Photocatalytic Activation of Carboxylic Acids and Diol Derivatives

Dissertation

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Johanna Schwarz
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Board of examiners:

Prof. Dr. Arno Pfitzner	(Chair)
Prof. Dr. Burkhard König	(1st Referee)
Prof. Dr. Frank-Michael Matysik	(2nd Referee)
Prof. Dr. Alexander Breder	(Examiner)

to Michael and Jonas

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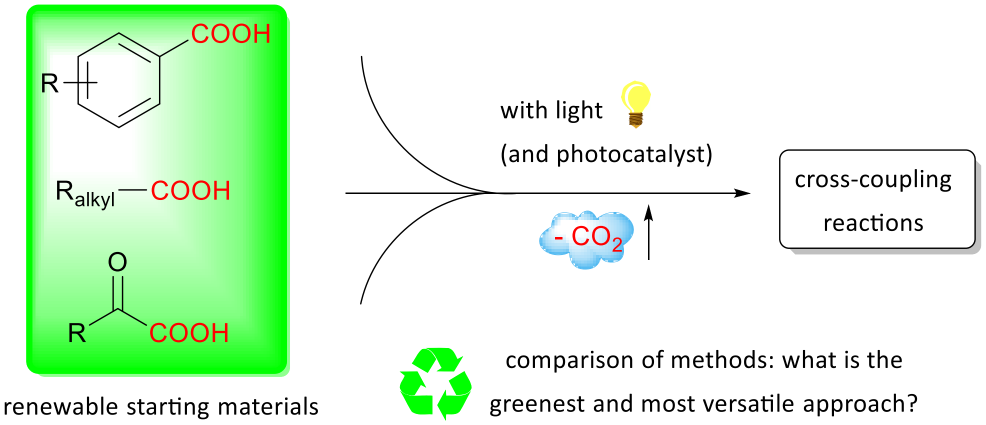

During the last years, the field of photocatalytic decarboxylations has emerged rapidly. Carboxylic acids are inexpensive, non-toxic and renewable starting materials for the synthesis of pharmacfffeuticals or platform chemicals. The traceless extrusion of CO_2 gives radical intermediates, that react in diverse cross-coupling reactions. Merging photocatalysis with metal catalysis enables even broader substrate scopes or enantioselective reactions. An overview of photocatalytic decarboxylative reactions of different classes of carboxylic acids is given within this chapter.

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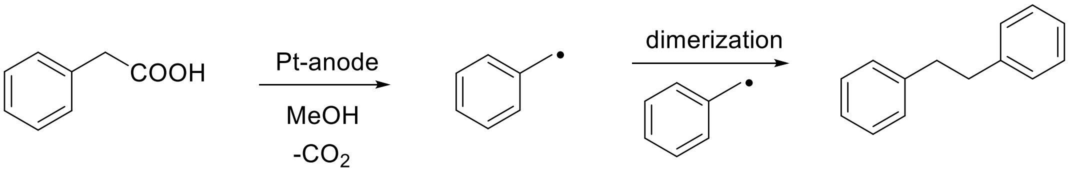
For a more detailed version (including decarboxylative reactions which are not light-mediated) see: “Decarboxylative reactions with and without light – a comparison”, J. Schwarz and B. König, *Green Chem.*, **2018**, *20*, 323-361.

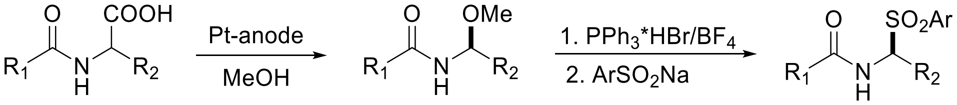
1.1. Introduction

Carboxylic acids exhibit several interesting properties, which predestines them as suitable starting materials for photocatalysis or synthesis in general: they are bench-stable, non-toxic, abundant and therefore cheap. Furthermore, a lot of carboxylic acids can be derived directly from renewable feedstocks instead of fossil resources like oil and gas.[1] A broad structural diversity of carboxylic acids can be found in nature. E.g. amino acids, fatty acids or sugar acids could be employed as suitable starting materials for different decarboxylative cross-coupling reactions.[2] The carboxy group serves as regio- and chemoselective leaving group. Compared to halides, CO_2 is less toxic and leaves the reaction mixture traceless by itself. Moreover, especially the natural chirality of many biomass-derived carboxylic acids is interesting. If decarboxylative C–C bond formations with these compounds could be carried out under retention of the configuration, the stereoselective synthesis of enantiopure pharmaceuticals could be achieved much more easily.

During the last few years, the number of reports on photocatalytic decarboxylation reactions has been growing rapidly and catches up with the classical metal-catalyzed methods. We give a brief overview of the history and the original utilization of carboxylic acids for organic synthesis. In 1848, the first decarboxylative C–C bond formation has been reported by Kolbe.[3] Scheme 1-1 shows a typical example for this electrochemical dimerization.[4] As cross-couplings are hard to achieve via this radical reaction, the application of this method is quite limited. Nevertheless, some modern electrochemical variants enable even cross-couplings (Scheme 1-2)[5].



Scheme 1-1. Kolbe reaction: decarboxylative dimerization of phenylacetic acid.



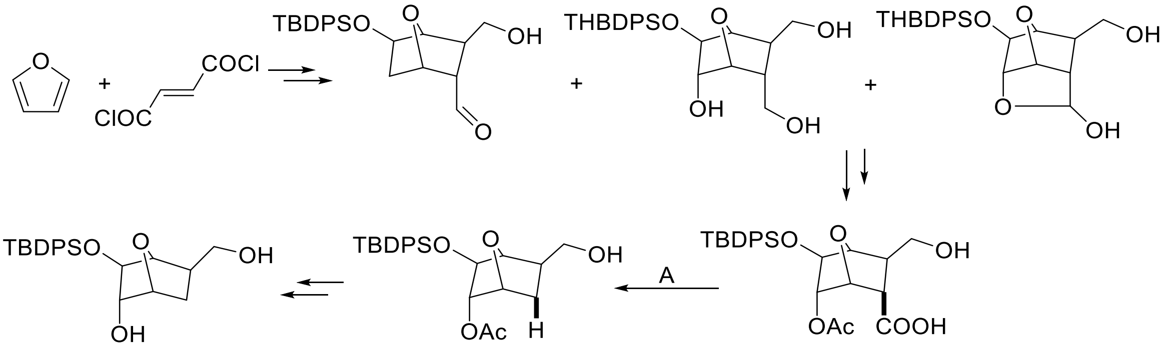
Scheme 1-2. Modern, decarboxylative cross-coupling via electrochemistry.

Also the Hunsdiecker reaction is a classic decarboxylation method, which has been developed further. Here, the oxidative decarboxylation is achieved by stoichiometric amounts of silver salt and subsequent trapping of the thus generated alkyl radicals by halides.[6] Modern procedures require only catalytic amounts of metal salts for the decarboxylative halogenation (Scheme 1-3).[7]

$$R_{alkyl}\text{–}COOH \xrightarrow[CH_3CN,\ rt\ or\ 45\ °C]{Ag(Phen)_2OTf\ (cat),\ t\text{-}BuOCl} R\text{–}Cl$$

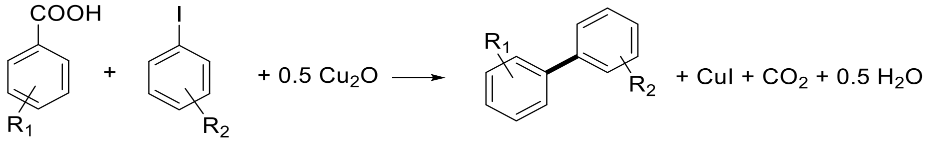
Scheme 1-3. Hunsdiecker-type reaction with catalytic amounts of silver salt.

A typical decarboxylative reduction is the Barton decarboxylation. For this reaction, highly toxic tin hydrides and additional activators (e.g. AIBN, *N*-hydroxypyridine-2-thione) are needed.[8] Therefore, the method is restricted almost exclusively to the last defunctionalizing steps in the synthesis of natural compounds (Scheme 1-4).[9]



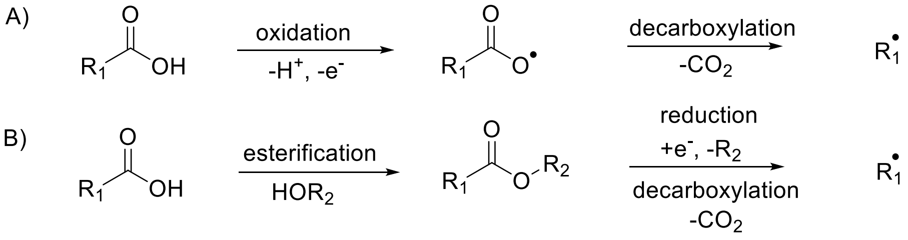
Scheme 1-4. An example of a Barton decarboxylation (A) for the synthesis of a natural compound.

The breakthrough for metal-catalyzed decarboxylative chemistry was the decarboxylative Ullman reaction. This cross-coupling of two aromatic compounds is catalyzed by copper and was reported by Nilsson *et al.* in 1966 (Scheme 1-5).[10] After that, especially after the year 2000, a vast range of transition metal-catalyzed, decarboxylative C_{sp2}–C_{sp2} bond formations have been developed, e.g. by Gooßen *et al.*[11] The carboxy group is used as versatile leaving group for cross-coupling reactions, for example for decarboxylative Suzuki reactions[11a, 12] or Heck-type olefinations.[13] However, the metal-catalyzed reactions show several disadvantages. First of all, alkyl acids, which are the most abundant carboxylic acids in nature, are usually not suitable for these reactions. Moreover, the reactions usually require high temperatures and the transition metal catalysts are often toxic and expensive.



Scheme 1-5. Decarboxylative Ullman reaction with aromatic carboxylic acids and aryl iodides.

Therefore, photochemical alternatives have been developed during the last years. With the energy source light instead of heat, milder reaction conditions can be applied. UV-light was usually used for the first methods, but this light source exhibits several drawbacks: high energy consumption, the formation of undesired side-products as well as the decomposition of the starting materials. Nowadays, photoredox-catalytic approaches are developed. Here, visible light is used for the generation of radicals from carboxylic acids. In contrast to metal-catalyzed approaches, the photocatalytic reactions are most suitable for alkyl acids and show in general a different substrate scope. A detailed comparison between light- and metal-catalyzed decarboxylative reactions is given in our recent review.[14] In principle, the decarboxylative radical formation can be achieved via two different mechanisms: either the carboxylate itself is oxidized or a pre-formed active ester is reduced by a photocatalyst (Scheme 1-6). In the following, an overview of the most important photocatalytic, decarboxylative reactions is given. The chapter is divided according to the hybridization of the radicals, which are generated upon decarboxylation, and by the substrate class of the carboxylic acid starting material.



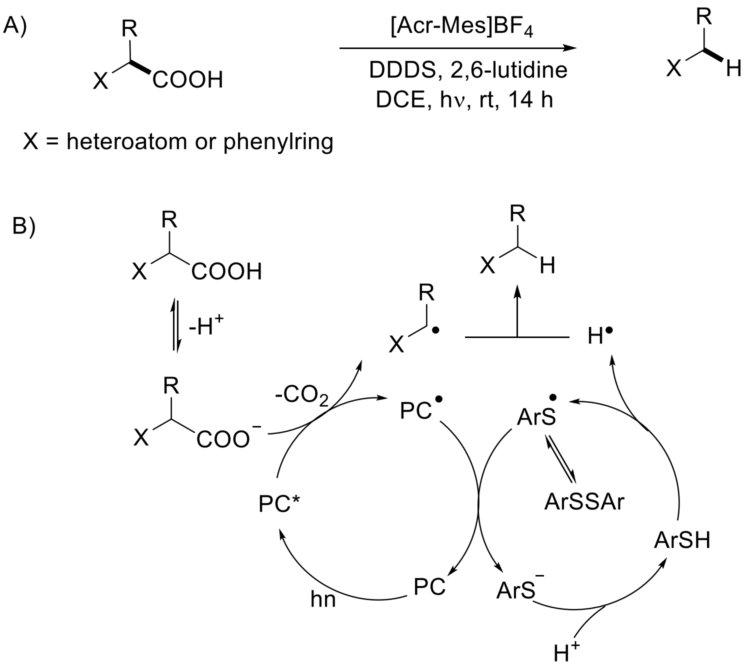
Scheme 1-6. Two mechanistic pathways for the decarboxylative generation of radicals from carboxylic acids. A) Via direct oxidation of the acid or rather the carboxylate; B) Via esterification and reduction of the formed active ester (R_2 is usually a phthalimide).

1.2. Decarboxylative Reactions

1.2.1. Reactions *via* sp^3-Hybridized Radicals from Alkyl Carboxylic Acids

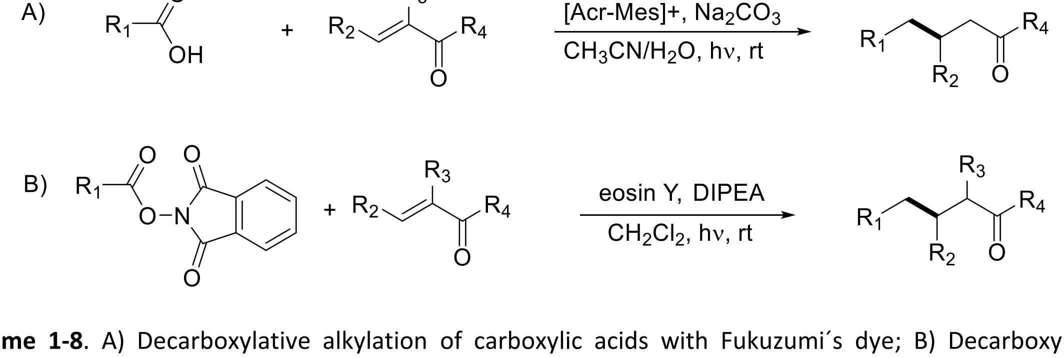
Many photocatalytic, decarboxylative cross-couplings of C_{sp3}–COOH carboxylic acids have been developed, especially during the last four years.[15] For these substrates, the photocatalytic methods are even more common and versatile than transition metal-catalyzed variants. By irradiation with visible light in the presence of a photocatalyst, CO_2 is extruded, which generates alkyl radicals. Typically, these photocatalytic decarboxylations work best for tertiary or benzylic acids, as the formed radicals show improved stability compared to primary acids, which often give only low product yields. First, several iridium-catalyzed methods were developed and the scope of trapping reagents for the alkyl radicals was investigated and extended enormously. Later on, several methods employed organic dyes as catalysts, which are a cheap and non-toxic alternative to transition metal-photocatalysts.[16]

Protodecarboxylation: The photocatalytic reduction of C_{sp3}–COOH to C_{sp3}–H has been reported first by Wallentin *et al.* in 2014.[17] The organic dye 9-mesityl-10-methylacridinium tetrafluoroborate ([Acr-Mes]BF_4) and blue light catalyze the reaction in the presence of disulfides as hydrogen atom donor and the base 2,6-lutidine, which generates the carboxylate (Scheme 1-7). Although the yields are good, the method works only for stabilized carboxylic acids like α-hetero acids and phenyl acids. One year later, Nicewicz reported a similar method for non-stabilized alkyl acids. Here, the same photocatalyst is used, but KO*t*Bu serves as the base and trifluoroethanol as the solvent.[18]



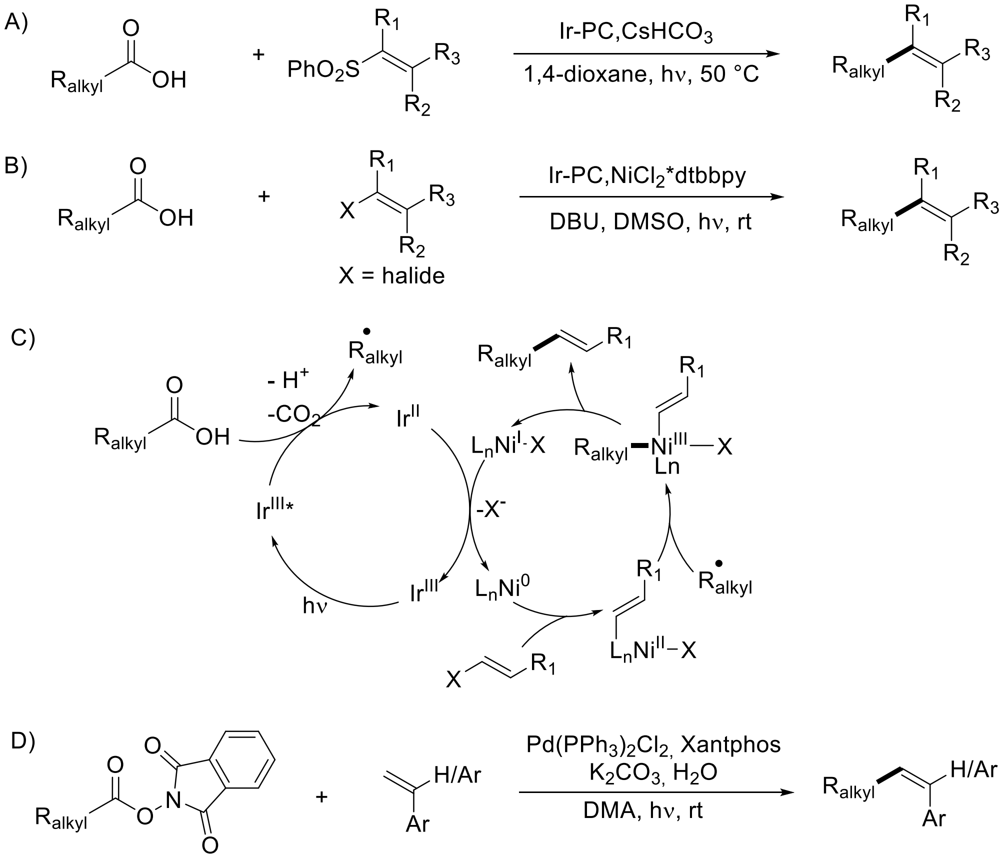
Scheme 1-7. A) General reaction for the protodecarboxylation catalyzed by Fukuzumi´s dye; B) Proposed mechanism for the photocatalytic protodecarboxylation.

Alkylation: The decarboxylative alkylation of alkyl acids is usually achieved by trapping of the alkyl radical with Michael acceptors (the so-called Giese reaction). The decarboxylation to the alkyl radical can be achieved oxidatively with an iridium-photocatalyst[19] or metal-free with Fukuzumi´s dye ([Acr-Mes]$^+$) (Scheme 1-8A).[20] Next to amino and α-oxy acids, even α-keto acids can be used for this reaction. For substrates without any heteroatom in the α-position, only secondary or tertiary acids give product. Besides this oxidative decarboxylation, also a reductive pathway is possible, if active esters are pre-formed from the carboxylic acids. This reductive alkylation of *N*-(acyloxy)phthalimides has been reported using Hantzsch ester and a ruthenium catalyst[21] or a fluorinated thiol.[22] König´s group developed a reductive approach using green light and the organic dye eosin Y as photocatalyst (Scheme 1-8B).[23] The scope of this method is broad and includes amino acids, α-oxy acids and other natural compounds like fatty acids, although the yield is lower for the latter substrates.



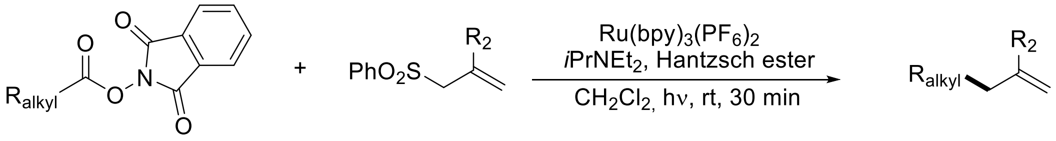
Scheme 1-8. A) Decarboxylative alkylation of carboxylic acids with Fukuzumi´s dye; B) Decarboxylative alkylation via active esters with eosin Y.

Vinylation: In contrast to the above mentioned decarboxylative addition to electron-deficient alkenes, which gives alkyls, cross-coupling with other alkenes is also possible under preservation of the double bond. The group of MacMillan developed iridium-catalyzed, photocatalytic approaches for the direct, decarboxylative vinylation. In 2014, they investigated the cross-coupling with vinyl sulfones (Scheme 1-9A)[24] and one year later, a method for the coupling with vinyl halides with an additional nickel-catalyst was developed (Scheme 1-9B).[25] This dual catalytic approach allowed the expansion of the scope from only amino acids to additionally α-oxy acids, a tertiary carboxylic acid and phenyl acetic acid. Compared to the reaction with sulfones, the photocatalytic system was improved in the case of vinyl halides as coupling-partners: the light source was changed to blue LEDs instead of a CFL-bulb and no additional heating to 50 °C is necessary anymore. However, a nickel-catalyst is needed, which reacts in an oxidative addition with the vinyl halide and adds to the formed alkyl radical. The detailed mechanism is shown in Scheme 1-9C. In 2018, Fu *et al.* developed a vinylation method for aliphatic acids with a palladium-photocatalyst (Scheme 1-9D).[26] The cross-coupling of *N*-(acyloxy)phthalimides with vinyl (hetero)arenes is catalyzed by $Pd(PPh_3)_2Cl_2$, Xantphos and blue light at room temperature. The scope of this Heck type reaction includes secondary, tertiary and quaternary carboxylates. Regarding the mechanism, it is believed that the photoexcited catalyst generates an alkyl palladium species and that undesired β-hydride elimination is suppressed by irradiation.



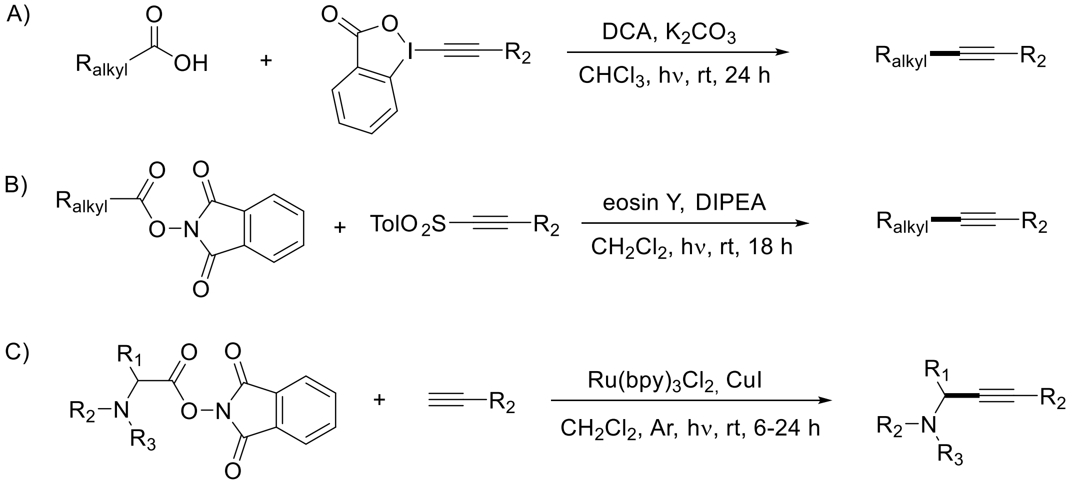
Scheme 1-9. A) Decarboxylative vinylation with vinyl sulfones and iridium; B) Decarboxylative vinylation with vinyl halides and dual catalysis; C) Mechanism of decarboxylative vinylation by dual catalysis; D) Decarboxylative vinylation with a palladium-photocatalyst.

Allylation: The intermolecular, decarboxylative allylation of alkyl acids has been reported by Chen *et al.*[27] In the presence of [Ru(bpy)$_3$](PF$_6$)$_2$, Hantzsch ester, *i*PrNEt$_2$ and blue light, the *N*-(acyloxy)-phthalimides of carboxylic acids are reduced to alkyl radicals, that react with allylic sulfones (Scheme 1-10). This reaction is with 30 min fast and gives the allylated product in good yields, but both starting-materials have to be pre-synthesized and due to the big leaving groups, a lot of atomic waste is generated. For the direct, decarboxylative allylation via C–H activation, Ir(ppy)$_2$(bpy)PF$_6$ and Cs$_2$CO$_3$ can be employed, but then the substrate scope of acids is limited to *N*-arylglycine derivatives.[28]



Scheme 1-10. Decarboxylative allylation with allylic sulfones.

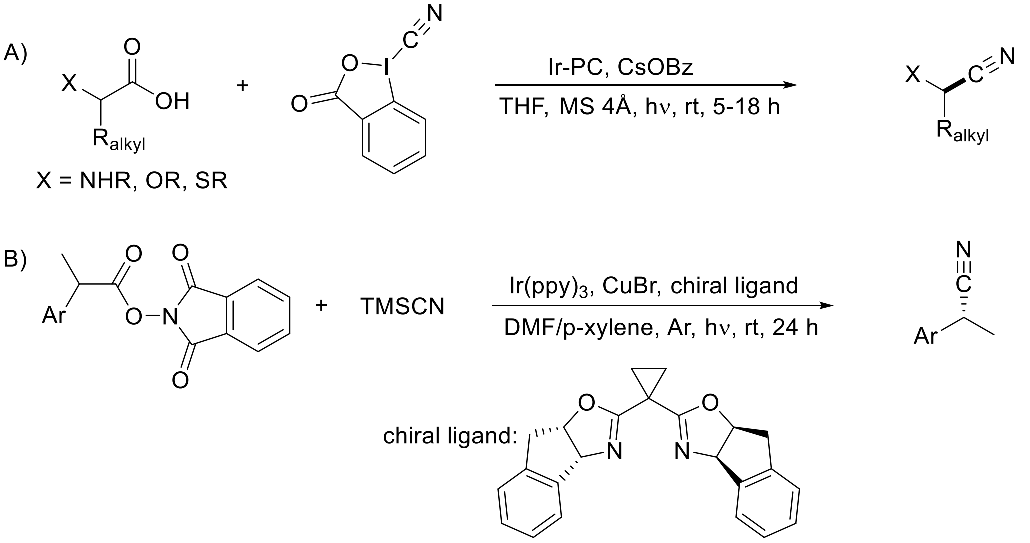
Alkynylation: For the synthesis of e.g. pharmaceuticals, the introduction of a triple bond by decarboxylation is an important reaction. Usually, this is achieved via activation of a leaving group (LG) on the alkyne. Cheng´s group used a hypervalent iodine reagent as cross-coupling partner for carboxylic acids and the method is carried out with the metal-free catalyst 9,10-dicyanoanthracene and blue light (Scheme 1-11A).[29] Similar methods have been reported previously using iridium-photocatalysts.[30] Another suitable leaving group is the sulfone moiety. This alkynylation was recently developed further by König *et al.* and works in the presence of the organic dye eosin Y, DIPEA (*N,N*-diisopropylethylamine) and under irradiation with green LEDs (Scheme 1-11B).[31] This method was initially carried out with a much more expensive ruthenium-catalyst.[32] Notably, the eosin Y-catalyzed method shows good yields and a very broad substrate scope including amino acids, α-oxy acids (like sugar acids), fatty acids and complex natural compounds. Nevertheless, the corresponding *N*-(acyloxy)phthalimides have to be synthesized from the corresponding acids *in situ* or in advance. More efficient is the alkynylation via direct C–H activation of a terminal alkyne, because besides the active ester, no additional leaving group is required. In 2017, a dual catalytic method was published by Fu *et al.*: copper iodide was merged with the photocatalyst [Ru(bpy)$_3$]Cl$_2$



Scheme 1-11. Decarboxylative alkynylation of alkyl acids. A) With hypervalent iodine reagents and DCA; B) With sulfone alkynes and eosin Y; C) With terminal alkynes and dual catalysis.

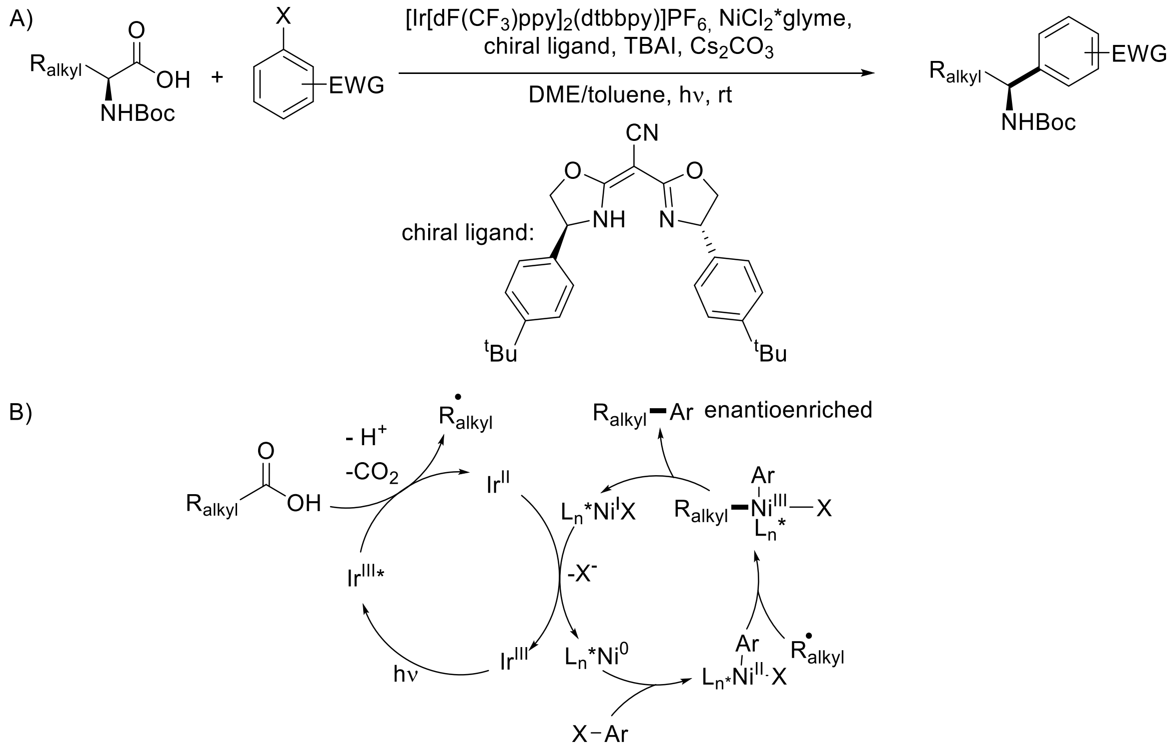
and irradiated with the substrates under argon atmosphere (Scheme 1-11C).[33] However, this method works only for amino acid derivatives.

A very special form of alkynylation is the **cyanation**. A recently developed method utilizes cyanobenziodoxone (CBX) reagents in the presence of the photocatalyst $[Ir[dF(CF_3)ppy](dtbbpy)]PF_6$, the base CsOBz and blue LEDs (Scheme 1-12A).[30c, 34] The reaction works for α-amino, oxy or thio acids. Liu *et al.* reported recently even an enantioselective method.[35] The combination of an iridium-photocatalyst, blue light and an asymmetric copper-catalyst yields enantiomerically enriched alkyl nitriles (Scheme 1-12B). According to the proposed mechanism, the active esters are decarboxylated via reduction by the excited photocatalyst. This gives benzylic radicals, which react with the chiral copper-complex that has a cyano ligand from TMSCN. The method gives high enantioselectivities (82-99% *ee*), especially for sterically bulky substrates. Moreover, functional group compatibility and yields are good, but the substrate scope is limited to benzylic derivatives.



Scheme 1-12. A) Decarboxylative cyanation with an iridium-photocatalyst; B) Enantioselective cyanation of benzylic acids by dual catalysis.

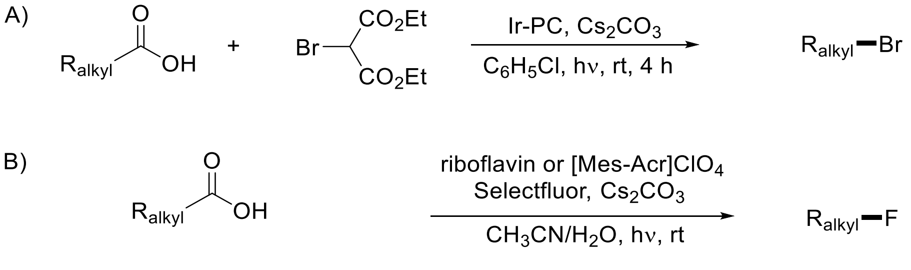
Arylation: The cross-coupling of alkyl acids with aromatic compounds can be achieved via activation of different leaving groups on the aromatic ring. Initially, MacMillan *et al.* developed in 2014 the decarboxylative arylation of amino acids by utilization of the cyano leaving group. In the presence of the catalyst Ir[*p*F(*t*Bu)ppy]$_3$, electron-deficient arenes were suitable coupling-partners.[36] The same year, they published the arylation of amino acids with aryl halides, but therefore, a dual catalytic system consisting of $[Ir[dF(CF_3)ppy]_2(dtbbpy)]PF_6$ and $NiCl_2$*glyme is necessary.[37] Notably, in 2016, this method was extended to one of the rare examples for an enantioselective, decarboxylative reaction (Scheme 1-13A).[38] By addition of a chiral ligand, good enantiomeric excesses (82-93% *ee*) are achieved. The prochiral α-amino radical is presumably intercepted by the chiral nickel-catalyst, which enables the formation of benzylic amines, starting from readily available amino acids (Scheme 1-13B). Next to cyanides and halides, also sulfonates are suitable leaving groups. Phenol-derived mesylates, tosylates and triflates can react with *N*-aryl glycines by combining again an iridium- and a nickel-catalyst.[39]



Scheme 1-13. A) General reaction scheme for the enantioselective, decarboxylative arylation of alkyl acids by dual catalysis; B) Proposed mechanism for the enantioselective arylation.

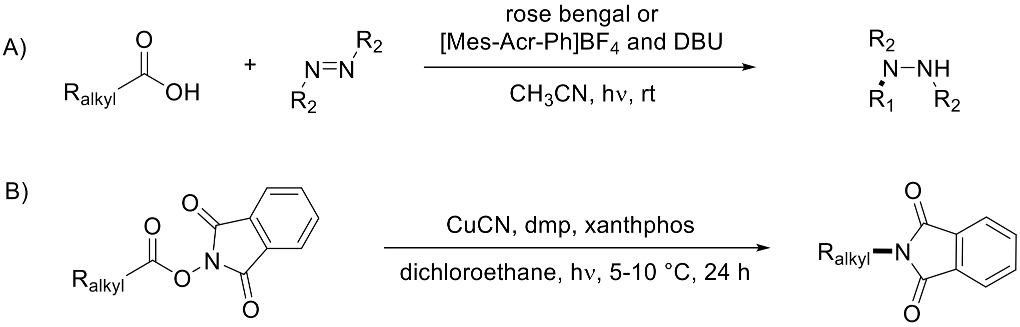
C–Heteroatom bond formations:

Photocatalytic **halogenations** are good alternatives to classical Hunsdiecker reactions, which require stoichiometric amounts of metal salts.[6] The decarboxylative bromination has been developed by Glorius *et al.* Therefore, the photocatalyst $[Ir[dF(CF_3)ppy](dtbbpy)]PF_6$, diethyl bromomalonate as bromine source, Cs_2CO_3 and blue light is required (Scheme 1-14A).[40] Under these mild conditions, primary, secondary and tertiary alkyl acids can be brominated within 4 h. For primary acids, lower product yields (about 50%) are observed. This approach can be employed even for chlorinations and iodinations if the corresponding *N*-halogen succinimides are used instead of bromomalonate. For fluorinations, the metal-free, organic dyes riboflavin or $[Mes\text{-}Acr]ClO_4$ can be used in combination with Selectfluor® as fluorinating agent (Scheme 1-14B).[41] Although secondary or tertiary alkyl acids as well as amino or α-oxy acids work, the scope of this method does not include primary (fatty) acids without any heteroatoms.



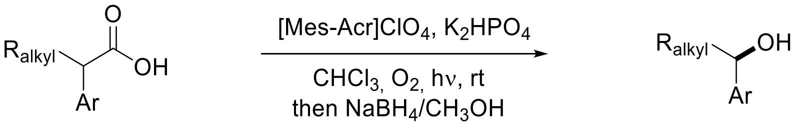
Scheme 1-14. A) Decarboxylative bromination by iridium-catalysis; B) Decarboxylative fluorination with organic dyes.

The decarboxylative **amination** has been reported by cross-coupling of alkyl acids with electrophilic diazo compounds in the presence of organic dyes (Scheme 1-15A). This reaction works for indoline-2-carboxylic acids with the photocatalyst rose bengal[42] or for a broad range of different substituted alkyl acids with [Mes-Acr-Ph]BF_4 and the base DBU.[43] Starting from the *N*-(acyloxy)phthalimides of alkyl acids, reductive decarboxylation and cross-coupling of the alkyl radical with the nitrogen of the phthaloyl leaving group can be achieved by photocatalysis with CuCN (Scheme 1-15B).[44] For this extrusion of CO_2, which yields protected amines, a temperature of 5 to 10 °C and blue light is necessary.



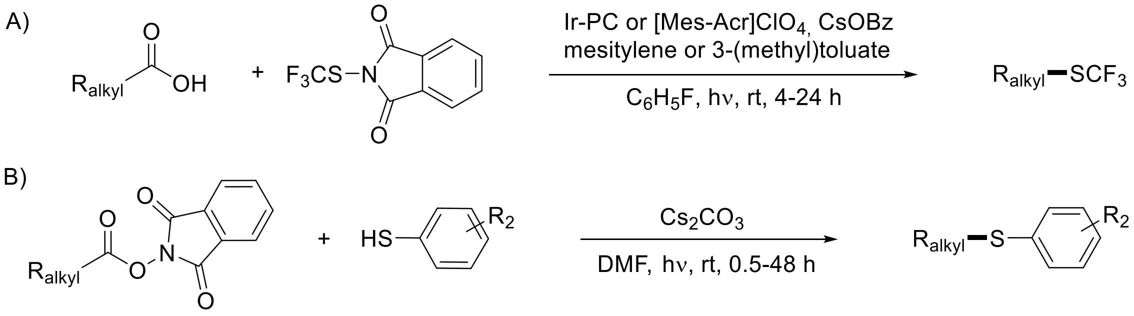
Scheme 1-15. A) Decarboxylative amination with diazocompounds and organic dyes; B) Copper-catalyzed decarboxylative amination by CO_2-extrusion of active esters.

Regarding photocatalytic, decarboxylative C–O bond formations, only one **hydroxylation** is known up to now. The method, developed by Xiao´s group, utilizes the organic photocatalyst [Mes-Acr]ClO_4 and molecular oxygen and works for cyclic or benzylic carboxylic acids (Scheme 1-16).[45] As intermediates, the hydroperoxides or ketones are formed and reduced subsequently to the final products with $NaBH_4$ and methanol.



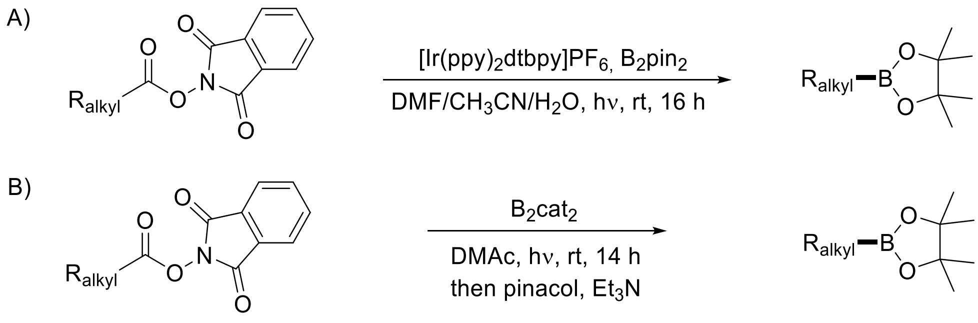
Scheme 1-16. Decarboxylative hydroxylation of benzylic carboxylic acids.

C–S bond formations are important for the synthesis of drugs and pharmaceuticals. Especially the trifluoromethylthiolation helps to improve the lipophilicity and metabolic stability of a compound.[46] The introduction of the SCF_3-group can be achieved with the photocatalyst [Ir[dF(CF_3)ppy]$_2$(dtbbpy)]PF_6 or [Mes-Acr]ClO_4, a phthalimide-SCF_3-reagent and blue LEDs (Scheme 1-17A).[47] In addition, the base CsOBz, a sacrificial hydrogen atom donor (mesitylene or 3-(methyl)toluate) and the solvent fluorobenzene are required. In principle, the method is suitable for primary, secondary and tertiary aliphatic carboxylic acids. Although the acridinium catalyst is a green, metal-free alternative for the iridium catalyst, it gives lower yields and is not suitable for all substrates, e.g. not for primary alkyl acids. Moreover, the iridium catalyst allows even the decarboxylative difluoromethylthiolation. Another possible, decarboxylative C–S bond formation is the arylthiation, which was reported in 2016 without any catalyst and oxidants or reductants (Scheme 1-17B).[48] In addition to the active ester and the aromatic thiol, only the base Cs_2CO_3 is required. It is assumed that this base forms a complex with the *N*-(acyloxy)phthalimide of the carboxylic acid and thus, the light of the CFL bulb can be absorbed. The excited phthalimide complex can be reduced by Ar-S$^-$, which triggers the extrusion of CO_2 and gives the alkyl radical, that undergoes cross-coupling with the thiol. The scope is broad and includes even primary aliphatic acids and structural demanding natural compounds.



Scheme 1-17. A) Decarboxylative, photocatalytic trifluoromethylthiolation; B) Catalyst-free, decarboxylative arylthiation.

In 2017, the light-mediated **borylation** of alkyl carboxylic acids after activation via esterification has been developed. The synthesized boronic esters are potent medicines and versatile building blocks. A photocatalytic method works with $[Ir(ppy)_2dtbpy]PF_6$, B_2pin_2 and CFL in a ternary solvent mixture (Scheme 1-18A).[49] The scope of alkyl acids is limited to simple, primary ones. However, also the synthesis of alkyl tetrafluoroborates is possible, if tetrahydroxydiboron and KHF_2 are used for the borylation. Another published approach requires no catalyst, but irradiation with blue LEDs and bis(catecholato)diboron (B_2cat_2) as diboron species (Scheme 1-18B).[50] Pinacol and triethylamine have to be added after 14 h in order to complete the reaction to the boron ester. It was shown that the active ester, B_2cat_2 and DMAc form a heteroleptic ternary complex, which absorbs the blue light. The method is suitable for primary, secondary as well as tertiary acids including complex structures.

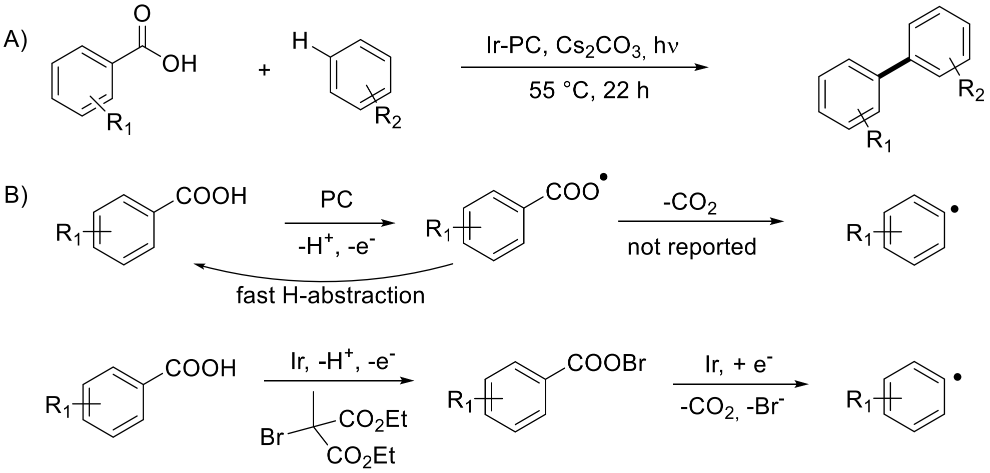


Scheme 1-18. A) Iridium-catalyzed, decarboxylative borylation; B) Catalyst-free, decarboxylative borylation.

1.2.2. Reactions *via* sp^2-Hybridized Radicals

1.2.2.1. From Aromatic Carboxylic Acids

Decarboxylative reactions with aromatic carboxylic acids are usually carried out under transition metal catalysis and only one photocatalytic method has been reported up to now. Glorius *et al.* managed the **arylation** via decarboxylation of aromatic acids and direct C–H activation of the coupling-partner (Scheme 1-19A).[51] Usually, hydrogen atom abstraction (e.g. from the solvent) of the carboxy radical, that is formed by oxidation of the carboxylate is much faster than decarboxylation to the desired aryl radical. Glorius´ strategy to circumvent this problem is the introduction of an irreversible bromo-leaving group, which avoids the backreaction to the starting material via hydrogen atom transfer. For the photocatalytic system, Ir[dF(CF$_3$)ppy]$_2$(dtbbpy)PF$_6$ and blue light is used. However, large amounts of brominating agent with additional heating to 55 °C is necessary and the aromatic coupling partner has to be used as the solvent. Nevertheless, this method finally made aromatic acids accessible for photocatalytic decarboxylations and will hopefully find some successors. The proposed mechanism is shown in Scheme 1-19B. After deprotonation of the aromatic acid and oxidation by the excited iridium-catalyst, the generated carboxy radical is trapped by bromine, which gives the acyl hypobromide. This intermediate can be decarboxylated, which yields the aryl radical, that reacts with an aromatic compound to the biaryl after rearomatization.



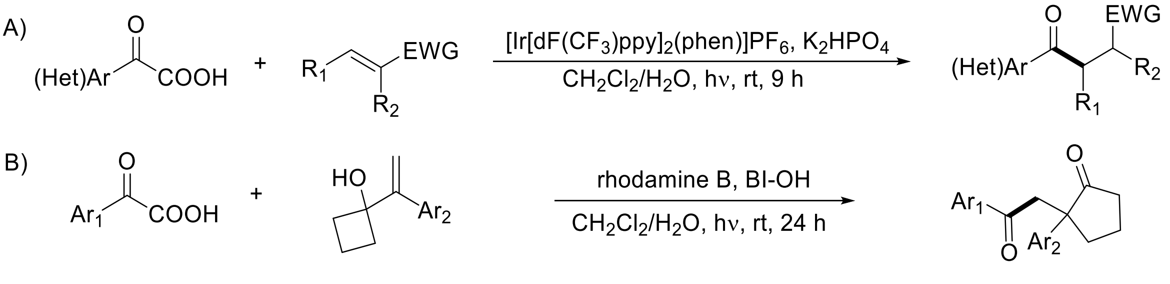
Scheme 1-19. A) Decarboxylative arylation of aromatic carboxylic acids; B) Without a leaving group, the fast back reaction by hydrogen atom abstraction prevents decarboxylation to the aryl radical. Introduction of a bromo-leaving group according to Glorius` approach avoids the back reaction.

