the evaporation of solvents to yield high purity products. Both **2-ox** and **3-ox** have poor solubilities in common organic solvents, therefore classical purification steps such as column chromatography or recrystallisation could not be carried out. Instead, following the BF₃·Et₂O/DDQ induced transformation, we opted for several washing steps with copious amounts of different solvents (see the Supporting Information). According to the ¹H NMR spectra of the pure compounds, this method sufficed. Additionally, UV–vis spectroscopy confirmed that all residual DDQ/DDQH₂ was successfully removed. For device fabrication purposes, further purification by sublimation of these compounds could prove successful.

Complementary to the synthesis of naphthodithiophenes **1-ox**, **2-ox** and **3-ox** that were discussed above, we also studied the formation of biphenylene-fused benzodithiophene **4-ox** using the Mallory conditions (Fig. 6). Notably, the benzene ring of biphenylene in **4-o** that contains the thiophene substituents exhibits lower aromaticity than benzene [26], which facilitates the first, photochemical electrocyclization step towards **4-ox** [27]. Compound **4-o** was accessible through a palladium catalyzed twofold Suzuki-Miyaura cross-coupling between 2,3-diiodobiphenylene and commercially available 3-thienylboronic acid (for synthetic details, see Supporting Information). The photochemical behaviour of **4-o** was investigated by UV–vis spectroscopy. Its absorption spectra displayed an intense absorption band at 270 nm and three less intense peaks at 335 nm, 354 nm, and 374 nm. No changes in the absorption bands were detected when the spectra were recorded in different protic or aprotic solvents.

Next, a sample of compound **4-o** was irradiated with 365 nm light under air, which yielded new, sharp absorption bands at 290 nm, 300 nm, 330 nm, 380 nm, and 400 nm irreversibly (Fig. 6). After prolonged irradiation the photoproduct was isolated and characterized, which supported the formation of **4-ox**.

Overall, we have shown the Mallory reaction is a reasonable approach to access π -extended naphthodithiophenes with different electronic characters from dithienylbenzenes and the method can be extended to backbones with antiaromatic character. Nevertheless, for a synthetically practical photochemical process further tuning of the oxidants and conditions will be necessary.

3. Conclusions

In conclusion, we have demonstrated the possibility to use UV-light and air as an oxidant to access thiophene-containing polycyclic aromatic systems from dithienyl-arene derivatives. The formation of the product from dithienylbenzene derivatives was monitored by UV–vis spectroscopy. Preparative-scale photochemical transformation has proved to be challenging due to uncontrolled side-reactions. As a complementary approach, to support their photochemical formation, the products were also prepared using the combination of BF₃·Et₂O and DDQ. Overall, the photoinduced electrocyclization/aerobic oxidation sequence could be used as a greener alternative of metal-catalyzed approaches, however further tuning of reaction conditions is necessary for larger-scale synthesis.

CRediT authorship contribution statement

Barnabás Zsignár-Nagy: Writing – original draft, Methodology, Investigation, Formal analysis. **Viktória Kümmel:** Methodology, Investigation. **Tamás Gazdag:** Supervision, Methodology, Investigation, Formal analysis. **Péter J. Mayer:** Supervision, Methodology, Investigation, Formal analysis. **Zsófia Bokor:** Methodology, Investigation. **Tamás Holczbauer:** Methodology, Investigation, Formal analysis. **Gábor London:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Data availability

Data is available in the Supporting Information.

CCDC 2417162 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/structures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tgchem.2025.100076>.

Data availability

Data is available in the Supporting Information. CCDC 2417162 contains the supplementary crystallographic data for this paper.

References

- [1] F.B. Mallory, C.S. Wood, J.T. Gordon, Photochemistry of Stilbenes. III. Some aspects of the mechanism of photocyclization to phenanthrenes, *J. Am. Chem. Soc.* 86 (15) (1964) 3094–3102.
- [2] K.B. Jørgensen, Photochemical oxidative cyclisation of stilbenes and stilbenoids—the mallory-reaction, *Molecules* 15 (6) (2010) 4334–4358.