1.2.2.2. From α-Keto Acids

The mild, photocatalytic decarboxylation of α-keto acids gives acyl radicals, that can be trapped with a wide variety of substrates. This enables the introduction of a carbonyl group into an organic molecule. As an alternative to keto acids, other substrates like anhydrides, acyl halogenides or thio-/seleno-/telluroesters are able to give the same radical intermediates, but not via decarboxylation. Therefore, these acylation reagents are not discussed within this chapter, but in relevant reviews.[52]

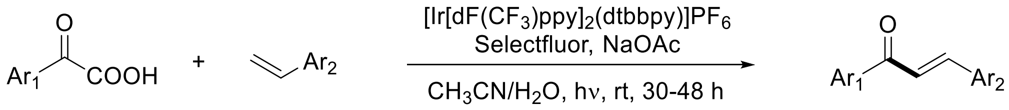
Alkylation: The decarboxylative cross-coupling of α-keto acids with olefins under formation of ketones is relatively rare but has been achieved e.g. with Michael-acceptors. 1,4-Addition of the acyl radical to the olefin occurs under irradiation with blue light in the presence of

$[Ir[dF(CF_3)ppy]_2(phen)]PF_6$ and K_2HPO_4 (Scheme 1-20A).[53] Suitable substrates for these method are aromatic and heteroaromatic keto acids on the one side and α,β-unsaturated esters, ketones, aldehydes, amides, nitriles and sulfones as cross-coupling partners on the other side. A more special method enables the alkylation with vinylcyclobutanols under ring-expansion, which gives cyclopentanones. Therefore, blue LEDs, rhodamine B and a hypervalent iodine(III) reagent (BI-OH) are required (Scheme 1-20B).[54]



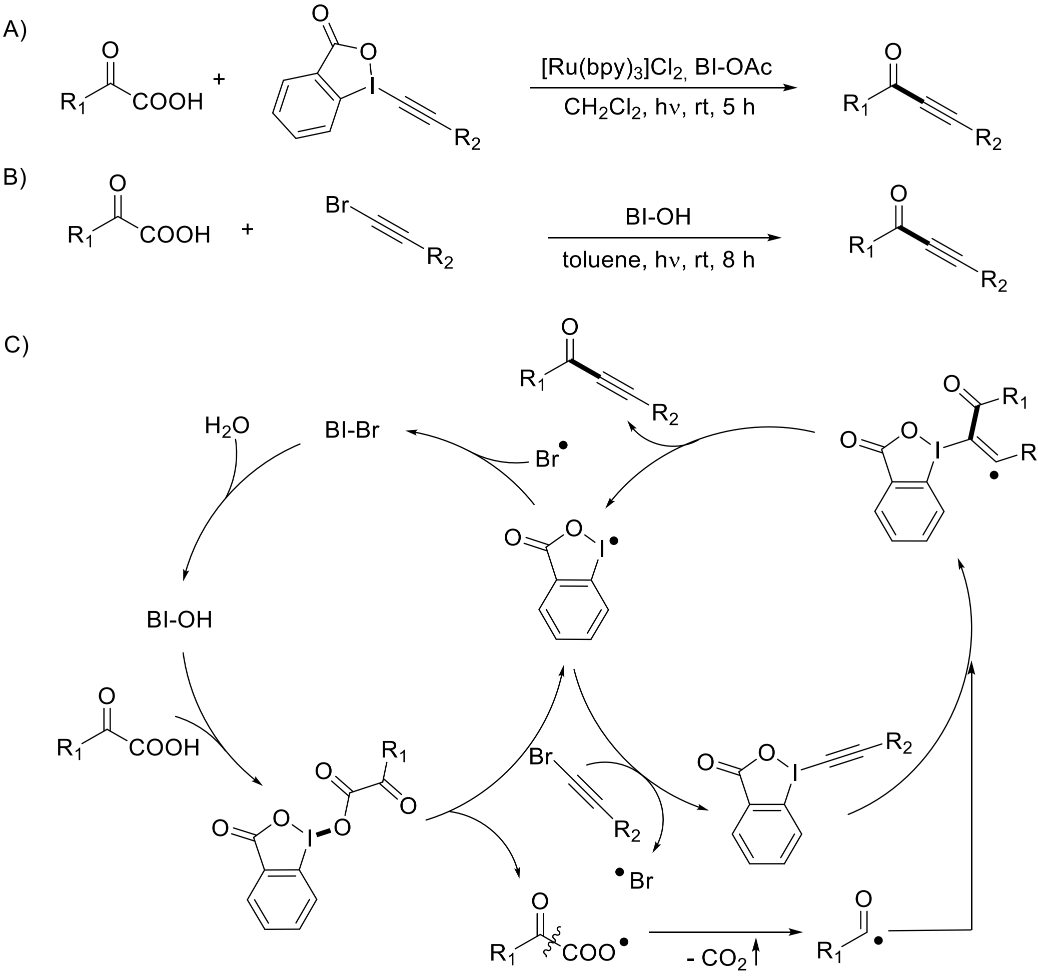
Scheme 1-20. A) Decarboxylative alkylation with electron-deficient olefins and iridium-photocatalyst; B) Decarboxylative alkylation with vinylcyclobutanols under ring-expansion.

Vinylation: This reaction of α-keto acids gives α,β-unsaturated carbonyl compounds. In 2017, Zhu *et al.* developed a method that utilizes $[Ir[dF(CF_3)ppy]_2(dtbbpy)]PF_6$, Selectfluor® and NaOAc (Scheme 1-21).[55] Under irradiation with visible-light, the cross-coupling with styrene derivatives is possible. Therefore, Selectfluor® acts as fluorine atom transfer reagent, that prevents typical side-reactions, which occur often during radical reactions with styrenes. By addition of the acyl radical to styrene, a benzylic radical is formed, which is subsequently fluorinated. This suppresses side-reactions of the benzylic radical. Afterwards, a base is added, that abstracts HF, which finally yields the desired product. Disadvantages of this method are the long reaction time of 30 to 48 h and the limited substrate scope, which is restricted to aromatic keto acids and aromatic olefins.



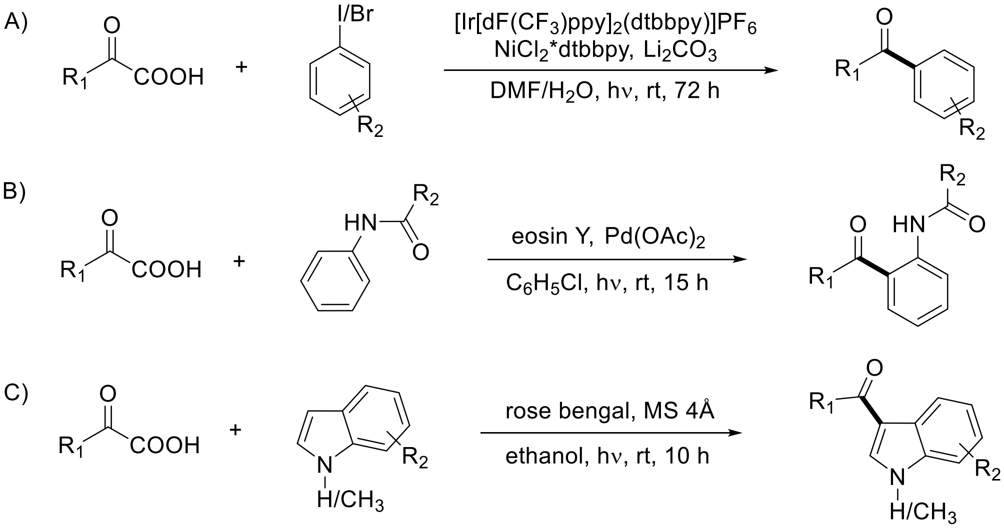
Scheme 1-21. Decarboxylative vinylation via iridium-photocatalysis.

Alkynylation: The products of the decarboxylative alkynylation of α-keto acids are ynones, which are important for the synthesis of heterocycles or other building blocks.[56] Up to now, the photocatalytic reaction works only with benziodoxole(BI)-alkynes (generated *in situ* or synthesized in advance) as coupling partners. In 2015, Chen *et al.* used $[Ru(bpy)_3](PF_6)_2$, blue LEDs, the benziodoxole(BI)-alkyne and BI-OAc, which enables short reaction times of typically 5 h (Scheme 1-22A).[57] Another approach was developed the same year by Wang´s group and works photochemically without any catalyst, but in the presence of sunlight.[58] Moreover, bromo alkynes can be applied and only catalytic amounts of BI-OH are required, as it is regenerated during the reaction pathway (Scheme 1-22B). Regarding the proposed mechanism (Scheme 1-22C), the benziodoxole-alkyne is generated *in situ* by the reaction of the α-keto acid with BI-OH. This intermediate is cleaved by sunlight, which entails decarboxylation. The thus generated acyl radical attacks subsequently the triple bond of the BI-alkyne. Both methods show good yields and high functional group compatibility.



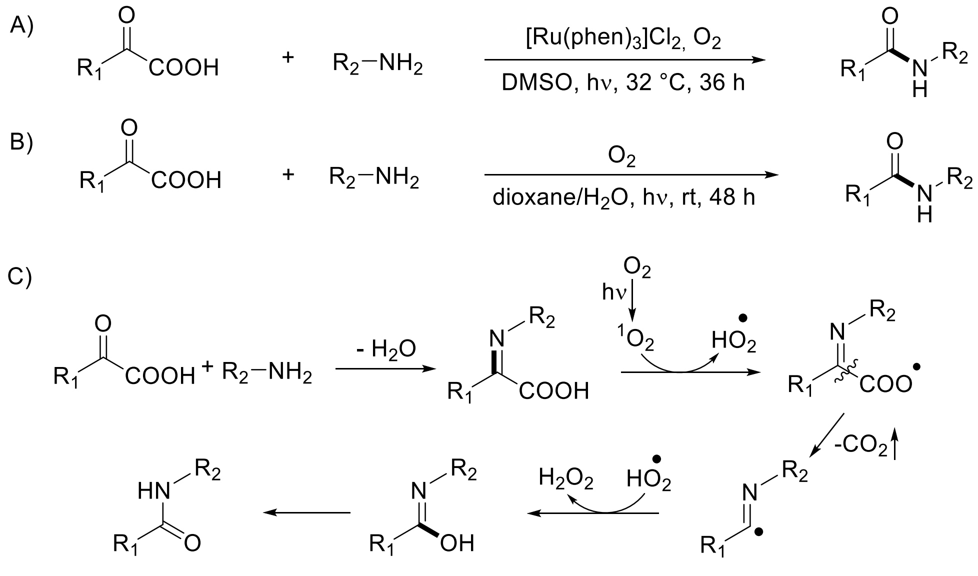
Scheme 1-22. A) Decarboxylative alkynylation promoted by a ruthenium-catalyst; B) Catalyst-free, sunlight-mediated alkynylation; C) Mechanism of catalyst-free alkynylation.

Arylation: The decarboxylative arylation is usually known with metal-catalysts. However, also photocatalytic methods have been developed recently, especially dual-catalytic approaches, which combine photocatalysis with metal catalysis. The cross-coupling can be achieved either via direct C–H activation of the aromatic compound or via activation of a leaving group. For the latter case, MacMillan *et al.* developed a dual approach that combines the catalysts [Ir[dF(CF$_3$)ppy]$_2$(dtbbpy)]PF$_6$ and NiCl$_2$*dtbbpy (Scheme 1-23A).[59] With blue light and the base Li$_2$CO$_3$, cross-coupling of aryl or alkyl substituted α-keto acids with aromatic halides can be achieved within 72 h. One year later, a similar method utilizing the same photocatalyst, but [Pd(PhCN)$_2$Cl$_2$] as co-catalyst was reported and enables shorter reaction times of 20 h.[60] In both cases, aryl bromides and aryl iodides can serve as coupling-partners. For the arylation via C–H activation, a dual catalytic system consisting of the organic dye eosin Y and the metal-catalyst Pd(OAc)$_2$ has been developed. The method is suitable for the arylation of α-keto acids with anilides in the presence of green light (Scheme 1-23B).[61] Moreover, it is one rare example for a dual-catalytic approach with an organic dye as the photocatalyst. Again, aryl as well as alkyl α-keto acids are suitable and the scope of anilides is broad. Another example for the direct C–H activation is the decarboxylative arylation with indoles, that can be achieved either by merging again an iridium- and a nickel-catalyst,[62] or much simpler by catalysis with the organic dye rose bengal and green light, without further additives (except molecular sieve) (Scheme 1-23C).[63] This system works for free (N–H) indoles and N-alkylated indoles and acylation takes place in the C3-position.



Scheme 1-23. Decarboxylative arylations of α-keto acids; A) With aryl halides and iridium-photocatalyst; B) With anilides and dual catalysis; C) With indole derivatives and rose bengal.

Amidation: The formation of C–N bonds by trapping the acyl radical, which is generated upon decarboxylation, with amines yields amides without the need for protecting groups. The decarboxylative amidation with the photocatalyst $[Ru(phen)_3]Cl_2$ in the presence of a household light bulb and oxygen was investigated by Lei *et al.* (Scheme 1-24A).[64] A similar approach works even without photocatalyst, but with CFL (Scheme 1-24B).[65] For the mechanism (Scheme 1-24C), the authors propose that illumination triggers the formation of singlet oxygen, which abstracts an electron from the α-imino acid that is formed by the two starting materials. This should give a radical intermediate, that decarboxylates and reacts with water to give the desired product. Interestingly, no additives except oxygen are required and the reaction can be performed even in gram-scale. For both reactions, alkyl as well as aromatic substituents are suitable for both starting materials.

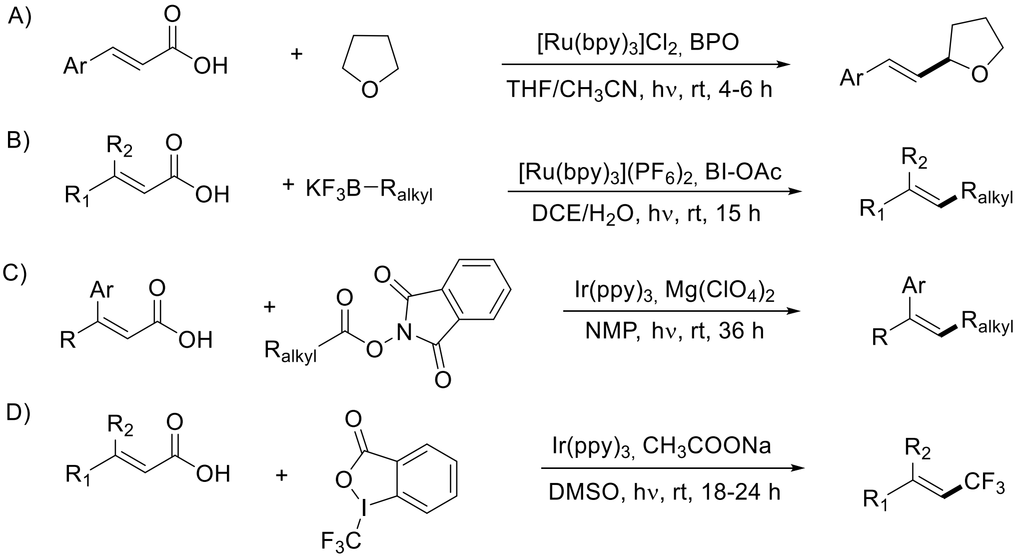


Scheme 1-24. A) Decarboxylative amidation with a ruthenium-photocatalyst; B) Catalyst-free decarboxylative amidation; C) Mechanism of catalyst-free amidation.

1.2.2.3. From α,β-Unsaturated Carboxylic Acids

Although cinnamic acids are inexpensive and interesting starting materials, photocatalytic methods for the decarboxylative cross-coupling of this class of compounds are still rare. The decarboxylation of these compounds gives vinylic radicals, which are quite unstable and therefore hard to trap. This is presumably the reason why most decarboxylative reactions of α,β-unsaturated carboxylic acids can be achieved only by metal-catalysis. In 2015, Borah and Yan published a review, which summarizes vinylic decarboxylations with these substrates,[66] but some new, photocatalytic examples have been reported afterwards.

Alkylation: Photocatalytic alkylations of cinnamic acids are up to now only known with metal-photocatalysts. Possible alkylating agents are THF-derivatives, that can be used by C–H activation with $[Ru(bpy)_3]Cl_2$, light and the oxidant benzoyl peroxide (BPO) (Scheme 1-25A).[67] Although the introduction of leaving groups is here superfluous, the substrate scope is limited to aromatic α,β-unsaturated acids and only a few α-oxy acids. For a more general alkylation, alkyl-trifluoroborates can be employed as coupling-partners if blue light, $[Ru(bpy)_3](PF_6)_2$ and BI-OAc are added (Scheme 1-25B).[68] Thereby, aryl as well as acyl substituted α,β-unsaturated carboxylic acids on the one side and primary, secondary and tertiary alkyl trifluoroborates or boronic acids on the other side can be applied for the reaction. Another interesting approach enables the alkylation via a redox-neutral, double-decarboxylative pathway: Cinnamic acid derivatives as well as *N*-(acyloxy)phthalimides of different substituted alkyl acids are decarboxylated in the presence of $Ir(ppy)_3$, $Mg(ClO_4)_2$ and visible light (Scheme 1-25C).[69] Cross-coupling to olefins takes about 36 h in the solvent NMP. An analogous method has been reported recently with $[Ru(bpy)_3]Cl_2$ and DABCO.[70] $Ir(ppy)_3$ can even catalyze the decarboxylative trifluoromethylation of α,β-unsaturated carboxylic acids. With Togni reagent as CF_3-source, light and sodium acetate, trifluoromethylated (*E*)-alkenes are obtained at room temperature within 24 h (Scheme 1-25D).[71]



Scheme 1-25. A) Decarboxylative alkylation via C–H activation of THF-derivatives; B) Alkylation with alkyl-trifluoroborates; C) Alkylation via iridium-catalyzed double-decarboxylation; D) Decarboxylative trifluoromethylation with Togni-reagent.

Sulfonylation: The sulfonylation with sulfonyl hydrazines is up to now the only example for a photocatalytic, decarboxylative C–S bond formation with cinnamic acids. With eosin Y as the photocatalyst, oxygen as the oxidant, KI and Cs_2CO_3, the reaction takes place under irradiation with visible light (Scheme 1-26).[72] Regarding the mechanism, it is believed that the excited organic dye oxidizes the hydrazine, which subsequently loses N_2 and gives the sulfonyl radical. This radical attacks the double bond of the acid and decarboxylation gives the final product. The scope of sulfonyl hydrazines and vinylic acids is limited to aromatic ones; especially electron-deficient cinnamic acids work well.

Scheme 1-26. Decarboxylativ sulfonylation of cinnamic acids with sulfonyl hydrazines.

1.3. Conclusion

An overview on photocatalytic, decarboxylative reaction was given within this chapter. The scope of photocatalytic, decarboxylative reactions has increased enormously during the last years and just the most interesting examples were shown. In general, these photocatalytic approaches are usually milder than traditional, metal-catalyzed variants, but are applicable for different substrate scopes. Especially aromatic and alkynyl carboxylic acids can almost exclusively be decarboxylated by metal-catalysis, whereas a huge variety of photocatalytic methods exists for aliphatic carboxylic acids. It is striking, that iridium- or ruthenium-catalyzed methods are developed in general first and later on, they are often replaced by cheaper and non-toxic organic dyes. It is desirable that these metal-free catalysts are screened more often as potential photocatalysts. Moreover, catalyst-free, photochemical reactions, which are driven directly by sunlight or LEDs are in principle favorable, but a rational reaction design is difficult as a deeper mechanistic understanding is lacking in many cases.

Regarding enantioselective decarboxylations, dual-catalytic approaches merging a chiral metal-catalyst with a photocatalyst are up to now the only successful strategy. Even more interesting would be the maintenance of the existing chirality of biomass-derived carboxylic acids. Although the decarboxylation generates a radical at the chiral center, the chiral information must not be lost necessarily. The configuration of the stereocenter could be maintained e.g. by fast reactions in the solid state or at low temperatures.[73] This would enable the enantioselective synthesis starting from renewable and easily available compounds.

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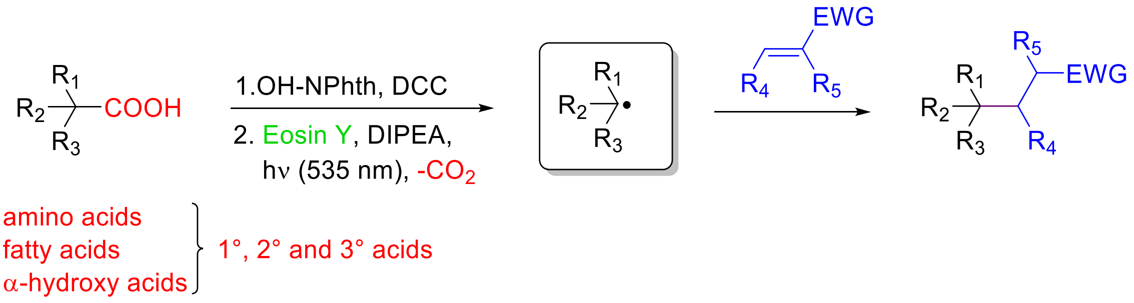
2. Metal-Free, Visible-Light-Mediated, Decarboxylative Alkylation of Biomass-Derived Compounds



This work describes a mild, environmentally friendly method to activate natural carboxylic acids for decarboxylative alkylation. After esterification of biomass-derived acids to *N*-(acyloxy)-phthalimides, the active esters are cleaved reductively by photocatalysis to give alkyl radicals, which undergo C–C bond formation with electron-deficient alkenes. This reaction is catalyzed by the organic dye eosin Y and green light (535 nm) and the scope of acids includes abundant amino acids, α-oxy acids and fatty acids which are available from renewable resources.

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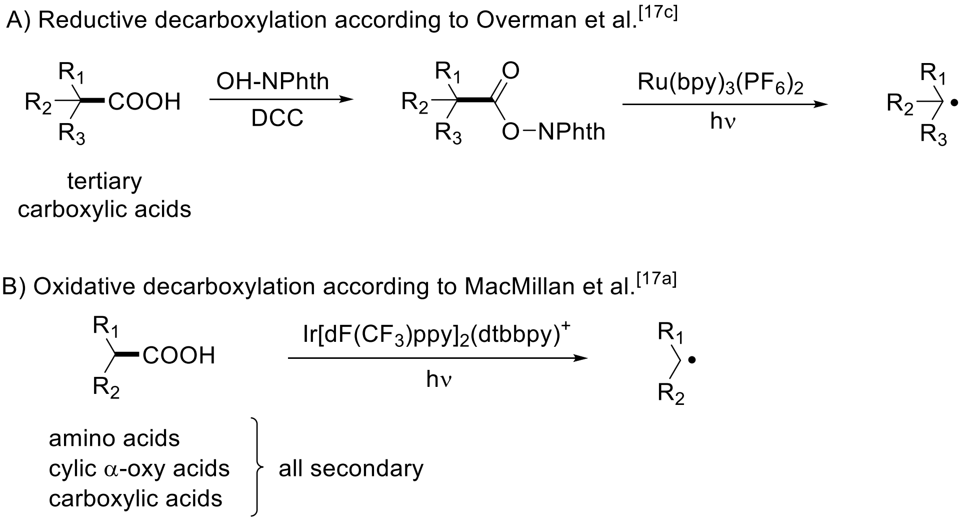
2.1. Introduction

Carboxylic acids are among the most abundant, renewable feedstocks on our planet. They are non-toxic, stable and inexpensive and therefore valuable starting materials for “green chemistry”.[1] Due to shortage of fossil resources and rising energy demand, alternative sources of raw materials gain in importance.[2] In order to generate platform chemicals and high-value chemicals like pharmaceuticals from biomass-derived compounds, the carboxy group can be targeted as chemo- and regioselective leaving group for C–C bond formation reactions.[3] In principle, decarboxylative reactions are known for a long time, but old protocols (e.g. according to Hunsdiecker[4], Barton[5] and Kolbe[6]) are not suitable for cross-coupling reactions between acids and other substrates under benign conditions. Over the last two decades, many transition metal-catalysed, decarboxylative C–C and C–X coupling methods were reported by Gooßen,[7] Myers[8] and many others.[9] Even though these methods are versatile in application and often compatible with multiple step reactions, they require high temperatures as well as palladium or copper reagents. Moreover, they are usually limited to decarboxylation of C_{sp2}–COOH or C_{sp}–COOH bonds.

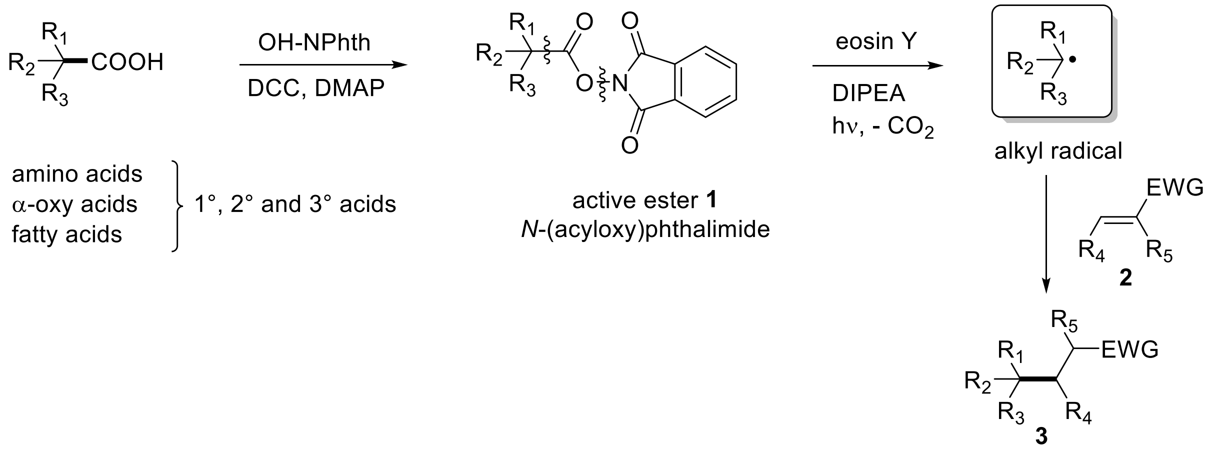
Recently, first photoredox-mediated processes were developed for the activation of the carboxy group. The usage of photocatalysts and visible light enables reactions under mild conditions and low energy consumption. During the last years, photocatalytic, decarboxylative reactions like arylations,[10] vinylations,[11] allylations,[12] alkynylations,[13] fluorinations[14] and hydrodecarboxylations[15] have been reported by MacMillan and other groups.[16] Also different methods for decarboxylative alkylations have already been investigated.[17] Here, alkyl radicals which are generated from carboxylic acids upon extrusion of CO_2 react with activated alkenes, typically Michael acceptors. The alkyl radicals can either be formed by esterification of carboxylic acids and subsequent reductive cleavage of the ester bond (Scheme 2-1A)[17c,18] or by oxidative cleavage of the acid itself (Scheme 2-1B).[17a] These methods have already been reported by different groups, but expensive and toxic transition metal catalysts are needed in all cases and the scope of carboxylic acids is limited.


A) Reductive decarboxylation according to Overman et al.[17c]

B) Oxidative decarboxylation according to MacMillan et al.[17a]

Scheme 2-1. Photocatalytic generation of alkyl radicals from carboxylic acids for subsequent coupling with electron-deficient alkenes.

Herein, we report for the first time a metal-free, photo-catalytic, decarboxylative alkylation which is applicable for a broad variety of natural carboxylic acids involving amino acids, α-oxy acids and fatty acids (Scheme 2-2). Therefore, *N*-(acyloxy)phthalimides were synthesized from the corresponding acid according to a simple method developed by Okada [18b, 19] analogously to Overman´s approach. These active esters undergo C–C bond formation with electron-deficient alkenes under irradiation with green light in the presence of DIPEA and the organic, non-toxic and cheap dye eosin Y. Thus, valuable chemicals can be obtained from renewable biomass under eco-friendly and mild conditions.



Scheme 2-2. Our work: general approach for the decarboxylative alkylation of natural compounds by reductive cleavage of N-(acyloxy)phthalimide 1.

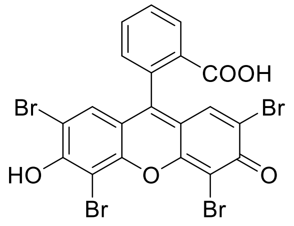
2.2. Results and Discussion

2.2.1. Synthesis and Scope

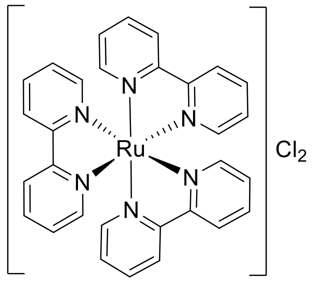
For investigation of the reaction conditions of the decarboxylative alkylation, the *N*-(acyloxy)phthalimide of *N*-Boc-protected proline (**1a**) and n-butyl acrylate (**2a**) served as test substrates. A mixture of both compounds, the base DIPEA and a homogeneous photocatalyst was irradiated with LEDs under nitrogen atmosphere. For this reaction, no heterogeneous catalysts have been investigated, although an application would be conceivable.[20] First, the catalytic activity of the photocatalysts eosin Y (**A**) and $[Ru(bpy)_3]Cl_2$ (**B**) in different solvents was screened (Table 2-1). The inexpensive organic dye **A** enabled higher yields than metal catalyst **B** in almost every solvent (except DMF: Table 2-1, entries 2 and 7). As $[Ru(bpy)_3]Cl_2$ is known to be a stronger reductant than eosin Y,[21] the reason for the better performance of the metal-free catalyst **A** is probably its better solubility and stability in these solvents. Decomposition of **B** was indicated by darkening of the reaction mixtures after several minutes. The best product yield of 96% was obtained with photocatalyst **A** and CH_2Cl_2 as solvent (Table 2-1, entry 9).

For further optimization, different reaction conditions and control reactions were investigated (Table 2-2). Reducing the amount of catalyst to 5 mol% (Table 2, entry 1) or the amount of alkene from 5 to 2 eq. (Table 2-2, entry 4) resulted in lower yields of about 85%. Also a shorter reaction time (Table 2-2, entry 2) or the use of less base (Table 2-2, entry 3) had a clearly negative impact. However, running the reaction in the presence of air (Table 2-2, entry 5) gave the same yield as after degassing the reaction mixture (Table 2-1, entry 9). Measuring the oxygen concentration during the non-degassed reaction showed that the oxygen was consumed within two hours (see Experimental Section). Control experiments without light, DIPEA or catalyst led to no product formation at all, independent if oxygen was present or not (Table 2-2, entry 6 to 11).

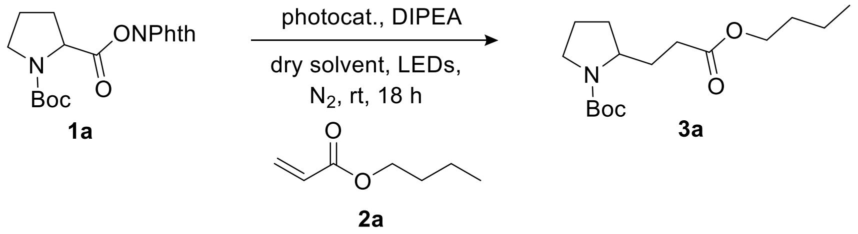
Table 2-1. Evaluation of catalyst and solvent.[a]



eosin Y (**A**)



[Ru(bpy)₃]Cl₂ (**B**)

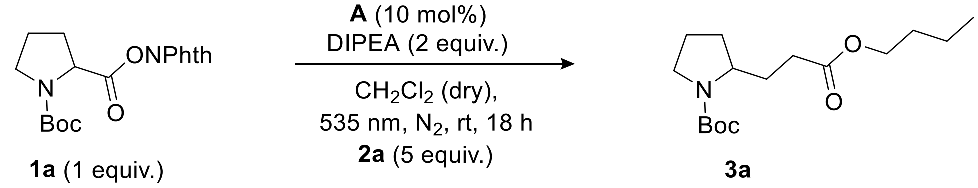


Entry	Photocatalytic system	Solvent	Yield [%][b]
1	$[Ru(bpy)_3]Cl_2$ (2 mol%, 455 nm)	DMSO	30
2	$[Ru(bpy)_3]Cl_2$ (2 mol%, 455 nm)	DMF	47
3	$[Ru(bpy)_3]Cl_2$ (2 mol%, 455 nm)	CH_3CN	60
4	$[Ru(bpy)_3]Cl_2$ (2 mol%, 455 nm)	CH_2Cl_2	18
5	$[Ru(bpy)_3]Cl_2$ (2 mol%, 455 nm)	THF	7
6	Eosin Y (10 mol%, 535 nm)	DMSO	30
7	Eosin Y (10 mol%, 535 nm)	DMF	37
8	Eosin Y (10 mol%, 535 nm)	CH_3CN	65
9	Eosin Y (10 mol%, 535 nm)	CH_2Cl_2	96
10	Eosin Y (10 mol%, 535 nm)	THF	53

[a] Reactions were performed using 1 equiv. **1a**, 5 equiv. **2a** and 2 equiv. DIPEA. [b] Determined by GC analysis using naphthalene as internal standard.

With these optimized reaction conditions, the scope and limitations of the decarboxlative alkylation were explored. Therefore, the reaction of different electron-deficient alkenes with active ester **1a** was investigated (Table 2-3). The expected cross coupling products were observed in moderate to excellent yields when α,β-unsaturated esters and ketones were used as coupling partners. Unsubstituted or β-methylated aliphatic Michael acceptors gave the desired products **3a**, **3b** and **3e** in good yields of 73 to 80%. Benzylic, α,β-unsaturated esters **2g** and **2h** were suitable reaction partners in the same way. Also reactions with cyclic ketones gave products **3d** and **3e** in about 75% yield. However, introduction of a phenyl ring at the attacked carbon inhibited formation of product **3l** almost completely, presumably due to steric hindrance by the bigger substituent in β-position. In contrast, if the phenyl ring was positioned on the α-carbon of the Michael acceptor, the best yield of 92% (**3i**) was observed. This result indicates that after attack of the *N*-Boc proline fragment at the double bond, a radical is formed at the α-position, which is stabilized by an adjacent phenyl ring in the case of **3i**. Next to Michael acceptors, also the electrophilic, heteroaromatic styrene derivative vinylpyridine (**2k**) yielded the corresponding product **3k** in 40%.

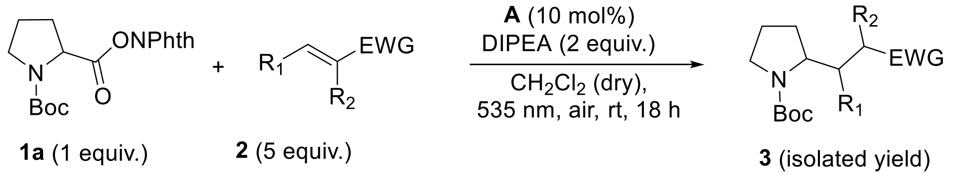
Table 2-2. Optimization of reaction conditions.

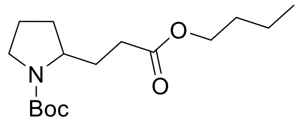


Entry	Modification	Yield [%][a]
1	5 mol% **A**	85
2	9 h irradiation time	64
3	1 equiv. DIPEA	26
4	2 equiv. **2a**	83
5	Air atmosphere[b]	96
6	No base	0
7	No light	0
8	No photocatalyst	0
9	Air atmosphere, no base	0
10	Air atmosphere, no light	0
11	Air atmosphere, no photocatalyst	0

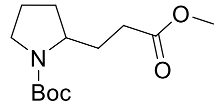
[a] Determined by GC analysis using naphthalene as internal standard.

Table 2-3. Scope of electron-deficient alkenes.

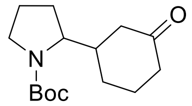




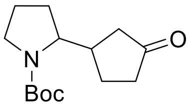
3a (80%)



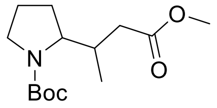
3b (78%)



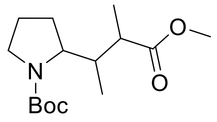
3c (76%)



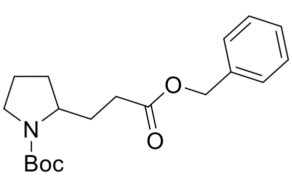
3d (73%)



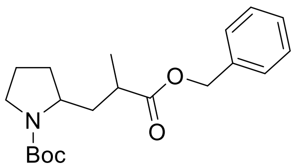
3e (73%)



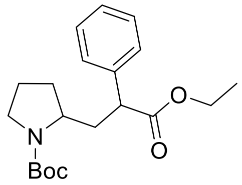
3f (59%)



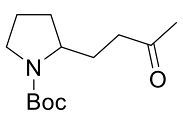
3g (69%)



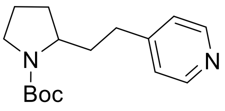
3h (85%)



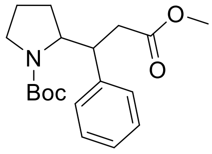
3i (92%)



3j (55%)



3k (40%)



3l (< 5%)[a]

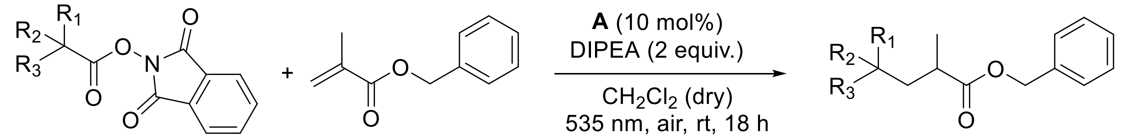
[a] Product not isolated. Yield estimated by ^{1}H-NMR.

After establishing the scope of activated alkenes, *N*-(acyloxy)phthalimide **1** was varied (Table 2-4). Here, benzyl methacrylate **2h** served as model alkene and again, the optimized conditions of Table 2-2, entry 5 were applied. A broad variety of esterified acids, including readily available, biomass-derived compounds could be employed. This photocatalytic cross-coupling reaction works on the one hand for primary (**1c**, **1k**, **1n**-**s**), secondary (**1b**, **1c**-**j**, **1l**) as well as for tertiary carboxylic acids (**1l**) and on the other hand for different substrate classes like amino acids (**1b-g**), α-oxy acids (**1h**-**j**) and even fatty acids (**1n-s**).

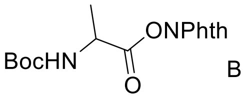
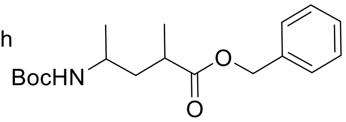
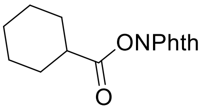
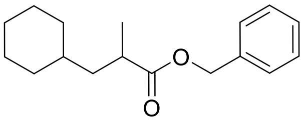
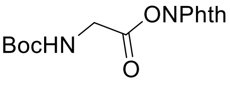
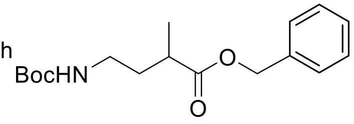
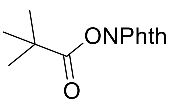
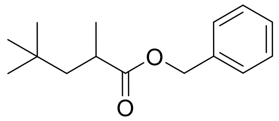
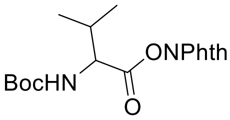
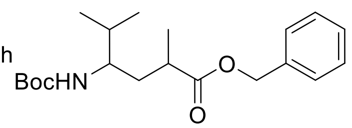
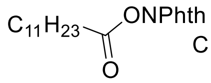
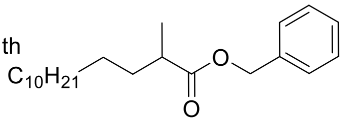
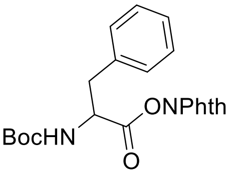
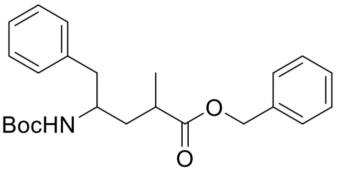
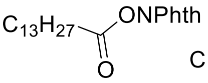
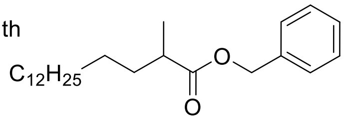
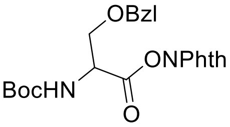
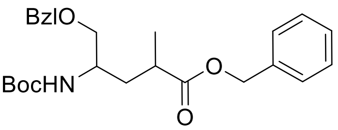
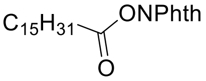
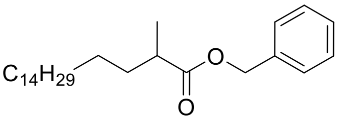
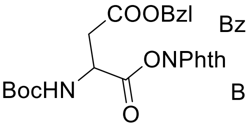
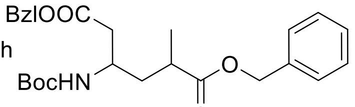
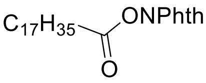
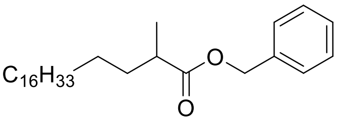
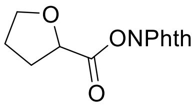
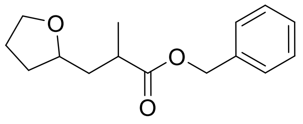
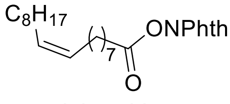
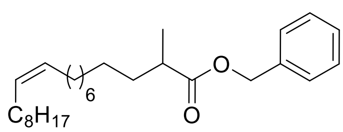
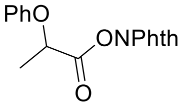
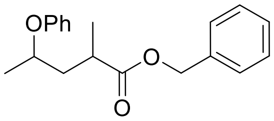
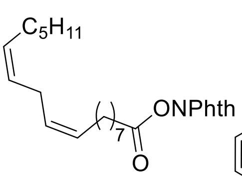
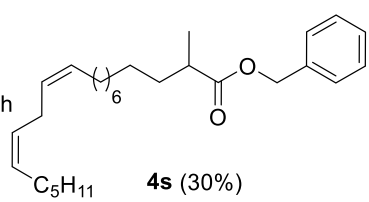
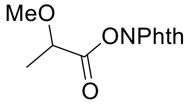
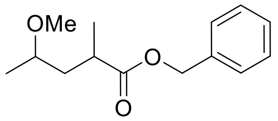
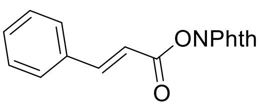
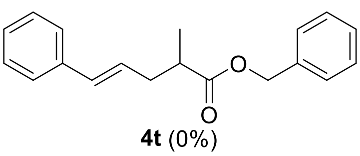
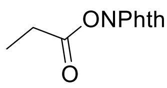
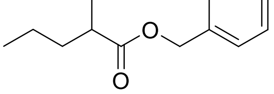
The active esters of simple, Boc-protected, secondary amino acids proline (**1a**, Table 3), alanine (**1b**) or valine (**1d**) gave the highest yields (68-89%). The *N*-(acyloxy)phthalimide of the primary amino acid glycine showed slightly less product formation (**4c**, 62%). Also amino acid derivatives with aromatic side chains like phenylalanine (**1e**) or benzyl-protected serine (**1f**) and aspartic acid (**1g**) yielded the corresponding products **4e-g** in about 60%. As a typical natural α-hydroxy acid, lactic acid with different protecting groups was investigated. Here, the phenoxy- (**1i**) and methoxy-protected derivatives (**1j**) gave with 50 and 58% yield, respectively, less coupling product than cyclic α-oxy starting material **1h** (72%).

Applying active esters of simple carboxylic acids without any heteroatom in α-position to the carboxy moiety also resulted in product formation, although the yields decreased to 30-45% (**4k**-**s**). This decline in efficiency indicates that the stability of the alkyl radical generated after decarboxylation is the decisive point for successful product formation. In the case of amino and α-oxy compounds, the radical is stabilized by electron-donation from the lone pair of the heteroatom to the single-occupied p orbital of the neighboring radical centered carbon, which explains the higher yields.[22] Considering the decarboxylative alkylation of *N*-(acyloxy)phthalimides of simple carboxylic acids, secondary (**1l**, 40%) or even more tertiary carboxylic acids (**1m**, 45%) are more prone to decarboxylate than primary, linear carboxylic acids (**1k**, **1n**-**s**; all about 30%). Again, tertiary alkyl radicals are more stable than secondary and especially primary radicals, which is in good accordance with the observed yields.[22b] Nonetheless, several fatty acids, which are widespread in nature could be applied for this photocatalytic reaction. Saturated (**1n**-**q**), mono-unsaturated (**1r**) and di-unsaturated (**1s**) fatty acid derivatives with different chain lengths (12-18 C) all gave products **4n-s** in about 30% yield. The reaction with the active ester of cinnamic acid (**1t**) yielded no product, because the vinylic radical intermediate, which is formed upon decarboxylation is apparently not stable enough to undergo further reactions. In summary, we could show that cheap and abundant compounds from renewable biomass are suitable starting materials for this cross-coupling reaction.

Table 2-4. Scope of *N*-(acyloxy)phthalimides.

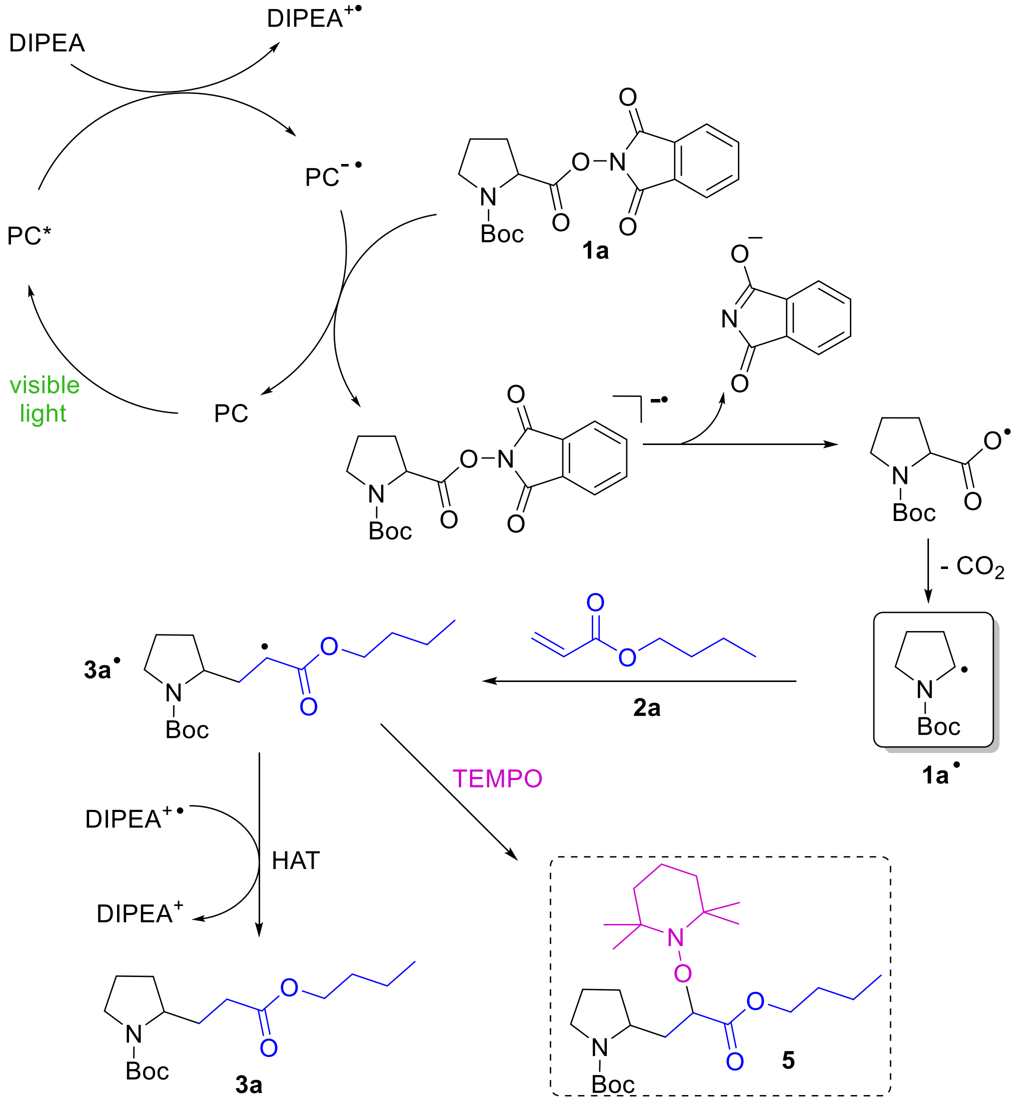


1 (1 equiv.) **2h** (5 equiv.) **4** (isolated yield)

N-(acyloxy)phthalimide	product	*N*-(acyloxy)phthalimide	product
 Boc-Ala-NPhth (**1b**)	 **4b** (68%)	 **1l**	 **4l** (40%)
 Boc-Gly-NPhth (**1c**)	 **4c** (62%)	 pivalic acid-NPhth (**1m**)	 **4m** (45%)
 Boc-Val-NPhth (**1d**)	 **4d** (89%)	 lauric acid-NPhth (**1n**)	 **4n** (31%)
 Boc-Phe-NPhth (**1e**)	 **4e** (57%)	 myristic acid-NPhth (**1o**)	 **4o** (32%)
 Boc-Ser(Bzl)-NPhth (**1f**)	 **4f** (55%)	 palmitic acid-NPhth (**1p**)	 **4p** (31%)
 Boc-Asp(OBzl)-NPhth (**1g**)	 **4g** (64%)	 stearic acid-NPhth (**1q**)	 **4q** (30%)
 **1h**	 **4h** (72%)	 oleic acid-NPhth (**1r**)	 **4r** (28%)
 OPh-lactic acid-NPhth (**1i**)	 **4i** (50%)	 linoleic acid-NPhth (**1s**)	 **4s** (30%)
 OMe-lactic acid-NPhth (**1j**)	 **4j** (58%)	 28 cinnamic acid-NPhth (**1t**)	 **4t** (0%)
 **1k**	 **4k** (29%)		

2.2.2. Mechanistic Investigations

Based on the report by Overman *et al.*[17c], the known photochemistry of eosin Y[23] and our own results, we propose the following mechanism for the decarboxylative alkylation of *N*-(acyloxy)phthalimides with electron-deficient alkenes (Scheme 2-3): Irradiation of a photocatalyst (PC) with visible light generates the excited catalyst PC*, which is reductively quenched by the sacrificial electron donor DIPEA to give DIPEA$^{+\bullet}$. Regeneration of the PC is presumably achieved by reduction of *N*-(acyloxy)phthalimide **1a**, which gives the corresponding radical anion. Splitting of the N–O bond and subsequent elimination of CO_2 generates alkyl radical **1a**$^\bullet$. This radical can attack the double bond of Michael acceptor **2a** to form the intermediate **3a**$^\bullet$. It is assumed that hydrogen atom abstraction from DIPEA$^{+\bullet}$ or the solvent finally enables formation of product **3a**.



Scheme 2-3. Proposed reaction mechanism for the photocatalytic, decarboxylative alkylation of *N*-(acyloxy)-phthalimide **1a** with *n*-butylacrylate (**2a**).

This mechanistic proposal was confirmed by several spectroscopic studies. Single electron transfer (SET) from DIPEA to the excited PC should be exergonic according to the redox potentials of DIPEA (+0.72 V vs. SCE in CH_3CN)[24] and the excited PC **A** (eosin Y*/eosin $Y^{\bullet-}$: +0.83 V vs. SCE in CH_3CN-H_2O, 1:1)[21b] or **B** (Ru^{2+}*/Ru^+: +0.77 V vs. SCE in CH_3CN)[25] and is a well documented process in literature.[21, 26] Furthermore, this step was confirmed by luminescence quenching experiments with both photocatalysts. In the case of eosin Y, fluorescence quenching could hardly be observed with DIPEA, *N*-(acyloxy)-phthalimide **1a** or alkene **2a** (see Experimental Section for graphs and further details). This indicates that excited PC **A** does rather react from the triplet than from the singlet state which was already shown by our group for another reaction.[27] For verification of this triplet reactivity, transient absorption measurements were performed, due to the short triplet lifetime of eosin Y (τ_T = 320 ± 10 ns).[27a] Performing fluorescence experiments with $[Ru(bpy)_3]Cl_2$ (**B**) revealed that the emission of **B*** is quenched by the electron donor DIPEA, which proves SET between both species (Figure 2-1). Upon titration of B* with **1a** or **2a**, no quenching was observed (see Experimental Section).

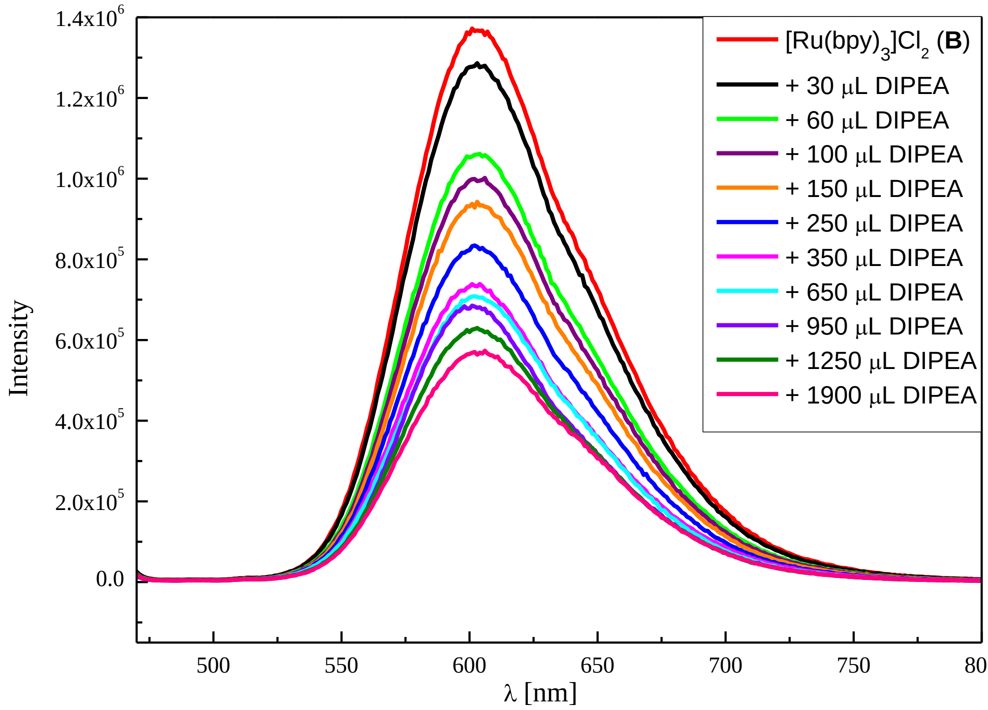


Figure 2-1. Fluorescence quenching of $[Ru(bpy)_3]Cl_2$ (**B**, 15.0 μM in CH_3CN) upon titration with DIPEA (100 mM in CH_3CN).

The next step of the catalytic cycle was assumed to be regeneration of the PC by SET from $PC^{\bullet-}$ to **1a**. Cyclic voltammetry measurements of the active ester **1a** (-1.20 V vs SCE in CH_3CN, see Experimental Section) showed that reduction by the strongly reducing PC B (Ru^+/Ru^{2+}: -1.33 V vs. SCE in CH_3CN)[21a] is thermodynamically feasible. Although redox potentials are not directly comparable with each other in the case of PC **A** (eosin $Y^{\bullet-}$/eosin Y: -1.06 V vs. SCE in CH_3CN-H_2O, 1:1),[21b] this catalyst is also known to be a powerful reductant. Eosin Y shows an absorption maximum at 527 nm which corresponds to an energy of 2.35 eV. After intersystem crossing to its reactive triplet state, 1.89 eV are still available for photocatalytic reactions.[21b] To confirm the formation of radical **3a**$^\bullet$ during the reaction, this intermediate was captured by the persistent radical TEMPO giving product **5**

(Scheme 2-3), which was determined by LC-MS analysis (see Experimental Section). Furthermore, the quantum yield of the photocatalytic model reaction was determined (see Experimental Section). The low value of $\Phi = 2.6 \pm 0.5\%$ corresponds to the relatively long reaction times of 18 h and indicates that efficient radical chain processes are very unlikely in this mechanism.[28] For further insight, the stability of the photocatalyst eosin Y has been investigated by measuring UV-vis absorption spectra during the reaction (see Supporting Information). Over the reaction time of 18 h, the catalysts gets slowly degraded and a precipitate occurs which slows down the product formation after some hours (see Experimental Section for the time course of the reaction). However, there seems to be still enough photocatalytic active species to reach almost complete conversion within this reaction time.

2.3. Conclusions

In conclusion, we have developed a metal-free, photocatalytic method for the decarboxylative alkylation of biomass-derived compounds. The advantage of this procedure over other methods reported in literature is the broad substrate scope including cheap and abundant α-amino acids, α-oxy acids and fatty acids as well as primary, secondary and tertiary substrates. In addition, the reactions can be carried out under mild, environmentally friendly conditions with the metal-free, organic dye eosin Y as photocatalyst. The carboxylic acids are activated by esterification to *N*-(acyloxy)phthalimides and then reductively cleaved upon irradiation with green light. This generates alkyl radicals, which undergo cross-coupling with electron-deficient alkenes. Thereby, largely new compounds for the synthesis of pharmaceuticals or fine chemicals are generated. The method contributes to the ongoing efforts replacing fossil resources by renewable feedstocks in the synthesis of chemical intermediates.

2.4. Experimental Section

2.4.1. General Information

Commercially available reagents and solvents were used without further purification. Dry solvents were used for all photoreactions. Industrial grade of solvents was used for automated flash column chromatography.

Nuclear magnetic resonance spectroscopy

All NMR spectra were measured at room temperature using a Bruker Avance 300 (300 MHz for ^{1}H, 75 MHz for ^{13}C, 282 MHz for ^{19}F) or a Bruker Avance 400 (400 MHz for ^{1}H, 101 MHz for ^{13}C, 376 MHz for ^{19}F)[29] NMR spectrometer. All chemical shifts are reported in δ-scale as parts per million [ppm] (multiplicity, coupling constant *J*, number of protons) relative to the solvent residual peaks as the internal standard.[30] The spectra were analyzed by first order and coupling constants *J* are given in Hertz [Hz]. Abbreviations used for signal multiplicity: ^{1}H-NMR: br = broad, s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, ddd = doublet of doublet of doublets, dt = doublet of triplets, qd = quartet of doublets and m = multiplet; ^{13}C-NMR: (+) = primary/tertiary, (–) = secondary, (C_q) = quaternary carbon.

Mass spectrometry and gas chromatography

The mass spectrometrical measurements were performed at the Central Analytical Laboratory of the University of Regensburg. All mass spectra were recorded on a Finnigan MAT 95, ThermoQuest Finnigan TSQ 7000, Finnigan MAT SSQ 710 A or an Agilent Q-TOF 6540 UHD instrument. GC measurements were performed on a GC 7890 from Agilent Technologies. Data acquisition and evaluation was done with Agilent ChemStation Rev.C.01.04. GC-MS measurements were performed on a 7890A GC system from Agilent Technologies with an Agilent 5975 MSD Detector. Data acquisition and evaluation was done with MSD ChemStation E.02.02.1431. A capillary column HP-5MS/30 m x 0.25 mm/0.25 µM film and helium as carrier gas (flow rate of 1 mL/min) were used. The injector temperature (split injection: 40:1 split) was 280 °C, detection temperature 300 °C (FID). GC measurements were performed and investigated via integration of the signal obtained. The GC oven temperature program was adjusted as follows: initial temperature 40 °C was kept for 3 min, the temperature was increased at a rate of 15 °C/min over a period of 16 min until 280 °C was reached and kept for 5 min, the temperature was again increased at a rate of 25 °C/min over a period of 48 seconds until the final temperature (300 °C) was reached and kept for 5 min. Naphthalene or biphenyl was chosen as internal standard.

Thin layer and column chromatography

Analytical TLC was performed on silica gel coated alumina plates (MN TLC sheets ALUGRAM® Xtra SIL G/UV254). UV light (254 or 366 nm) was used for visualization. If necessary, potassium permanganate, ninhydrin, bromocresol green or ceric ammonium molybdate was used for chemical staining. Purification by column chromatography was performed with silica gel 60 M (40-63 µm, 230-440 mesh, Merck) or pre-packed Biotage® SNAP Ultra HP-Sphere columns (25 µm spherical silica gel) on a Biotage® Isolera™ Spektra One device.

UV-vis absorption and fluorescence spectroscopy

UV-vis absorption spectroscopy was performed on a Varian Cary BIO 50 UV-vis/NIR spectrometer with a 10 mm Hellma® quartz fluorescence cuvette at room temperature. Fluorescence spectra were recorded on a HORIBA FluoroMax®-4 Spectrofluorometer with a 10 mm Hellma® quartz fluorescence cuvette at room temperature. FluorEssence Version 3.5.1.20 was used as software. Fluorescence measurements were performed under nitrogen atmosphere.

Irradiation sources

For irradiation with blue light, OSRAM Oslon SSL 80 LDCQ7P-1U3U (blue, λ_{max} = 455 nm, I_{max} = 1000 mA, 1.12 W) was used. For irradiation with green light, Cree XPEGRN G4 Q4 (green, λ_{max} = 535 nm, I_{max} = 1000 mA, 1.12 W) was used.

Cyclic voltammetry measurements

CV measurements were performed with the three-electrode potentiostat galvanostat PGSTAT302N from Metrohm Autolab using a glassy carbon working electrode, a platinum wire counter electrode, a silver wire as a reference electrode and TBATFB 0.1 M as supporting electrolyte. The potentials were achieved relative to the Fc/Fc^+ redox couple with ferrocene as internal standard. [24a] The control of the measurement instrument, the acquisition and processing of the cyclic voltammetric data were performed with the software Metrohm Autolab NOVA 1.10.4. The measurements were carried out as follows: a 0.1 M solution of TBATFB in CH_3CN was added to the measuring cell and the solution was degassed by argon purge for 5 min. After recording the baseline the electroactive compound was added (0.01 M) and the solution was again degassed a stream of argon for 5 min. The cyclic voltammogram was recorded with one to three scans. Afterwards ferrocene (2.20 mg, 12.0 µmol) was added to the solution which was again degassed by argon purge for 5 min and the final measurement was performed with three scans.

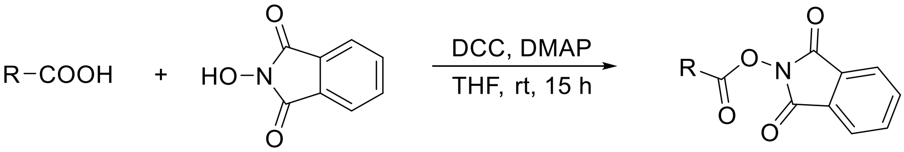
Quantum yield determination

The quantum yield was measured with a quantum yield determination setup: translation stages (horizontal and vertical): Thorlabs DT 25/M or DT S25/M; photographic lens with f = 50 mm; magnetic stirrer: Faulhaber motor (1524B024S R) with 14:1 gear (15A); PS19Q power sensor from Coherent; PowerMax software; adjustable power supply “Basetech BT-153 0–15 V/DC 0–3 A 45 W”.[31]

2.4.2. Synthesis of *N*-(Acyloxy)phthalimides as Starting Materials

General procedure for the synthesis of *N*-(acyloxy)phthalimides (1)

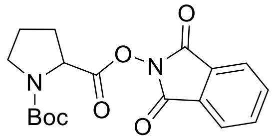
N-(Acyloxy)phthalimides (**1**) were synthesized by a slightly modified procedure based on Reiser *et al.*[18a] and Overman *et al.*[32]



The respective carboxylic acid (8.00 mmol, 1.0 equiv.), *N*-hydroxyphthalimide (1.43 g, 8.80 mmol, 1.1 equiv.), *N,N´*-dicyclohexylcarbodiimide (1.98 g, 9.60 mmol, 1.2 equiv.) and 4-dimethylaminopyridine (0.98 g, 0.80 mmol, 0.1 equiv.) were mixed in a flask with a magnetic stirring bar. Dry THF (40 mL) was added and the orange reaction mixture was stirred for 15 h at rt. The white precipitate was filtered off and the solution was concentrated by evaporation of the solvent. Purification by column chromatography on flash silica gel (CH_2Cl_2 or CH_2Cl_2/CH_3OH = 9:1) gave a white solid (**1a-q**) or a clear liquid (**1r** and **1s**).

Characterization of *N*-(acyloxy)phthalimides (1)

1-(*tert*-Butyl) 2-(1,3-dioxoisoindolin-2-yl) pyrrolidine-1,2-dicarboxylate (1a)[33]



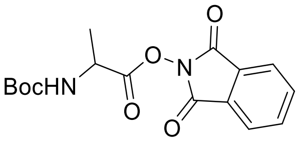
Yield: 2.16 g, 5.99 mmol, 75%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide);[36] δ [ppm] = 7.89 – 7.81 (m, 2H), 7.80–7.72 (m, 2H), 4.68 (dd, *J* = 7.0 Hz, 5.1 Hz, 0.2H), 4.59 (dd, *J* = 8.6 Hz, 3.9 Hz, 0.8H), 3.65 – 3.35 (m, 2H), 2.50 – 2.27 (m, 2H), 2.12 – 1.89 (m, 2H), 1.54 – 1.40 (m, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 169.7 and 169.4 (C_q), 161.8 and 161.7 (C_q), 153.5 (C_q), 134.9 and 134.8 (+), 128.9 (C_q), 124.0 (+), 81.2 and 80.4 (C_q), 57.24 and 57.15 (+), 46.5 and 46.3 (–), 31.5 and 30.3 (–), 28.4 and 28.2 (+), 24.5 and 23.6 (–).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{18}H_{21}N_2O_6$) calc.: 361.1394, found: 361.1397.
MF: $C_{18}H_{20}N_2O_6$
MW: 360.37 g/mol

1,3-Dioxoisoindolin-2-yl (*tert*-butoxycarbonyl)alaninate (1b)[33]



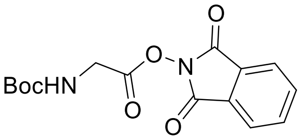
Yield: 1.83g, 5.46 mmol, 68%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.91 – 7.81 (m, 2H), 7.80 – 7.73 (m, 2H), 5.29 – 4.93 (m, 1H), 4.87 – 4.33 (m, 1H), 1.60 (d, *J* = 7.3 Hz, 3H), 1.53 – 1.40 (m, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 170.1 (C_q), 161.6 (C_q), 154.8 (C_q), 134.9 (+), 128.9 (C_q), 124.1 (+), 80.6 (C_q), 47.8 (+), 28.3 (+) and 28.1 (+), 18.9 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{16}H_{19}N_2O_6$) calc.: 335.1238, found: 335.1238.
MF: $C_{16}H_{18}N_2O_6$
MW: 334.33 g/mol

1,3-Dioxoisoindolin-2-yl (*tert*-butoxycarbonyl)glycinate (1c)[33]



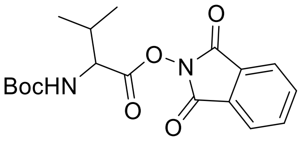
Yield: 668 mg, 2.09 mmol, 26%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.94 – 7.85 (m, 2H), 7.84 – 7.76 (m, 2H), 5.22 – 4.76 (m, 1H), 4.43 – 4.15 (m, 2H), 1.55 – 1.40 (m, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 167.3 (C_q), 161.6 (C_q), 155.4 (C_q), 135.0 (+), 128.9 (C_q), 124.2 (+), 80.8 (C_q), 40.5 (–), 28.4 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{15}H_{17}N_2O_6$) calc.: 321.1081, found: 321.1084.
MF: $C_{15}H_{16}N_2O_6$
MW: 320.30 g/mol

1,3-Dioxoisoindolin-2-yl (*tert*-butoxycarbonyl)valinate (1d)



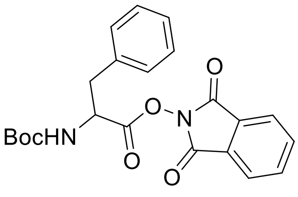
Yield: 2.26 g, 6.24 mmol, 78%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.90 – 7.82 (m, 2H), 7.81 – 7.74 (m, 2H), 5.25 – 4.76 (m, 1H), 4.75 – 4.15 (m, 1H), 2.43 – 2.24 (m, 1H), 1.56 – 1.39 (m, 9H), 1.08 (t, *J* = 7.2 Hz, 6H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 169.0 (C_q), 161.6 (C_q), 155.3 (C_q), 134.9 (+), 128.9 (C_q), 124.1 (+), 81.5 and 80.5 (C_q), 58.8 and 57.2 (+), 31.8 and 31.2 (+), 28.3 and 28.1 (+), 18.8 (+), 17.5 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{18}H_{23}N_2O_6$) calc.: 363.1551, found: 363.1551.
MF: $C_{18}H_{22}N_2O_6$
MW: 362.38 g/mol

1,3-Dioxoisoindolin-2-yl (*tert*-butoxycarbonyl)phenylalaninate (1e)



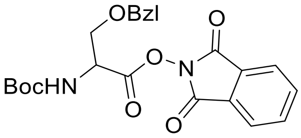
Yield: 2.68 g, 6.52 mmol, 82%.

^{1}H NMR (300 MHz, DMSO-*d$_6$*): (rotamers around the tertiary amide); δ [ppm] = 8.03 – 7.91 (m, 4H), 7.84 – 7.70 (m, 1H), 7.42 – 7.22 (m, 5H), 4.76 – 4.39 (m, 1H), 3.30 – 3.00 (m, 2H), 1.41 – 1.28 (m, 9H).

^{13}C NMR (75 MHz, DMSO-*d$_6$*): δ [ppm] = 169.6 and 169.3 (C_q), 161.7 and 161.6 (C_q), 155.3 and 154.0 (C_q), 136.6 (C_q), 135.6 (+), 129.4 and 129.3 (+), 128.4 and 128.3 (+), 128.2 (C_q), 126.9 and 126.8 (+), 124.1 and 123.0 (+), 79.6 and 78.9 (C_q), 55.0 and 53.6 (+), 36.4 and 36.2 (–), 28.1 and 27.6 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{22}H_{23}N_2O_6$) calc.: 411.1551, found: 411.1551.
MF: $C_{22}H_{22}N_2O_6$
MW: 410.43 g/mol

1,3-Dioxoisoindolin-2-yl *O*-benzyl-*N*-(*tert*-butoxycarbonyl)serinate (1f)



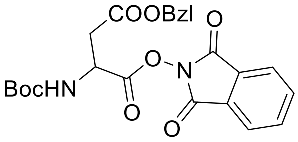
Yield: 2.94 g, 6.67 mmol, 83%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.94 – 7.83 (m, 2H), 7.83 – 7.74 (m, 2H), 7.46 – 7.27 (m, 5H), 5.50 (d, *J* = 9.1 Hz, 1H), 5.32 – 5.12 (m, 0.2H), 4.98 – 4.83 (m, 0.8H), 4.74 – 4.57 (m, 2H), 4.15 – 3.99 (m, 1H), 3.86 (dd, *J* = 9.7 Hz, 3.4 Hz, 1H), 1.54 – 1.40 (m, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 167.8 (C_q), 161.5 (C_q), 155.1 (C_q), 137.4 (C_q), 134.9 (+), 129.0 (C_q), 128.6 (+), 128.0 (+), 124.1 (+), 80.7 (C_q), 73.8 (–), 69.9 (–), 54.1 and 52.8 (+), 28.4 and 28.1 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{23}H_{25}N_2O_7$) calc.: 441.1656, found: 441.1656.
MF: $C_{23}H_{24}N_2O_7$
MW: 440.45 g/mol

4-Benzyl 1-(1,3-dioxoisoindolin-2-yl) (*tert*-butoxycarbonyl)aspartate (1g)



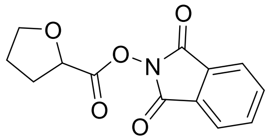
Yield: 2.84 g, 6.07 mmol, 76%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.92 – 7.83 (m, 2H), 7.82 – 7.76 (m, 2H), 7.43 – 7.27 (m, 5H), 5.77 – 5.30 (m, 1H), 5.28 – 5.19 (m, 2H), 5.12 – 4.84 (m, 1H), 3.27 – 2.98 (m, 2H), 1.54 – 1.40 (m, 9H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 170.2 (C$_q$), 168.0 (C$_q$), 161.4 (C$_q$), 155.0 (C$_q$), 135.4 (C$_q$), 134.9 (+), 128.9 (C$_q$), 128.7 (+), 128.60 (+), 128.55 (+), 124.1 and 123.5 (+), 80.9 (C$_q$), 67.4 (–), 48.8 (+), 37.1 (–), 28.3 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{24}H_{25}N_2O_8$) calc.: 469.1605, found: 469.1606.
MF: $C_{24}H_{24}N_2O_8$
MW: 468.46 g/mol

1,3-Dioxoisoindolin-2-yl tetrahydrofuran-2-carboxylate (1h)[34]



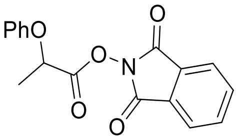
Yield: 996 mg, 3.81 mmol, 48%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.91 – 7.82 (m, 2H), 7.82 – 7.75 (m, 2H), 4.86 (dd, *J* = 8.4 Hz, 5.1 Hz, 1H), 4.12 – 3.95 (m, 2H), 2.50 – 2.30 (m, 2H), 2.15 – 1.93 (m, 2H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 169.9 (C$_q$), 161.8 (C$_q$), 135.0 (+), 128.9 (C$_q$), 124.1 (+), 75.0 (+), 70.0 (–), 31.0 (–), 25.2 (–).

HRMS (APCI) (m/z): [M + H]$^+$ ($C_{13}H_{12}NO_5$) calc.: 262.0710, found: 262.0713.
MF: $C_{13}H_{11}NO_5$
MW: 261.23 g/mol

1,3-Dioxoisoindolin-2-yl 2-phenoxypropanoate (1i)



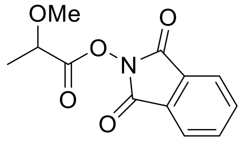
Yield: 1.90 g, 6.10 mmol, 76%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = δ 7.90 – 7.83 (m, 2H), 7.81 – 7.74 (m, 2H), 7.39 – 7.31 (m, 2H), 7.08 – 6.96 (m, 3H), 5.12 (q, *J* = 6.9 Hz, 1H), 1.87 (d, *J* = 6.9 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 168.8 (C$_q$), 161.7 (C$_q$), 157.0 (C$_q$), 135.0 (+), 129.8 (+), 128.9 (C$_q$), 124.2 (+), 122.4 (+), 115.4 (+), 71.0 (+), 19.0 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{17}H_{14}NO_5$) calc.: 312.0866, found: 312.0874.
MF: $C_{17}H_{13}NO_5$
MW: 311.29 g/mol

1,3-Dioxoisoindolin-2-yl 2-methoxypropanoate (1j)



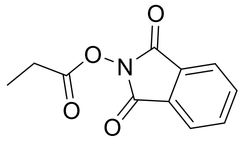
Yield: 1.33 g, 5.32 mmol, 67%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.90 – 7.81 (m, 2H), 7.80 – 7.72 (m, 2H), 4.26 (q, *J* = 6.9 Hz, 1H), 3.49 (s, 3H), 1.61 (d, *J* = 6.9 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 169.6 (C$_q$), 161.7 (C$_q$), 134.9 (+), 128.9 (C$_q$), 124.1 (+), 74.9 (+), 58.2 (+), 18.8 (+).

HRMS (APCI) (m/z): [M + H]$^+$ ($C_{12}H_{12}NO_5$) calc.: 250.0710, found: 250.0715.
MF: $C_{12}H_{11}NO_5$
MW: 249.06 g/mol

1,3-Dioxoisoindolin-2-yl propionate (1k)[35]



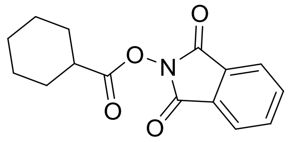
Yield: 1.32 g, 6.01 mmol, 75%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.93 – 7.84 (m, 2H), 7.82 – 7.75 (m, 2H), 2.70 (q, *J* = 7.5 Hz, 2H), 1.30 (t, *J* = 7.5 Hz, 3H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 170.5 (C$_q$), 162.1 (C$_q$), 134.9 (+), 129.1 (C$_q$), 124.1 (+), 24.7 (–), 8.8 (+).

HRMS (ESI) (m/z): [M + Na]$^+$ ($C_{11}H_9NNaO_4$) calc.: 242.0424, found: 242.0425.
MF: $C_{11}H_9NO_4$
MW: 219.20 g/mol

1,3-Dioxoisoindolin-2-yl cyclohexanecarboxylate (1l)[34]



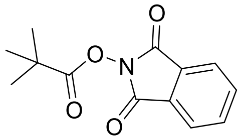
Yield: 1.83 g, 6.69 mmol, 84%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.92 – 7.80 (m, 2H), 7.80 – 7.67 (m, 2H), 2.71 (tt, *J* = 10.9 Hz, 3.7 Hz, 1H), 2.14 – 2.01 (m, 2H), 1.86 – 1.74 (m, 2H), 1.71 – 1.55 (m, 3H), 1.44 – 1.22 (m, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 171.9 (C$_q$), 162.1 (C$_q$), 134.8 (+), 129.0 (C$_q$), 123.9 (+), 40.5 (+), 28.8 (–), 25.5 (–), 25.1 (–).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{15}H_{16}NO_4$) calc.: 274.1074, found: 274.1075.
MF: $C_{15}H_{15}NO_4$
MW: 273.29 g/mol

1,3-Dioxoisoindolin-2-yl pivalate (1m)[36]



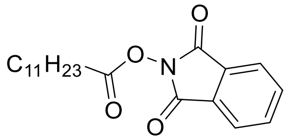
Yield: 1.63 g, 6.60 mmol, 83%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.92 – 7.81 (m, 2H), 7.81 – 7.73 (m, 2H), 1.43 (s, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 174.5 (C_q), 162.2 (C_q), 134.8 (+), 129.1 (C_q), 124.0 (+), 38.5 (C_q), 27.1 (+).

HRMS (APCI) (m/z): $[M + NH_4]^+$ ($C_{13}H_{17}N_2O_4$) calc.: 265.1183, found: 265.1189.
MF: $C_{13}H_{13}NO_4$
MW: 247.25 g/mol

1,3-Dioxoisoindolin-2-yl dodecanoate (1n)



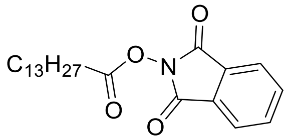
Yield: 2.43 g, 7.04 mmol, 88%.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.90 – 7.79 (m, 2H), 7.79 – 7.69 (m, 2H), 2.63 (t, *J* = 7.5 Hz, 2H), 1.81 – 1.71 (m, 2H), 1.46 – 1.21 (m, 16H), 0.85 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 169.7 (C_q), 162.0 (C_q), 134.8 (+), 129.0 (C_q), 124.0 (+), 32.0 (–), 31.0 (–), 29.7 (–), 29.6 (–), 29.43 (–), 29.39 (–), 29.2 (–), 28.9 (–), 24.7 (–), 22.7 (–), 14.2 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{20}H_{28}NO_4$) calc.: 346.2013, found: 346.2014.
MF: $C_{20}H_{27}NO_4$
MW: 345.44 g/mol

1,3-Dioxoisoindolin-2-yl tetradecanoate (1o)[37]



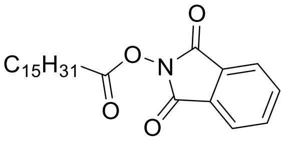
Yield: 2.61 g, 7.00 mmol, 87%.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.92 – 7.80 (m, 2H), 7.80 – 7.72 (m, 2H), 2.65 (t, *J* = 7.5 Hz, 2H), 1.82 – 1.73 (m, 2H), 1.47 – 1.21 (m, 20H), 0.87 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 169.8 (C_q), 162.1 (C_q), 134.8 (+), 129.0 (C_q), 124.1 (+), 32.0 (–), 31.1 (–), 29.79 (–), 29.76 (–), 29.75 (–), 29.68 (–), 29.49 (–), 29.48 (–), 29.2 (–), 24.8 (–), 22.8 (–), 14.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{22}H_{32}NO_4$) calc.: 374.2326, found: 374.2332.
MF: $C_{22}H_{31}NO_4$
MW: 373.49 g/mol

1,3-Dioxoisoindolin-2-yl palmitate (1p)[38]



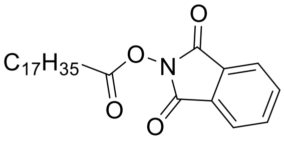
Yield: 1.90 g, 4.74 mmol, 59%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.92 – 7.81 (m, 2H), 7.81 – 7.72 (m, 2H), 2.66 (t, *J* = 7.5 Hz, 2H), 1.84 – 1.71 (m, 2H), 1.48 – 1.21 (m, 24H), 0.87 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 169.8 (C$_q$), 162.1 (C$_q$), 134.9 (+), 129.1 (C$_q$), 124.1 (+), 32.1 (–), 31.1 (–), 29.82 (–), 29.80 (–), 29.76 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.0 (–), 24.8 (–), 22.8 (–), 14.3 (+).

HRMS (APCI) (m/z): [M + H]$^+$ ($C_{24}H_{36}NO_4$) calc.: 402.2639, found: 402.2641.
MF: $C_{24}H_{35}NO_4$
MW: 401.55 g/mol

1,3-Dioxoisoindolin-2-yl stearate (1q)[37]



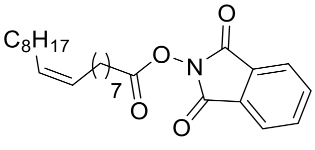
Yield: 2.88 g, 6.69 mmol, 84%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.93 – 7.81 (m, 2H), 7.81 – 7.72 (m, 2H), 2.65 (t, *J* = 7.5 Hz, 2H), 1.83 – 1.72 (m, 2H), 1.48 – 1.21 (m, 28H), 0.87 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 169.8 (C$_q$), 162.1 (C$_q$), 134.8 (+), 129.1 (C$_q$), 124.1 (+), 32.1 (–), 31.1 (–), 29.83 (–), 29.80 (–), 29.76 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.0 (–), 24.8 (–), 22.8 (–), 14.3 (+).

HRMS (CI) (m/z): [M + H]$^+$ ($C_{26}H_{40}NO_4$) calc.: 430.2952, found: 430.2953.
MF: $C_{26}H_{39}NO_4$
MW: 429.60 g/mol

1,3-Dioxoisoindolin-2-yl oleate (1r)[38]



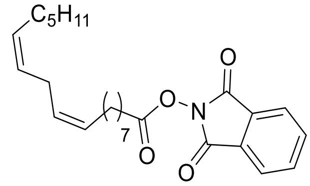
Yield: 3.18 g, 7.44 mmol, 93%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.91 – 7.80 (m, 2H), 7.80 – 7.68 (m, 2H), 5.40 – 5.27 (m, 2H), 2.64 (t, *J* = 7.5 Hz, 2H), 2.14 – 1.88 (m, 4H), 1.82 – 1.71 (m, 2H), 1.50 – 1.18 (m, 20H), 0.86 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 169.7 (C$_q$), 162.0 (C$_q$), 134.8 (+), 130.1 (+), 129.8 (+), 129.0 (C$_q$), 124.0 (+), 32.0 (–), 31.0 (–), 29.8 (–), 29.7 (–), 29.6 (–), 29.4 (–), 29.10 (–), 29.09 (–), 28.9 (–), 27.3 (–), 27.2 (–), 24.7 (–), 22.8 (–), 14.2 (+).

HRMS (ESI) (m/z): [M + Na]$^+$ ($C_{26}H_{37}NNaO_4$) calc.: 450.2615, found: 450.2617.
MF: $C_{26}H_{37}NO_4$
MW: 427.59 g/mol

1,3-Dioxoisoindolin-2-yl (9*Z*,12*Z*)-octadeca-9,12-dienoate (1s)



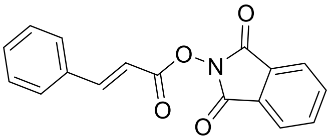
Yield: 2.54 g, 5.97 mmol, 75%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.92 – 7.81 (m, 2H), 7.81 – 7.71 (m, 2H), 5.43 – 5.25 (m, 4H), 2.77 (t, *J* = 5.8 Hz, 2H), 2.65 (t, *J* = 7.5 Hz, 2H), 2.10 – 1.98 (m, 4H), 1.83 – 1.69 (m, 2H), 1.48 – 1.23 (m, 14H), 0.87 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 169.7 (C$_q$), 162.1 (C$_q$), 134.8 (+), 130.3 (+), 130.1 (+), 129.0 (C$_q$), 128.2 (+), 128.0 (+), 124.0 (+), 31.6 (–), 31.1 (–), 29.6 (–), 29.4 (–), 29.1 (–), 28.9 (–), 27.28 (–), 27.26 (–), 25.7 (–), 24.7 (–), 22.7 (–), 14.2 (+).

HRMS (APCI) (m/z): [M + NH$_4$]$^+$ ($C_{26}H_{39}N_2O_4$) calc.: 443.2904, found: 443.2903.
MF: $C_{26}H_{35}NO_4$
MW: 425.57 g/mol

1,3-Dioxoisoindolin-2-yl cinnamate (1t)[39]



Yield: 2.03 g, 6.93 mmol, 87%.

^{1}H NMR (400 MHz, CDCl$_3$): δ [ppm] = 7.96 (d, *J* = 16.1 Hz, 1H), 7.94 – 7.87 (m, 2H), 7.83 – 7.77 (m, 2H), 7.62 – 7.57 (m, 2H), 7.50 – 7.39 (m, 3H), 6.66 (d, *J* = 16.1 Hz, 1H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 163.1 (C$_q$), 162.2 (C$_q$), 150.1 (+), 134.9 (+), 133.7 (C$_q$), 131.7 (+), 129.3 (+), 129.1 (C$_q$), 128.8 (+), 124.1 (+), 111.9 (+).

HRMS (APCI) (m/z): [M + H]$^+$ ($C_{17}H_{12}NO_4$) calc.: 294.0761, found: 294.0767.
MF: $C_{17}H_{11}NO_4$
MW: 293.28 g/mol

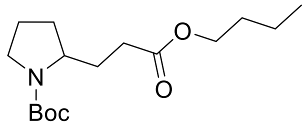
2.4.3. Photocatalytic Reactions

General procedure for the photocatalytic decarboxylative alkylation

In a 5 mL crimp cap vial with a stirring bar, eosin Y (**A**, 19.4 mg, 0.03 mmol, 0.1 equiv.) and *N*-(acyloxy)phthalimide **1** (0.30 mmol, 1.0 equiv.) were added. After addition of DIPEA (102 µL, 0.60 mmol, 2.0 equiv.), the corresponding olefin **2** (1.50 mmol, 5.0 equiv.) and dry CH_2Cl_2 (4 mL), the vial was capped to prevent evaporation. The reaction mixture was stirred and irradiated through the vials´ plane bottom side using green LEDs (535 nm) for 18 h at rt. The reaction mixture of two vials with the same content was combined and diluted with saturated aqueous solution of $NaHCO_3$ (20 mL). It was extracted with EA (3 x 20 mL) and the combined organic phases were washed with brine (20 mL), dried over Na_2SO_4 and concentrated in vacuum. Purification of the crude product was performed by automated flash column chromatography (PE/EA = 19:1 to 1:1) yielding the corresponding product as colorless oil.

Characterization of photocatalytic products 3 and 4

***tert*-Butyl 2-(3-butoxy-3-oxopropyl)pyrrolidine-1-carboxylate (3a)**



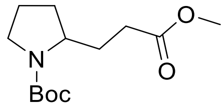
Yield: 144 mg, 0.48 mmol, 80%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 4.04 (t, *J* = 6.6 Hz, 2H), 3.77 (brs, 1H), 3.54 – 3.16 (m, 2H), 2.28 (brs, 2H), 2.01 – 1.76 (m, 4H), 1.71 –1.54 (m, 4H), 1.44 (s, 9H), 1.35 (q, *J* = 7.4 Hz, 2H), 0.91 (t, *J* = 7.4 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 173.6 and 173.1 (C_q), 154.8 (C_q), 79.4 and 79.1 (C_q), 64.4 (–), 56.7 (+), 46.6 and 46.2 (–), 31.5 (–), 30.8 (–), 30.1 and 29.8 (–), 28.6 (+), 23.8 (–), 23.2 (–), 19.2 (–), 13.8 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{16}H_{30}NO$) calc.: 300.2169, found: 300.2170.
MF: $C_{16}H_{29}NO$
MW: 299.41 g/mol

***tert*-Butyl 2-(3-methoxy-3-oxopropyl)pyrrolidine-1-carboxylate (3b)**[40]



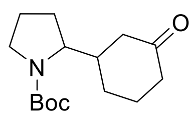
Yield: 120 mg, 0.47 mmol, 78%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 3.80 (brs, 1H), 3.65 (s, 3H), 3.52 – 3.16 (m, 2H), 2.31 (brs, 2H), 2.03 – 1.59 (m, 6H), 1.45 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 174.0 (C_q), 154.9 (C_q), 79.5 and 79.2 (C_q), 56.7 (+), 51.7 (+), 46.6 and 46.2 (–), 31.2 and 30.9 (–), 30.1 and 29.8 (–), 28.6 (+), 23.9 (–), 23.2 (–).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{13}H_{24}NO_4$) calc.: 258.1700, found: 258.1706.
MF: $C_{13}H_{23}NO_4$
MW: 257.33 g/mol

tert-Butyl 2-(3-oxocyclohexyl)pyrrolidine-1-carboxylate (3c)[41]



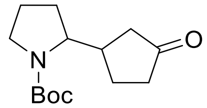
Yield: 122 mg, 0.46 mmol, 76%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 3.83 (brs, 1H), 3.46 (brs, 1H), 3.29 – 3.14 (m, 1H), 2.41 – 1.97 (m, 6H), 1.96 – 1.50 (m, 7H), 1.49 – 1.42 (m, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): (rotameric and diastereomeric mixture); δ [ppm] = 211.6 (C_q), 155.3 (C_q), 79.5 (C_q), 61.0 and 61.1 (+), 46.9 (–), 45.4 (–), 43.9 (–), 43.1 (+), 41.5 (–), 28.7 (+), 28.6 (–), 27.9 (–), 25.5 (–).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{15}H_{26}NO_3$) calc.: 268.1907, found: 268.1911.
MF: $C_{15}H_{25}NO_3$
MW: 267.37 g/mol

tert-Butyl 2-(3-oxocyclopentyl)pyrrolidine-1-carboxylate (3d)



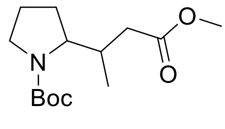
Yield: 111 mg, 0.44 mmol, 73%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 3.91 (brs, 1H), 3.44 (brs, 1H), 3.30 – 3.22 (m, 1H), 2.45 – 1.62 (m, 11H), 1.49 – 1.41 (m, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 219.0 (C_q), 155.5 (C_q), 79.5 (C_q), 60.3 and 60.1 (+), 46.9 and 46.6 (–), 43.0 and 42.2 (–), 41.7 (+), 38.8 and 38.5 (–), 29.6 and 28.6 (+), 26.9 (–), 26.4 (–), 24.0 and 23.2 (–).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{14}H_{24}NO_3$) calc.: 254.1751, found: 254.1751.
MF: $C_{14}H_{23}NO_3$
MW: 253.34 g/mol

tert-Butyl 2-(4-methoxy-4-oxobutan-2-yl)pyrrolidine-1-carboxylate (3e)[42]



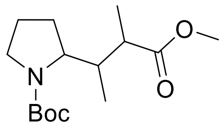
Yield: 119 mg, 0.44 mmol, 73%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 3.87 – 3.28 (m, 5H), 3.24 – 3.04 (m, 1H), 2.69 – 2.15 (m, 2H), 2.14 – 1.95 (m, 1H), 1.91 – 1.58 (m, 4H), 1.43 (s, 9H), 0.87 (m, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 173.9 and 173.7 and 173.5 (C_q), 155.4 and 155.2 (C_q), 79.5 and 79.1 (C_q), 61.5 and 61.4 (+), 51.6 and 51.5 (+), 47.4 and 47.2 and 46.9 and 46.7 (–), 38.9 and 38.7 (–), 33.9 and 33.8 and 33.4 (+), 28.6 (+), 27.7 (–), 24.0 and 23.4 (–), 17.0 and 16.3 and 15.7 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{14}H_{26}NO_4$) calc.: 272.1856, found: 272.1861.
MF: $C_{14}H_{25}NO_4$
MW: 271.36 g/mol

***tert*-Butyl 2-(4-methoxy-3-methyl-4-oxobutan-2-yl)pyrrolidine-1-carboxylate (3f)**



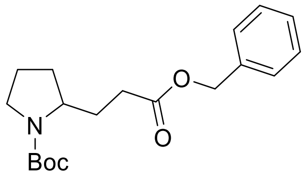
Yield: 102 mg, 0.36 mmol, 59%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 4.06 – 3.23 (m, 5H), 3.23 – 3.01 (m, 1H), 2.57 – 1.61 (m, 6H), 1.44 (s, 9H), 1.21 – 1.05 (m, 3H), 0.91 – 0.72 (m, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.6 and 176.2 (C_q), 155.4 and 154.8 (C_q), 79.5 and 79.1 (C_q), 61.0 and 60.6 and 59.6 (+), 51.6 and 51.5 and 51.4 (+), 47.0 and 46.8 and 46.3 (–), 43.6 and 41.8 and 41.1 and 40.7 (+), 39.0 and 38.8 (+), 29.8 and 28.6 (+), 28.1 and 27.7 (–), 24.2 and 24.0 and 23.6 and 23.3 (–), 16.1 and 15.7 and 15.3 and 14.1 (+),12.3 and 11.9 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{15}H_{28}NO_4$) calc.: 286.2013, found: 286.2017.
MF: $C_{15}H_{27}NO_4$
MW: 285.38 g/mol

***tert*-Butyl 2-(3-(benzyloxy)-3-oxopropyl)pyrrolidine-1-carboxylate (3g)[43]**



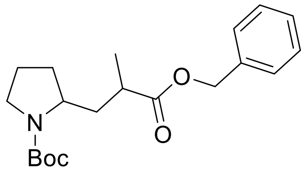
Yield: 138 mg, 0.41 mmol, 69%.

^{1}H NMR (400 MHz, DMSO-*d*$_6$): (rotamers around the tertiary amide); δ [ppm] = 7.38 – 7.30 (m, 5H), 5.08 (s, 2H), 3.69 (brs, 1H), 3.31 – 3.04 (m, 2H), 2.42 – 2.25 (m, 2H), 1.97 – 1.50 (m, 6H), 1.37 (s, 9H).