- [3] A.G. Lvov, Switching the mallorey reaction to synthesis of Naphthalenes, Benzannulated heterocycles, and their derivatives, *J. Org. Chem.* 85 (14) (2020) 8749–8759.
- [4] B. Oruganti, P.P. Kalapos, V. Bhargav, G. London, B. Durbjee, Photoinduced changes in aromaticity facilitate electrocyclization of dithienylbenzene switches, *J. Am. Chem. Soc.* 142 (32) (2020) 13941–13953.
- [5] A.A.O. Sarhan, C. Bolm, Iron(III) chloride in oxidative C–C coupling reactions, *Chem. Soc. Rev.* 38 (9) (2009) 2730–2744.
- [6] H.T. Black, S. Liu, V.S. Ashby, Synthesis, crystal structures, and electronic properties of nonlinear fused thienoacene semiconductors, *Org. Lett.* 13 (24) (2011) 6492–6495.
- [7] I. Nagao, M. Shimizu, T. Hiyama, 9-Stannfluorenes: 1,4-dimetal equivalents for aromatic annulation by double cross-coupling, *Angew. Chem. Int. Ed.* 48 (41) (2009) 7573–7576.
- [8] B. Rungtaweeworani, A. Butsuri, K. Wongma, K. Sadorn, K. Neranon, C. Nerungsi, T. Thongpanchang, A facile two-step synthesis of thiophene end-capped aromatic systems, *Tetrahedron Lett.* 53 (14) (2012) 1816–1818.
- [9] M. Schubert, S. Trosien, L. Schulz, C. Brandscheid, D. Schollmeyer, S.R. Waldvogel, Oxidative (Cross-)Coupling reactions mediated by C–H activation of thiophene derivatives by using molybdenum(V) reagents, *Eur. J. Org. Chem.* (32) (2014) 7091–7094.
- [10] T. Wirtanen, S. Aikonen, M. Muuronen, M. Melchionna, M. Kemell, F. Davodi, T. Kallio, T. Hu, J. Helaja, Carbocatalytic oxidative dehydrogenative couplings of (Hetero)Aryls by oxidized multi-walled carbon nanotubes in liquid phase, *Chem. Eur. J.* 25 (53) (2019) 12288–12293.
- [11] E.B.A. Adusei, V.T. Casetti, C.D. Goldsmith, M. Caswell, D. Alinj, J. Park, M. Zeller, A.A. Rusakov, Z.J. Kinney, Bent naphthodithiophenes: synthesis and characterization of isomeric fluorophores, *RSC Adv.* 14 (35) (2024) 25120–25129.
- [12] D. Waghay, W. Nulens, W. Dehaen, Efficient synthesis of Benzo fused Tetrathia[7] helicenes, *Org. Lett.* 13 (20) (2011) 5516–5519.
- [13] J.V. Milić, C. Schaack, N. Hellou, F. Isenrich, R. Gershoni-Poranne, D. Neshchadin, S. Egloff, N. Trapp, L. Ruhlmann, C. Boudon, G. Gescheidt, J. Crassous, F. Diederich, Light-responsive pyrazine-based systems: probing aromatic diarylethene photocyclization, *J. Phys. Chem. C* 122 (33) (2018) 19100–19109.
- [14] R. Antonioletti, M. D'Auria, F. D'Onofrio, G. Piancatelli, A. Scettri, Photochemical synthesis of phenyl-2-thienyl derivatives, *J. Chem. Soc., Perkin Trans. 1* (1986) 1755–1758.
- [15] M. D'Auria, C. Distefano, F. D'Onofrio, G. Mauriello, R. Racioppi, Photochemical substitution of polyhalogenothiophene and halogenothiazole derivatives, *J. Chem. Soc., Perkin Trans. 1* (2000) 3513–3518.
- [16] M. Amati, S. Belviso, M. D'Auria, F. Lelj, R. Racioppi, L. Viggiani, Tandem photoarylation–photoisomerization of halothiazoles: synthesis, photophysical and singlet oxygen activation properties of ethyl 2-Arylthiazole-5-carboxylates, *Eur. J. Org. Chem.* (2010) 3416–3427.
- [17] B. Roure, M. Alonso, G. Lonardi, D.B. Yildiz, C.S. Buettner, T. dos Santos, Y. Xu, M. Bossart, V. Derdau, M. Méndez, J. Llaveria, A. Ruffoni, D. Leonori, Photochemical permutation of Thiazoles, isothiazoles and other azoles, *Nature* 637 (2025) 860–867.
- [18] J.E. Anthony, Functionalized acenes and heteroacenes for organic electronics, *Chem. Rev.* 106 (12) (2006) 5028–5048.
- [19] I. Osaka, S. Shinamura, T. Abe, K. Takimiya, Naphthodithiophenes as building units for small molecules to polymers; a case study for in-depth understanding of structure–property relationships in organic semiconductors, *J. Mater. Chem. C* 1 (7) (2013) 1297–1304.
- [20] K. Takimiya, I. Osaka, Naphthodithiophenes: emerging building blocks for organic electronics, *Chem. Rec.* 15 (1) (2015) 175–188.
- [21] H.-A. Lin, N. Mitoma, L. Meng, Y. Segawa, A. Wakamiya, K. Itami, Hole-transporting materials based on thiophene-fused arenes from sulfur-mediated thienannulations, *Mater. Chem. Front.* 2 (2) (2018) 275–280.
- [22] X. Shen, X. Lai, H. Lai, T. Zhao, Y. Zhu, M. Pu, H. Wang, P. Tan, F. He, Isomerism strategy to optimize aggregation and morphology for superior polymer solar cells, *Macromolecules* 55 (15) (2022) 6384–6393.
- [23] M. Su, M. Lin, S. Mo, J. Chen, X. Shen, Y. Xiao, M. Wang, J. Gao, L. Dang, X.-c. Huang, F. He, Q. Wu, Manipulating the alkyl chains of naphthodithiophene imide-based polymers to concurrently boost the efficiency and stability of organic solar cells, *ACS Appl. Mater. Interfaces* 15 (31) (2023) 37371–37380.
- [24] D. Waghay, C. de Vet, K. Karypidou, W. Dehaen, Oxidative transformation to naphthodithiophene and thia[7]helicenes by intramolecular Scholl reaction of substituted 1,2-Bis(2-thienyl)benzene precursors, *J. Org. Chem.* 78 (22) (2013) 11147–11154.
- [25] D. Krakkó, Á. Illés, A. Domján, A. Demeter, S. Dóbe, G. Záray, UV and (V)UV irradiation of sitagliptin in ultrapure water and WWTP effluent: kinetics, transformation products and degradation pathway, *Chemosphere* 288 (2) (2022) 132393.
- [26] R. Ayub, O. El Bakouri, K. Jorner, M. Solà, H. Ottosson, Can Baird's and Clar's Rules combined explain triplet state energies of polycyclic conjugated hydrocarbons with fused $4n\pi$ - and $(4n + 2)\pi$ -rings? *J. Org. Chem.* 82 (12) (2017) 6327–6340.
- [27] P.P. Kalapos, P.J. Mayer, T. Gazdag, A. Demeter, B. Oruganti, B. Durbjee, G. London, Photoswitching of local (Anti)Aromaticity in biphenylene-based diarylethene molecular switches, *J. Org. Chem.* 87 (15) (2022) 9532–9542.