^{13}C NMR (101 MHz, DMSO-*d*$_6$): δ [ppm] = 172.5 (C_q), 153.7 and 153.6 (C_q), 136.2 (C_q), 128.4 (+), 128.0 (+), 127.9 (+), 78.2 (C_q), 65.4 (–), 56.1 (+), 46.2 and 45.9 (–), 30.5 and 30.0 (–), 29.3 and 28.9 (–), 28.1 (+), 23.2 (–), 22.5 (–).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{19}H_{28}NO_4$) calc.: 334.2015, found: 334.2013.
MF: $C_{19}H_{27}NO_4$
MW: 333.43 g/mol

***tert*-Butyl 2-(3-(benzyloxy)-2-methyl-3-oxopropyl)pyrrolidine-1-carboxylate (3h)**



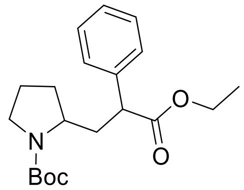
Yield: 178 mg, 0.51 mmol, 85%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 7.43 – 7.26 (m, 5H), 5.20 – 5.02 (m, 2H), 4.15 – 3.50 (m, 1H), 3.46 – 3.15 (m, 2H), 2.85 – 1.95 (m, 2H), 1.95 – 1.48 (m, 5H), 1.46 – 1.38 (m, 9H), 1.21 (d, *J* = 7.0 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 176.2 (C_q), 154.8 and 154.6 (C_q), 136.2 and 136.1 (C_q), 128.57 (+), 128.55 (+), 128.2 (+), 79.3 and 79.1 (C_q), 66.5 and 66.2 and 66.1 (–), 55.6 and 55.3 (+), 46.0 (–), 38.9 and 38.3 (–), 37.2 and 37.1 (+), 30.9 and 30.5 (–), 28.6 (+), 23.7 and 23.1 (–), 17.9 and 17.3 and 17.1 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{20}H_{30}NO_4$) calc.: 348.2169, found: 348.2175.
MF: $C_{20}H_{29}NO_4$
MW: 347.46 g/mol

tert-Butyl 2-(3-ethoxy-3-oxo-2-phenylpropyl)pyrrolidine-1-carboxylate (3i)



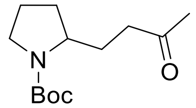
Yield: 191 mg, 0.55 mmol, 92%.

^{1}H NMR (400 MHz, acetone-*d₆*): (rotameric and diasteromeric mixture); δ [ppm] = 7.39 – 7.22 (m, 5H), 4.18 – 4.03 (m, 2H), 3.95 – 3.40 (m, 2H), 3.40 – 3.09 (m, 2H), 2.60 (brs, 0.8H), 2.32 – 2.23 (m, 0.2H), 2.01 – 1.55 (m, 5H), 1.55 – 1.34 (m, 9H), 1.17 (t, *J* = 7.1 Hz, 3H).

^{13}C NMR (101 MHz, acetone-*d₆*): δ [ppm] = 174.2 and 174.1 (C_q), 155.3 and 155.0 (C_q), 141.2 (C_q), 129.6 (+), 129.1 and 128.9 (+), 128.1 (+), 79.3 (C_q), 61.6 and 61.3 (–), 57.0 and 56.3 (+), 49.9 and 49.8 (+), 47.2 and 46.9 (–), 40.0 and 39.7 and 39.5 and 39.4 (–), 31.4 (–), 29.0 (+), 24.6 and 23.7 (–), 14.7 and 14.4 (+).

HRMS (ESI) (m/z): $[M + Na]^+$ ($C_{20}H_{29}NNaO_4$) calc.: 370.1989, found: 390.1992.
MF: $C_{20}H_{29}NO_4$
MW: 347.46 g/mol

tert-Butyl 2-(3-oxobutyl)pyrrolidine-1-carboxylate (3j)[41]



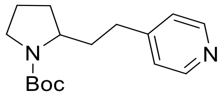
Yield: 79 mg, 0.33 mmol, 55%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 3.79 (brs, 1H), 3.48 – 3.22 (m, 2H), 2.44 (t, *J* = 7.5 Hz, 2H), 2.14 (s, 3H), 1.94 – 1.75 (m, 4H), 1.69 – 1.56 (m, 2H), 1.45 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 208.6 (C_q), 155.0 (C_q), 79.3 (C_q), 56.7 (+), 46.4 (–), 41.0 and 40.8 (–), 30.7 (–), 30.0 and 29.8 (+), 28.9 (–), 28.7 (+), 24.0 and 23.6 (–).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{13}H_{24}NO_3$) calc.: 242.1751, found: 242.1755.
MF: $C_{13}H_{23}NO_3$
MW: 241.33 g/mol

tert-Butyl 2-(2-(pyridin-4-yl)ethyl)pyrrolidine-1-carboxylate (3k)



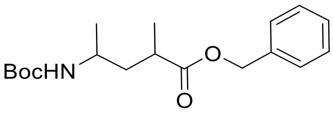
Yield: 66 mg, 0.24 mmol, 40%.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 8.44 (brs, 2H), 7.09 (brs, 2H), 3.95 – 3.60 (m, 1H), 3.47 – 3.21 (m, 2H), 2.64 – 2.49 (m, 2H), 2.15 – 1.55 (m, 6H), 1.42 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 154.7 (C_q), 151.2 and 151.0 (C_q), 149.8 (+), 123.9 (+), 79.3 and 79.1 (C_q), 57.0 and 56.7 (+), 46.7 and 46.3 (–), 35.3 and 34.8 (–), 32.2 (–), 30.7 and 30.2 (–), 28.6 (+), 23.9 and 23.2 (–).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{16}H_{25}N_2O_2$) calc.: 277.1911, found: 277.1914.
MF: $C_{16}H_{24}N_2O_2$
MW: 276.38 g/mol

Benzyl 4-((*tert*-butoxycarbonyl)amino)-2-methylpentanoate (4b)



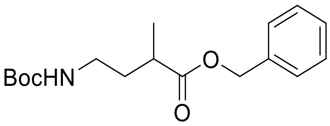
Yield: 132 mg, 0.41 mmol, 68%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 7.39 – 7.30 (m, 5H), 5.20 – 5.02 (m, 2H), 4.52 – 3.96 (m, 1H), 3.74 (brs, 1H), 2.67 – 2.46 (m, 1H), 1.89 – 1.48 (m, 2H), 1.45 – 1.36 (m, 9H), 1.23 – 1.16 (m, 3H), 1.12 (t, *J* = 6.5 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.8 and 176.3 (C_q), 155.5 and 155.3 (C_q), 136.23 and 136.18 (C_q), 128.69 and 128.66 (+), 128.3 (+), 128.25 and 128.22 (+), 79.2 (C_q), 66.7 and 66.41 and 66.39 (–), 44.9 (+), 41.2 and 40.8 (–), 37.1 and 36.7 (+), 28.5 (+), 22.3 and 21.4 (+), 17.7 and 17.3 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{18}H_{28}NO_4$) calc.: 322.2013, found: 322.2017.
MF: $C_{18}H_{27}NO_4$
MW: 321.42 g/mol

Benzyl 4-((*tert*-butoxycarbonyl)amino)-2-methylbutanoate (4c)



Yield: 114 mg, 0.37 mmol, 62%.

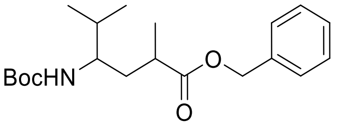
^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.38 – 7.31 (m, 5H), 5.21 – 5.07 (m, 2H), 4.75 – 4.19 (m, 1H), 3.37 – 2.97 (m, 2H), 2.60 – 2.49 (m, 1H), 1.93 – 1.78 (m, 1H), 1.80 – 1.58 (m, 1H), 1.45 – 1.40 (m, 9H), 1.23 (d, *J* = 5.9 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.5 and 176.2 (C_q), 156.0 and 155.8 (C_q), 136.2 and 136.0 (C_q), 128.71 and 128.68 (+), 128.37 and 128.35 (+), 128.2 (+), 79.4 (C_q), 66.8 and 66.4 (–), 38.6 (–), 37.3 (+), 33.9 (–), 28.5 (+), 17.2 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{17}H_{26}NO_4$) calc.: 308.1856, found: 308.1857.

MF: $C_{17}H_{25}NO_4$
MW: 307.39 g/mol

Benzyl 4-((*tert*-butoxycarbonyl)amino)-2,5-dimethylhexanoate (4d)[44]



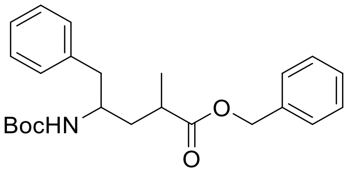
Yield: 187 mg, 0.54 mmol, 89%.

^{1}H NMR (300 MHz, $CDCl_3$): (rotameric and diasteromeric mixture); δ [ppm] = 7.38 – 7.29 (m, 5H), 5.20 – 4.94 (m, 2H), 4.45 – 3.88 (m, 1H), 3.88 – 3.20 (m, 1H), 2.75 – 1.44 (m, 4H), 1.44 – 1.34 (m, 9H), 1.22 – 1.10 (m, 3H), 0.93 – 0.76 (m, 6H).

^{13}C NMR (75 MHz, $CDCl_3$) δ [ppm] = 177.1 and 176.9 and 176.5 and 176.3 (C_q), 156.0 and 155.8 and 155.4 (C_q), 136.3 and 136.2 and 136.99 and 135.98 (C_q), 128.66 and 128.63 and 128.60 and 128.56 (+), 128.23 and 128.22 and 128.19 (+), 128.1 and 128.0 (+), 79.04 and 78.97 (C_q), 66.6 and 66.5 and 66.4 and 66.3 (–), 53.73 and 53.65 and 51.84 and 51.79 (+), 45.0 and 44.6 and 44.4 and 44.2 (–), 37.1 and 36.7 and 36.4 and 35.8 (+), 33.7 and 33.1 and 32.4 (+), 28.5 (+), 20.1 and 19.1 and 19.0 and 18.9 (+), 18.0 and 17.9 (+), 17.7 and 17.6 and 17.1 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{20}H_{32}NO_4$) calc.: 350.2326, found: 350.2334.
MF: $C_{20}H_{31}NO_4$
MW: 349.47 g/mol

Benzyl 4-((*tert*-butoxycarbonyl)amino)-2-methyl-5-phenylpentanoate (4e)[45]



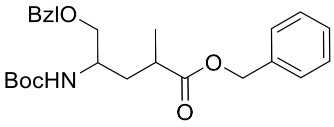
Yield: 120 mg, 0.34 mmol, 57%.

^{1}H NMR (300 MHz, CD_2Cl_2) (rotameric and diasteromeric mixture); δ [ppm] = 7.53 – 6.95 (m, 10H), 5.18 – 4.92 (m, 2H), 4.56 – 4.13 (m, 1H), 4.13 – 3.68 (m, 1H), 2.90 – 1.44 (m, 5H), 1.43 – 1.22 (m, 9H), 1.20 – 1.08 (m, 3H).

^{13}C NMR (101 MHz, CD_2Cl_2): δ [ppm] = 176.9 and 176.8 and 176.5 and 176.2 (C_q), 155.6 and 155.5 and 155.1 (C_q), 138.8 and 138.64 and 138.58 (C_q), 136.81 and 136.77 and 136.66 and 136.5 (C_q), 129.88 and 129.84 and 129.80 (+), 128.89 and 128.87 (+), 128.67 and 128.65 and 128.62 (+), 128.47 and 128.44 (+), 128.40 and 128.37 and 128.33 (+), 126.68 and 126.65 (+), 79.22 and 79.19 (C_q), 66.9 and 66.8 and 66.54 and 66.49 (–), 50.4 and 50.3 and 48.9 (+), 44.5 and 43.5 and 42.5 and 41.9 (–), 38.6 and 38.4 (–), 37.3 and 36.9 and 36.1 (+), 30.1 and 28.5 (+), 20.3 and 20.1 and 18.0 and 17.2 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{24}H_{32}NO_4$) calc.: 398.2326, found: 398.2334.
MF: $C_{24}H_{31}NO_4$
MW: 397.52 g/mol

Benzyl 5-(benzyloxy)-4-((*tert*-butoxycarbonyl)amino)-2-methylpentanoate (4f)



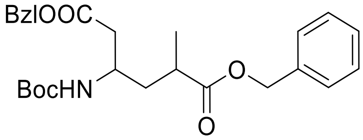
Yield: 141 mg, 0.33 mmol, 55%.

^{1}H NMR (300 MHz, CDCl$_3$): (rotameric and diasteromeric mixture); δ [ppm] = 7.41 – 7.27 (m, 10H), 5.19 – 5.04 (m, 2H), 4.90 – 4.57 (m, 1H), 4.56 – 4.38 (m, 2H), 4.17 – 3.73 (m, 1H), 3.73 – 3.26 (m, 2H), 2.71 – 2.48 (m, 1H), 2.10 – 1.91 (m, 1H), 1.68 – 1.58 (m, 1H), 1.53 – 1.31 (m, 9H), 1.25 – 1.16 (m, 3H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 176.7 and 176.2 (C$_q$), 155.7 and 155.6 (C$_q$), 138.3 (C$_q$), 136.3 and 136.2 (C$_q$), 128.71 and 128.68 and 128.6 (+), 128.52 and 128.45 (+), 128.34 and 128.28 (+), 128.2 (+), 127.8 (+), 127.70 and 127.69 (+), 79.4 and 79.3 (C$_q$), 73.3 (–), 72.7 and 72.3 (–), 66.7 and 66.38 and 66.36 (–), 48.71 and 48.66 (+), 36.9 and 36.6 (+), 36.0 and 35.9 (–), 29.8 and 28.5 (+), 17.9 and 17.2 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{25}H_{34}NO_5$) calc.: 428.2431, found: 428.2437.
MF: $C_{25}H_{33}NO_5$
MW: 427.54 g/mol

Dibenzyl 4-((*tert*-butoxycarbonyl)amino)-2-methylhexanedioate (4g)



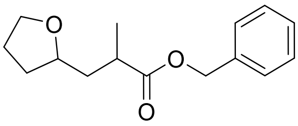
Yield: 174 mg, 0.38 mmol, 64%.

^{1}H NMR (300 MHz, CDCl$_3$): (rotameric and diasteromeric mixture); δ [ppm] = 7.38 – 7.29 (m, 10H), 5.20 – 4.84 (m, 5H), 4.08 (brs, 1H), 2.70 – 2.39 (m, 3H), 2.05 – 1.53 (m, 2H), 1.46 – 1.35 (m, 9H), 1.21 – 1.10 (m, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 176.4 and 176.0 (C$_q$), 171.6 and 171.3 (C$_q$), 155.34 and 155.27 (C$_q$), 136.2 and 136.1 (C$_q$), 135.8 (C$_q$), 128.71 and 128.68 (+), 128.6 (+), 128.5 (+), 128.4 (+), 128.31 and 128.30 (+), 128.2 (+), 79.6 and 79.4 (C$_q$), 66.58 and 66.55 (–), 66.46 and 66.43 (–), 46.0 (+), 40.0 and 39.3 (–), 38.0 and 37.9 (–), 37.0 and 36.6 (+), 28.5 (+), 17.9 and 17.1 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{26}H_{34}NO_6$) calc.: 456.2381, found: 456.2384.
MF: $C_{26}H_{33}NO_6$
MW: 455.55 g/mol

Benzyl 2-methyl-3-(tetrahydrofuran-2-yl)propanoate (4h)



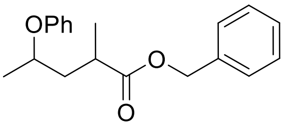
Yield: 108 mg, 0.43 mmol, 72%.

^{1}H NMR (300 MHz, CDCl$_3$): (mixture of diastereomers); δ [ppm] = 7.38 – 7.30 (m, 5H), 5.17 – 5.05 (m, 2H), 3.92 – 3.62 (m, 2H), 2.78 – 1.29 (m, 8H), 1.26 – 1.16 (m, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.6 (C_q), 136.4 (C_q), 128.7 and 128.6 (+), 128.5 (+), 128.21 and 128.18 (+), 77.4 (+), 67.8 and 67.7 (–), 66.23 and 66.19 (–), 39.8 and 39.5 (+), 37.3 (–), 31.7 and 29.9 (–), 25.8 (–), 18.2 and 17.2 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{15}H_{21}O_3$) calc.: 249.1488, found: 249.1493.
MF: $C_{15}H_{20}O_3$
MW: 248.32 g/mol

Benzyl 2-methyl-4-phenoxypentanoate (4i)



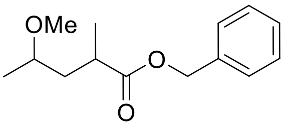
Yield: 90 mg, 0.30 mmol, 50%.

^{1}H NMR (300 MHz, DMSO-*d₆*): (mixture of diastereomers); δ [ppm] = 7.39 – 7.19 (m, 7H), 6.93 – 6.78 (m, 3H), 5.22 – 4.96 (m, 2H), 4.70 – 4.30 (m, 1H), 2.82 – 2.52 (m, 1H), 2.13 – 1.84 (m, 1H), 1.84 – 1.54 (m, 1H), 1.27 – 1.04 (m, 6H).

^{13}C NMR (75 MHz, DMSO-*d₆*): δ [ppm] = 175.5 and 175.4 (C_q), 157.5 and 157.4 (C_q), 136.2 (C_q), 129.7 and 129.5 (+), 128.44 and 128.41 (+), 128.03 and 127.97 (+), 127.9 (+), 120.5 and 120.4 (+), 115.5 and 115.4 (+), 71.0 and 70.9 (+), 65.6 and 65.5 (–), 40.2 and 39.9 (–), 36.1 and 35.6 (+), 19.6 and 19.5 (+), 17.4 and 17.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{19}H_{23}O_3$) calc.: 299.1642, found: 299.1644.
MF: $C_{19}H_{22}O_3$
MW: 298.38 g/mol

Benzyl 4-methoxy-2-methylpentanoate (4j)



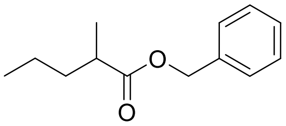
Yield: 82 mg, 0.35 mmol, 58%.

^{1}H NMR (400 MHz, $CDCl_3$): (mixture of diastereomers); δ [ppm] = 7.39 – 7.29 (m, 5H), 5.16 – 5.09 (m, 2H), 3.34 – 3.25 (m, 1H), 3.25 – 3.22 (m, 3H), 2.80 – 2.60 (m, 1H), 2.03 – 1.76 (m, 1H), 1.60 – 1.40 (m, 1H), 1.21 – 1.16 (m, 3H), 1.14 – 1.08 (m, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.8 and 176.7 (C_q), 136.4 (C_q), 128.6 (+), 128.3 (+), 128.22 and 128.21 (+), 75.0 and 74.9 (+), 66.17 and 66.15 (–), 56.3 and 56.1 (+), 41.2 and 40.8 (–), 36.8 and 36.3 (+), 19.3 and 19.1 (+), 18.1 and 17.5 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{14}H_{21}O_3$) calc.: 237.1485, found: 237.1488.
MF: $C_{14}H_{20}O_3$
MW: 236.31 g/mol

Benzyl 2-methylpentanoate (4k)[46]



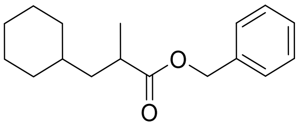
Yield: 36 mg, 0.17 mmol, 29%.[a]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.38 – 7.31 (m, 5H), 5.12 (s, 2H), 2.59 – 2.40 (m, 1H), 1.73 – 1.58 (m, 1H), 1.48 – 1.37 (m, 1H), 1.34 – 1.25 (m, 2H), 1.16 (d, *J* = 7.0 Hz, 3H), 0.89 (t, *J* = 7.2 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.4 (C_q), 128.7 (+), 128.22 (+), 128.16 (+), 66.1 (–), 39.5 (+), 36.1 (–), 20.5 (–), 17.2 (+), 14.1 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{13}H_{19}O_2$) calc.: 207.1380, found: 207.1382.
MF: $C_{13}H_{18}O_2$
MW: 206.29 g/mol

Benzyl 3-cyclohexyl-2-methylpropanoate (4l)[46]



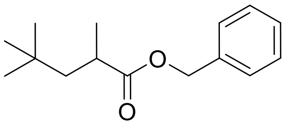
Yield: 63 mg, 0.24 mmol, 40%. [a]

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.39 – 7.29 (m, 5H), 5.20 – 5.08 (m, 2H), 2.68 – 2.53 (m, 1H), 1.75 – 1.57 (m, 6H), 1.27 – 1.19 (m, 8H), 0.90 – 0.80 (m, 2H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 177.2 (C_q), 136.5 (C_q), 128.7 (+), 128.2 (+), 66.1 (–), 41.8 (–), 37.1 (+), 35.5 (+), 33.3 (–), 26.7 (–), 26.4 (–), 17.8 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{17}H_{25}O_2$) calc.: 261.1849, found: 261.1855.
MF: $C_{17}H_{24}O_2$
MW: 260.38 g/mol

Benzyl 2,4,4-trimethylpentanoate (4m)[47]



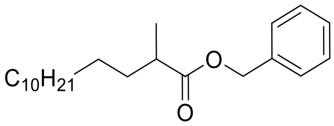
Yield: 63 mg, 0.27 mmol, 45%.[a]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.39 – 7.33 (m, 5H), 5.09 (s, 2H), 2.65 – 2.46 (m, 1H), 2.02 – 1.80 (m, 2H), 1.18 (d, *J* = 7.1 Hz, 3H), 0.86 (s, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 177.9 (C_q), 136.2 (C_q), 128.7 (+), 128.32 (+), 128.26 (+), 66.3 (–), 47.9 (–), 36.4 (+), 30.9 (C_q), 29.5 (+), 20.5 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{15}H_{23}O_2$) calc.: 235.1693, found: 235.1693.
MF: $C_{15}H_{22}O_2$
MW: 234.34 g/mol

Benzyl 2-methyltetradecanoate (4n)



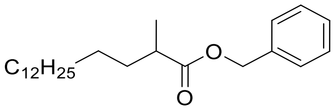
Yield: 62 mg, 0.19 mmol, 31%.[a]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.45 – 7.26 (m, 5H), 5.12 (s, 2H), 2.58 – 2.25 (m, 1H), 1.74 – 1.59 (m, 1H), 1.51 – 1.38 (m, 1H), 1.36 – 1.21 (m, 20H), 1.17 (d, *J* = 7.0 Hz, 3H), 0.89 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.4 (C_q), 128.6 (+), 128.21 (+), 128.18 (+), 66.1 (–), 39.7 (+), 34.0 (–), 32.1 (–), 29.81 (–), 29.79 (–), 29.7 (–), 29.64 (–), 29.63 (–), 29.5 (–), 27.3 (–), 22.8 (–), 17.2 (+), 14.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{22}H_{37}O_2$) calc.: 333.2788, found: 333.2788.
MF: $C_{22}H_{36}O_2$
MW: 332.53 g/mol

Benzyl 2-methylhexadecanoate (4o)



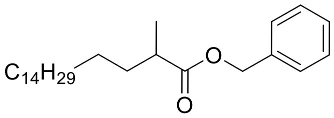
Yield: 69 mg, 0.19 mmol, 32%.[a]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.44 – 7.26 (m, 5H), 5.12 (s, 2H), 2.55 – 2.29 (m, 1H), 1.74 – 1.59 (m, 1H), 1.51 – 1.39 (m, 1H), 1.36 – 1.21 (m, 24H), 1.17 (d, *J* = 7.0 Hz, 3H), 0.89 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.4 (C_q), 128.6 (+), 128.21 (+), 128.18 (+), 66.1 (–), 39.7 (+), 34.0 (–), 32.1 (–), 29.84 (–), 29.80 (–), 29.7 (–), 29.6 (–),29.5 (–), 27.3 (–), 22.8 (–), 17.2 (+), 14.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{24}H_{41}O_2$) calc.: 361.3101, found: 361.3098.
MF: $C_{24}H_{40}O_2$
MW: 360.58 g/mol

Benzyl 2-methyloctadecanoate (4p)



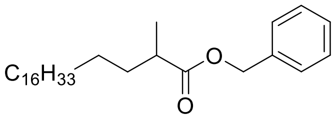
Yield: 72 mg, 0.19 mmol, 31%.[a]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.40 – 7.26 (m, 5H), 5.12 (s, 2H), 2.56 – 2.29 (m, 1H), 1.74 – 1.58 (m, 1H), 1.50 – 1.39 (m, 1H), 1.33 – 1.22 (m, 28H), 1.17 (d, *J* = 7.0 Hz, 3H), 0.89 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.4 (C_q), 128.6 (+), 128.20 (+), 128.17 (+), 66.1 (–), 39.7 (+), 34.0 (–), 32.1 (–), 29.9 (–), 29.8 (–), 29.7 (–), 29.6 (–), 29.5 (–), 27.3 (–), 22.8 (–), 17.2 (+), 14.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{26}H_{45}O_2$) calc.: 389.3414, found: 389.3413.
MF: $C_{26}H_{44}O_2$
MW: 388.64 g/mol

Benzyl 2-methylicosanoate (4q)



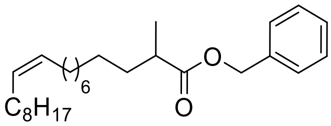
Yield: 75 mg, 0.18 mmol, 30%.[a]

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.39 – 7.29 (m, 5H), 5.12 (s, 2H), 2.57 – 2.41 (m, 1H), 1.73 – 1.61 (m, 1H), 1.47 – 1.39 (m, 1H), 1.31 – 1.23 (m, 32H), 1.17 (d, *J* = 7.0 Hz, 3H), 0.89 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.5 (C_q), 128.6 (+), 128.21 (+), 128.18 (+), 66.1 (–), 39.7 (+), 34.0 (–), 32.1 (–), 29.9 (–), 29.8 (–), 29.73 (–), 29.65 (–), 29.64 (–), 29.5 (–), 27.3 (–), 22.8 (–), 17.2 (+), 14.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{28}H_{49}O_2$) calc.: 417.3727, found: 417.3721.
MF: $C_{28}H_{48}O_2$
MW: 416.69 g/mol

Benzyl (*Z*)-2-methylicos-11-enoate (4r)



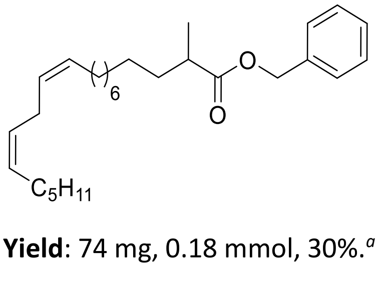
Yield: 69 mg, 0.17 mmol, 28%.[a]

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.42 – 7.26 (m, 5H), 5.44 – 5.26 (m, 2H), 5.22 – 5.00 (m, 2H), 2.54 – 2.29 (m, 1H), 2.10 – 1.93 (m, 4H), 1.76 – 1.57 (m, 1H), 1.49 – 1.38 (m, 1H), 1.37 – 1.21 (m, 24H), 1.16 (d, *J* = 7.0 Hz, 3H), 0.88 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.5 (C_q), 130.1 (+), 130.0 (+), 128.7 (+), 128.22 (+), 128.19 (+), 66.1 (–), 39.7 (+), 34.0 (–), 32.1 (–), 29.92 (–), 29.91 (–), 29.7 (–), 29.64 (–), 29.62 (–), 29.61 (–), 29.5 (–), 29.4 (–), 27.4 (–), 27.3 (–), 22.8 (–), 17.2 (+), 14.3 (+).

HRMS (APCI) (m/z): $[M + H]^+$ ($C_{28}H_{47}O_2$) calc.: 415.3571, found: 415.3569.
MF: $C_{28}H_{46}O_2$
MW: 414.67 g/mol

Benzyl (11*Z*,14*Z*)-2-methylicosa-11,14-dienoate (4s)



Yield: 74 mg, 0.18 mmol, 30%.[a]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.43 – 7.26 (m, 5H), 5.44 – 5.28 (m, 4H), 5.12 (s, 2H), 2.78 (t, *J* = 5.9 Hz, 2H), 2.57 – 2.40 (m, 1H), 2.10 – 1.99 (m, 4H), 1.76 – 1.60 (m, 1H), 1.50 – 1.22 (m, 19H), 1.16 (d, *J* = 7.0 Hz, 3H), 0.89 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 176.9 (C_q), 136.4 (C_q), 130.34 (+), 130.29 (+), 128.7 (+), 128.22 (+), 128.19 (+), 128.10 (+), 128.07 (+), 66.1 (–), 39.7 (+), 33.9 (–), 31.7 (–), 29.8 (–), 29.63 (–), 29.61 (–), 29.60 (–), 29.5 (–), 29.4 (–), 27.4 (–), 27.3 (–), 25.8 (–), 22.7 (–), 17.2 (+), 14.2 (+).

HRMS (CI) (m/z): $[M + H]^+$ ($C_{28}H_{45}O_2$) calc.: 413.3414, found: 413.3412.
MF: $C_{28}H_{44}O_2$
MW: 412.66 g/mol

2.4.4. Monitoring of the Photocatalytic Reaction Over Time

Measurement of oxygen concentration during the reaction

For *in situ* monitoring of the oxygen concentration, Fibox 3 fibre optic oxygen sensor (PreSens GmbH) was used. In a 5 mL crimp cap vial were weighed eosin Y (**A**, 4.9 mg, 0.01 mmol, 0.1 equiv.), *N*-(acyloxy)phthalimide **1a** (27.0 mg, 0.08 mmol, 1.0 equiv.), **2a** (53.0 µL, 0.38 mmol, 5.0 equiv.) and DIPEA (26.0 µL, 0.15 mmol, 2.0 equiv.). After addition of a magnetic stirring bar and dry CH_3CN (1 mL), the vessel was capped and the reaction mixture was stirred and irradiated with a green LED (535 nm) for 18 h at rt while the concentration of oxygen was measured.

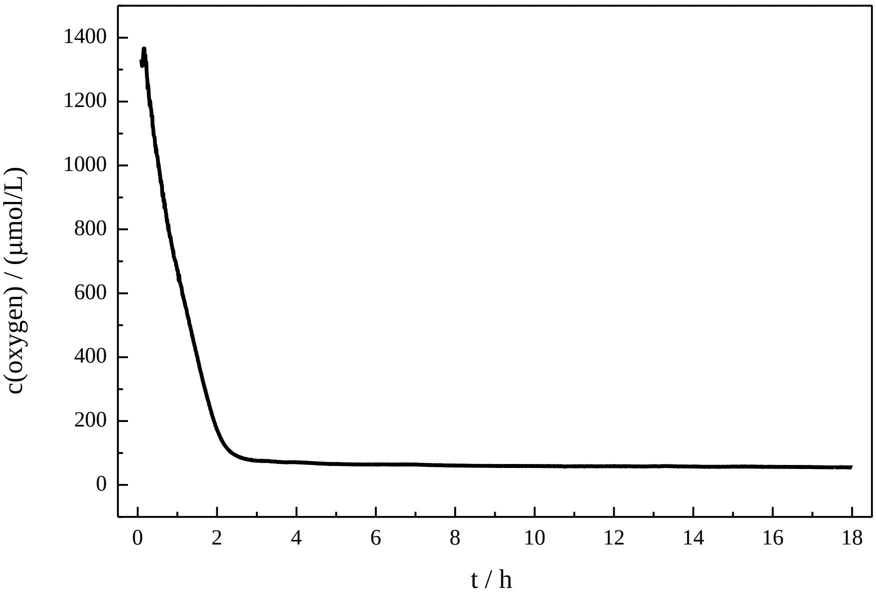


Figure S2-1. Concentration of oxygen during the reaction of *N*-(acyloxy)phthalimide **1a** with n-butylacrylate (**2a**) in the presence of DIPEA and eosin Y (with CH_3CN as solvent).

Stability of eosin Y and time course of the photoreaction

The stability of the photocatalyst and the time course of product formation during the reaction were investigated in parallel. In a 5 mL crimp cap vial were weighed eosin Y (**A**, 19.4 mg, 0.03 mmol, 0.1 equiv.), *N*-(acyloxy)phthalimide **1a** (108 mg, 0.30 mmol, 1.0 equiv.), **2a** (214 µL, 1.50 mmol, 5.0 equiv.) and DIPEA (102 µL, 0.60 mmol, 2.0 equiv.). After addition of a magnetic stirring bar and dry CH_2Cl_2 (4 mL), the vessel was capped and the reaction mixture was stirred and irradiated with green LEDs (535 nm) for 19 h at rt.

The slow degradation of the eosin Y was investigated by hourly measurement of the UV-vis absorption spectrum of the reaction mixture. Therefore, the mixture was diluted to a catalyst concentration of 4.65 µM.

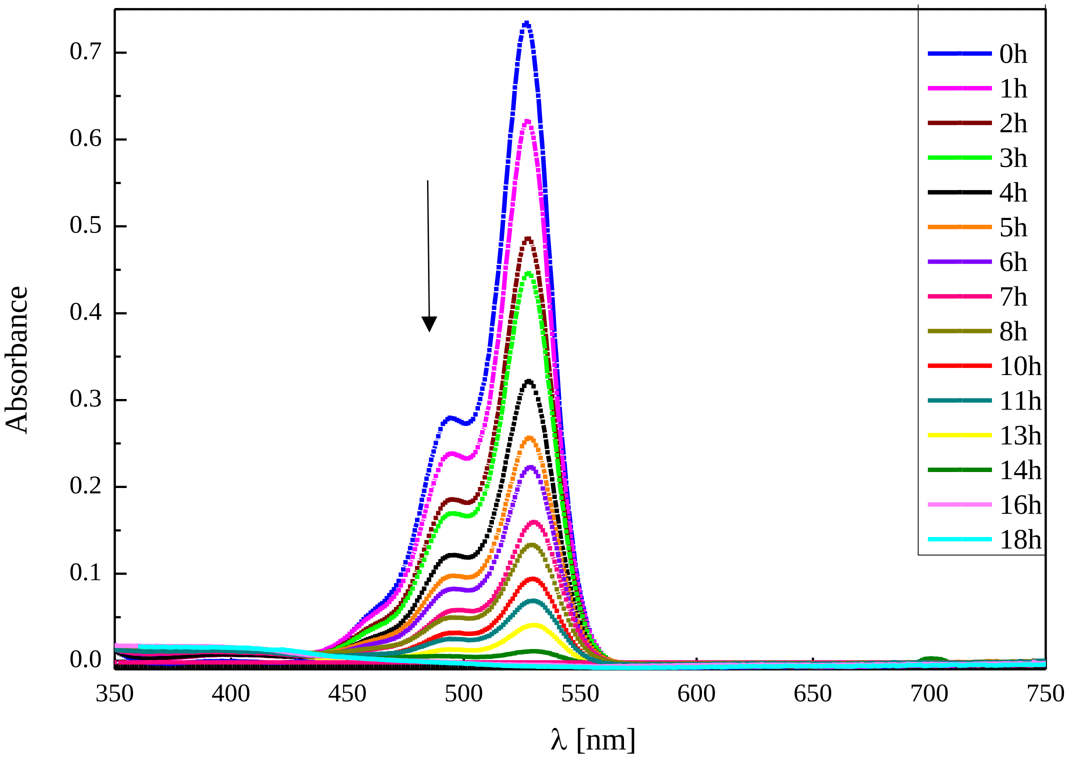


Figure S2-2. Changes in the UV-Vis absorption spectra of the reaction mixture (4.65 µM eosin Y) upon irradiation with green LEDs.

For determination of the time course of the product formation, the yield was determined every hour by quantitative GC using naphthalene as internal standard.

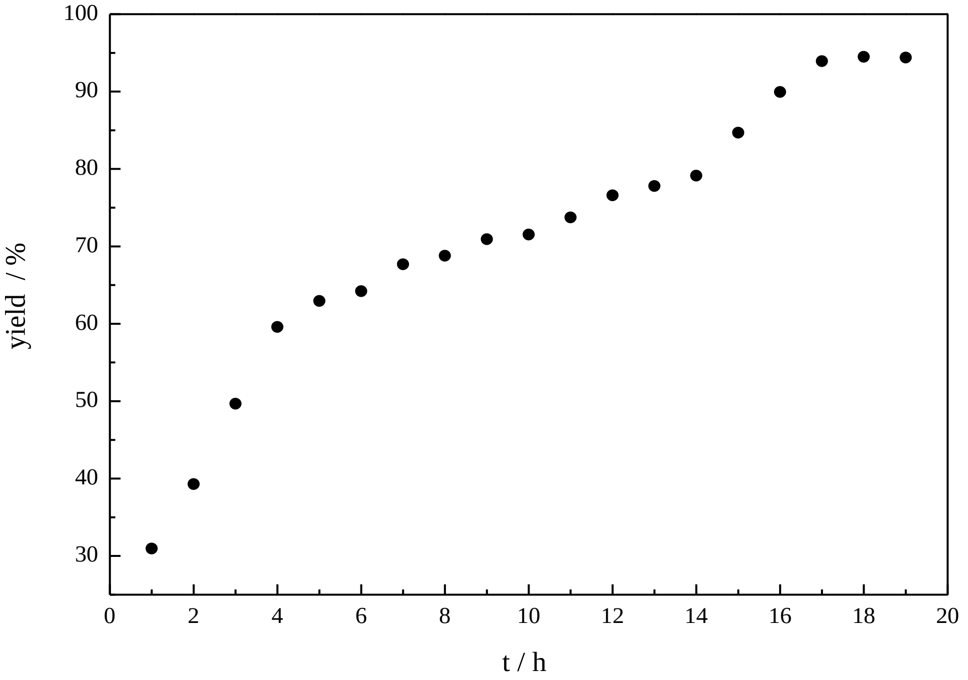


Figure S2-3. Time course of the photocatalytic product formation determined by quantitative GC using naphthalene as internal standard.

2.4.5. Cyclic Voltammetry Measurement of Boc-Proline-*N*-(acyloxy)phthalimide

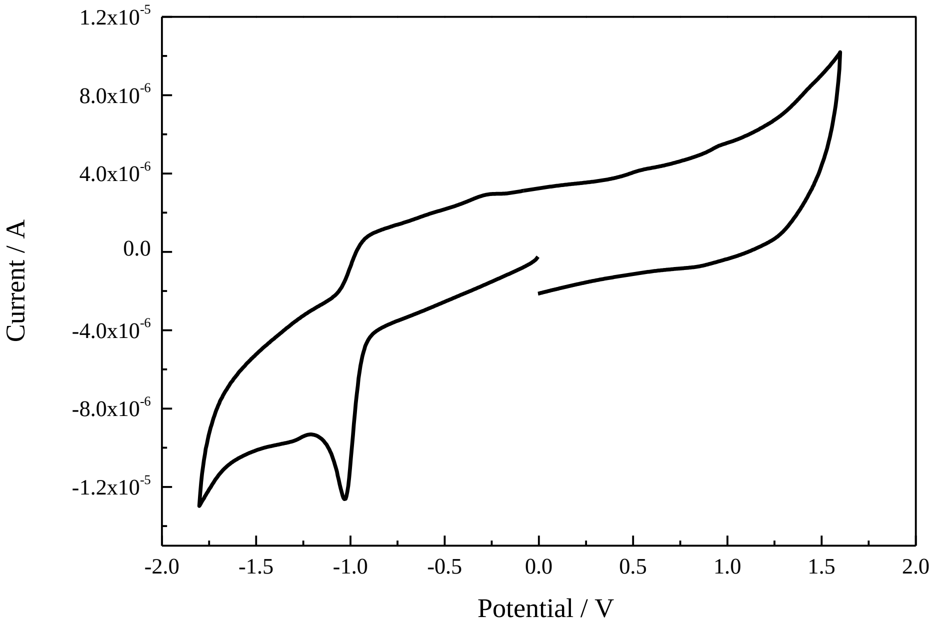
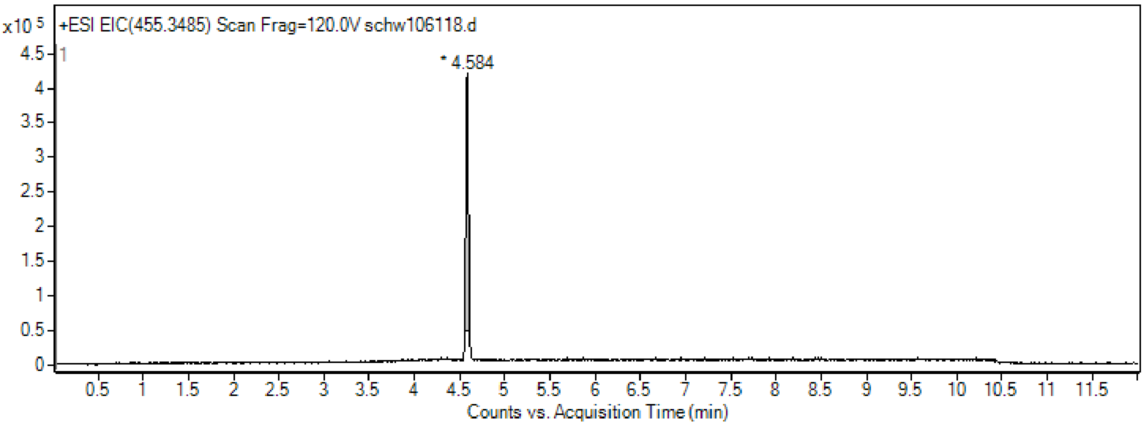
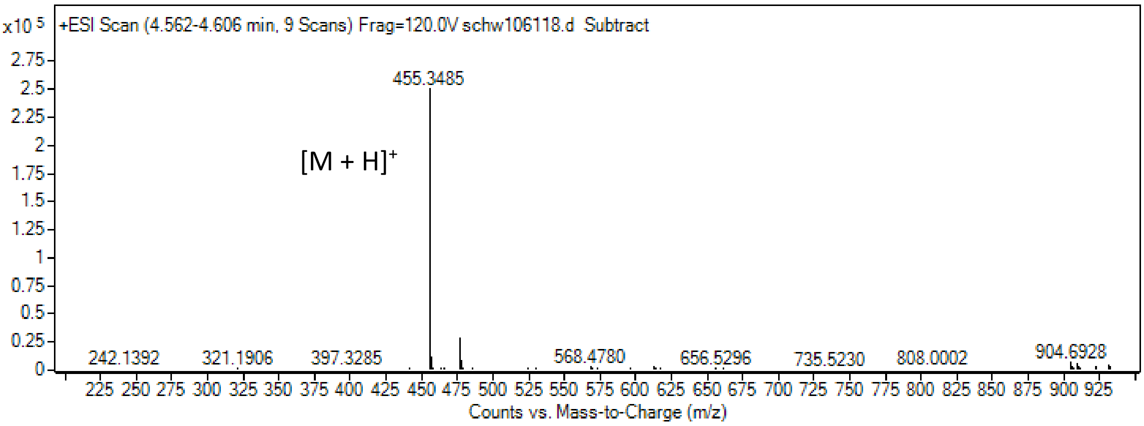


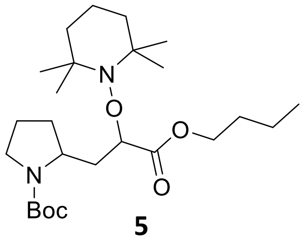
Figure S2-4. Cyclic voltammogram of Boc-proline-*N*-(acyloxy)phthalimide (**1a**) in CH_3CN under argon. The irreversible peak at -1.03 V shows the reduction of **1a** which corresponds to the reduction potential of -1.20 V vs. SCE.

2.4.6. TEMPO Trapping of Radical Intermediates

In a 5 mL crimp cap vial with a stirring bar were weighed eosin Y (**A**, 48.6 mg, 0.08 mmol, 1.0 equiv.), *N*-(acyloxy)phthalimide **1a** (27.0 mg, 0.08 mmol, 1.0 equiv.), **2a** (53.0 µL, 0.38 mmol, 5.0 equiv.), DIPEA (26.0 µL, 0.15 mmol, 2.0 equiv.) and TEMPO (14.6 mg, 0.09 mmol, 1.25 equiv.). After addition of dry CH_2Cl_2 (1 mL), the vessel was capped and the reaction mixture was stirred and irradiated with green LEDs (535 nm) for 18 h at rt. After irradiation, the orange reaction mixture was submitted to mass spectrometry (LC-MS) without any further work-up.







5

MS (ESI) (m/z): $[M + H]^+$ ($C_{25}H_{47}N_2O_5$) calc.: 455.3479, found: 455.3485.

2.4.7. Fluorescence Titration of Photocatalysts

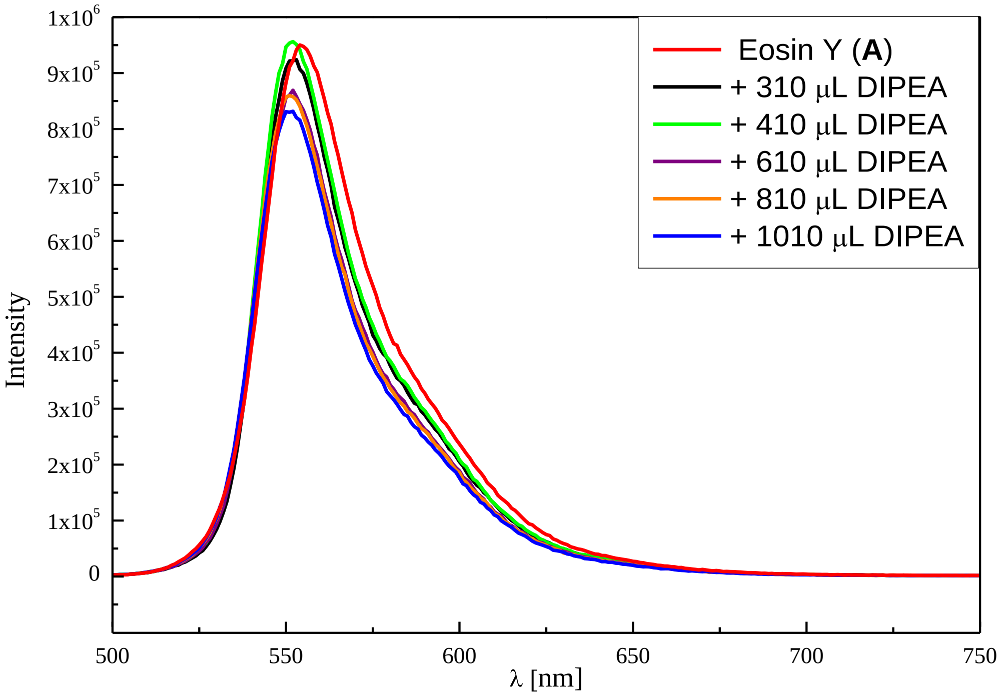


Figure S2-5. Changes in the fluorescence spectrum of eosin Y (**A**, 15.0 μM in CH_2Cl_2) upon titration with DIPEA (100 mM in CH_2Cl_2).

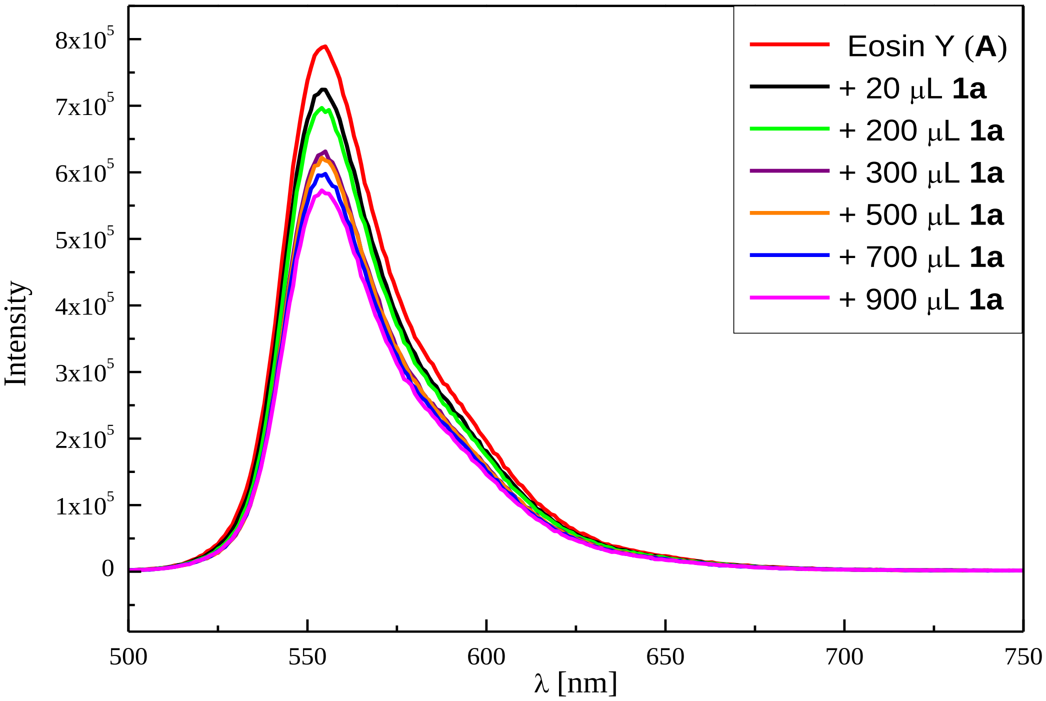


Figure S2-6. Fluorescence response of eosin Y (**A**, 15.0 μM in CH_2Cl_2) upon successive addition of active ester **1a** (100 mM in CH_2Cl_2).

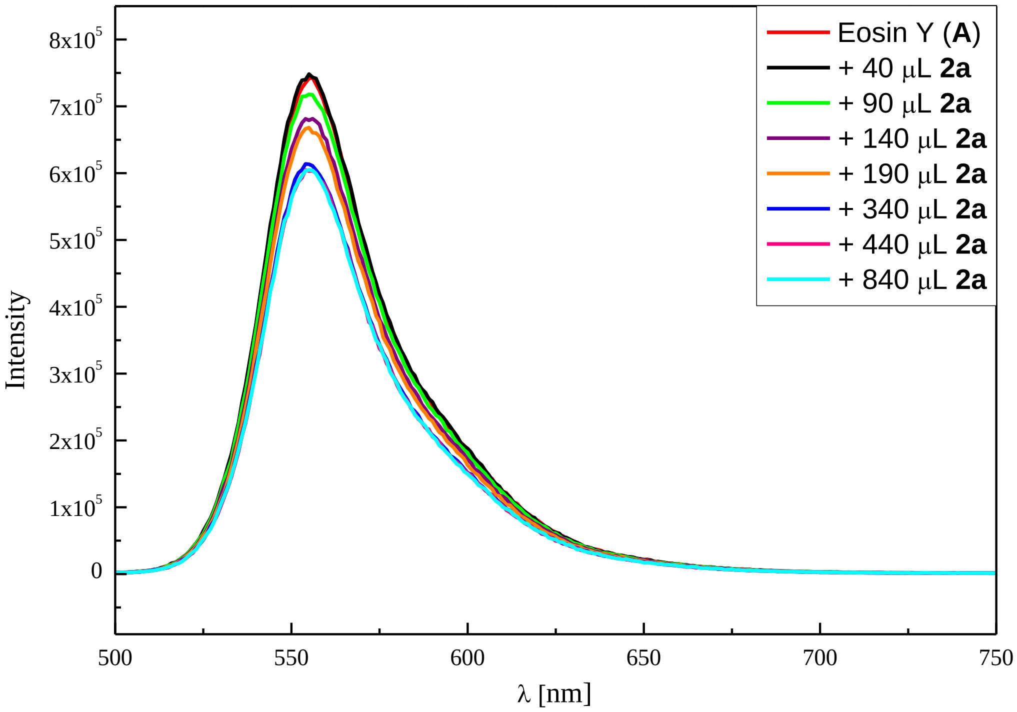


Figure S2-7. Fluorescence titration of eosin Y (**A**, 15.0 µM in CH_2Cl_2) with n-butylacrylate (**2a**, 100 mM in CH_2Cl_2).

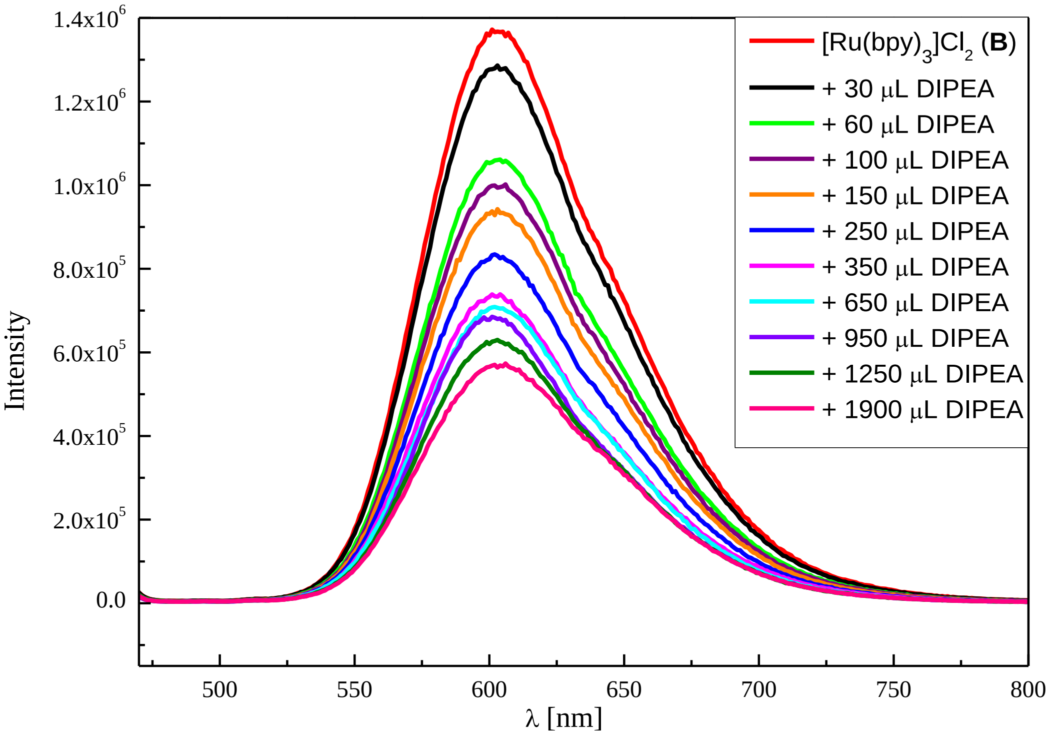


Figure S2-8. Fluorescence quenching of $[Ru(bpy)_3]Cl_2$ (**B**, 15.0 µM in CH_3CN) upon titration with DIPEA (100 mM in CH_3CN).

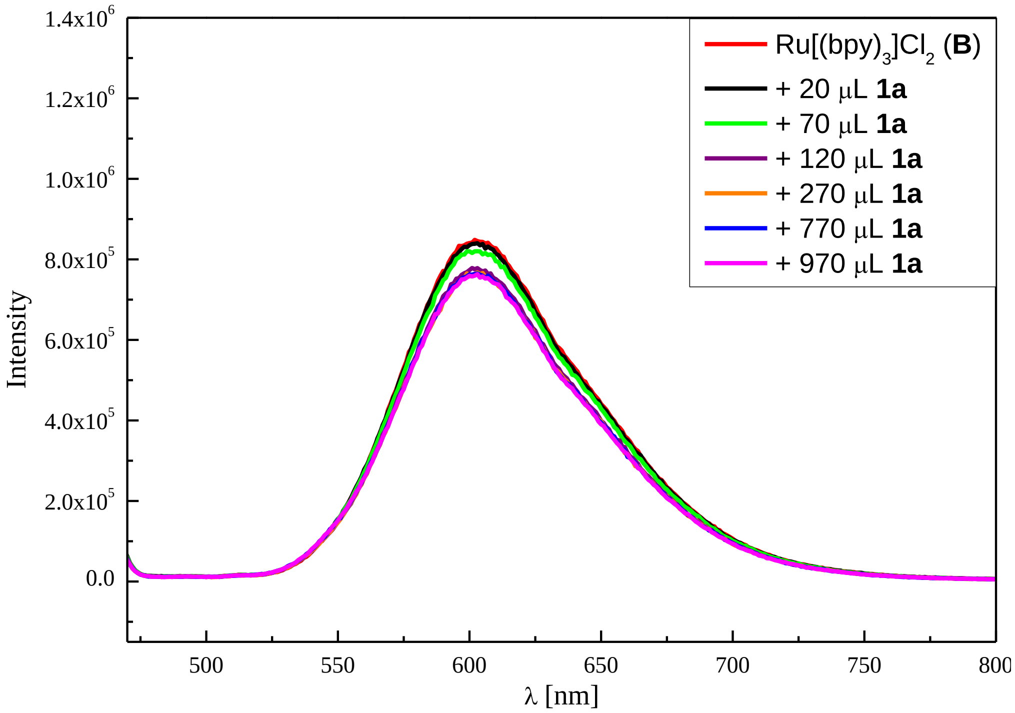


Figure S2-9. Fluorescence response of [Ru(bpy)$_3$]Cl$_2$ (**B**, 15.0 µM in CH$_3$CN) upon successive addition of active ester **1a** (100 mM in CH$_3$CN).

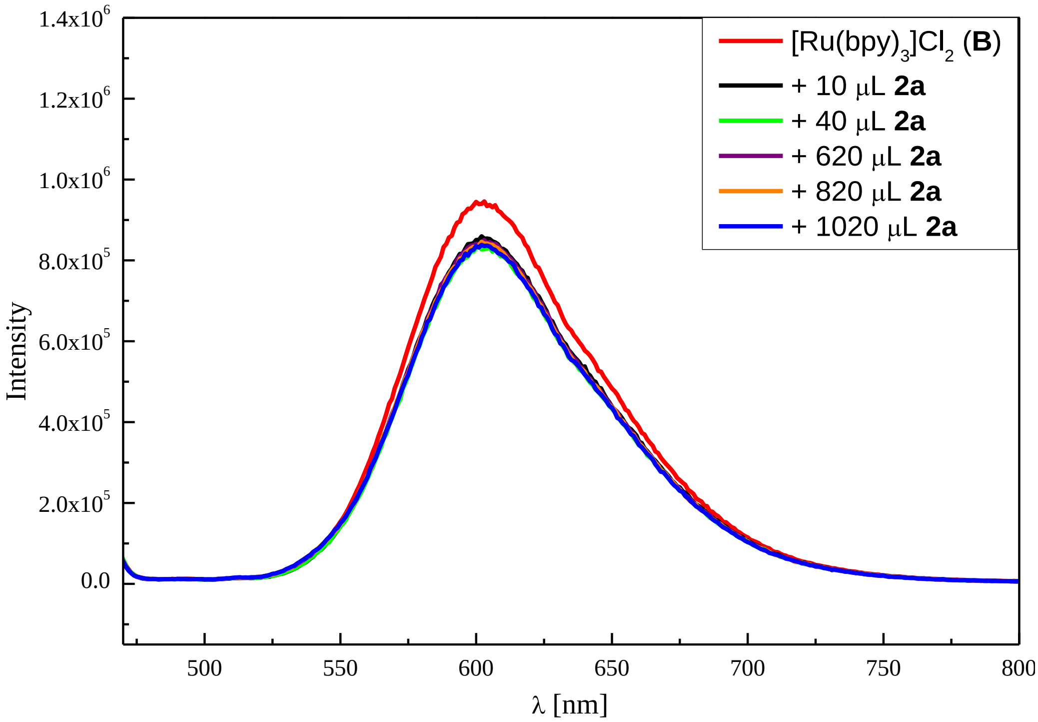


Figure S2-10. Fluorescence titration of [Ru(bpy)$_3$]Cl$_2$ (**B**, 15.0 µM in CH$_3$CN) with n-butylacrylate (**2a**, 100 mM in CH$_3$CN).

2.4.8. Quantum Yield Determination

The quantum yield of a model photocatalytic reaction was determined by a method developed by our group.[31] A reaction mixture of **1a** (54.1 mg, 0.15 mmol, 1 equiv.), **2a** (107 µL, 0.75 mmol, 5 equiv.), DIPEA (51.0 µL, 0.30 mmol, 2 equiv.), eosin Y (**A**, 9.7 mg, 10 mol%) and CH_2Cl_2 (2 mL) was prepared in a 10 mm Hellma® quartz fluorescence cuvette with a stirring bar. The measurement of quantum yield was accomplished in covered apparatus to minimize the ambient light. The cuvette with solvent (CH_2Cl_2, 2 mL) and a stirring bar was placed in the beam of a 528 nm LED and the transmitted power (P_{ref} = 19.6 mW) was measured by a calibrated photodiode horizontal to the cuvette. The content of the cuvette was changed to the reaction mixture and the transmitted power (P_{sample} = 95.2 µW) was measured analogously to the blank solution. The sample was further irradiated and the transmitted power as well as the respective yield of photocatalytic product (measured by quantitative GC using naphthalene as internal standard) were recorded after different times (Table **S2-1**).

The quantum yield was calculated from equation **E1**:

$$\Phi = \frac{N_{product}}{N_{ph}} = \frac{N_{\text{A}} * n_{product}}{\frac{E_{light}}{E_{ph}}} = \frac{N_{\text{A}} * n_{product}}{\frac{P_{absorbed} * t}{\frac{h * c}{\lambda}}} = \frac{h * c * N_{\text{A}} * n_{product}}{\lambda * \left(P_{ref} - P_{sample}\right) * t} \quad \textbf{(E1)}$$

where Φ is the quantum yield, $N_{product}$ is the number of product molecules created, N_{ph} is the number of photons absorbed, N_{A} is Avogadro's constant in moles^{-1}, $n_{product}$ is the molar amount of molecules created in moles, E_{light} is the energy of light absorbed in Joules, E_{ph} is the energy of a single photon in Joules, $P_{absorbed}$ is the radiant power absorbed in Watts, t is the irradiation time in sec, h is the Planck's constant in J×s, c is the speed of light in m s^{-1}, λ is the wavelength of irradiation source (528 nm) in meters, P_{ref} is the radiant power transmitted by a blank vial in Watts and P_{sample} is the radiant power transmitted by the vial with reaction mixture in Watts.

Table S2-1. Calculation of the quantum yield Φ after different irradiation times.

entry	irradiation time / h	P_{sample} / µW	yield / %	Φ / %
1	1	163.5	7	3.2
2	5	5.5	26	2.2
3	8.75	1.1	52	2.5

From these three measurements the mean value for the quantum yield was calculated to be

Φ = 2.6 ± 0.5 %.

2.5. References

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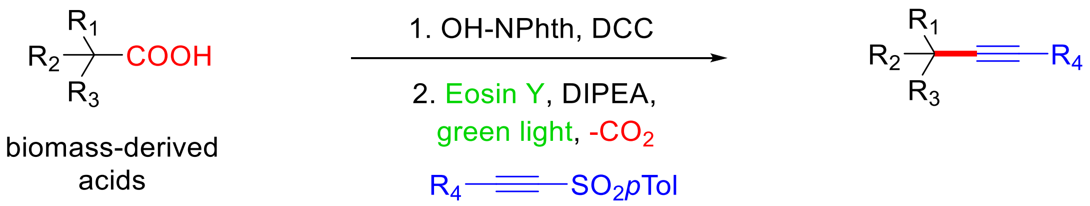
[a] Isolated with special, pre-packed Biotage SNAP Ultra HP-Sphere columns (see General information).

3. Decarboxylative Alkynylation of Biomass-Derived Compounds by Metal-Free Visible Light Photocatalysis



We report a mild method for the decarboxylative C–C bond formation between natural carboxylic acids and alkynes. Activation of a very broad scope of carboxylic acids derived from renewable resources is achieved by esterification to *N*-(acyloxy)phthalimides. The cross-coupling with acetylenic sulfones proceeds under irradiation with green light (528 nm) in the presence of the organic photocatalyst eosin Y and provides a metal-free, environmentally friendly and inexpensive alternative to known decarboxylative alkynylations.

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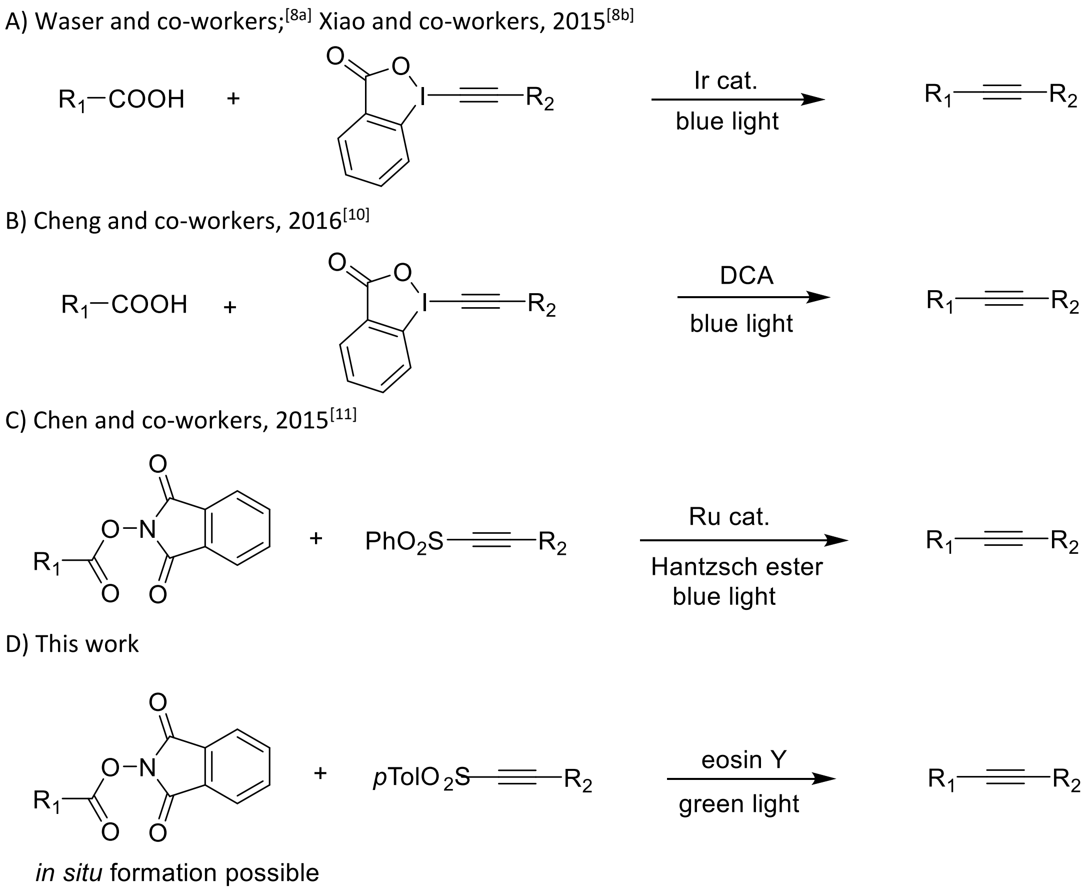
3.1. Introduction

Starting materials for medicinal and synthetic chemistry, chemical biology or material science should be easily available, stable, non-hazardous and inexpensive. Biomass-derived compounds fulfil all these requirements and are compared to fossil resources not limited, but renewable and often even cheaper.[1] Moreover, many biological molecules already bear different functional groups and complex structural motifs which could save several steps in the synthesis of certain pharmaceuticals. Especially carboxylic acids gain more and more in importance when it comes to sustainable starting materials. These compounds are one of the most abundant feedstocks in nature and show broad structural diversity (e.g. amino acids, sugar acids, fatty acids).[2] Even more important is their ability to extrude CO_2 during reactions, which enables chemo- and site-selective cross-couplings with different substrates.

On the other hand, also alkynes are important and versatile building blocks. The internal alkyne moiety allows numerous modifications for the synthesis of pharmacophores, fine chemicals and agro chemicals.[3] Therefore, the decarboxylative formation of C(sp^3)–C(sp) bonds has captivated researchers´ interest during the last years and some examples have been developed. The first alkynylations of carboxylic acids required increased temperatures as well as copper and/or silver catalysts. As coupling partners, terminal alkynes,[4] alkynyl bromides[5] or ethynylbenziodoxolone (EBX) reagents[6] could be used.[7] Recent reports apply photocatalyzed decarboxylative alkynylations at room temperature (Scheme 3-1).


A) Waser and co-workers;[8a] Xiao and co-workers, 2015[8b]

B) Cheng and co-workers, 2016[10]

C) Chen and co-workers, 2015[11]

D) This work

Scheme 3-1. Photocatalytic decarboxylative alkynylations.

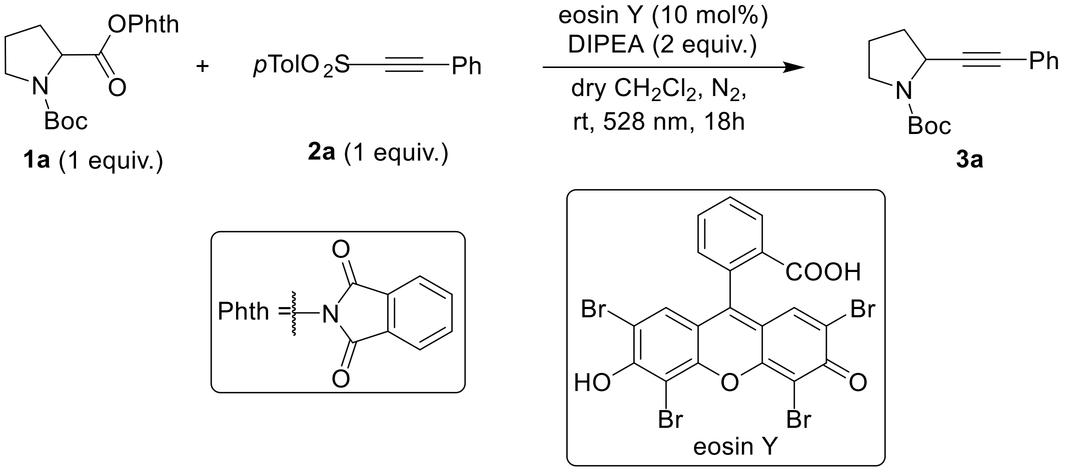
For the direct, oxidative decarboxylation of carboxylic acids, usually expensive and toxic iridium catalysts are required (Scheme 3-1A).[8] But also some organocatalytic variants of oxidative, decarboxylative reactions have been developed.[9] In 2016, Cheng *et al.* reported the first metal-free decarboxylative alkynylation with DCA as photocatalyst (Scheme 3-1B).[10] However, EBX reagents, which are expensive and often troublesome to synthesize, are still needed as coupling partners. Another approach for decarboxylations can be achieved by activation of the carboxy group *via* esterification to *N*-(acyloxy)phthalimides and subsequent reduction of the moiety. Different cross-coupling reactions can be carried out in this way.[12] Chen and co-workers applied this approach to alkynylations with acetylenic sulfones in the presence of a ruthenium catalyst and Hantzsch ester (Scheme 3-1C).[11] We report herein the first metal-free, photocatalytic and reductive decarboxylative alkynylation of all kinds of natural carboxylic acids with acetylenic sulfones (Scheme 3-1D). Here, the organic dye eosin Y serves as a cheap, non-toxic and eco-friendly photocatalyst that enables decarboxylation of the preformed or *in situ* generated *N*-(acyloxy)phthalimides under irradiation with green light (528 nm). Thus, a mild and green method for the synthesis of a broad scope of platform and high-value chemicals is provided. For example, propargylamines, which are important precursors for biologically active compounds[13] can be obtained by a one-step synthesis, starting from easily available amino acids. Moreover, this work contributes to the increased efforts establishing renewable biomass for chemical processes instead of fossil resources like oil or gas.

3.2. Results and Discussion

3.2.1. Synthesis and Scope

Recently, we investigated the decarboxylative alkylation of biomass-derived carboxylic acids with Michael acceptors.[12i] As the reactions worked well with eosin Y and *N*-(acyloxy)phthalimides, we chose the same system for the corresponding alkynylation with acetylenic sulfones. The conditions were optimized by irradiating a mixture of the redox active ester of *N*-Boc-proline (**1a**), acetylenic sulfone **2a**, DIPEA and the photocatalyst eosin Y with green LEDs. Screening of different solvents showed that CH_2Cl_2 gave with 73% the highest product yield, whereas too polar solvents had a negative impact (Table 3-1, entries 1-6). Increasing the amount of **2a** did not change the yield (Table 3-1, entry 7), so we used a stoichiometric quantity of *N*-(acyloxy)phthalimide **1a** to acetylenic sulfone **2a**. With less base or NEt_3 instead of DIPEA, yields decrease to about 60% (Table 3-1, entries 8 and 9). Control experiments without photocatalyst, light or base confirmed that all components are necessary for an efficient product formation (Table 3-1, entries 10-12). On the contrary, degassing the reaction mixture by vacuum/nitrogen was not mandatory, but increases product yields by about 10% (Table 3-1, entries 1 and 13). The reaction was further optimized by screening different concentrations of the reactants (Table 3-1, entries 14-18). A 50 mM solution gave the best product yield of 83% (Table 3-1, entry 16). Moreover, also *in situ* formation of the redox active ester **1a** *via* DCC, DMAP and *N*-hydroxyphthalimide was possible. Starting the alkynylation directly from the carboxylic acid *N*-Boc-proline gave product **3a** in 63% yield (Table 3-1, entry 18).

Table 3-1. Optimization of the reaction conditions.

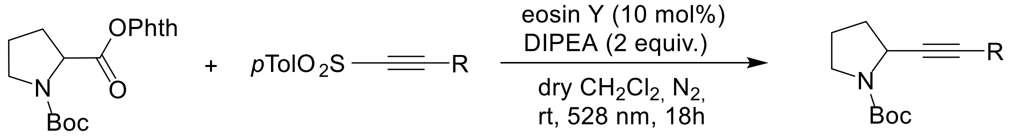


Entry	Deviation from standard conditions	Yield[a] [%]
1	None	73[b]
2	DMSO	57
3	DMF	69
4	CH_3CN	64
5	THF	71
6	EtOH	57
7	3 equiv. **2a**	73
8	1 equiv. DIPEA	61
9	2 equiv. NEt_3 instead of DIPEA	62
10	No photocatalyst	4
11	No light	0
12	No base	0
13	No degassing	61
14	Concentration of 200 mM	56
15	Concentration of 70 mM	73
16	Concentration of 50 mM	83
17	Concentration of 30 mM	72
18	*In situ* generation of **1a**[c]	63

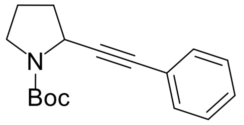
[a] Determined by GC analysis using biphenyl as an internal standard. [b] Reactions were performed with a concentration of 100 mM. [c] Reaction conditions: 1 equiv. *N*-Boc-proline, 1.3 equiv. DCC, 1.1 equiv. *N*-hydroxyphthalimide, 0.1 equiv. DMAP.

Next, we explored the substrate scope of the reaction using the optimized reaction conditions (Table 3-1, entry 16). Therefore, the cross coupling of different acetylenic sulfones with active ester **1a** was investigated (Table 3-2). We chose to apply preformed *N*-(acyloxy)phthalimides **1**, as the product yields of **3a** were higher compared to the reaction with *in situ* generated active esters. Nevertheless, we want to emphasize that also the direct decarboxylative alkynylation of the acid works well in a one-pot reaction.

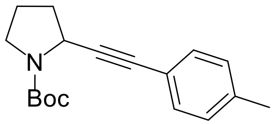
Table 3-2. Scope of acetylenic sulfones.



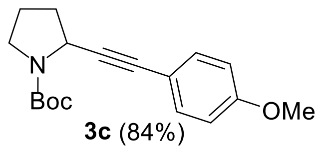
1a (1 equiv.) **2** (1 equiv.) **3** (isolated yield)



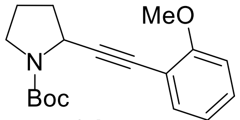
3a (78%; *in situ*: 63%[a])



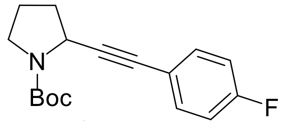
3b (80%)



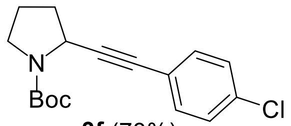
3c (84%)



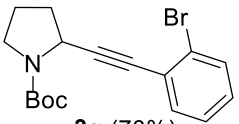
3d (80%)



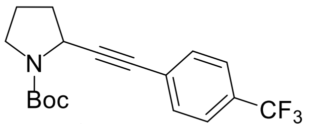
3e (77%)



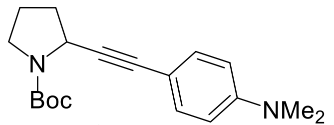
3f (73%)



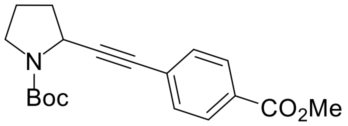
3g (70%)



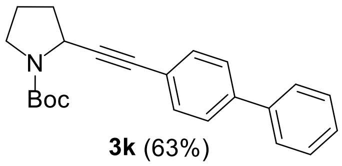
3h (59%)



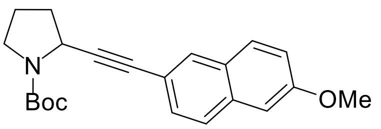
3i (73%)



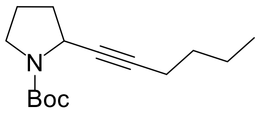
3j (49%)



3k (63%)



3l (74%)



3m (44%)

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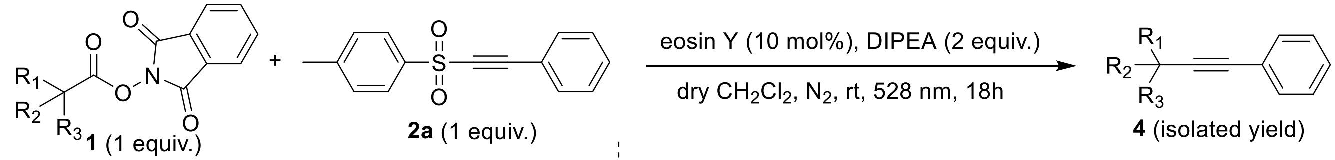
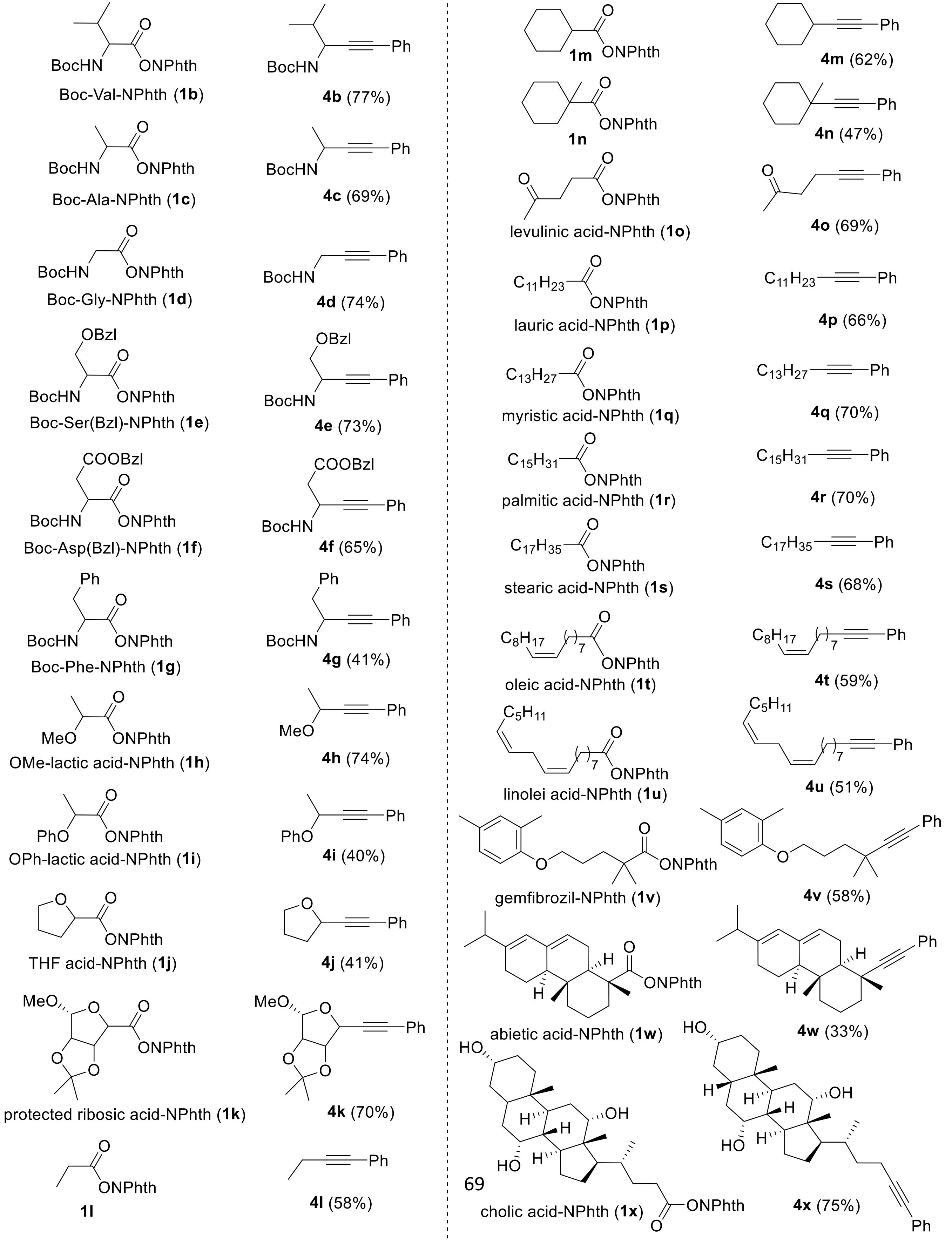
[a] Conditions for *in situ* generation of **1a**: 1 equiv. *N*-Boc-proline, 1.3 equiv. DCC, 1.1 equiv. *N*-hydroxyphthalimide, 0.1 equiv. DMAP.

Propargylamines **3a-m** could be isolated in moderate to very good yields. Especially electron-rich, aromatic acetylenic sulfones **3a-d** and **3l** gave the desired products in high yields of 78 to 84%. With halogenated aromatic alkynes (**2e-h**), slightly lower yields of 59 to 77% were obtained. The photocatalyzed reaction also tolerates amines (**3i**) as well as ester groups (**3j**) on the aromatic ring. Remarkably, in addition to aryl sulfones, even alkyl sulfones can be applied for the decarboxylative alkynylation, although the product yield decreased to 44% (**3m**).

Having established the scope of acetylenic sulfones, we chose **2a** as a model substrate and varied the *N*-(acyloxy)phthalimide **1** (Table 3-3). A broad variety of abundant, biomass-derived carboxylic acids like amino acids, fatty acids, sugar acids or more complex natural compounds could be applied for the decarboxylative C–C bond formation. The reaction tolerates a wide range of functional groups and works for primary, secondary and tertiary acids. Moreover, high yields could also be achieved for *N*-(acyloxy)phthalimides without any heteroatom in the α-position.

Table 3-3. Scope *N*-(acyloxy)phthalimides.





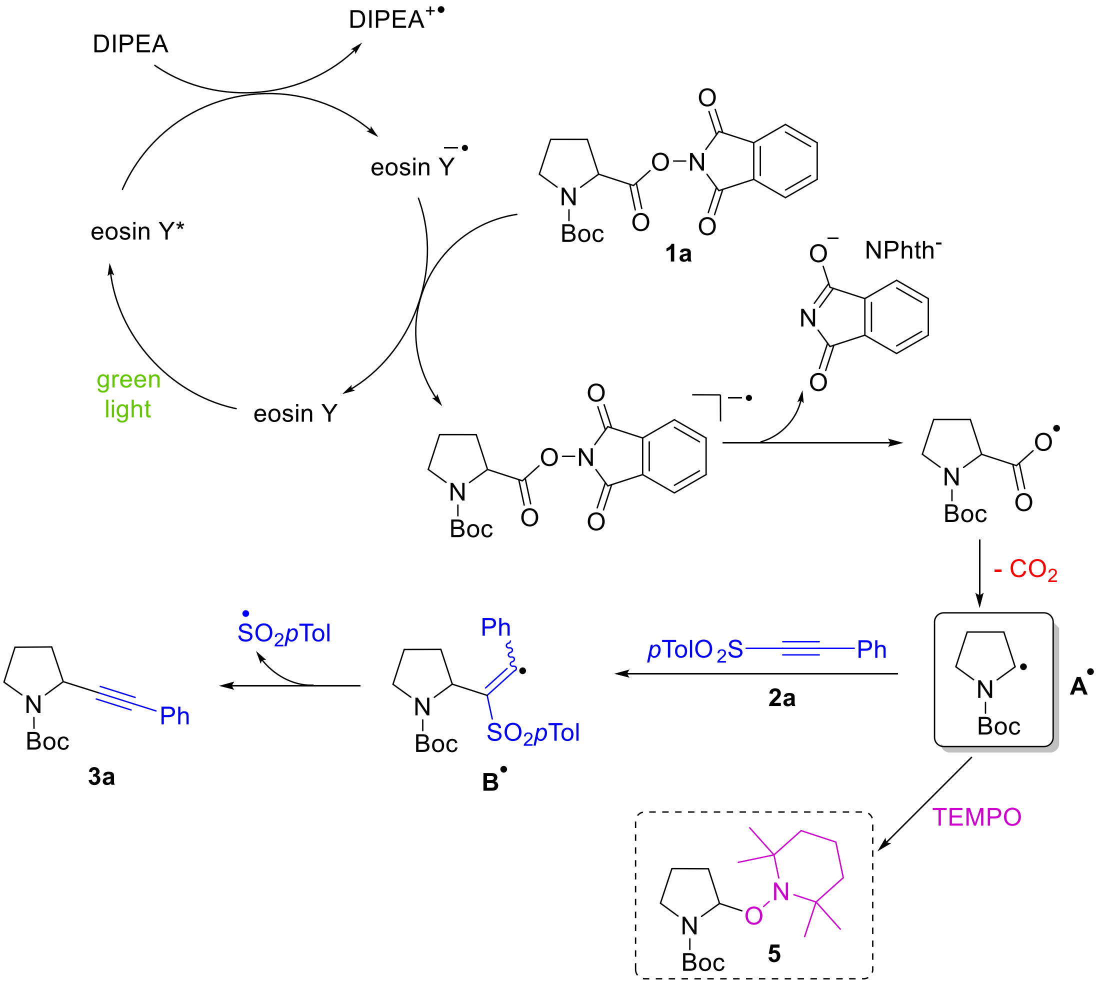
N-(acyloxy)phthalimide	product	*N*-(acyloxy)phthalimide	product
Boc-Val-NPhth (**1b**)	**4b** (77%)	**1m**	**4m** (62%)
Boc-Ala-NPhth (**1c**)	**4c** (69%)	**1n**	**4n** (47%)
Boc-Gly-NPhth (**1d**)	**4d** (74%)	levulinic acid-NPhth (**1o**)	**4o** (69%)
Boc-Ser(Bzl)-NPhth (**1e**)	**4e** (73%)	lauric acid-NPhth (**1p**)	**4p** (66%)
Boc-Asp(Bzl)-NPhth (**1f**)	**4f** (65%)	myristic acid-NPhth (**1q**)	**4q** (70%)
Boc-Phe-NPhth (**1g**)	**4g** (41%)	palmitic acid-NPhth (**1r**)	**4r** (70%)
OMe-lactic acid-NPhth (**1h**)	**4h** (74%)	stearic acid-NPhth (**1s**)	**4s** (68%)
OPh-lactic acid-NPhth (**1i**)	**4i** (40%)	oleic acid-NPhth (**1t**)	**4t** (59%)
THF acid-NPhth (**1j**)	**4j** (41%)	linolei acid-NPhth (**1u**)	**4u** (51%)
protected ribosic acid-NPhth (**1k**)	**4k** (70%)	gemfibrozil-NPhth (**1v**)	**4v** (58%)
1l	**4l** (58%)	abietic acid-NPhth (**1w**)	**4w** (33%)
		cholic acid-NPhth (**1x**)	**4x** (75%)

Starting from natural Boc-protected amino acids, the propargylic amines **4b**-**4f** could be synthesized in good yields (65 to 77%). Such compounds are versatile building blocks for the synthesis of nitrogen-containing heterocycles.[13b, 14] Additionally, they often show biological activity and are core structures of several pharmaceuticals.[15] Simple amino acids like alanine (**1c**), as well as more complex examples like side-chain protected serine (**1e**) or aspartic acid (**1f**) could be applied. Notably, phenylalanine (**1g**) gave the desired product with only 41% yield. It is assumed that the nearby phenyl ring partly blocks the reaction center of the radical intermediate, which is generated upon decarboxylation. Steric bulk may hamper the reaction with the acetylenic sulfone **2a**. The same observation was made with α-oxy acids: Phenyl protected lactic acid (**1i**) gave the corresponding product **4i** in 40% yield whereas methyl protected lactic acid (**1h**) gave product **4h** in 74%. Even the redox active ester of protected ribosic acid **1k** gave 70% of cross-coupling product **4k**. This illustrates that sugar acids, which are another widespread class of natural compounds, can be converted by this photocatalytic reaction.

Moreover, carboxylic acids without any heteroatom in α-position to the carboxyl moiety could be applied, although the yields slightly decreased in most cases (**4l**-**4v**). Simple, small molecules like propionic acid (**1l**) or easily available levulinic acid (**1o**), which is an extremely cheap by-product of the sugar industry[16] yielded the internal alkynes **4l-o** with 47 to 69%. For saturated fatty acids with different chain lengths (**1p**-**s**), good yields of 66 to 70% were obtained. With mono- and diunsaturated fatty acids **1t** and **1u** 59% and 51% were observed, respectively. This indicates that the presence of double bonds has a negative impact on the product yield. In addition, abietic acid (**1w**), which is a natural component of tree resin bearing two double bonds, gave the product in only 33% yield. A likely rational is the additionally steric hindrance at the tertiary carboxy group. On the contrary, free hydroxy groups were well compatible with the alkynylation. The *N*-(acyloxy)phthalimide of the primary bile acid cholic acid (**1x**) reacted smoothly in 75% yield, although it shows a complex structure containing three hydroxy groups. Next to keto groups (**1o**), also ether moieties like in the biologically active gemfibrozil (**1v**) were well tolerated (58% yield). However, aromatic and vinylic carboxylic acids like benzoic or cinnamic acid could not be alkynylated, presumably because of the instability of the aryl/vinyl radical, which is generated upon decarboxylation. Overall, the decarboxylative alkynylation showed excellent chemoselectivity and good functional group compatibility. The scope of suitable carboxylic acids is very broad and gives good yields with all classes of biomass-derived alkyls. This enables a mild and green synthesis of quite simple platform molecules as well as structural complex fine chemicals starting from renewable resources.

3.2.2. Mechanistic Proposal

The photochemistry and reactivity of the organic xanthene dye eosin Y has been extensively studied by our and other groups.[17] Also the photocatalytic reduction of *N*-(acyloxy)phthalimides is well-known in literature.[12i, 18] Based on these reports, our experimental results and the work of Chen *et al.*,[11] we propose the following reaction mechanism for the decarboxylative alkynylation with acetylenic sulfones (Scheme 3-2): Irradiation with green light (528 nm) generates the excited state of the photocatalyst eosin Y, which undergoes fast intersystem crossing to its reactive triplet state.[17a] Reductive quenching of the excited state by the sacrificial electron DIPEA should give the radical anion of eosin Y.[12i, 17b] The catalytic cycle is believed to be closed upon single electron transfer (SET) to the *N*-(acyloxy)phthalimide **1a** that subsequently undergoes splitting of the N–O bond. We could isolate the protonated form of the phthalimide fragment (NPhth) quantitatively. Fast extrusion of carbon dioxide from the remaining carboxyl residue generates the alkyl radical $\mathbf{A}^{\bullet}$. The occurrence of this intermediate was proven by capturing it with the persistent radical TEMPO giving product **5** that was identified by LC-MS analysis (see Experimental Section). When no TEMPO is present, the alkyl radical **A**$^\bullet$ attacks the triple bond of acetylenic sulfone **2a.** According to the report by Chen and his co-workers, this occurs *via* an α-addition, which gives the intermediate **B**$^\bullet$.[11] Elimination of the sulfonyl radical $^\bullet SO_2$*p*Tol finally yields the alkyne product **3a**. In order to check Chen´s proposal that no radical chain processes are involved in this mechanism,[11] we measured the quantum yield of this reaction. The low value of ϕ = 1.6 ± 0.5 % confirms the assumption that effective radical chain processes are unlikely for this mechanism and correlates with the quite long reaction times of about 18 h.



Scheme 3-2. Proposed mechanism for the photocatalytic, decarboxylative alkynylation of *N*-(acyloxy)phthalimide **1a** with acetylenic sulfone **2a**.

3.3. Conclusions

We have developed an environmental-friendly and inexpensive alternative procedure for decarboxylative alkynylations. The cross-coupling reaction between abundant, biomass-derived carboxylic acids or their *N*-(acyloxy)phthalimides and acetylenic sulfones is catalysed by the organic dye eosin Y and visible light. A broad scope of natural compounds is converted by the mild, metal-free method into various high-value chemicals, which are useful precursors of pharmaceutical or performance chemicals. This facilitates the replacement of fossil resources for chemical synthesis by renewable biomass.

3.4. Experimental Section

3.4.1. General Information

See chapter 2.4.1.

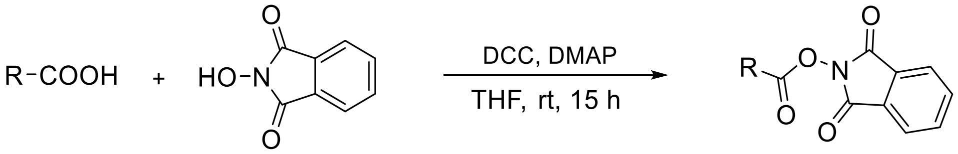
Additional information on irradiation source

For irradiation with green light, OSRAM Oslon SSL 80 LTCP7P-KXKZ (KZ) (green, λ_{max} = 528 nm, I_{max} = 1000 mA, 1.12 W) was used.

3.4.2. Synthesis of *N*-(Acyloxy)phthalimides as Starting Materials

General procedure for the synthesis of *N*-(acyloxy)phthalimides (1)

N-(Acyloxy)phthalimides (**1**) were synthesized by a slightly modified procedure based on Reiser *et al.*[12c] and Overman *et al.*[18a]

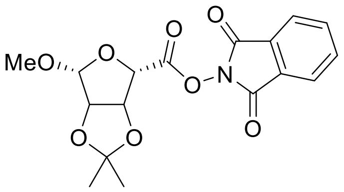


The respective carboxylic acid (8.00 mmol, 1.0 equiv.), *N*-hydroxyphthalimide (1.43 g, 8.80 mmol, 1.1 equiv.), *N,N´*-dicyclohexylcarbodiimide (1.98 g, 9.60 mmol, 1.2 equiv.) and 4-dimethylaminopyridine (0.98 g, 0.80 mmol, 0.1 equiv.) were mixed in a flask with a magnetic stirring bar. Dry THF (40 mL) was added and the orange reaction mixture was stirred for 15 h at rt. The resulting white precipitate was filtered off and the solution was concentrated by evaporation of the solvent. Purification by column chromatography on flash silica gel (CH_2Cl_2 or CH_2Cl_2/CH_3OH = 9:1) gave a white to yellowish solid (**1a-s** and **1v-x**) or a clear liquid (**1t** and **1u**).

Characterization of *N*-(acyloxy)phthalimides (1)

Experimental data for *N*-(acyloxy)phthalimides **1a**-**j**, **1l**, **1m** and **1p-u** were already published in our last paper on decarboxylative alkylations.[12i] Characteristic data for *N*-(acyloxy)phthalimides **1k**, **1n, 1o** and **1v-x** are given in the following.

1,3-Dioxoisoindolin-2-yl (4*S*,6*R*)-6-methoxy-2,2-dimethyltetrahydrofuro[3,4-d][1,3]diox-ole-4-carboxylate (1k)



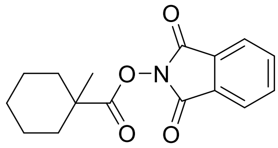
Yield: 1.91 g, 5.26 mmol, 66%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.91 – 7.86 (m, 2H), 7.83 – 7.78 (m, 2H), 5.36 (dd, *J* = 5.8 Hz, 0.9 Hz, 1H), 5.14 (s, 1H), 5.00 (s, 1H), 4.66 (d, *J* = 5.8 Hz, 1H), 3.49 (s, 3H), 1.51 (s, 3H), 1.35 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 166.9 (C_q), 161.6 (C_q), 135.0 (+), 128.9 (C_q), 124.2 (+), 113.4 (C_q), 109.8 (+), 84.3 (+), 82.3 (+), 82.1 (+), 56.2 (+), 26.5 (+), 25.2 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{17}H_{18}NO_8$) calc.: 364.1027, found: 364.1030.
MF: $C_{17}H_{17}NO_8$
MW: 363.32 g/mol

1,3-Dioxoisoindolin-2-yl 1-methylcyclohexane-1-carboxylate (1n) [18a]



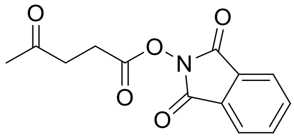
Yield: 2.29 g, 7.97 mmol, 100%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.95 – 7.82 (m, 2H), 7.82 – 7.72 (m, 2H), 2.23 (d, *J* = 13.3 Hz, 2H), 1.69 – 1.51 (m, 5H), 1.42 (s, 3H), 1.37 – 1.29 (m, 2H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 173.8 (C_q), 162.4 (C_q), 134.8 (+), 129.2 (C_q), 124.0 (+), 43.3 (C_q), 35.8 (–), 26.9 (+), 25.6 (–), 23.2 (–).

LRMS (ESI) (m/z): [M + Na]$^+$ ($C_{16}H_{17}NNaO_4$) calc.: 310.1055, found: 310.1049.
MF: $C_{16}H_{17}NO_4$
MW: 287.32 g/mol

1,3-Dioxoisoindolin-2-yl 4-oxopentanoate (1o)



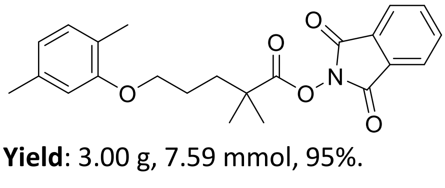
Yield: 1.11 g, 4.25 mmol, 53%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.89 – 7.81 (m, 2H), 7.80 – 7.74 (m, 2H), 2.99 – 2.85 (m, 4H), 2.20 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 205.1 (C_q), 169.3 (C_q), 161.8 (C_q), 134.9 (+), 128.9 (C_q), 124.1 (+), 37.7 (–), 29.8 (+), 25.2 (–).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{13}H_{12}NO_5$) calc.: 262.0710, found: 262.0713.
MF: $C_{13}H_{11}NO_5$
MW: 261.23 g/mol

1,3-Dioxoisoindolin-2-yl 5-(2,5-dimethylphenoxy)-2,2-dimethylpentanoate (1v)[18a]



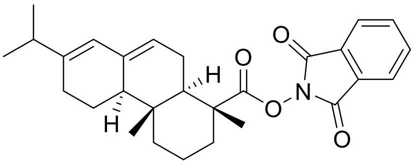
Yield: 3.00 g, 7.59 mmol, 95%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.93 – 7.83 (m, 2H), 7.82 – 7.75 (m, 2H), 7.02 (d, *J* = 7.8 Hz, 1H), 6.71 – 6.63 (m, 2H), 4.08 – 3.98 (m, 2H), 2.33 (s, 3H), 2.21 (s, 3H), 2.01 – 1.93 (m, 4H), 1.47 (s, 6H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 173.9 (C_q), 162.2 (C_q), 157.0 (C_q), 136.6 (C_q), 134.8 (+), 130.4 (+), 129.1 (C_q), 123.9 (+), 123.7 (C_q), 120.8 (+), 112.0 (+), 67.8 (–), 42.0 (C_q), 37.5 (–), 25.2 (+) , 25.1 (–), 21.5 (+), 15.9 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{23}H_{26}NO_5$) calc.: 396.1805, found: 396.1808.
MF: $C_{23}H_{25}NO_5$
MW: 395.46 g/mol

1,3-Dioxoisoindolin-2-yl(1*R*,4a*R*,4b*R*,10a*R*)-7-isopropyl-1,4a-dimethyl-1,2,3,4,4a,4b,5,6,10,10a-decahydrophenanthrene-1-carboxylate (1w)



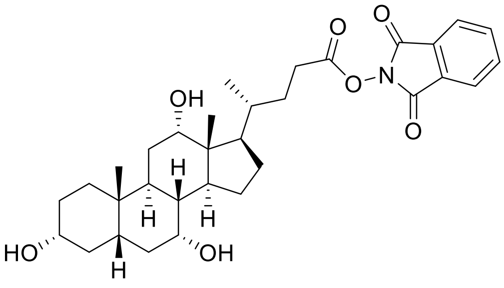
Yield: 3.20 g, 7.16 mmol, 89%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.89 – 7.82 (m, 2H), 7.80 – 7.74 (m, 2H), 5.80 (s, 1H), 5.54 – 5.37 (m, 1H), 2.32 – 1.13 (m, 4H), 2.13 – 1.86 (m, 6H), 1.86 – 1.78 (m, 1H), 1.72 – 1.62 (m, 2H), 1.44 (s, 3H), 1.28 – 1.16 (m, 2H), 1.01 (dd, *J* = 6.8 Hz, 3.1 Hz, 6H), 0.87 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 174.7 (C_q), 162.3 (C_q), 145.4 (C_q), 135.4 (C_q), 134.8 (+), 129.2 (C_q), 124.0 (+), 122.5 (+), 120.7 (+), 51.0 (+), 46.7 (C_q), 45.3 (+), 38.2 (–), 37.3 (–), 35.0 (C_q), 34.8 (+), 27.5 (–), 25.7 (–), 22.6 (–), 21.5 (+), 21.0 (+), 18.0 (–), 17.1 (+), 14.3 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{28}H_{34}NO_4$) calc.: 448.2488, found: 448.2486.
MF: $C_{28}H_{33}NO_4$
MW: 447.58 g/mol

1,3-Dioxoisoindolin-2-yl(*R*)-4-((3*R*,5*S*,7*R*,8*R*,9*S*,10*S*,12*S*,13*R*,14*S*,17*R*)-3,7,12-trihydro-xy-10,13-di-methylmethylhexadecahydro-1H-cyclopenta[a]phenanthren-17-yl)pentanoate (1x)[19]



Yield: 2.72 g, 4.93 mmol, 62%.

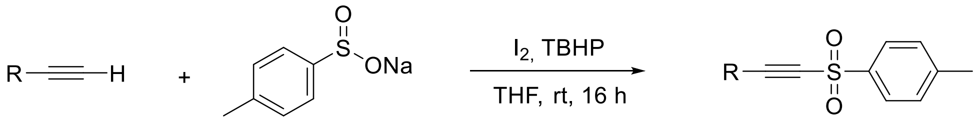
^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.92 – 7.84 (m, 2H), 7.82 – 7.74 (m, 2H), 3.98 (s, 1H), 3.85 (d, *J* = 2.4 Hz, 1H), 3.50 – 3.39 (m, 1H), 2.78 – 2.68 (m, 1H), 2.66 – 2.57 (m, 1H), 2.44 – 2.16 (m, 5H), 1.98 – 1.79 (m, 5H), 1.77 – 1.62 (m, 4H), 1.62 – 1.47 (m, 6H), 1.44 – 1.29 (m, 3H), 1.19 – 1.09 (m, 1H), 1.05 (d, *J* = 6.0 Hz, 3H), 0.97 (td, *J* = 14.1 Hz, 3.0 Hz, 1H), 0.88 (s, 3H), 0.71 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 170.3 (C_q), 162.2 (C_q), 134.9 (+), 129.1 (C_q), 124.1 (+), 73.1 (+), 72.1 (+), 68.6 (+), 47.0 (+), 46.7 (C_q), 41.9 (+), 41.6 (+), 39.74 (–), 39.68 (+), 35.4 (C_q), 35.2 (–), 34.9 (+), 34.8 (–), 30.8 (–), 30.6 (–), 28.4 (–), 28.2 (–), 27.6 (–), 26.6 (+), 23.4 (–), 22.6 (+), 17.4 (+), 12.6 (+).

HRMS (ESI) (m/z): [M + Na]$^+$ ($C_{32}H_{43}NNaO_7$) calc.: 576.2932, found: 576.2930.
MF: $C_{32}H_{43}NO_7$
MW: 553.70 g/mol

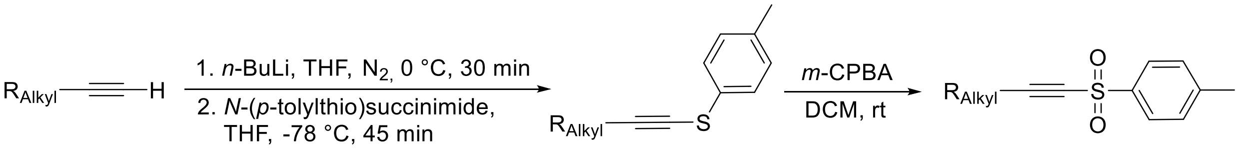
3.4.3. Synthesis of Acetylenic Sulfones as Starting Materials

General procedure A: Synthesis of acetylenic sulfones 2a-l from arylacetylenes[20]



To a solution of arylacetylene (3.00 mmol, 1 equiv.) with sodium *p*-toluenesulfinate (1.07 g, 6.00 mmol, 2.0 equiv.) and iodine (0.38 g, 1.50 mmol, 0.5 equiv.) in THF (15 mL) was added *tert*-butyl hydroperoxide solution (70% in water, 1.25 mL, 9.00 mmol). The resulting mixture was stirred for 16 h at rt. The reaction mixture was quenched by addition of saturated aqueous $Na_2S_2O_3$ (40 mL) and extracted with EA (3 × 40 mL). The combined organic phases were washed with H_2O (40 mL) and brine (40 mL), dried over Na_2SO_4, filtered and concentrated in vacuum. The residue was purified by automated column chromatography on flash silica gel using EA/PE as eluent to afford the corresponding product as slightly yellowish solid.

General procedure B: Synthesis of acetylenic sulfones 2m and 2n from alkylacetylenes[21]



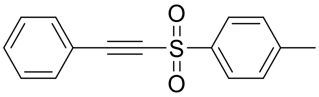
To a flask containing a solution of alkylacetylene (6.00 mmol, 1.05 equiv.) in dry THF (15 mL), a solution of *n*-BuLi (2.5 M in hexanes, 2.42 mL, 6.04 mmol, 1.06 equiv.) was added under nitrogen atmosphere at 0 ºC. This mixture was stirred for 30 min and was then allowed to warm up to rt. After 5 min, it was cooled again to -78 ºC. A solution of *N*-(*p*-tolylthio)succinimide (1.26 g, 5.70 mmol, 1.0 equiv.) in dry THF (15 mL) was added and it was stirred at -78 ºC until the TLC spot of *N*-(*p*-tolylthio)succinimide had disappeared.

The reaction mixture was quenched with a saturated aqueous solution of NH_4Cl (20 mL) and extracted with Et_2O (2 x 20 mL). The organic phases were washed with brine (2 x 20 mL), dried with Na_2SO_4 and the solvent was removed under vacuum to give the corresponding thioether.

A solution of *m*-CPBA (5.11 g, 22.8 mmol, 4.0 equiv.) in CH_2Cl_2 (30 mL) was prepared and dried over Na_2SO_4. This solution was added slowly *via* dropping funnel to a stirring solution of the thioether in CH_2Cl_2 (15 mL). The progress of the reaction was monitored by TLC (EA/PE = 1:9). After completion of the reaction, it was quenched carefully with an aqueous solution of $NaHCO_3$ (40 mL). The aqueous phase was extracted with CH_2Cl_2 (3 x 20 mL), and the combined organic phases were washed with aqueous $NaHCO_3$ (30 mL), water (30 mL) and brine (30 mL) consecutively. After evaporation of the solvent, the crude product was purified by automated column chromatography (EA/PE = 1:9) with flash silica gel to give a white solid.

Characterization of acetylenic sulfones (2)

1-Methyl-4-((phenylethynyl)sulfonyl)benzene (2a)[20]



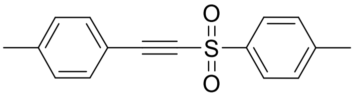
Yield: 472 mg, 1.84 mmol, 61%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.98 – 7.92 (m, 2H), 7.53 – 7.42 (m, 3H), 7.41 – 7.31 (m, 4H), 2.46 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 145.5 (C_q), 138.9 (C_q), 132.8 (+), 131.6 (+), 130.1 (+), 128.8 (+), 127.6 (+), 118.0 (C_q), 93.1 (C_q), 85.6 (C_q), 21.8 (+).

LRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{15}H_{12}O_2S$) calc.: 256.0553, found: 256.0529.
MF: $C_{15}H_{12}O_2S$
MW: 256.32 g/mol

1-Methyl-4-((*p*-tolylethynyl)sulfonyl)benzene (2b)[20]



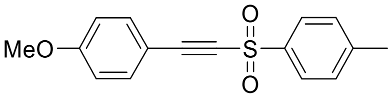
Yield: 566 mg, 2.09 mmol, 70%.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.94 (d, *J* = 8.3 Hz, 2H), 7.38 (t, *J* = 7.5 Hz, 4H), 7.15 (d, *J* = 8.0 Hz, 2H), 2.45 (s, 3H), 2.35 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 145.4 (C_q), 142.4 (C_q), 139.2 (C_q), 132.7 (+), 130.1 (+), 129.5 (+), 127.5 (+), 114.9 (C_q), 93.8 (C_q), 85.3 (C_q), 21.8 (+).

LRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{16}H_{14}O_2S$) calc.: 270.0709, found: 270.0705.
MF: $C_{16}H_{14}O_2S$
MW: 270.35 g/mol

1-Methoxy-4-(tosylethynyl)benzene (2c)[20]



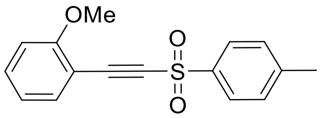
Yield: 581 mg, 2.03 mmol, 68%.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.95 (d, *J* = 8.4 Hz, 2H), 7.50 – 7.42 (m, 2H), 7.38 (d, *J* = 8.0 Hz, 2H), 6.90 – 6.82 (m, 2H), 3.82 (s, 3H), 2.46 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 162.2 (C_q), 145.3 (C_q), 139.4 (C_q), 134.8 (+), 130.1 (+), 127.5 (+), 114.5 (+), 109.8 (C_q), 94.2 (C_q), 85.0 (C_q), 55.6 (+), 21.9 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{16}H_{14}O_3S$) calc.: 286.0658, found: 286.0650.
MF: $C_{16}H_{14}O_3S$
MW: 286.35 g/mol

1-Methoxy-2-(tosylethynyl)benzene (2d)



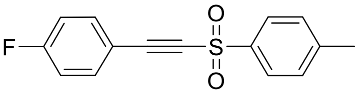
Yield: 604 mg, 2.11 mmol, 70%.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.96 (d, *J* = 8.3 Hz, 2H), 7.44 – 7.33 (m, 4H), 6.94 – 6.80 (m, 2H), 3.82 (s, 3H), 2.45 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 161.8 (C_q), 145.2 (C_q), 139.5 (C_q), 134.5 (+), 133.3 (+), 130.0 (+), 127.4 (+), 120.6 (+), 111.1 (+), 107.4 (C_q), 91.1 (C_q), 89.2 (C_q), 55.9 (+), 21.8 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_{16}H_{14}O_3S$) calc.: 286.0658, found: 286.0659.
MF: $C_{16}H_{14}O_3S$
MW: 286.35 g/mol

1-Fluoro-4-(tosylethynyl)benzene (2e)[20]



Yield: 304 mg, 1.11 mmol, 37%.

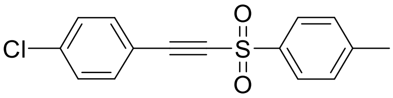
^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.95 (d, *J* = 8.4 Hz, 2H), 7.55 – 7.49 (m, 2H), 7.39 (d, *J* = 8.0 Hz, 2H), 7.10 – 7.01 (m, 2H), 2.46 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 164.5 (d, $^1J_{CF}$ = 255.1 Hz, C_q), 145.6 (C_q), 138.9 (C_q), 135.2 (d, $^3J_{CF}$ = 9.1 Hz, +), 130.2 (+), 127.6 (+), 116.4 (d, $^2J_{CF}$ = 22.5 Hz, +), 114.3 (d, $^4J_{CF}$ = 3.6 Hz, C_q), 92.0 (C_q), 85.7 (C_q), 21.9 (+).

^{19}F NMR (376 MHz, $CDCl_3$): δ [ppm] = - 105.2 (s).

LRMS (EI) (m/z): $[M^\bullet]^+$ ($C_{15}H_{11}FO_2S$) calc. 274.0458, found: 274.0448.
MF: $C_{15}H_{11}FO_2S$
MW: 274.31 g/mol

1-Chloro-4-(tosylethynyl)benzene (2f)[22]



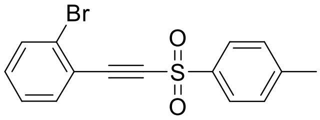
Yield: 233 mg, 0.80 mmol, 27%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.98 – 7.88 (m, 2H), 7.45 – 7.38 (m, 3H), 7.37 – 7.29 (m, 3H), 2.44 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 145.7 (C_q), 138.6 (C_q), 138.0 (C_q), 133.9 (+), 130.1 (+), 129.2 (+), 127.6 (+), 116.4 (C_q), 91.5 (C_q), 86.4 (C_q), 21.8 (+).

HRMS (ESI) (m/z): $[M + Na]^+$ ($C_{15}H_{11}ClNaO_2S$) calc. 313.0060, found: 313.0072.
MF: $C_{15}H_{11}ClO_2S$
MW: 290.76 g/mol

1-Brom-2-(tosylethynyl)benzene (2g)[20]



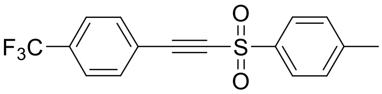
Yield: 608 mg, 1.81 mmol, 60%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 8.01 – 7.89 (m, 2H), 7.58 – 7.50 (m, 1H), 7.50 – 7.43 (m, 1H), 7.37 (d, *J* = 8.0 Hz, 2H), 7.32 – 7.25 (m, 2H), 2.44 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 145.6 (C_q), 138.7 (C_q), 134.4 (+), 132.9 (+), 132.6 (+), 130.0 (+), 127.5 (+), 127.4 (+), 126.4 (C_q), 120.6 (C_q), 91.0 (C_q), 89.1 (C_q), 21.8 (+).

HRMS (EI) (m/z): $[M^•]^+$ ($C_{15}H_{11}BrO_2S$) calc. 333.9658, found: 333.9656.
MF: $C_{15}H_{11}BrO_2S$
MW: 335.22 g/mol

1-Methyl-4-(((4-(trifluoromethyl)phenyl)ethynyl)sulfonyl)benzene (2h)[20]



Yield: 291 mg, 0.90 mmol, 30%.

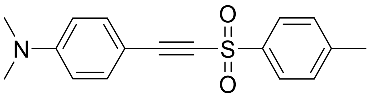
^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.99 – 7.93 (m, 2H), 7.63 (s, 4H), 7.41 (d, *J* = 8.0 Hz, 2H), 2.48 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 146.0 (C_q), 138.6 (C_q), 133.2 (+), 130.3 (+), 127.8 (+), 125.8 (q, J_{CF} = 3.6 Hz, +), 122.0 (C_q), 90.5 (C_q), 87.5 (C_q), 21.9 (+).

^{19}F NMR (376 MHz, $CDCl_3$): δ [ppm] = - 63.8 (s).

LRMS (EI) (m/z): $[M^•]^+$ ($C_{16}H_{11}F_3O_2S$) calc. 324.0426, found: 324.0419.
MF: $C_{16}H_{11}F_3O_2S$
MW: 324.32 g/mol

N,*N*-Dimethyl-4-(tosylethynyl)aniline (2i)



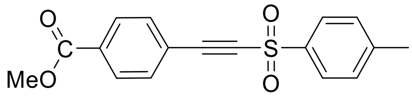
Yield: 428 mg, 1.43 mmol, 48%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.92 (d, *J* = 8.3 Hz, 2H), 7.33 (d, *J* = 8.8 Hz, 4H), 6.54 (d, *J* = 9.0 Hz, 2H), 2.97 (s, 6H), 2.42 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 151.9 (C_q), 144.8 (C_q), 139.8 (C_q), 134.3 (+), 129.8 (+), 127.1 (+), 111.3 (+), 102.8 (C_q), 97.4 (C_q), 84.5 (C_q), 39.9 (+), 21.7 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{17}H_{18}NO_2S$) calc.: 300.1053, found: 300.1058.
MF: $C_{17}H_{17}NO_2S$
MW: 299.39 g/mol

Methyl 4-(tosylethynyl)benzoate (2j)[23]



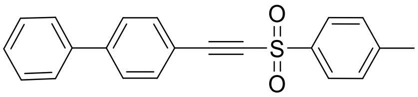
Yield: 451 mg, 1.43 mmol, 48%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 8.05 – 7.99 (m, 2H), 7.98 – 7.93 (m, 2H), 7.63 – 7.54 (m, 2H), 7.43 – 7.38 (m, 2H), 3.92 (s, 3H), 2.48 (s, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 166.0 (C$_q$), 145.9 (C$_q$), 138.6 (C$_q$), 132.8 (+), 132.5 (C$_q$), 130.3 (+), 129.8 (+), 127.8 (+), 122.5 (C$_q$), 91.3 (C$_q$), 87.7 (C$_q$), 52.7 (+), 21.9 (+).

HRMS (ESI) (m/z): [M + K]$^+$ ($C_{17}H_{14}KO_4S$) calc.: 353.0244, found: 353.0247.
MF: $C_{17}H_{14}O_4S$
MW: 314.36 g/mol

4-(Tosylethynyl)-1,1'-biphenyl (2k)

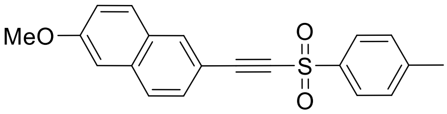


^{1}H NMR (400 MHz, CDCl$_3$): δ [ppm] = 7.99 (d, *J* = 8.2 Hz, 2H), 7.62 – 7.55 (m, 6H), 7.46 (t, *J* = 7.4 Hz, 2H), 7.40 (d, *J* = 8.1 Hz, 3H), 2.48 (s, 3H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 145.5 (C$_q$), 144.4 (C$_q$), 139.6 (C$_q$), 139.1 (C$_q$), 133.3 (+), 130.1 (+), 129.1 (+), 128.5 (+), 127.6 (+), 127.4 (+), 127.2 (+), 116.7 (C$_q$), 93.2 (C$_q$), 86.3 (C$_q$), 21.9 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{21}H_{17}O_2S$) calc.: 333.0944, found: 333.0949.
MF: $C_{21}H_{16}O_2S$
MW: 332.42 g/mol

2-Methoxy-6-(tosylethynyl)naphthalene (2l)



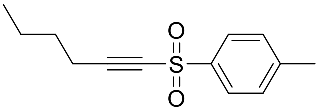
Yield: 600 mg, 1.78 mmol, 59%.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 8.03 – 7.93 (m, 3H), 7.66 (d, *J* = 8.7 Hz, 2H), 7.45 – 7.35 (m, 3H), 7.16 (dd, *J* = 9.0 Hz, 2.5 Hz, 1H), 7.08 (d, *J* = 2.4 Hz, 1H), 3.90 (s, 3H), 2.45 (s, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 159.7 (C$_q$), 145.4 (C$_q$), 139.2 (C$_q$), 135.9 (C$_q$), 134.1 (+), 130.1 (+), 129.9 (+), 128.3 (+), 127.9 (C$_q$), 127.5 (+), 127.4 (+), 120.3 (+), 112.4 (C$_q$), 105.9 (+), 94.4 (C$_q$), 85.3 (C$_q$), 55.5 (+), 21.8 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{20}H_{16}KO_3S$) calc.: 375.0452, found: 375.0452.
MF: $C_{20}H_{16}O_3S$
MW: 336.41 g/mol

1-(Hex-1-yn-1-ylsulfonyl)-4-methylbenzene (2m)[24]



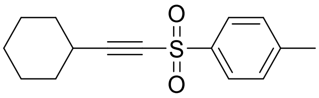
Yield: 701 mg, 2.97 mmol, 52%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.85 (d, *J* = 8.3 Hz, 2H), 7.38 – 7.30 (m, 2H), 2.44 (s, 3H), 2.33 (t, *J* = 7.1 Hz, 2H), 1.56 – 1.44 (m, 2H), 1.41 – 1.27 (m, 2H), 0.85 (t, *J* = 7.3 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 145.2 (C_q), 139.2 (C_q), 129.9 (+), 127.3 (+), 97.4 (C_q), 78.4 (C_q), 29.0 (–), 21.9 (–), 21.8 (+), 18.7 (–), 13.4 (+).

LRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{13}H_{16}O_2S$) calc. 236.0866, found: 236.0858.
MF: $C_{13}H_{16}O_2S$
MW: 236.33 g/mol

1-((Cyclohexylethynyl)sulfonyl)-4-methylbenzene (2n)



Yield: 1.08 g, 4.11 mmol, 72%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.86 (d, *J* = 8.3 Hz, 2H), 7.34 (d, *J* = 8.5 Hz, 2H), 2.59 – 2.47 (m, 1H), 2.44 (s, 3H), 1.83 – 1.71 (m, 2H), 1.70 – 1.56 (m, 2H), 1.54 – 1.39 (m, 3H), 1.35 – 1.21 (m, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 145.1 (C_q), 139.4 (C_q), 129.9 (+), 127.3 (+), 100.5 (C_q), 78.4 (C_q), 30.9 (–), 29.1 (+), 25.5 (–), 24.5 (–), 21.8 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{15}H_{19}O_2S$) calc.: 263.1100, found: 263.1104.
MF: $C_{15}H_{18}O_2S$
MW: 262.37 g/mol

3.4.4. Photocatalytic Reactions

General procedure A: Decarboxylative alkynylation with preformed active esters

In order to ensure optimal illumination of the solutions by the LEDs, three 5 mL vials with the same reaction mixtures were irradiated and combined for the work-up. Each crimp cap vial was equipped with a magnetic stirring bar, eosin Y (13.0 mg, 0.02 mmol, 10 mol%), *N*-(acyloxy)phthalimide **1** (0.20 mmol, 1.0 equiv.) and acetylenic sulfone **2** (0.20 mmol, 1.0 equiv.). The vials were capped with septa and nitrogen atmosphere was introduced *via* three cycles of vacuum/nitrogen. Degassed DIPEA (70.0 µL, 0.40 mmol, 2.0 equiv.) and dry CH_2Cl_2 (4 mL) were added *via* syringe. The reaction mixtures were stirred and irradiated through the vials´ plane bottom side using green LEDs (528 nm) for 18 h at rt. The content of the three vials was combined and diluted with saturated aqueous solution of $NaHCO_3$ (20 mL). It was extracted with EA (3 x 20 mL) and the combined organic phases were washed with brine (20 mL), dried over Na_2SO_4 and concentrated in vacuum. Purification of the crude product was performed by automated flash column chromatography (PE or PE/EA = 19:1 to 4:1) yielding the corresponding product **3** or **4**.

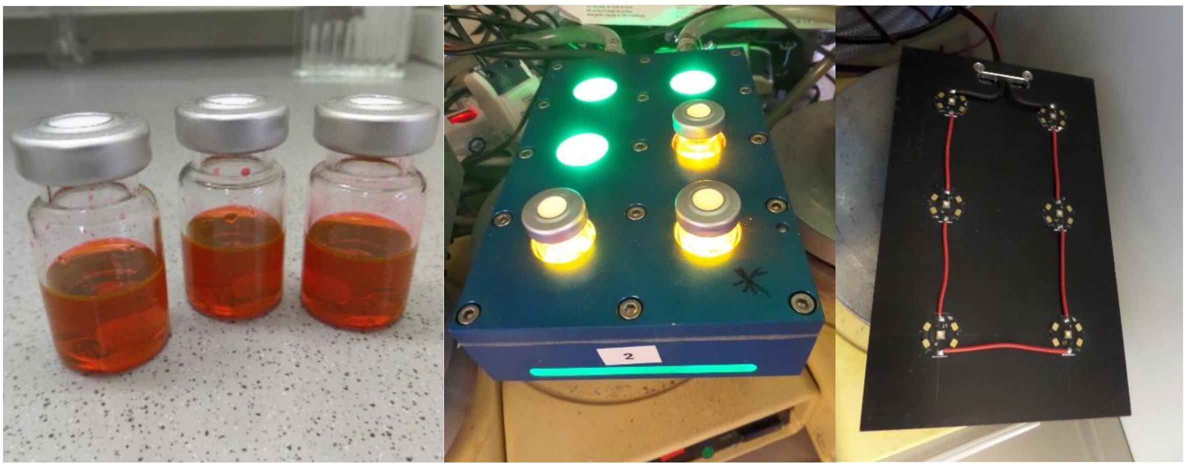


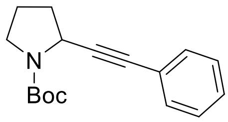
Figure S3-1. Left: Three crimp cap vials with the same reaction mixture. Center: Irradiation of the vials. Right: Setup for irradiation: magnetic stirrer, LEDs (one per vial) and cooling block.

General procedure B: Decarboxylative alkynylation with *in situ* formed active esters

In order to ensure optimal illumination of the solutions by the LEDs, three 5 mL vials with the same reaction mixtures were irradiated and combined for the work-up. Each crimp cap vial was equipped with a magnetic stirring bar, eosin Y (13.0 mg, 0.02 mmol, 10 mol%), the corresponding carboxylic acid (0.20 mmol, 1.0 equiv.), DCC (54.5 mg, 0.26 mmol, 1.3 equiv.), DMAP (3.2 mg, 0.02 mmol, 0.1 equiv.), *N*-hydroxy-phthalimide (35.9 mg, 0.22 mmol, 1.1 equiv.) and acetylenic sulfone **2** (0.20 mmol, 1.0 equiv.). The vials were capped with septa and nitrogen atmosphere was introduced *via* three cycles of vacuum/nitrogen. Degassed DIPEA (70.0 µL, 0.40 mmol, 2.0 equiv.) and dry CH$_2$Cl$_2$ (4 mL) were added *via* syringe. The reaction mixtures were stirred and irradiated through the vials´ plane bottom side using green LEDs (528 nm) for 18 h at rt. The content of three vials was combined and diluted with saturated aqueous solution of NaHCO$_3$ (20 mL). It was extracted with EA (3 x 20 mL) and the combined organic phases were washed with brine (20 mL), dried over Na$_2$SO$_4$ and concentrated in vacuum. Purification of the crude product was performed by automated flash column chromatography (PE/EA = 19:1 to 4:1) yielding the corresponding product **3a** as colorless oil.

Characterization of photocatalytic products 3 and 4

tert-Butyl 2-(phenylethynyl)pyrrolidine-1-carboxylate (3a)[25]



Yield: procedure A: 127 mg, 0.47 mmol, 78%; procedure B: 103 mg, 0.38 mmol, 63%; colorless oil.

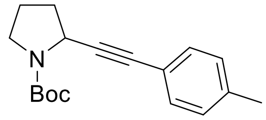
^{1}H NMR (300 MHz, CDCl$_3$): (rotamers around the tertiary amide); δ [ppm] = 7.37 (brs, 2H), 7.26 (brs, 3H), 4.90 – 4.43 (m, 1H), 3.49 (brs, 1H), 3.33 (brs, 1H), 2.09 (brs, 3H), 1.89 (brs, 1H), 1.48 (s, 9H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 154.2 (C$_q$), 131.6 (+), 128.2 (+), 128.0 (+), 123.2 (C$_q$), 90.0 (C$_q$), 81.5 (C$_q$), 79.6 (C$_q$), 48.7 (+), 45.9 and 45.6 (–), 33.8 and 33.3 (–), 28.5 (+), 24.5 and 23.8 (–).

HRMS (ESI) (m/z): [M + H]$^+$ (C$_{17}$H$_{22}$NO$_2$) calc.: 272.1645, found: 272.1646.

MF: $C_{17}H_{21}NO_2$
MW: 271.36 g/mol

***tert*-Butyl 2-(*p*-tolylethynyl)pyrrolidine-1-carboxylate (3b)**



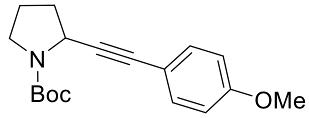
Yield: 137 mg, 0.48 mmol, 80%; colorless oil.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.27 (d, *J* = 7.6 Hz, 2H), 7.07 (d, *J* = 7.3 Hz, 2H), 4.84 – 4.49 (m, 1H), 3.49 (brs, 1H), 3.33 (brs, 1H), 2.31 (s, 3H), 2.08 (brs, 3H), 1.89 (brs, 1H), 1.48 (s, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 154.2 (C_q), 138.0 (C_q), 131.4 (+), 129.0 (+), 120.2 (C_q), 89.2 (C_q), 81.6 (C_q), 79.6 (C_q), 48.8 (+), 45.9 and 45.6 (–), 33.8 and 33.3 (–), 28.5 (+), 24.5 and 23.8 (–), 21.4 (+).

HRMS (ESI) (m/z): $[M + Na]^+$ ($C_{18}H_{23}NNaO_2$) calc.: 308.1621, found: 308.1623.
MF: $C_{18}H_{23}NO_2$
MW: 285.39 g/mol

***tert*-Butyl 2-((4-methoxyphenyl)ethynyl)pyrrolidine-1-carboxylate (3c)**



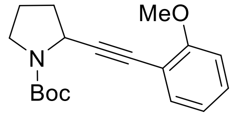
Yield: 152 mg, 0.50 mmol, 84%; slightly yellowish oil.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.29 (d, *J* = 8.3 Hz, 2H), 6.77 (d, *J* = 8.1 Hz, 2H), 4.84 – 4.43 (m, 1H), 3.74 (s, 3H), 3.46 (brs, 1H), 3.31 (brs, 1H), 2.06 (brs, 3H), 1.86 (brs, 1H), 1.46 (s, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 159.3 (C_q), 154.1 (C_q), 132.9 (+), 115.3 (C_q), 113.8 (+), 88.4 (C_q), 81.3 (C_q), 79.5 (C_q), 55.2 (+), 48.8 (+), 45.8 and 45.6 (–), 33.8 and 33.3 (–), 28.5 (+), 24.5 and 23.8 (–).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{18}H_{24}NO_3$) calc.: 302.1751, found: 302.1750.
MF: $C_{18}H_{23}NO_3$
MW: 301.39 g/mol

***tert*-Butyl 2-((2-methoxyphenyl)ethynyl)pyrrolidine-1-carboxylate (3d)**



Yield: 144 mg, 0.48 mmol, 80%; colorless oil.

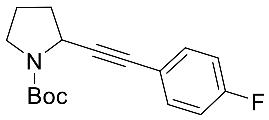
^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.32 (d, *J* = 6.1 Hz, 1H), 7.21 (brs, 1H), 6.93 – 6.66 (m, 2H), 4.89 – 4.56 (m, 1H), 3.80 (s, 3H), 3.49 (brs, 1H), 3.32 (brs, 1H), 2.10 (brs, 3H), 1.87 (brs, 1H), 1.47 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 160.0 (C_q), 154.2 (C_q), 133.6 (+), 129.4 (+), 120.3 (+), 112.4 (C_q), 110.7 (+), 93.9 (C_q), 79.5 (C_q), 77.8 (C_q), 55.6 (+), 49.0 (+), 45.6 (–), 33.9 and 33.4 (–), 28.5 (+), 24.5 and 23.8 (–).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{18}H_{24}NO_3$) calc.: 302.1751, found: 302.1749.

MF: $C_{18}H_{23}NO_3$
MW: 301.39 g/mol

tert-Butyl 2-((4-fluorophenyl)ethynyl)pyrrolidine-1-carboxylate (3e)



Yield: 134 mg, 0.46 mmol, 77%; yellowish oil.

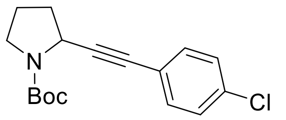
^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.33 (brs, 2H), 6.94 (brs, 2H), 4.83 – 4.44 (m, 1H), 3.47 (brs, 1H), 3.32 (brs, 1H), 2.06 (brs, 3H), 1.88 (brs, 1H), 1.46 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 162.3 (d, $^1J_{CF}$ = 248.9 Hz, C_q), 154.1 (C_q), 133.5 (+), 119.4 (d, $^3J_{CF}$ = 3.4 Hz, C_q), 115.5 (d, $^2J_{CF}$ = 20.9 Hz, +), 89.7 (C_q), 80.5 (C_q), 79.6 (C_q), 48.7 (+), 45.7 (–), 33.8 and 33.3 (–), 28.5 (+), 24.6 and 23.8 (–).

^{19}F NMR (376 MHz, $CDCl_3$): δ [ppm] = - 111.9 (s).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{17}H_{21}FNO_2$) calc.: 290.1551, found: 290.1552.
MF: $C_{17}H_{20}FNO_2$
MW: 289.35 g/mol

tert-Butyl 2-((4-chlorophenyl)ethynyl)pyrrolidine-1-carboxylate (3f)



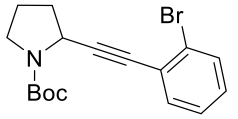
Yield: 44.7 mg, 0.15 mmol, 73%;[a] colorless oil.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.31 (d, *J* = 8.3 Hz, 2H), 7.25 (d, *J* = 8.5 Hz, 2H), 4.86 – 4.47 (m, 1H), 3.50 (brs, 1H), 3.36 (brs, 1H), 2.10 (brs, 3H), 1.92 (brs, 1H), 1.48 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 154.2 (C_q), 134.1 (C_q), 132.9 (+), 128.7 (+), 121.9 (C_q), 91.1 (C_q), 80.6 (C_q), 79.8 (C_q), 48.8 (+), 46.0 and 45.8 (–), 33.9 and 33.4 (–), 28.7 (+), 24.7 and 24.0 (–).

HRMS (ESI) (m/z): $[M + Na]^+$ ($C_{17}H_{20}ClNNaO_2$) calc.: 328.1075, found: 328.1074.
MF: $C_{17}H_{20}ClNO_2$
MW: 305.80 g/mol

tert-Butyl 2-((2-bromophenyl)ethynyl)pyrrolidine-1-carboxylate (3g)



Yield: 147 mg, 0.42 mmol, 70%; yellow oil.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.52 (d, *J* = 7.8 Hz, 1H), 7.38 (d, *J* = 6.7 Hz, 1H), 7.20 (t, *J* = 7.1 Hz, 1H), 7.10 (t, *J* = 7.1 Hz, 1H), 4.97 – 4.44 (m, 1H), 3.51 (brs, 1H), 3.32 (brs, 1H), 2.12 (brs, 3H), 1.91 (brs, 1H), 1.47 (s, 9H).

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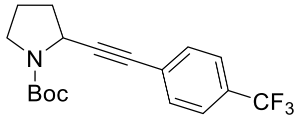
[a] The product was isolated on a smaller scale (one vial with 0.20 mmol instead of three vials was used).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 154.1 (C$_q$), 133.3 (+), 132.3 (+), 129.2 (+), 127.0 (+), 125.6 (C$_q$), 125.2 (C$_q$), 94.8 (C$_q$), 80.2 (C$_q$), 79.7 (C$_q$), 48.9 and 48.7 (+), 45.8 and 45.6 (–), 33.8 and 33.1 (–), 28.5 (+), 24.5 and 23.8 (–).

HRMS (ESI) (m/z): [M + H]$^+$ (C$_{17}$H$_{21}$BrNO$_2$) calc.: 350.0750, found: 350.0751.
MF: C$_{17}$H$_{20}$BrNO$_2$
MW: 350.26 g/mol

tert-Butyl 2-((4-(trifluoromethyl)phenyl)ethynyl)pyrrolidine-1-carboxylate (3h)



Yield: 119 mg, 0.35 mmol, 59%, yellowish oil.

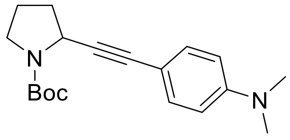
^{1}H NMR (300 MHz, CDCl$_3$): (rotamers around the tertiary amide); δ [ppm] = 7.64 – 7.35 (m, 4H), 4.82 – 4.50 (m, 1H), 3.49 (brs, 1H), 3.35 (brs, 1H), 2.10 (brs, 3H), 1.92 (brs, 1H), 1.47 (s, 9H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 154.2 (C$_q$), 131.9 (+), 127.2 (C$_q$), 125.8 (C$_q$), 125.2 (+), 122.2 (C$_q$), 92.6 (C$_q$), 80.4 (C$_q$), 79.9 (C$_q$), 48.8 (+), 46.0 and 45.8 (–), 33.7 and 33.2 (–), 28.6 (+), 24.6 and 24.0 (–).

^{19}F NMR (282 MHz, CDCl$_3$): δ [ppm] = - 63.3 (s).

HRMS (ESI) (m/z): [M + H]$^+$ (C$_{18}$H$_{21}$F$_3$NO$_2$) calc.: 340.1519, found: 340.1518.
MF: C$_{18}$H$_{20}$F$_3$NO$_2$
MW: 339.36 g/mol

tert-Butyl 2-((4-(dimethylamino)phenyl)ethynyl)pyrrolidine-1-carboxylate (3i)



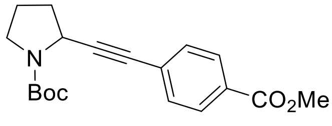
Yield: 137 mg, 0.44 mmol, 73%; yellowish oil.

^{1}H NMR (300 MHz, CDCl$_3$): (rotamers around the tertiary amide); δ [ppm] = 7.25 (d, J = 8.6 Hz, 2H), 6.58 (d, J = 8.5 Hz, 2H), 4.92 – 4.42 (m, 1H), 3.49 (brs, 1H), 3.33 (brs, 1H), 2.92 (s, 6H), 2.08 (brs, 3H), 1.87 (brs, 1H), 1.48 (s, 9H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 154.2 (C$_q$), 149.9 (C$_q$), 132.6 (+), 111.7 (+), 110.1 (C$_q$), 87.4 (C$_q$), 82.2 (C$_q$), 79.4 (C$_q$), 48.9 (+), 45.6 (–), 40.2 (+), 33.9 and 33.5 (–), 28.5 (+), 24.5 and 23.8 (–).

HRMS (ESI) (m/z): [M + H]$^+$ (C$_{19}$H$_{27}$N$_2$O$_2$) calc.: 315.2067, found: 315.2068.
MF: C$_{19}$H$_{26}$N$_2$O$_2$
MW: 314.43 g/mol

tert-Butyl 2-((4-(methoxycarbonyl)phenyl)ethynyl)pyrrolidine-1-carboxylate (3j)



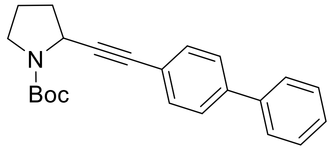
Yield: 95.9 mg, 0.29 mmol, 49%; yellowish oil.

^{1}H NMR (400 MHz, CDCl$_3$): (rotamers around the tertiary amide); δ [ppm] = 7.93 (d, *J* = 7.6 Hz, 2H), 7.41 (d, *J* = 7.9 Hz, 2H), 4.91 – 4.46 (m, 1H), 3.87 (s, 3H), 3.48 (brs, 1H), 3.33 (brs, 1H), 2.17 – 2.02 (m, 3H), 1.90 (brs, 1H), 1.46 (s, 9H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 166.6 (C$_q$), 154.1 (C$_q$), 131.5 (+), 129.5 (+), 128.0 (C$_q$), 127.2 and 126.6 (C$_q$), 93.2 (C$_q$), 81.0 (C$_q$), 79.8 (C$_q$), 52.2 (+), 48.8 (+), 46.0 and 45.7 (–), 33.7 and 33.2 (–), 28.6 (+), 24.6 and 23.9 (–).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{19}H_{24}NO_4$) calc.: 330.1700, found: 330.1699.
MF: $C_{19}H_{23}NO_4$
MW: 329.40 g/mol

***tert*-Butyl 2-([1,1'-biphenyl]-4-ylethynyl)pyrrolidine-1-carboxylate (3k)**



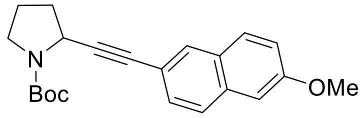
Yield: 88.2 mg, 0.25 mmol, 63%;[b] yellowish oil.

^{1}H NMR (300 MHz, CDCl$_3$): (rotamers around the tertiary amide); δ [ppm] = 7.61 – 7.51 (m, 4H), 7.50 – 7.40 (m, 4H), 7.39 – 7.31 (m, 1H), 4.96 – 4.50 (m, 1H), 3.53 (brs, 1H), 3.37 (brs, 1H), 2.14 (brs, 3H), 1.94 (brs, 1H), 1.52 (s, 9H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 154.3 (C$_q$), 140.8 (C$_q$), 140.5 (C$_q$), 132.1 (+), 128.9 (+), 127.7 (+), 127.1 (+), 127.0 (+), 122.3 (C$_q$), 90.7 (C$_q$), 81.5 (C$_q$), 79.8 (C$_q$), 48.9 (+), 45.8 (–), 33.9 and 33.4 (–), 28.7 (+), 24.6 and 23.9 (–).

HRMS (ESI) (m/z): [M + Na]$^+$ ($C_{23}H_{25}NNaO_2$) calc.: 370.1778, found: 370.1778.
MF: $C_{23}H_{25}NO_2$
MW: 347.46 g/mol

***tert*-Butyl 2-((6-methoxynaphthalen-2-yl)ethynyl)pyrrolidine-1-carboxylate (3l)**



Yield: 157 mg, 0.45 mmol, 74%, yellowish oil.

^{1}H NMR (300 MHz, CDCl$_3$): (rotamers around the tertiary amide); δ [ppm] = 7.89 – 7.79 (m, 1H), 7.65 (t, *J* = 7.8 Hz, 2H), 7.41 (d, *J* = 8.3 Hz, 1H), 7.13 (d, *J* = 9.0 Hz, 1H), 7.08 (s, 1H), 4.90 – 4.53 (m, 1H), 3.89 (s, 3H), 3.54 (brs, 1H), 3.38 (brs, 1H), 2.14 (brs, 3H), 1.93 (brs, 1H), 1.52 (s, 9H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 158.2 (C$_q$), 154.3 (C$_q$), 134.0 (C$_q$), 131.2 (+), 129.3 (+), 129.2 (+), 128.5 (C$_q$), 126.8 (+), 119.4 (+), 118.2 (C$_q$), 105.8 (+), 89.6 (C$_q$), 82.1 (C$_q$), 79.7 (C$_q$), 55.4 (+), 48.9 (+), 45.7 (–), 33.9 and 33.6 (–), 28.6 (+), 24.6 and 23.9 (–).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{22}H_{26}NO_3$) calc.: 352.1907, found: 352.1908.
MF: $C_{22}H_{25}NO_3$
MW: 351.45 g/mol

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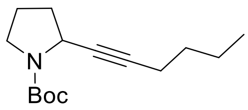
[b] The product was isolated on a smaller scale (two vials a 0.20 mmol instead of three vials were combined).

tert-Butyl 2-(hex-1-yn-1-yl)pyrrolidine-1-carboxylate (3m)[26]



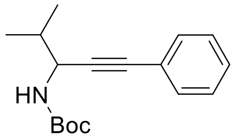
Yield: 66.6 mg, 0.26 mmol, 44%, yellowish oil.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 4.60 – 4.28 (m, 1H), 3.43 (brs, 1H), 3.28 (brs, 1H), 2.15 (dt, *J* = 6.8 Hz, 1.9 Hz, 2H), 2.04 – 1.80 (m, 4H), 1.47 (s, 9H), 1.44 – 1.35 (m, 4H), 0.89 (t, *J* = 7.0 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 154.3 (C_q), 81.7 (C_q), 80.7 (C_q), 79.4 (C_q), 48.5 (+), 45.6 (–), 34.1 (–), 31.0 (–), 28.6 (+), 23.8 (–), 22.0 (–), 18.5 (–), 13.7 and 14.3 (+).

HRMS (ESI) (m/z): $[M + Na]^+$ ($C_{15}H_{25}NNaO_2$) calc.: 274.1778, found: 274.1783.
MF: $C_{15}H_{25}NO_2$
MW: 251.37 g/mol

tert-Butyl (4-methyl-1-phenylpent-1-yn-3-yl)carbamate (4b)[25c]



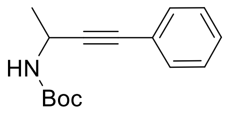
Yield: 126 mg, 0.46 mmol, 77%; yellowish oil.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.44 – 7.37 (m, 2H), 7.32 – 7.25 (m, 3H), 5.00 – 4.75 (m, 1H), 4.63 – 4.40 (m, 1H), 2.02 – 1.90 (m, 1H), 1.46 (s, 9H), 1.04 (d, *J* = 6.8 Hz, 6H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 155.1 (C_q), 131.8 (+), 128.3 (+), 128.25 (+), 123.0 (C_q), 87.6 (C_q), 83.8 (C_q), 79.8 (C_q), 49.3 (+), 33.5 (+), 28.5 (+), 19.0 (+), 17.8 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{17}H_{24}NO_2$) calc.: 274.1802, found: 274.1801.
MF: $C_{17}H_{23}NO_2$
MW: 273.38 g/mol

tert-Butyl (4-phenylbut-3-yn-2-yl)carbamate (4c)[25c, 27]



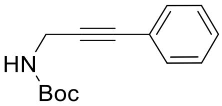
Yield: 102 mg, 0.41 mmol, 69%; white solid.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.45 – 7.34 (m, 2H), 7.32 – 7.23 (m, 3H), 5.02 – 4.48 (m, 2H), 1.47 (s, 3H), 1.46 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 154.8 (C_q), 131.8 (+), 128.32 (+), 128.30 (+), 122.9 (C_q), 90.0 (C_q), 82.2 (C_q), 79.9 (C_q), 39.1 (+), 28.5 (+), 23.0 (+).

HRMS (ESI) (m/z): $[M + Na]^+$ ($C_{15}H_{19}NNaO_2$) calc.: 268.1308, found: 268.1310.
MF: $C_{15}H_{19}NO_2$
MW: 245.32 g/mol

tert-Butyl (3-phenylprop-2-yn-1-yl)carbamate (4d)[28]



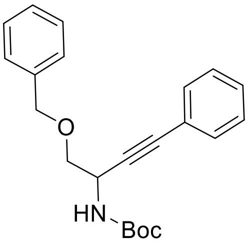
Yield: 103 mg, 0.44 mmol, 74%; white solid.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.44 – 7.37 (m, 2H), 7.34 – 7.26 (m, 3H), 4.80 (brs, 1H), 4.15 (d, *J* = 5.0 Hz, 2H), 1.47 (s, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 155.4 (C_q), 131.8 (+), 128.5 (+), 128.4 (+), 122.8 (C_q), 85.5 (C_q), 83.2 (C_q), 80.2 and 80.1 (C_q), 31.4 and 31.3 (–), 28.5 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{14}H_{18}NO_2$) calc.: 232.1332, found: 232.1334.
MF: $C_{14}H_{17}NO_2$
MW: 231.30 g/mol

tert-Butyl (1-(benzyloxy)-4-phenylbut-3-yn-2-yl)carbamate (4e)[25c]



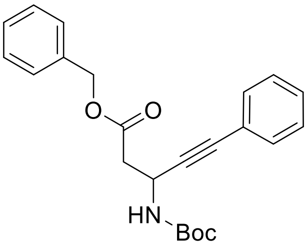
Yield: 154 mg, 0.44 mmol, 73%; yellowish oil.

^{1}H NMR (300 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.47 – 7.27 (m, 10H), 5.08 (brs, 1H), 4.88 (brs, 1H), 4.71 – 4.59 (m, 2H), 3.68 (d, *J* = 4.8 Hz, 2H), 1.47 (s, 9H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 155.0 (C_q), 138.0 (C_q), 131.9 (+), 128.5 (+), 128.4 (+), 128.3 (+), 127.82 (+), 127.76 (+), 122.8 (C_q), 87.0 (C_q), 83.2 (C_q), 80.1 (C_q), 73.2 (–), 72.1 (–), 43.5 (+), 28.4 (+).

HRMS (ESI) (m/z): $[M + H]^+$ ($C_{22}H_{26}NO_3$) calc.: 352.1907, found: 352.1906.
MF: $C_{22}H_{25}NO_3$
MW: 351.45 g/mol

Benzyl 3-((*tert*-butoxycarbonyl)amino)-5-phenylpent-4-ynoate (4f)



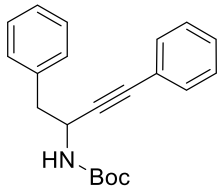
Yield: 148 mg, 0.39 mmol, 65%; yellowish oil.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.40 – 7.25 (m, 10H), 5.41 (brs, 1H), 5.18 (q, *J* = 12.3 Hz, 2H), 5.05 (brs, 1H), 2.86 (qd, *J* = 15.7 Hz, 5.7 Hz, 2H), 1.46 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 170.3 (C_q), 154.7 (C_q), 135.7 (C_q), 131.9 (+), 128.7 (+), 128.5 (+), 128.4 (+), 128.34 (+), 128.32 (+), 122.5 (C_q), 87.2 (C_q), 83.4 (C_q), 80.3 (C_q), 66.7 (–), 40.8 (–), 40.2 (+), 28.5 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{23}H_{26}NO_4$) calc.: 380.1856, found: 380.1854.
MF: $C_{23}H_{25}NO_4$
MW: 379.46 g/mol

tert-Butyl (1,4-diphenylbut-3-yn-2-yl)carbamate (4g)[29]



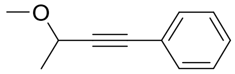
Yield: 79.8 mg, 0.25 mmol, 41%; yellowish solid.

^{1}H NMR (400 MHz, $CDCl_3$): (rotamers around the tertiary amide); δ [ppm] = 7.39 – 7.26 (m, 10H), 5.00 – 4.65 (m, 2H), 3.14 – 2.97 (m, 2H), 1.45 (s, 9H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 154.8 (C_q), 136.8 (C_q), 131.7 (+), 130.1 (+), 128.5 (+), 128.4 (+), 127.0 (+), 122.8 (C_q), 88.3 (C_q), 84.4 (C_q), 80.1 (C_q), 44.8 (+), 42.3 (–), 28.5 (+).

HRMS (ESI) (m/z): [M + H]$^+$ ($C_{21}H_{24}NO_2$) calc.: 322.1802, found: 322.1801.
MF: $C_{21}H_{23}NO_2$
MW: 321.42 g/mol

(3-Methoxybut-1-yn-1-yl)benzene (4h)[30]



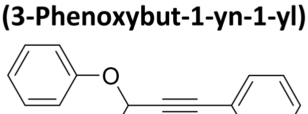
Yield: 70.8 mg, 0.44 mmol, 74%; colorless oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.48 – 7.42 (m, 2H), 7.34 – 7.29 (m, 3H), 4.31 (q, *J* = 6.6 Hz, 1H), 3.48 (s, 3H), 1.53 (d, *J* = 6.6 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 131.8 (+), 128.41 (+), 128.37 (+), 122.9 (C_q), 88.9 (C_q), 85.2 (C_q), 67.4 (+), 56.5 (+), 22.1 (+).

HRMS (EI) (m/z): [M$^\bullet$]$^+$ ($C_{11}H_{12}O$) calc.: 160.0883, found: 160.0883.
MF: $C_{11}H_{12}O$
MW: 160.22 g/mol

(3-Phenoxybut-1-yn-1-yl)benzene (4i)[31]



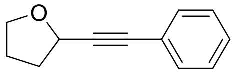
Yield: 53.4 mg, 0.24 mmol, 40%; slightly yellowish oil.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.45 – 7.37 (m, 2H), 7.37 – 7.26 (m, 5H), 7.14 – 7.05 (m, 2H), 7.04 – 6.97 (m, 1H), 5.11 (q, *J* = 6.6 Hz, 1H), 1.76 (d, *J* = 6.6 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 157.7 (C_q), 131.9 (+), 129.5 (+), 128.6 (+), 128.4 (+), 122.6 (C_q), 121.4 (+), 116.0 (+), 88.4 (C_q), 85.8 (C_q), 64.4 (+), 22.5 (+).

HRMS (EI) (m/z): [M$^\bullet$]$^+$ ($C_{16}H_{14}O$) calc.: 222.1039, found: 222.1031.
MF: $C_{16}H_{14}O$
MW: 222.29 g/mol

2-(Phenylethynyl)tetrahydrofuran (4j)[29]



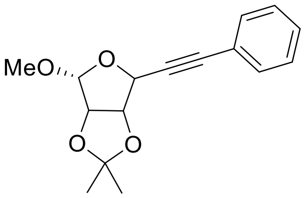
Yield: 42.5 mg, 0.25 mmol, 41%; yellowish oil.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.47 – 7.39 (m, 2H), 7.33 – 7.26 (m, 3H), 4.81 (dd, *J* = 7.1 Hz, 5.1 Hz, 1H), 4.06 – 3.97 (m, 1H), 3.90 – 3.81 (m, 1H), 2.30 – 2.16 (m, 1H), 2.15 – 2.02 (m, 2H), 2.01 – 1.87 (m, 1H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 131.8 (+), 128.4 (+), 128.3 (+), 122.9 (C$_q$), 89.2 (C$_q$), 84.6 (C$_q$), 68.7 (+), 68.1 (–), 33.5 (–), 25.6 (–).

HRMS (EI) (m/z): [M$^•$]$^+$ ($C_{12}H_{12}O$) calc.: 172.0883, found: 172.0880.
MF: $C_{12}H_{12}O$
MW: 172.23 g/mol

(4*R*)-4-Methoxy-2,2-dimethyl-6-(phenylethynyl)tetrahydrofuro[3,4-*d*][1,3]dioxole (4k)[32]



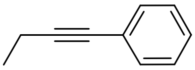
Yield: 115 mg, 0.42 mmol, 70%; slightly yellowish solid.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.44 – 7.36 (m, 2H), 7.35 – 7.26 (m, 3H), 5.09 (s, 1H), 5.03 (s, 1H), 4.98 (d, *J* = 5.8 Hz, 1H), 4.74 (d, *J* = 5.8 Hz, 1H), 3.44 (s, 3H), 1.49 (s, 3H), 1.33 (s, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 131.6 (+), 128.5 (+), 128.4 (+), 122.6 (C$_q$), 112.8 (C$_q$), 109.3 (+), 86.9 (C$_q$), 85.9 (C$_q$), 85.6 (+), 85.4 (+), 75.7 (+), 54.5 (+), 26.4 (+), 25.1 (+).

HRMS (EI) (m/z): [M$^•$]$^+$ ($C_{16}H_{18}O_4$) calc.: 274.1200, found: 274.1207.
MF: $C_{16}H_{18}O_4$
MW: 274.32 g/mol

But-1-yn-1-ylbenzene (4l)[33]



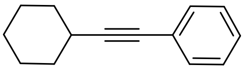
Yield: 45.2 mg, 0.35 mmol, 58%; colorless liquid.

^{1}H NMR (400 MHz, CDCl$_3$): δ [ppm] = 7.47 – 7.35 (m, 2H), 7.33 – 7.24 (m, 3H), 2.43 (q, *J* = 7.5 Hz, 2H), 1.25 (t, *J* = 7.5 Hz, 3H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.6 (+), 124.2 (C$_q$), 91.8 (C$_q$), 80.0 (C$_q$), 14.1 (+), 13.2 (–).

HRMS (EI) (m/z): [M$^•$]$^+$ ($C_{10}H_{10}$) calc.: 130.0777, found: 130.0779.
MF: $C_{10}H_{10}$
MW: 130.19 g/mol

(Cyclohexylethynyl)benzene (4m)



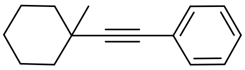
Yield: 68.4 mg, 0.37 mmol, 62%; colorless liquid.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.47 – 7.36 (m, 2H), 7.33 – 7.23 (m, 3H), 2.68 – 2.53 (m, 1H), 1.96 – 1.85 (m, 2H), 1.83 – 1.72 (m, 2H), 1.63 – 1.49 (m, 3H), 1.44 – 1.28 (m, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.5 (+), 124.2 (C_q), 94.6 (C_q), 80.6 (C_q), 32.8 (–), 29.8 (+), 26.1 (–), 25.0 (–).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_{14}H_{16}$) calc.: 184.1247, found: 184.1243.
MF: $C_{14}H_{16}$
MW: 184.28 g/mol

((1-Methylcyclohexyl)ethynyl)benzene (4n)[34]



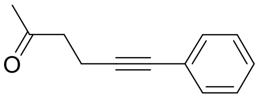
Yield: 56.4 mg, 0.28 mmol, 47%; colorless oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.45 – 7.40 (m, 2H), 7.32 – 7.26 (m, 3H), 1.94 – 1.42 (m, 8H), 1.30 (s, 3H), 1.28 – 1.21 (m, 2H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.5 (+), 124.4 (+), 96.9 (C_q), 81.9 (C_q), 39.7 (–), 33.3 (C_q), 30.4 (+), 26.1 (–), 23.6 (–).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_{15}H_{18}$) calc.: 198.1403, found: 198.1398.
MF: $C_{15}H_{18}$
MW: 198.31 g/mol

6-Phenylhex-5-yn-2-one (4o)[35]



Yield: 71.5 mg, 0.42 mmol, 69%; yellowish liquid.[c]

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.41 – 7.34 (m, 2H), 7.30 – 7.24 (m, 3H), 2.80 – 2.72 (m, 2H), 2.70 – 2.62 (m, 2H), 2.20 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 206.8 (C_q), 131.7 (+), 128.3 (+), 127.9 (+), 123.7 (C_q), 88.6 (C_q), 81.1 (C_q), 42.6 (–), 30.1 (+), 14.1 (–).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_{12}H_{12}O$) calc.: 172.0883, found: 172.0873.
MF: $C_{12}H_{12}O$
MW: 172.23 g/mol

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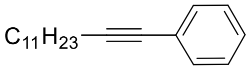
[c] Isolated with special, pre-packed Biotage SNAP Ultra HP-Sphere columns (see general information).

Tridec-1-yn-1-ylbenzene (4p)[36]



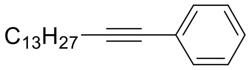
Yield: 102 mg, 0.30 mmol, 66%; colorless liquid.

^{1}H NMR (400 MHz, CDCl$_3$): δ [ppm] = 7.46 – 7.38 (m, 2H), 7.33 – 7.23 (m, 3H), 2.42 (t, *J* = 7.1 Hz, 2H), 1.68 – 1.59 (m, 2H), 1.51 – 1.43 (m, 2H), 1.39 – 1.28 (m, 14H), 0.92 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.6 (+), 124.3 (C_q), 90.6 (C_q), 80.7 (C_q), 32.1 (–), 29.8 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.1 (–), 28.9 (–), 22.9 (–), 19.6 (–), 14.3 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{19}H_{28}$) calc.: 256.2186, found: 256.2182.
MF: $C_{19}H_{28}$
MW: 256.43 g/mol

Pentadec-1-yn-1-ylbenzene (4q)



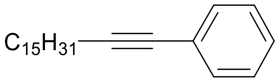
Yield: 119 mg, 0.42 mmol, 70%; slightly yellowish liquid.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.47 – 7.37 (m, 2H), 7.34 – 7.24 (m, 3H), 2.43 (t, *J* = 7.0 Hz, 2H), 1.69 – 1.57 (m, 2H), 1.53 – 1.43 (m, 2H), 1.39 – 1.28 (m, 18H), 0.92 (t, *J* = 6.6 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.5 (+), 124.3 (C_q), 90.6 (C_q), 80.7 (C_q), 32.1 (–), 29.9 (–), 29.84 (–), 29.83 (–), 29.81 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.1 (–), 28.9 (–), 22.9 (–), 19.6 (–), 14.3 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{21}H_{32}$) calc.: 284.2499, found: 284.2496.
MF: $C_{21}H_{32}$
MW: 284.49 g/mol

Heptadec-1-yn-1-ylbenzene (4r)



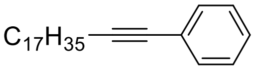
Yield: 132 mg, 0.42 mmol, 70%; colorless liquid.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.47 – 7.36 (m, 2H), 7.34 – 7.25 (m, 3H), 2.42 (t, *J* = 7.0 Hz, 2H), 1.69 – 1.57 (m, 2H), 1.53 – 1.41 (m, 2H), 1.38 – 1.26 (m, 22H), 0.91 (t, *J* = 6.6 Hz, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.6 (+), 124.3 (C_q), 90.6 (C_q), 80.7 (C_q), 32.1 (–), 29.9 (–), 29.85 (–), 29.81 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.1 (–), 28.9 (–), 22.9 (–), 19.6 (–), 14.3 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{23}H_{36}$) calc.: 312.2812, found: 312.2805.
MF: $C_{23}H_{36}$
MW: 312.54 g/mol

Nonadec-1-yn-1-ylbenzene (4s)



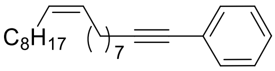
Yield: 139 mg, 0.41 mmol, 68%; white solid.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.45 – 7.35 (m, 2H), 7.33 – 7.24 (m, 3H), 2.42 (t, *J* = 7.0 Hz, 2H), 1.67 – 1.56 (m, 2H), 1.52 – 1.42 (m, 2H), 1.37 – 1.26 (m, 26H), 0.90 (t, *J* = 6.7 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 131.7 (+), 128.3 (+), 127.6 (+), 124.3 (C_q), 90.6 (C_q), 80.7 (C_q), 32.1 (–), 29.9 (–), 29.84 (–), 29.81 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.1 (–), 28.9 (–), 22.9 (–), 19.6 (–), 14.3 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{25}H_{40}$) calc.: 340.3125, found: 340.3119.
MF: $C_{25}H_{40}$
MW: 340.60 g/mol

(*Z*)-Nonadec-10-en-1-yn-1-ylbenzene (4t)



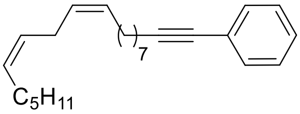
Yield: 121 mg, 0.36 mmol, 59%; colorless liquid.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.44 – 7.37 (m, 2H), 7.31 – 7.24 (m, 3H), 5.43 – 5.31 (m, 2H), 2.41 (t, *J* = 7.1 Hz, 2H), 2.10 – 1.96 (m, 4H), 1.67 – 1.57 (m, 2H), 1.51 – 1.42 (m, 2H), 1.39 – 1.25 (m, 18H), 0.90 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 131.7 (+), 130.1 (+), 129.9 (+), 128.3 (+), 127.6 (+), 124.3 (C_q), 90.6 (C_q), 80.7 (C_q), 32.1 (–), 29.93 (–), 29.88 (–), 29.7 (–), 29.5 (–), 29.3 (–), 29.2 (–), 29.1 (–), 28.9 (–), 27.4 (–), 27.3 (–), 22.8 (–), 19.6 (–), 14.3 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{25}H_{38}$) calc.: 338.2968, found: 338.2959.
MF: $C_{25}H_{38}$
MW: 338.58 g/mol

((10*Z*,13*Z*)-Nonadeca-10,13-dien-1-yn-1-yl)benzene (4u)



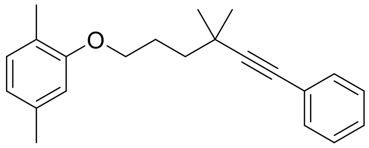
Yield: 102 mg, 0.30 mmol, 51%; colorless liquid.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 7.44 – 7.34 (m, 2H), 7.31 – 7.24 (m, 3H), 5.47 – 5.29 (m, 4H), 2.82 – 2.71 (m, 2H), 2.41 (t, *J* = 7.1 Hz, 2H), 2.11 – 1.96 (m, 4H), 1.65 – 1.57 (m, 2H), 1.51 – 1.42 (m, 2H), 1.40 – 1.27 (m, 12H), 0.90 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 131.7 (+), 130.4 (+), 130.2 (+), 128.3 (+), 128.2 (+), 128.1 (+), 127.6 (+), 124.2 (C_q), 90.6 (C_q), 80.7 (C_q), 31.7 (–), 29.8 (–), 29.5 (–), 29.3 (–), 29.2 (–), 29.0 (–), 28.9 (–), 27.4 (–), 25.8 (–), 22.7 (–), 19.6 (–), 14.2 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{25}H_{36}$) calc.: 336.2812, found: 336.2807.
MF: $C_{25}H_{36}$
MW: 336.56 g/mol

2-((4,4-Dimethyl-6-phenylhex-5-yn-1-yl)oxy)-1,4-dimethylbenzene (4v)



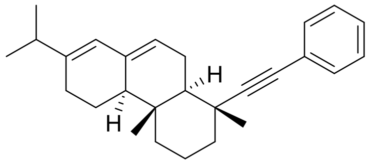
Yield: 107 mg, 0.35 mmol, 58%; colorless oil.

^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.44 – 7.32 (m, 2H), 7.31 – 7.24 (m, 3H), 7.02 (d, *J* = 7.3 Hz, 1H), 6.71 – 6.63 (m, 2H), 4.02 (t, *J* = 6.4 Hz, 2H), 2.31 (s, 3H), 2.21 (s, 3H), 2.10 – 2.00 (m, 2H), 1.73 – 1.65 (m, 2H), 1.35 (s, 6H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 157.2 (C$_q$), 136.6 (C$_q$), 131.7 (+), 130.4 (+), 128.3 (+), 127.6 (+), 124.1 (C$_q$), 123.7 (C$_q$), 120.7 (+), 112.1 (+), 97.1 (C$_q$), 80.7 (C$_q$), 68.2 (–), 40.1 (–), 31.6 (C$_q$), 29.4 (+), 25.9 (–), 21.5 (+), 16.0 (+).

HRMS (EI) (m/z): [M$^•$]$^+$ ($C_{22}H_{26}O$) calc.: 306.1978, found: 306.1981.
MF: $C_{22}H_{26}O$
MW: 306.45 g/mol

(1*R*,4a*R*,4b*R*,10a*R*)-7-Isopropyl-1,4a-dimethyl-1-(phenylethynyl)-1,2,3,4,4a,4b,5,6,10,10a-decahydrophenanthrene (4w)



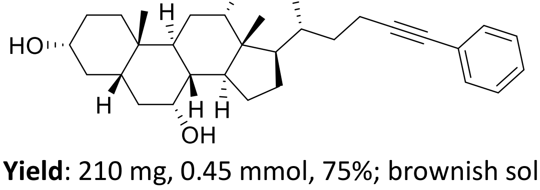
Yield: 72.0 mg, 0.20 mmol, 33%; colorless liquid[d]

^{1}H NMR (400 MHz, CDCl$_3$): δ [ppm] = 7.41 – 7.30 (m, 2H), 7.29 – 7.21 (m, 3H), 5.81 (s, 1H), 5.53 – 5.41 (m, 1H), 2.60 – 2.45 (m, 1H), 2.28 – 2.03 (m, 4H), 1.97 – 1.71 (m, 6H), 1.64 – 1.52 (m, 2H), 1.34 (s, 3H), 1.27 – 1.10 (m, 2H), 1.03 (dd, *J* = 6.8 Hz, 3.9 Hz, 6H), 0.83 (s, 3H).

^{13}C NMR (101 MHz, CDCl$_3$): δ [ppm] = 145.3 (C$_q$), 135.6 (C$_q$), 131.6 (+), 128.2 (+), 127.4 (+), 124.3 (C$_q$), 122.6 (+), 121.5 (+), 100.1 (C$_q$), 79.3 (C$_q$), 51.1 (+), 49.1 (+), 40.9 (–), 38.7 (–), 35.2 (C$_q$), 35.1 (C$_q$), 35.0 (+), 27.7 (–), 25.7 (–), 22.7 (–), 21.6 (+), 21.5 (+), 21.0 (+), 18.3 (–), 14.2 (+).

HRMS (EI) (m/z): [M$^•$]$^+$ ($C_{27}H_{34}$) calc.: 358.2655, found: 358.2646.
MF: $C_{27}H_{34}$
MW: 358.57 g/mol

(3*R*,5*S*,7*R*,8*R*,9*S*,10*S*,12*S*,13*R*,14*S*,17*R*)-10,13-dimethyl-17-((*R*)-6-phenylhex-5-yn-2-yl) hexadecahydro-1H-cyclopenta[*a*]phenanthrene-3,7,12-triol (4x)



Yield: 210 mg, 0.45 mmol, 75%; brownish solid.

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[d] Isolated with special, pre-packed Biotage SNAP Ultra HP-Sphere columns (see general information).

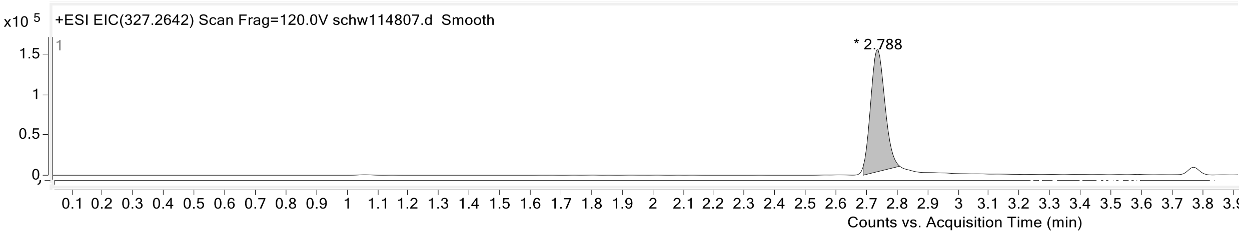
^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.44 – 7.28 (m, 2H), 7.30 – 7.18 (m, 3H), 3.96 (brs, 1H), 3.82 (brs, 1H), 3.56 – 2.96 (m, 4H), 2.49 – 2.17 (m, 4H), 1.96 – 1.82 (m, 4H), 1.79 – 1.63 (m, 6H), 1.59 – 1.45 (m, 6H), 1.41 – 1.24 (m, 4H), 1.02 (d, *J* = 6.3 Hz, 3H), 0.87 (s, 3H), 0.68 (s, 3H).

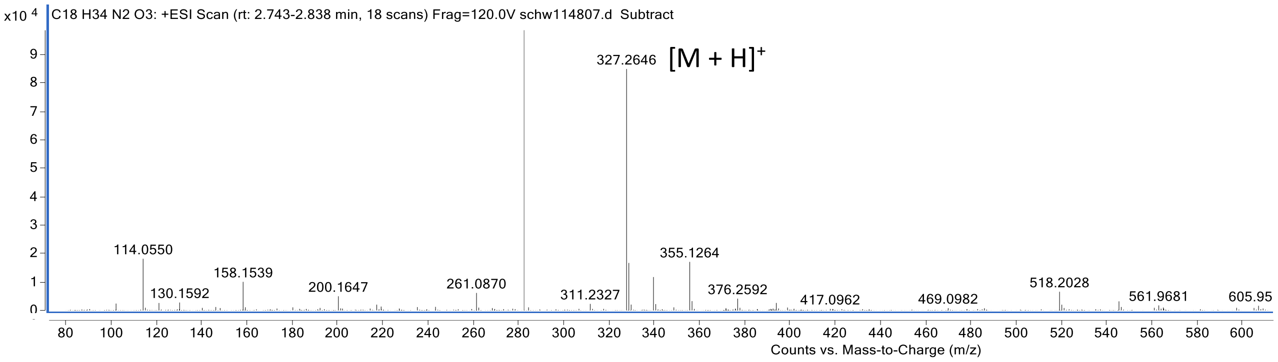
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 131.6 (+), 128.2 (+), 127.5 (+), 124.2 (C_q), 91.0 (C_q), 80.5 (C_q), 73.2 (+), 71.9 (+), 68.5 (+), 47.2 (+), 46.6 (C_q), 41.7 (+), 39.6 (+ and –), 35.4 (–), 35.3 (+), 35.0 (–), 34.9 (C_q), 34.8 (–), 30.5 (–), 28.2 (–), 27.7 (–), 26.4 (+), 23.3 (–), 22.6 (+), 17.4 (+), 16.7 (–), 12.6 (+), 10.7 (+).

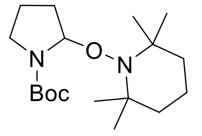
HRMS (ESI) (m/z): $[M + Cl]^-$ ($C_{31}H_{44}ClO_3$) calc.: 499.2984, found: 499.3011.
MF: $C_{31}H_{44}O_3$
MW: 464.69 g/mol

3.4.5. TEMPO Trapping of Radical Intermediates

In a 5 mL crimp cap vial with a stirring bar were weighed eosin Y (32.4 mg, 0.05 mmol, 1.0 equiv.), *N*-(acyloxy)phthalimide **1a** (18.0 mg, 0.05 mmol, 1.0 equiv.), **2a** (12.8 mg, 0.05 mmol, 1.0 equiv.) and TEMPO (9.8 mg, 0.06 mmol, 1.25 equiv.). The vial was capped with a septum and nitrogen atmosphere was introduced *via* three cycles of vacuum/nitrogen. Degassed DIPEA (12.9 µL, 0.10 mmol, 2.0 equiv.) and dry CH_2Cl_2 (1 mL) were added *via* syringe. The reaction mixture was stirred and irradiated with a green LED (528 nm) for 18 h at rt. After irradiation, the orange reaction mixture was submitted to mass spectrometry (LC-MS) without any further work-up.







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MS (ESI) (m/z): $[M + H]^+$ ($C_{18}H_{35}N_2O_3$) calc.: 327.2642, found: 327.2646.

3.4.6. Quantum Yield Determination

The measurement was accomplished in a covered apparatus to minimize the ambient light. A 10 mm Hellma® quartz fluorescence cuvette with solvent (CH_2Cl_2, 2 mL) and a stirring bar was placed in the beam of a 528 nm LED and the transmitted power (P_{ref} = 28.1 mW) was measured by a calibrated photodiode horizontal to the cuvette. The content of the cuvette was changed to the degassed reaction mixture of **1a** (36.0 mg, 0.10 mmol, 1 equiv.), **2a** (25.6 mg, 0.10 mmol, 1 equiv.), DIPEA (35.0 µL, 0.20 mmol, 2 equiv.), eosin Y (6.5 mg, 10 mol%) in CH_2Cl_2 (2 mL) with a stirring bar. The transmitted power (P_{sample} = 410 µW) was measured analogously to the blank solution. The sample was further irradiated and the transmitted power as well as the respective yield of photocatalytic product (measured by quantitative GC using biphenyl as internal standard) were recorded after different times (Table **S3-1**).

The quantum yield was calculated from equation **E1**:

$$\Phi = \frac{N_{product}}{N_{ph}} = \frac{N_{\mathrm{A}} * n_{product}}{\frac{E_{light}}{E_{ph}}} = \frac{N_{\mathrm{A}} * n_{product}}{\frac{P_{absorbed} * t}{\frac{h * c}{\lambda}}} = \frac{h * c * N_{\mathrm{A}} * n_{product}}{\lambda * \left(P_{ref} - P_{sample}\right) * t} \quad \mathbf{(E1)}$$

where Φ is the quantum yield, $N_{product}$ is the number of product molecules created, N_{ph} is the number of photons absorbed, N_{A} is Avogadro's constant in moles^{-1}, $n_{product}$ is the molar amount of molecules created in moles, E_{light} is the energy of light absorbed in Joules, E_{ph} is the energy of a single photon in Joules, $P_{absorbed}$ is the radiant power absorbed in Watts, t is the irradiation time in sec, h is the Planck's constant in J×s, c is the speed of light in m s^{-1}, λ is the wavelength of irradiation source (528 nm) in meters, P_{ref} is the radiant power transmitted by a blank vial in Watts and P_{sample} is the radiant power transmitted by the vial with reaction mixture in Watts.

Table S3-1. Calculation of the quantum yield Φ after different irradiation times.

entry	irradiation time	P_{sample} / µW	yield / %	Φ / %
1	1 h	490	9	2.0
2	4 h 20 min	230	34	1.7
3	15 h 10 min	355	70	1.0

From these three measurements, the mean value yield was calculated to be ***Φ* = 1.6 ± 0.5 %**.

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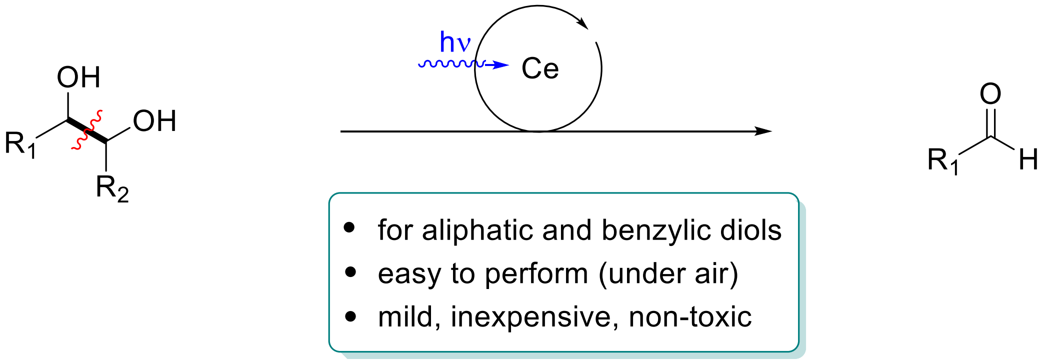
4. Visible-Light Mediated C–C Bond Cleavage of 1,2-Diols to Carbonyls by Cerium-Photocatalysis



We describe a photocatalytic method for the cleavage of vicinal diols to aldehydes and ketones. The reaction is catalyzed by blue light and a cerium-catalyst and the scope includes aryl as well as alkyl substituted diols. The simple protocol which works under air and at room temperature enables the valorization of abundant diols.

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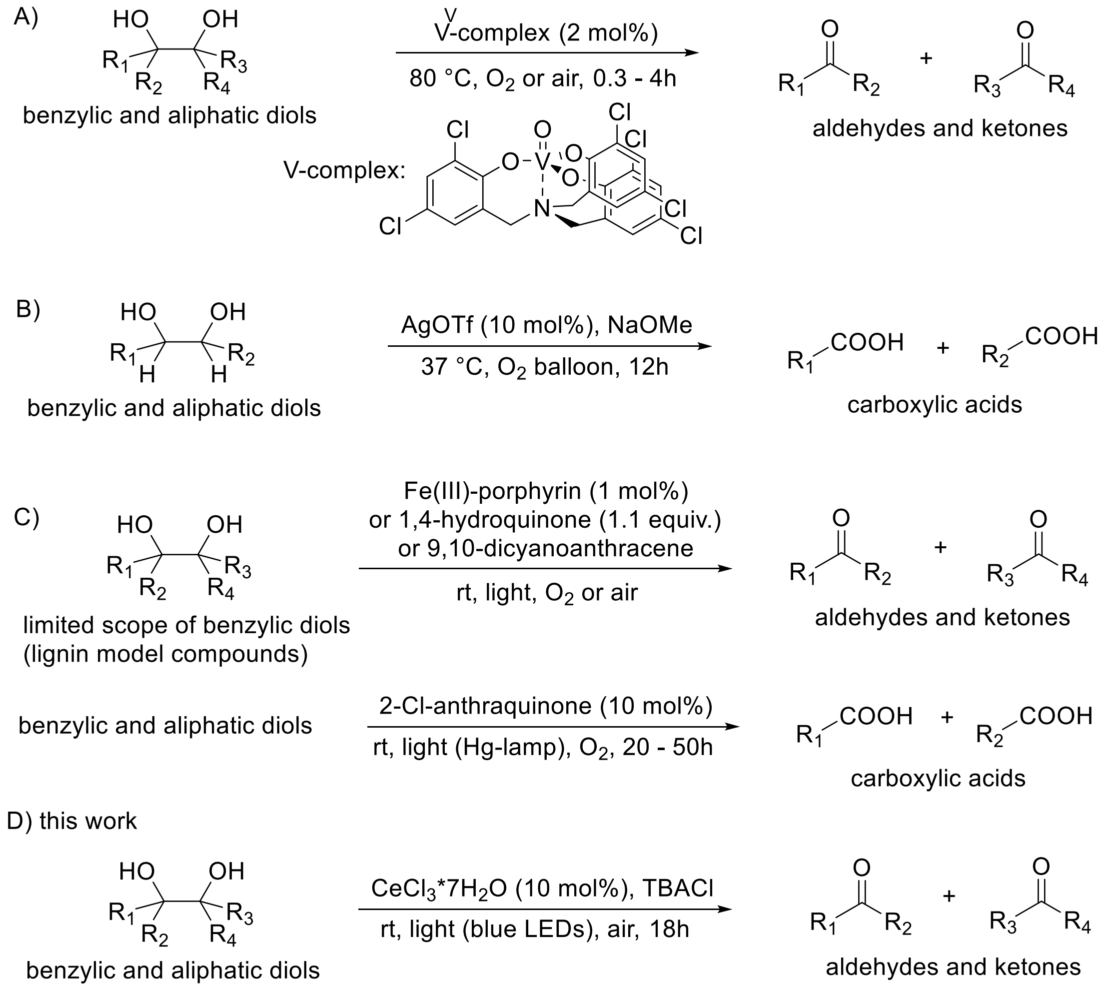
4.1. Introduction

The oxidative C–C bond cleavage of 1,2-diols (glycol cleavage) is an important organic reaction and was originally developed around 1930 by Malaprade[1] and Criegee[2] with stoichiometric amounts of periodic acid or lead tetraacetate, respectively. Although these are established methods, they have severe drawbacks like limited solubility, high toxicity and especially the generation of stoichiometric amounts of hazardous waste. In order to extend the cleavage of vicinal diols to modern transformations of renewable and abundant feedstocks like lignin, glycol or sugars, catalytic methods have to be developed. Several thermal, metal-catalysed diol cleavage reactions have been published during the years, for example with vanadium[3], molybdenum[4], ruthenium[5] or palladium.[6] In 2017, Anastas *et al.* reported an efficient method catalysed by a sodium-manganese layered oxide (Na-Mn LMO), but the reaction does not work for aliphatic diols.[7] Recently, Licini, Amadio and co-workers showed that the cleavage of aromatic as well as aliphatic diols to aldehydes works with vanadium-catalysis under air or oxygen atmosphere and heating (Scheme 4-1A).[3a] Also a silver-catalysed reaction with a broad substrate scope was developed (Scheme 4-1B).[8] This method requires only slightly increased temperatures of 37 °C, but gives carboxylic acids as products. In general, photocatalytic alternatives are known for being milder and more selective as they proceed at room temperature. Several light-mediated, oxidative cleavages of vicinal diols have been reported since 1991, e.g. with iron(III)-porphyrin[9], 2-chloroanthraquinone[10], hydroquinone[11] or 9,10-dicyanoanthracene[12].



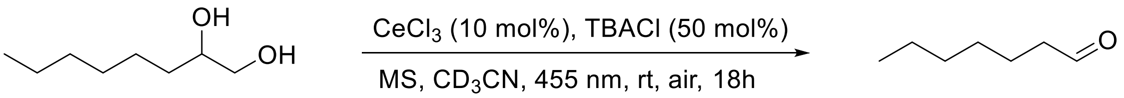
Scheme 4-1. Methods for the oxidative C–C bond cleavage of vicinal diols.

However, these methods give either acids as products or are limited to aromatic substituted diols, usually lignin model compounds (Scheme 4-1C). Herein, we report the first photocatalytic cleavage of 1,2-diols to aldehydes, which allows the conversion of alkyl substrates (Scheme 4-1D).

4.2. Results and Discussion

Inspired by the recent work of Zuo *et al.*, who generated alkoxy radicals from alcohols with a cerium-photocatalyst,[13] we wondered how 1,2-diols would behave under similar reactions conditions. Interestingly, we observed oxidative C–C bond cleavage to aldehydes when the diols were irradiated with blue LEDs (455 nm) in the presence of $CeCl_3$, tetrabutyl ammonium chloride (TBACl) and air. With this photocatalytic system, 1,2-octanediol gave 87% of the product heptanal (Table 4-1, entry 1). Other cerium-catalysts were less or not at all suitable for the reaction (Table 4-1, entries 2-5). One possible explanation could be a lower solubility of these catalysts in acetonitrile. Without molecular sieve (MS) or TBACl, the yields are significantly lower (Table 4-1, entries 6 and 7) and it was observed that the yields were less reproducible and varied about 20% if less molecular sieve, less catalyst or less TBACl was used. Light and cerium-catalyst are required for the oxidative cleavage (Table 4-1, entries 8 and 9) and air is the optimal atmosphere. Under nitrogen or O_2 atmosphere or with the oxidant $K_2S_2O_8$, only low product yields were obtained (Table 4-1, entries 10-12). Moreover, the much cheaper heptahydrated cerium-catalyst gives with 87% aldehyde the same yield than the anhydrous one (Table 4-1, entry 13).

Table 4-1. Optimization of cerium-catalysed, oxidative cleavage of 1,2-diols.[a]

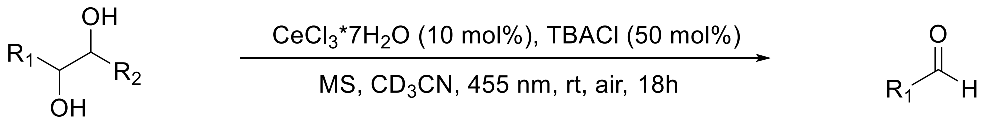


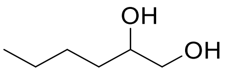
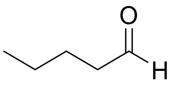
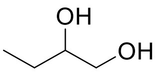
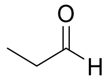
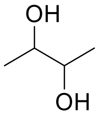
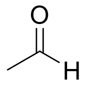
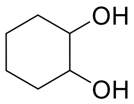
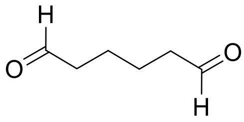
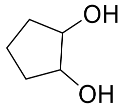
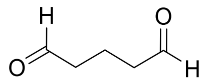
Entry	Deviation from standard conditions	Yield[b] [%]
1	none	87
2	CeO_2(4 mol%)	traces
3	$Ce(SO_4)_2$(4 mol%)	traces
4	$[Ce(NO_3)_6](NH_4)_2$(4 mol%)	traces
5	$Ce(OTf)_4*H_2O$ (4 mol%)	57
6	no MS	67
7	no TBACl	45
8	no catalyst	0
9	no light	0
10	under nitrogen atmosphere	10
11	with O_2 balloon	26
12	with $K_2S_2O_8$	6
13	**$CeCl_3*7H_2O$**	**87** (79)[c]

[a] Standard reaction conditions: 0.1 mmol 1,2-octanediol, 100 mg MS (molecular sieve), 10 mol% PC, 50 mol% TBACl and 1 mL solvent. [b] Determined by ^1H NMR analysis using *p*-Cl-benzaldehyde as internal standard. [c] Isolated yield of the dinitrophenyl hydrazone of the aldehyde.

With these optimized and simple reaction conditions in hand, we investigated the scope of diols for the oxidative cleavage. Terminal, internal, linear as well as cyclic 1,2-diols gave the corresponding aldehydes in good to very good yields (Table 4-2). Comparable yields of dialdehydes were observed for *cis*- and *trans*-diols (Table 4-2, entry 4 and 5), which shows that the spatial arrangement of the two hydroxy groups has no significant effect on the reaction. Different aromatic 1,2-diols also gave good product yields of 71 to 86% (Table 4-3). Remarkably, the oxidative cleavage works even with tertiary hydroxy groups, which yields the corresponding ketone (Table 4-3, entry 2).

Table 4-2. Scope of aliphatic 1,2-diols.[a]

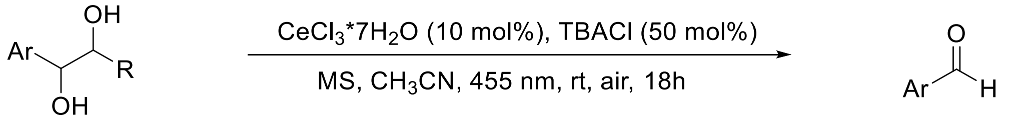


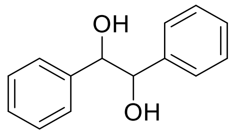
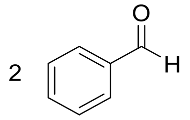
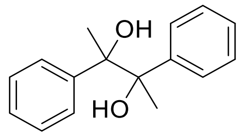
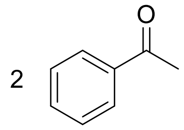
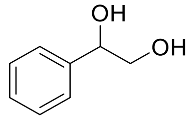
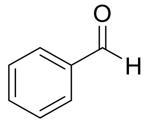
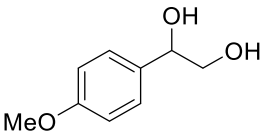
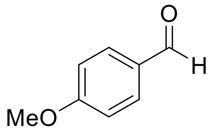
Entry	Substrate		Product	Yield[b] [%]
1				79
2				78
3			2 	95
4		a) *cis* b) *trans*		a) 57 b) 69
5		a) *cis* b) *trans*		a) 66 b) 69

[a] Reaction conditions: 0.1 mmol 1,2-diol, 100 mg MS, 10 mol% $CeCl_3*7H_2O$, 50 mol% TBACl and 1 mL CD_3CN.
[b] Determined by ^{1}H NMR analysis using *p*-Cl-benzaldehyde as internal standard.

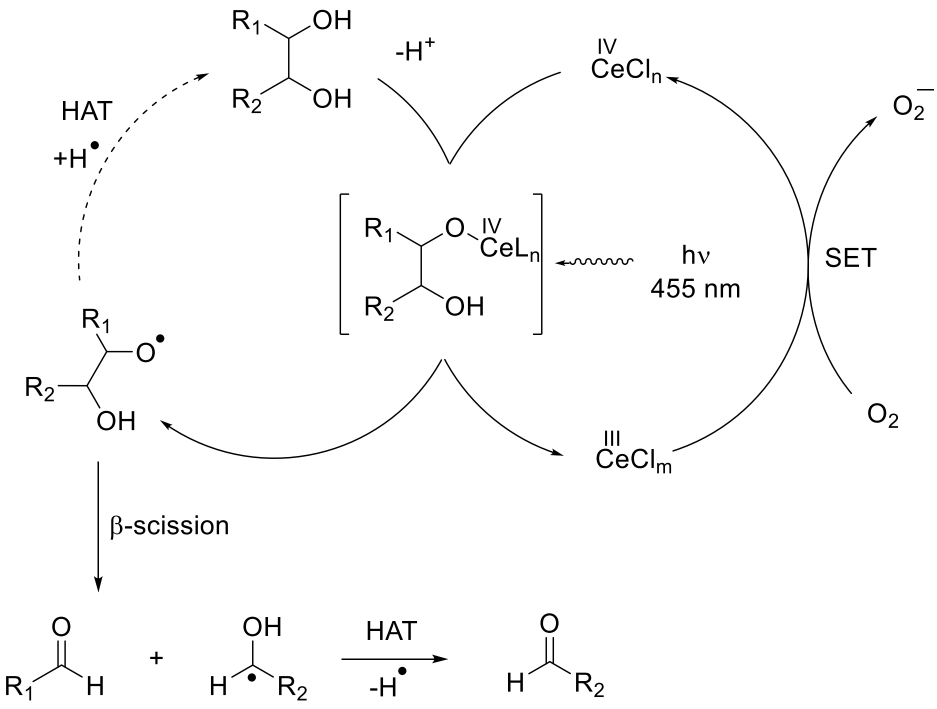
Based on the investigations of Zuo *et al.*, we propose that the cleavage reaction of 1,2-diols to two aldehydes works via ligand-to-metal-charge-transfer (LMCT), which generates the key alkoxy radical.[13] The detailed mechanistic proposal is shown in Scheme 4-2. By oxidation of $CeCl_3$ with O_2, a cerium(IV) species could be generated. It is assumed that in the presence of TBACl, the catalytically active complex $(n\text{-}Bu_4N)_2Ce(IV)Cl_6$ is formed.[13a] Upon deprotonation of the diol, presumably only one of the hydroxy groups coordinates to the cerium(IV) catalyst.[14] This complex absorbs blue light (455 nm), which triggers homolytic bond cleavage of the O–Ce bond. On the one side, this regenerates the cerium(III) catalyst. On the other side, an alkoxy radical is formed which is believed to undergo β-scission to an aldehyde and an α-hydroxy radical. Hydrogen atom transfer (HAT) from this α-hydroxy radical to the solvent or another alkoxy radical would give the second aldehyde.

Table 4-3. Scope of benzylic 1,2-diols.[a]



Entry	Substrate	Product	Yield[b] [%]
1			85
2			86
3			71
4			85

[a] Reaction conditions: 0.1 mmol 1,2-octanediol, 100 mg MS, 10 mol% $CeCl_3*7H_2O$, 50 mol% TBACl and 1 mL CD_3CN. [b] Isolated yield.



Scheme 4-2. Proposed mechanism for the photocatalytic cleavage of 1,2-diols with cerium.

4.3. Conclusions

In summary, we have developed a cerium-catalysed, light- mediated method for the cleavage of vicinal diols to aldehydes or ketones. The protocol is equally well applicable for benzylic and aliphatic diols and gives the aldehyde cleavage products in good to very good yields. Moreover, the reaction works under air, is easy to perform and does not require expensive or toxic additives. With further investigations and optimization, we want to extend the scope to natural and abundant polyols like sugars in order to make this class of compounds accessible for selective C–C bond cleavage.

4.4. Experimental Section

4.4.1. General Information

See chapter 2.4.1.

4.4.2. Photocatalytic Reactions

General procedure A: cleavage of aliphatic 1,2-diols

A 5 mL crimp cap vial was equipped with a magnetic stirring bar, $CeCl_3*7H_2O$ (3.7 mg, 0.01 mmol, 10 mol%), an aliphatic 1,2-diol (0.10 mmol, 1.0 equiv.), tetrabutyl ammonium chloride (TBACl, 14 mg, 0.05 mmol, 0.5 equiv.) and grinded molecular sieve (3 Å, 100 mg). CD_3CN (1 mL) was added with a syringe and the vial was capped in order to prevent evaporation. The reaction mixture was stirred and irradiated through the vial´s plane bottom side using blue LEDs (455 nm) for 18 h at rt.

4-Chlorobenzaldehyde (14.1 mg, 0.10 mmol) was added as standard and the reaction mixture was stirred for about 10 min. The mixture was filtered and submitted to NMR and GC-MS. The product yield was obtained by integration of the ^1H-NMR signals of the aldehyde-protons.

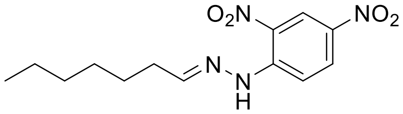
In the case of the starting material 1,2-octanediol, the product and the yield were also confirmed by the formation and isolation of the 2,4-dinitrophenylhydrazone of the product heptanal. Therefore, a solution of DNPH (2,4-dinitrophenylhydrazine) was prepared as follows: To a mixture of 3 mL conc. H_2SO_4 and 600 mg DNPH, 4.5 mL H_2O were added dropwise under stirring. 15 mL distilled EtOH were added to the warm solution.[15] For derivatization of heptanal, the content of four vials after irradiation was combined (4 mL, without filtration) and 6 mL DNPH solution, 20 mL EtOH and 36 mL H_2O were added. This mixture was stirred for one hour at rt and then put in the freezer for one to two hours. The yellow precipitate was filtered off, washed thoroughly with $NaHCO_3$ (5% in water) and a small amount of EtOH. In order to separate the precipitate from the grinded molecular sieve, the product was washed into a 50 mL flask with EtOAc and the solvent was removed under vacuum. The crude product was purified by recrystallization from distilled EtOH or by automated flash column chromatography (0-8% EtOAc in PE).

General procedure B: cleavage of benzylic 1,2-diols

A 5 mL crimp cap vial was equipped with a magnetic stirring bar, $CeCl_3*7H_2O$ (3.7 mg, 0.01 mmol, 10 mol%), a benzylic 1,2-diol (0.10 mmol, 1.0 equiv.), tetrabutyl ammonium chloride (TBACl, 14 mg, 0.05 mmol, 0.5 equiv.) and grinded molecular sieve (3 Å, 100 mg). CH_3CN (1 mL) was added with a syringe and the vial was capped in order to prevent evaporation. The reaction mixture was stirred and irradiated through the vial´s plane bottom side using blue LEDs (455 nm) for 18 h at rt. For the isolation of the product, the identical content of four vials was combined (in order to ensure optimal illumination) and diluted with EtOAc or Et_2O for volatile products (20 mL). The mixture was extracted with water (2 x 20 mL). The combined aqueous phases were extracted again with EtOAc or Et_2O (20 mL) and the organic phases were dried over Na_2SO_4 and concentrated in vacuum. The crude product was purified by automated flash column chromatography (PE/EtOAc, 0-15% EtOAc) yielding the corresponding aldehyde.

Characterization of isolated products

Heptanal 2,4-dinitrophenylhydrazone[16]



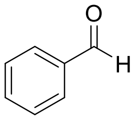
$C_{13}H_{18}N_4O_4$, 294.31 g/mol, yellow solid, yield: 79%

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 11.01 (s, 1H), 9.09 (d, *J* = 2.6 Hz, 1H), 8.27 (ddd, *J* = 9.6 Hz, 2.6 Hz, 0.6 Hz, 1H), 7.91 (d, *J* = 9.6 Hz, 1H), 7.55 (t, *J* = 5.3 Hz, 1H), 2.47 – 2.37 (m, 2H), 1.66 – 1.55 (m, 2H), 1.44 – 1.28 (m, 6H), 0.89 (t, *J* = 6.9 Hz, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 153.0 (–), 145.2 (C_q), 137.7 (C_q), 130.0 (–), 128.8 (C_q), 123.6 (–), 116.6 (–), 32.6 (+), 31.6 (+), 28.9 (+), 26.4 (+), 22.6 (+), 14.2 (–).

LRMS (ESI) (m/z): $[M + H]^+$ ($C_{13}H_{19}N_4O_4$) calc.: 295.1406, found: 295.1409.

Benzaldehyde[17]

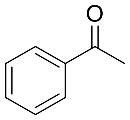


C_7H_6O, 106.12 g/mol, colorless liquid, yield: 85% from hydrobenzoin and 71% from 1-phenyl-1,2-ethanediol

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 10.02 (s, 1H), 7.94 – 7.83 (m, 2H), 7.68 – 7.59 (m, 1H), 7.59 – 7.49 (m, 2H).

LRMS (EI) (m/z): $[M^•]^+$ (C_7H_6O) calc.: 106.0419, found: 106.0426.

1-Phenylethanone[17]

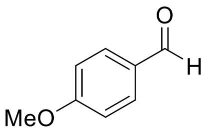


C_8H_8O, 120.15 g/mol, colorless liquid, yield: 86%

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.99 – 7.86 (m, 2H), 7.59 – 7.49 (m, 1H), 7.48 – 7.38 (m, 2H), 2.58 (s, 3H).

LRMS (EI) (m/z): $[M^•]^+$ (C_7H_6O) calc.: 120.0575, found: 120.0562.

4-Methoxybenzaldehyde[18]



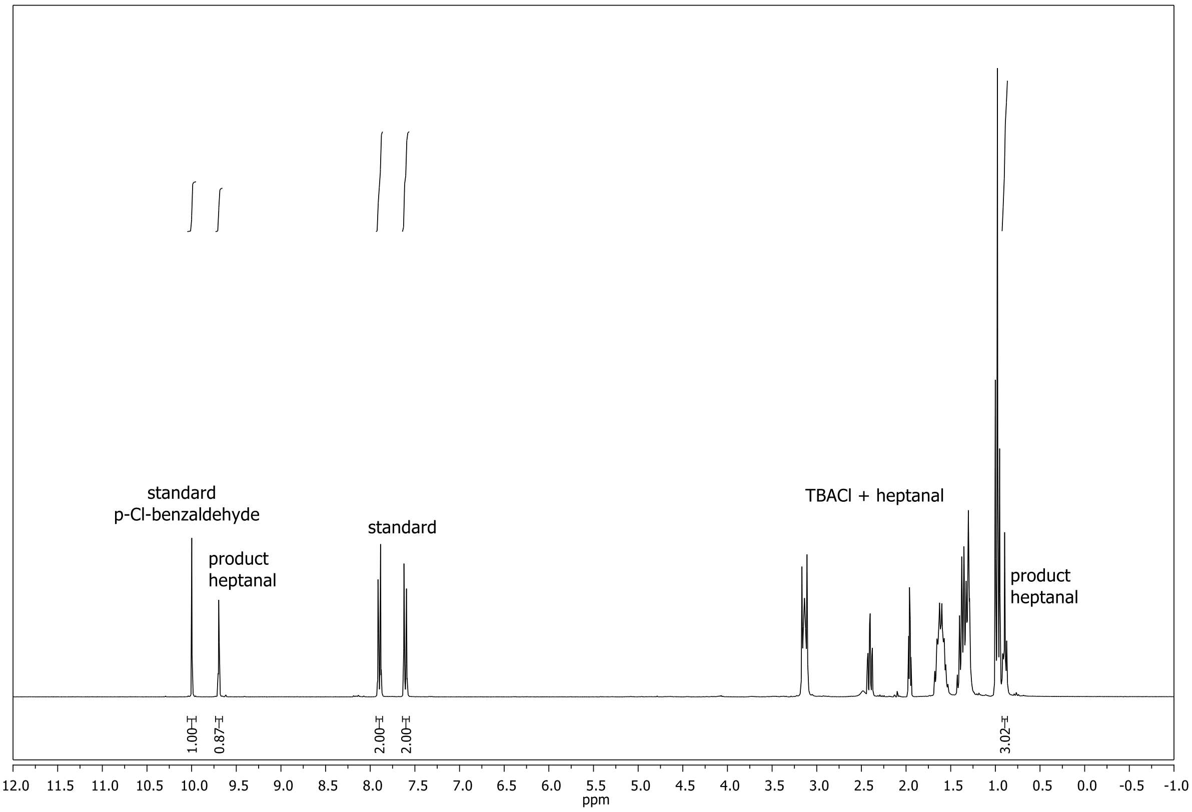
$C_8H_8O_2$, 136.15 g/mol, colorless solid, yield: 85%

^1H NMR (300 MHz, $CDCl_3$): δ [ppm] = 9.87 (s, 1H), 7.88 – 7.77 (m, 2H), 7.03 – 6.95 (m, 2H), 3.87 (s, 3H).

LRMS (ESI) (m/z): $[M + H]^+$ ($C_8H_9O_2$) calc.: 137.0603, found: 137.0593.

4.4.3. Quantitative NMR

Representative ^1H-NMR for determination of the yield of volatile aldehydes: It shows the crude reaction mixture (CD_3CN) with 0.10 mmol standard *p*-chlorobenzaldehyde. In this case, the product heptanal was formed in 87% yield.



4.5. References

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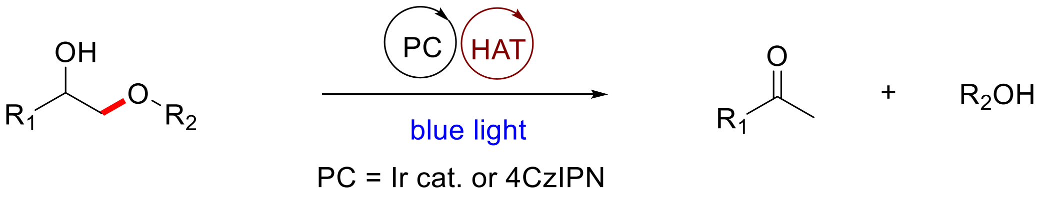
5. Visible Light Induced Redox Neutral Fragmentation of 1,2-Diol Derivatives



Photo/HAT dual catalytic redox-neutral reaction

No stoichiometric external reducants required

A homogeneous, redox-neutral photo fragmentation of diol derivatives was developed. Under photo/HAT dual catalysis, diol derivatives such as lignin model compounds and diol monoesters undergo selective β C(sp^3)–O bond cleavage to afford ketones, phenols and acids effectively.

This chapter is a manuscript that has been submitted to *Chemical Communications*:

K. Chen, J. Schwarz, T. Karl and B. König, **2019**.

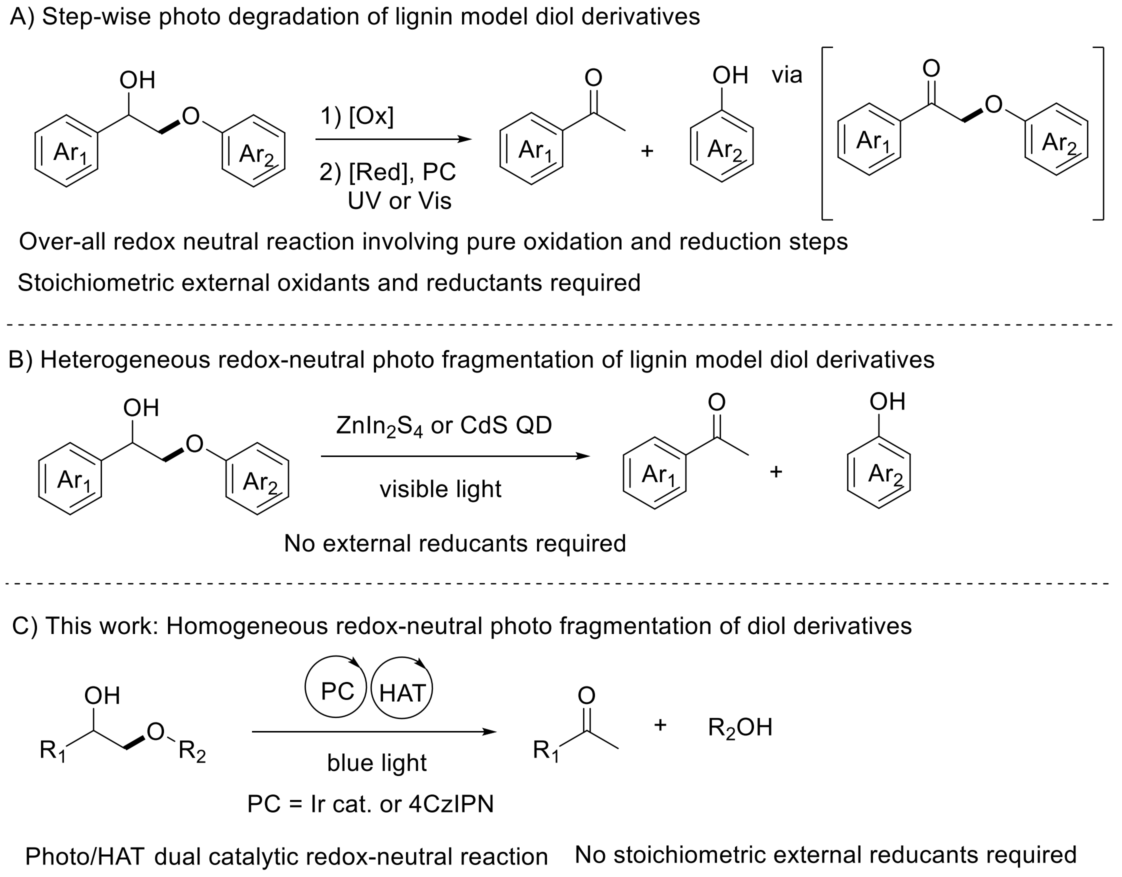
Author contribution:

KC wrote the manuscript, synthesized starting materials **1a**, **1b**, **1d**, **1i** and **4** and carried out the photo reactions for Table 5-1, entries 2-5; Table 5-3, entry 7; Tables S5-1; S5-2; S5-4; S5-5 and S5-12.
JS synthesized the starting materials **1c**, **1e-1h**, **1k-1m** and carried out the photo reactions for Table 5-1, entry 1 and entries 6-12; Table 5-2; Table 5-3, entries 1-5; Table S5-3 and S5-6 to S5-11.
TK synthesized the starting materials **1j**, **1n**, **1o** and **5** and carried out the photoreaction for Table 5-3, entry 6 and Scheme 5-2.
BK supervised the project and is corresponding author.

5.1. Introduction

Diol and polyol derivatives are the fundamental structural units of lignin, which is an important renewable non-fossil organic carbon source.[1] The selective C(sp^3)–O bond cleavage of diol or polyol derivatives could offer a sustainable approach to gain valuable oxygen-containing feedstock chemicals from lignin biomass.[2] Photochemical C–O bond cleavage processes may proceed under mild conditions,[3] opening perspectives of solar driven lignin valorization. The selective deoxygenation of lignin β-O-4 model compounds, a type of aromatic backbone diol derivative, has been realized by using Ir photocatalysts, organic copolymers or semi-conductors under UV-Vis irradiation (Scheme 5-1A).[4-6] These step-wise deoxygenation reactions involved oxidation and reduction processes to achieve an overall redox-neutral transformation. However, the use of stoichiometric amounts of external oxidants and reductants were still necessary.

The hydroxyl groups in diols are already a reductive hydrogen source. Thus, the catalytic hydrogen transfer[7] from the hydroxyl group to the β C(sp^3)–O bond would be an ideal strategy for the redox-neutral deoxygenation in one single step without external reductants. Very recently, heterogeneous photocatalysts such as $ZnIn_2S_4$ and CdS quantum dots were applied in the redox-neutral degradation of lignin β-O-4 model compounds in absence of stoichiometric external reductants (Scheme 5-1B).[8] Herein, we report the homogeneous, redox neutral photocatalytic fragmentation of diols using two different photo/HAT dual catalytic systems (Scheme 5-1C).

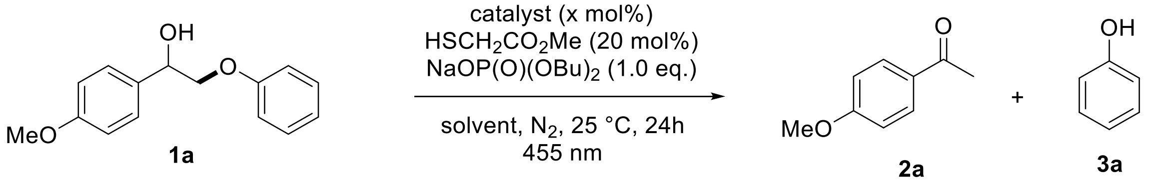


Scheme 5-1. Photo fragmentation of diol derivatives.

5.2. Results and Discussion

We began the optimization of the reaction conditions with diol derivative **1a**. After screening of metal photocatalysts, HAT catalysts, and solvents (see Experimental Part for detailed information), we discovered that the combination of [Ir(ppy)$_2$dtbpy]PF$_6$ and methyl 2-mercaptoacetate as co-catalyst in DMA solution facilitates the cleavage of **1a** into ketone (**2a**) and phenol (**3a**) in 91% and 81% yield, respectively (Table 5-1, entry 1). Sodium dibutylphosphate was the crucial base for this reaction, because it shows good solubility in organic solvents and accelerates the generation of thiyl radicals (S–H BDE = 87 kcal/mol)[9] as HAT agents.[10] Moreover, this base is also a good hydrogen bond acceptor, which could effectively activate the α C–H bond of the hydroxyl group to promote the following H-atom abstraction (α C–H bond BDE = 86 kcal/mol).[11, 12] Notably, the use of stoichiometric phosphate was necessary to achieve high yields of products (Table 5-1, entries 1 and 2). Other insoluble inorganic bases (K_2CO_3, Na_2HPO_4 etc.) or the organic base 2,4,6-collidine gave significantly lower yields (Table S5-2). Control experiments indicated that Ir catalyst, thiol catalyst, base, light irradiation (Table S5-5) and inert atmosphere (Table 5-1, entry 3) were all essential for this transformation.

Table 5-1. Optimization of redox-neutral fragmentation of **1a**.



Entry^a	Catalyst (x mol%)	Solvent	Yield ketone [%]	Yield phenol [%]
1	[Ir(ppy)$_2$dtbpy]PF$_6$ (1)	DMA	91 (86)^b	81 (71)^b
2^c	[Ir(ppy)$_2$dtbpy]PF$_6$ (1)	DMA	40	30
3^d	[Ir(ppy)$_2$dtbpy]PF$_6$ (1)	DMA	16	traces
4	Eosin Y (5)	DMA	nd	nd
5	Perylene (5)	DMA	nd	nd
6	4CzIPN (5)	DMA	26	26
7^d	4CzIPN (5)	DMA	59	48
8^{d,e}	4CzIPN (10)	DMA	72	44
9^{d,e}	4CzIPN (10)	DMSO	73	54
10^{d,e}	4CzIPN (8)	DMSO	76	58
11^{d,e}	4CzIPN (4)	DMSO	82	57
12^{c,d,e}	4CzIPN (4)	DMSO	80 (79)^b	57 (63)^b

^{a} 0.1 mmol scale reaction; yields determined by GC analysis with an internal standard. ^{b} Isolated yield. ^{c} 50 mol% NaOP(O)(OBu)$_2$. ^{d} Under air atmosphere. ^{e} 40 mol% $HSCH_2CO_2Me$.

Although the Ir catalyst performs quite well in this reaction, the high price and toxicity of iridium limits its application. We therefore tested different redox active organic dyes[13, 14] to explore the possibility of a transition-metal free catalytic system for this transformation. Eosin Y and perylene did not catalyze the C(sp^3)–O bond cleavage (Table 5-1, entries 4 and 5) while with 5 mol% 4CzIPN as catalyst, the generation of aryl ketone and phenol was observed, albeit in low yields (Table 5-1, entry 6). To our surprise, the 4CzIPN catalyzed reaction performed even better under air atmosphere (Table 5-1, entry 7). We could further improve the reaction efficiency by tuning the loading of 4CzIPN and thiol, as well as by using DMSO, instead of DMA (Table 5-1, entries 8-11). Additionally, the yields of both products remained almost the same even when the amount of $NaOP(O)(OBu)_2$ was decreased to 0.5 equiv. (Table 5-1, entry 12). Compared with Ir catalysis, the 4CzIPN catalyst system exhibits similar reaction efficiency under more robust conditions (Table 5-1, entries 1 and 12). Thus, we chose 4CzIPN catalysis for substrate scope investigation.

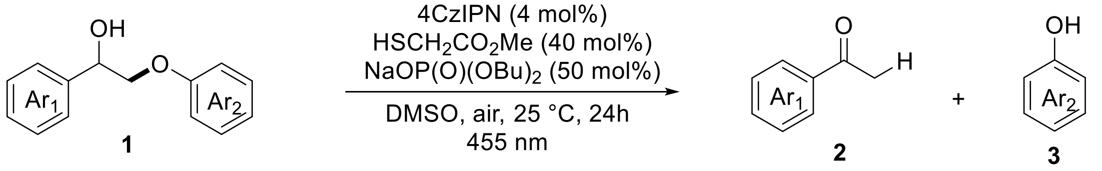
To probe the generality of this methodology, various lignin β-O-4 model compounds were investigated under the optimized conditions (Table 5-2). The electronic properties of both aromatic rings (Ar_1 and Ar_2) influence the reactivity of substrates (**1b**-**1d**). Generally, more electron-poor Ar_1 (**1d**) and more electron-rich Ar_2 (**1b**) decreased the conversion of starting material so that comparatively lower product yields were obtained. The coniferyl-derived substrates (**1e**-**1g**) convert smoothly, affording good to excellent yields of the corresponding fragmentation products. However, the sinapyl-derived substrate **1h** was not compatible with the aerobic conditions and reacted less efficient. The branched β-O-4 model compound **1i** did not react well with 4CzIPN or the Ir catalysis. Traces of deoxygenated ketone and not more than 20% phenol were detected. Increased steric hindrance of **1i** inhibiting the benzylic C–H abstraction by thiyl radicals may be a reason for the observation.

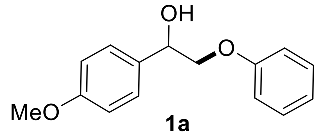
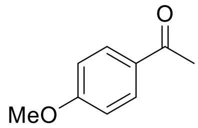
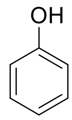
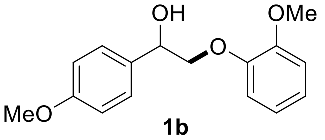
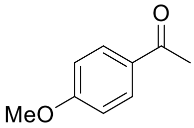
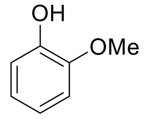
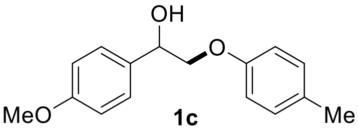
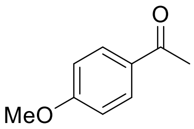
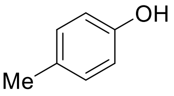
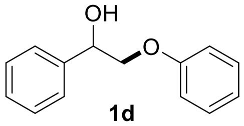
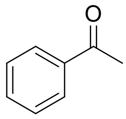
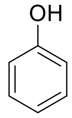
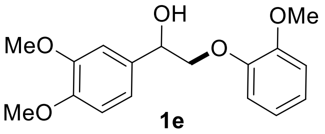
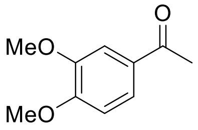
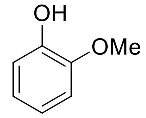
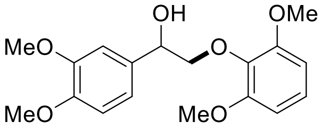
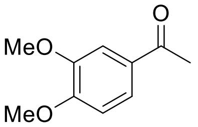
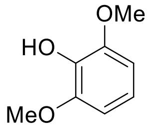
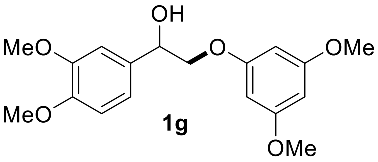
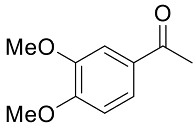
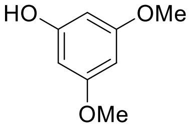
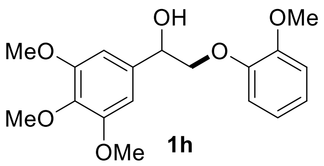
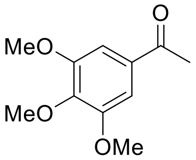
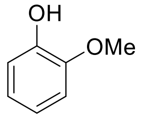
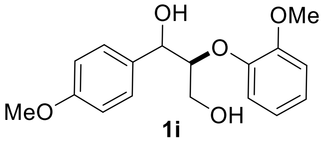
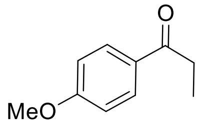
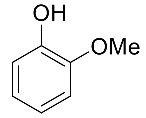
Furthermore, we investigated the influence of different leaving groups (Table 5-3). Similar to the diol mono-phenoxyethers, mono-acetates of diols bearing different substituents underwent selective β C(sp^3)–O bond cleavage to generate aryl ketones and the volatile AcOH (**1j**-**1m**). Halogen atoms such as F (**1m**) and Cl (**1l**) are tolerated. Moreover, we could isolate both aryl ketone and benzoic acid in good yields from the reaction of mono-benzoate (**1n**). An intramolecular fragmentation occurred with dihydrobenzofuran derivative **1o** to form the ring-open product 2-hydroxyacetophenone **2h** in moderate yield.

Finally, we also explored the conversion of aliphatic diol derivatives with the photo/HAT dual catalysis strategy. Unfortunately, the 4CzIPN system was not able to catalyze the fragmentation of **1p** under aerobic conditions. The Ir catalyst under inert atmosphere gave the desired phenol product, but higher Ir and thiol catalyst loadings and a longer reaction times were required (Table 5-3, entry 7). Due to the higher BDE of the aliphatic alcohol α C–H bond (BDE = 92 kcal/mol, *vs*. benzylic alcohol α C–H BDE = 86 kcal/mol),[11] cleavage of the α C–H bond of the aliphatic alcohol is more difficult with the thiyl radical.

We also explored the reactivity of free diol and full-protected diester. In case of diol **4**, the ketone product **2a** was detected only in a very low yield (Scheme 5-2, Eq. 1). Furthermore, the diol diacetate **5** remained untouched under the standard conditions (Scheme 5-2, Eq. 2). These results suggest that both unprotected hydroxyl group and the adjacent leaving group are crucial for the desired β C(sp^3)–O bond cleavage.

Table 5-2. Photo fragmentation of lignin β-O-4 model diol derivatives.



Entry[a]	Substrate	Ketone	Phenol
1	 **1a**	 **2a** (79%), (86%)[b]	 **3a** (63%), (71%)[b]
2	 **1b**	 **2a** (69%)	 **3b** (51%)
3	 **1c**	 **2a** (90%)	 **3c** (61%)
4	 **1d**	 **2b** (69%)	 **3a** (50%)
5	 **1e**	 **2c** (75%)	 **3b** (61%)
6	 **1f**	 **2c** (83%)	 **3d** (76%)
7	 **1g**	 **2c** (quant.)	 **3e** (84%)
8	 **1h**	 **2d** (68%)	 **3b** (33%)
9	 **1i**	 **2e** (traces), (traces)[bc]	 **3b** (20%)[c],(nd)[bc]

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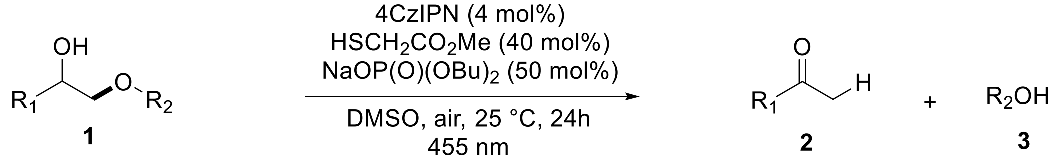
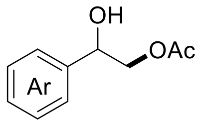
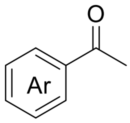
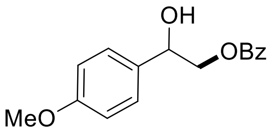
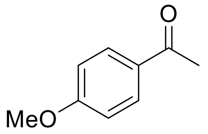
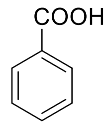
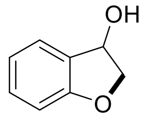
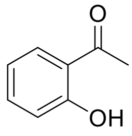
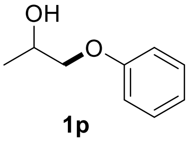
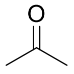
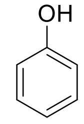
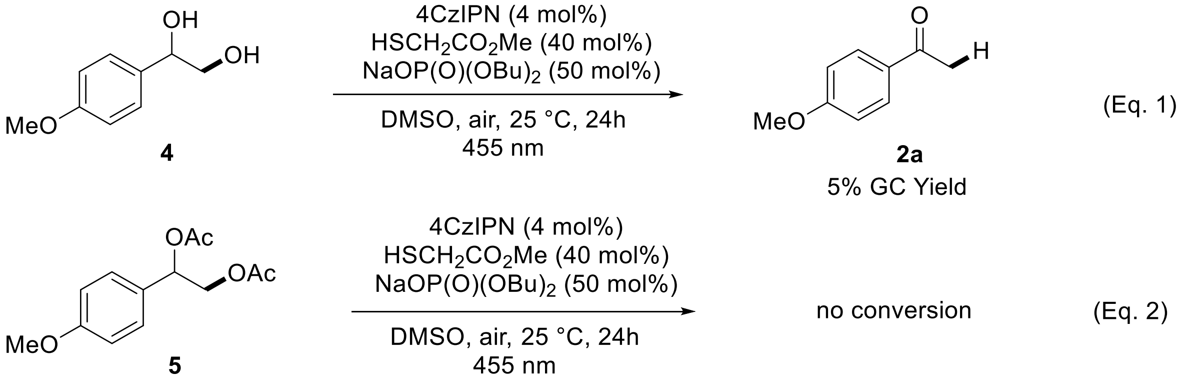
[a] Reactions were carried out in 0.1 mmol scale, isolated yields are reported. [b] 1 mol% of [Ir(ppy)$_2$dtbpy]PF$_6$, 20 mol% of HSCH$_2$CO$_2$Me and 1.0 equiv of NaOP(O)(OBu)$_2$ in 2.0 mL DMA (0.2 mmol scale) under N$_2$ atmosphere. [c] Determined by GC analysis.

Table 5-3. Photo fragmentation of diol derivatives with various backbones and leaving groups.



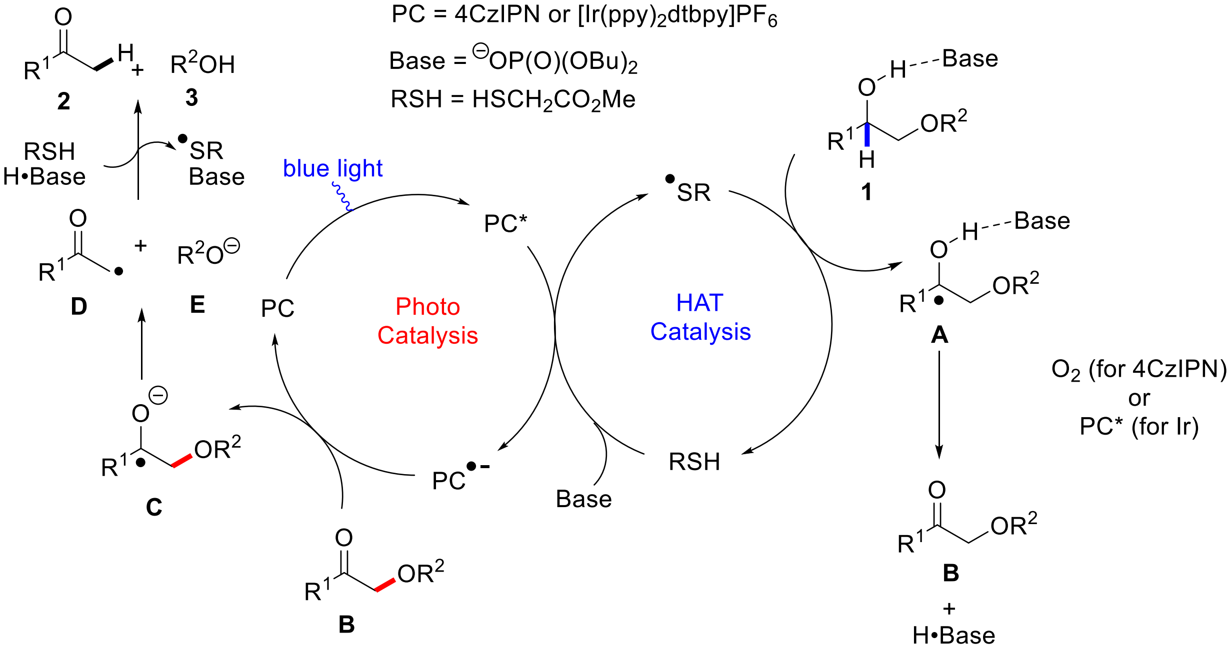
Entry[a]	Substrate	Products
1-4	 Ar = 4-MeOC$_6$H$_4$, **1j** Ar = C$_6$H$_5$, **1k** Ar = 4-ClC$_6$H$_4$, **1l** Ar = 4-FC$_6$H$_4$, **1m**	 + AcOH **2a** (70%) **2b** (74%) **2f** (61%) **2g** (75%) Not Isolated
5	 **1n**	 +  **2a** (73%) **3f** (70%)
6	 **1o**	 **2h** (45%)
7[b]	 **1p**	 +  Not Measured **3a** (72%)

[a] Reactions were carried out in 0.1 mmol scale, isolated yields are reported. [b] 2 mol% of [Ir(ppy)$_2$dtbpy]PF$_6$, 40 mol% of HSCH$_2$CO$_2$Me and 1.0 equiv of NaOP(O)(OBu)$_2$ in 1.0 mL DMA (0.1 mmol scale) under N$_2$ atmosphere for 72h. Yield determined by GC analysis with an internal standard.



Scheme 5-2. Control experiments with unprotected and full-protected diol derivatives.

According to our observations and literature reports, we assume the excited photocatalyst (4CzIPN or Ir catalyst) is reductively quenched in the presence of thiol and phosphate.[10] Then the generated thiyl radical abstracts the α H-atom of benzylic alcohol **1** to give a benzylic ketal radical **A**, which is further oxidized to the corresponding ketone **B**. A SET reduction of ketone **B** by the reduced photocatalyst results in ketal radical anion **C**. The Intermediate **C** is not stable so that a following β C(sp^3)–O bond cleavage takes place to form the carbonyl radical **D** and the anion of leaving group **E**,[3e, 4, 8] which are further converted to the final fragmentation products (Scheme 5-3).



Scheme 5-3. Proposed mechanism for the photo fragmentation of diol derivatives.

5.3. Conclusions

In summary, we have developed a redox neutral fragmentation of diol derivatives *via* photo/HAT dual catalysis without the use of stoichiometric external reductants. Both 4CzIPN and Ir photocatalysts facilitate the fragmentation of diol derivatives such as lignin β-O-4 model compounds and diol monoesters. Mechanistic studies suggest that the substrates are transformed to the corresponding ketones *via* HAT and oxidation. Subsequently, the photo reduction of the ketone generates the ketal radical anion and induces the β C(sp^3)–O bond cleavage to afford the desired products. The photocatalytic C–O bond cleavage strategy may find application in the valorization of biomass molecules.

5.4. Experimental Section

5.4.1. General Information

See chapter 2.4.1.

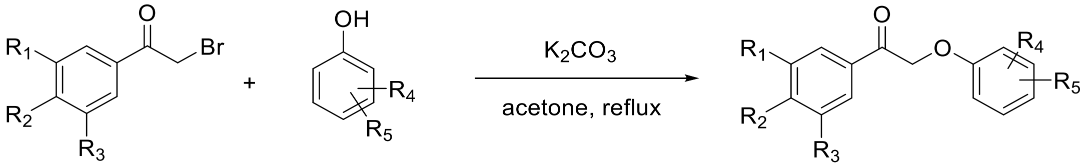
5.4.2. Synthesis of Starting Materials

5.4.2.1. Synthesis of Lignin Model Substrates

Compound **1p** is commercially available.

General procedure for the synthesis of unbranched lignin model substrates[15]

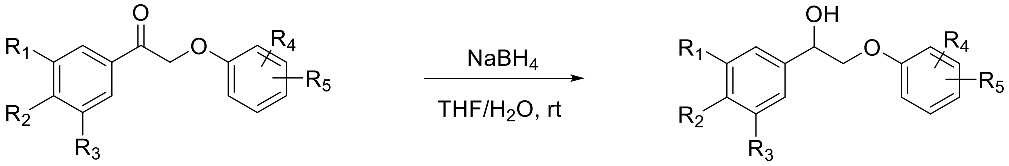
1.)



$R_{1,}$ $R_{2,}$ R_3 = H or OMe $R_{4,}$ $R_{5,}$ R_3 = H or OMe or Me

A 250 mL round-bottom flask was equipped with a reflux condenser and charged with the respective phenol (16.5 mmol, 1.1 equiv.), K_2CO_3 (22.5 mmol, 1.5 equiv.) and acetone (150 mL). The mixture was stirred at rt and the corresponding aromatic 2-bromo-ketone (15.0 mmol, 1.0 equiv.) was added in portions. The resulting suspension was stirred at reflux for 4 h. Then, the suspension was filtered and concentrated *in vacuo*. If necessary, the crude product was purified by column chromatography.

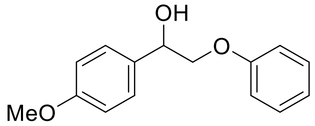
2.)



In a 100 mL round-bottom flask, the ketone from step 1 (5.0 mmol, 1.0 equiv.) and a THF/water mixture (25 mL, v/v = 4/1) were mixed. $NaBH_4$ (6.0 mmol, 1.2 equiv.) was added in one portion and the reaction mixture was stirred at rt for 2 h. Then, an aqueous saturated NH_4Cl solution (30 mL) was added. The crude product was extracted with EA (3 × 20 mL) and the combined organic extracts were dried over anhydrous Na_2SO_4. The organic solvent was evaporated *in vacuo* and the residue was purified by automated column chromatography on flash silica gel (PE/EA = 9:1 to 1:1) to obtain the desired product.

Characterization of unbranched lignin model substrates

1-(4-Methoxyphenyl)-2-phenoxyethan-1-ol (1a)[16]



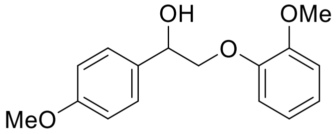
Yield: step 1: 99%, step 2: 80%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.43 – 7.35 (m, 2H), 7.35 – 7.26 (m, 2H), 7.04 – 6.88 (m, 5H), 5.08 (dd, *J* = 8.6 Hz, 3.4 Hz, 1H), 4.12 – 3.96 (m, 2H), 3.83 (s, 3H), 2.80 (brs, 1H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 159.6, 158.5, 131.9, 129.7, 127.7, 121.4, 114.7, 114.1, 73.4, 72.3, 55.4.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{15}H_{15}O_2$) calc.: 227.1072, found: 227.1092.
MF: $C_{15}H_{16}O_3$
MW: 244.29 g/mol

2-(2-Methoxyphenoxy)-1-(4-methoxyphenyl)ethan-1-ol (1b)[17]



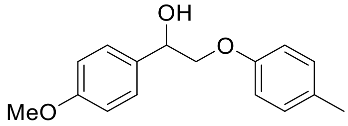
Yield: step 1: 89%, step 2: 99%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.41 – 7.32 (m, 2H), 7.04 – 6.85 (m, 6H), 5.07 (dd, *J* = 9.4 Hz, 2.9 Hz, 1H), 4.18 – 4.10 (m, 1H), 4.02 – 3.92 (m, 1H), 3.87 (s, 3H), 3.81 (s, 3H), 3.40 (brs, 1H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 159.5, 150.1, 148.1, 131.8, 127.7, 122.5, 121.1, 115.8, 114.0, 112.0, 76.2, 72.0, 55.9, 55.4.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{16}H_{17}O_3$) calc.: 257.1178, found: 257.1221.
MF: $C_{16}H_{18}O_4$
MW: 274.32 g/mol

1-(4-Methoxyphenyl)-2-(*p*-tolyloxy)ethan-1-ol (1c)[18]



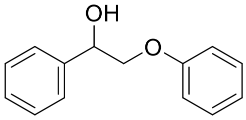
Yield: step 1: 100%, step 2: 97%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.46 – 7.35 (m, 2H), 7.14 (d, *J* = 8.2 Hz, 2H), 7.02 – 6.93 (m, 2H), 6.92 – 6.83 (m, 2H), 5.09 (dd, *J* = 8.1 Hz, 3.9 Hz, 1H), 4.12 – 3.96 (m, 2H), 3.84 (s, 3H), 3.32 (brs, 1H), 2.36 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 159.3, 156.3, 132.1, 130.3, 129.9, 127.5, 114.5, 113.8, 73.4, 72.0, 55.2, 20.4.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{16}H_{17}O_2$) calc.: 241.1229, found: 241.1290.
MF: $C_{16}H_{18}O_3$
MW: 258.32 g/mol

2-Phenoxy-1-phenylethan-1-ol (1d)[19]



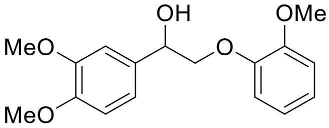
Yield: step 1: 94%, step 2: 86%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.50 – 7.26 (m, 7H), 7.03 – 6.89 (m, 3H), 5.14 (dd, *J* = 8.8 Hz, 3.2 Hz, 1H), 4.12 (dd, *J* = 9.6 Hz, 3.2 Hz, 1H), 4.08 – 3.96 (m, 1H), 2.76 (brs, 1H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 158.5 (C_q), 139.7 (C_q), 129.7 (+), 128.7 (+), 128.3 (+), 126.4 (+), 121.4 (+), 114.7 (+), 73.4 (–), 72.7 (+).

HRMS (EI) (m/z): $[M^{\bullet}]^+$ ($C_{14}H_{14}O_2$) calc.: 214.0994, found: 214.0993.
MF: $C_{14}H_{14}O_2$
MW: 214.26 g/mol

1-(3,4-Dimethoxyphenyl)-2-(2-methoxyphenoxy)ethan-1-ol (1e)[17]



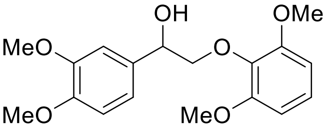
Yield: step 1: 99%, step 2: 71%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.04 – 6.81 (m, 7H), 5.05 (dd, *J* = 9.3 Hz, 3.0 Hz, 1H), 4.15 (dd, *J* = 10.0 Hz, 3.0 Hz, 1H), 4.03 – 3.93 (m, 1H), 3.89 (s, 3H), 3.87 (s, 3H), 3.86 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 150.1, 149.1, 148.8, 148.1, 132.3, 122.5, 121.1, 118.7, 115.9, 112.0, 111.0, 109.4, 76.3, 72.2, 56.0, 55.93, 55.88.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{17}H_{19}O_4$) calc.: 287.1283, found: 287.1283.
MF: $C_{17}H_{20}O_5$
MW: 304.34 g/mol

2-(2,6-Dimethoxyphenoxy)-1-(3,4-dimethoxyphenyl)ethan-1-ol (1f)[17]



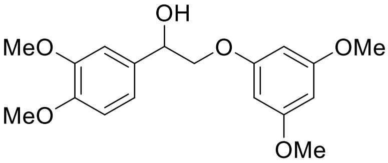
Yield: step 1: 83%, step 2: 88%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 6.96 (dd, *J* = 14.9 Hz, 4.8 Hz, 2H), 6.85 (d, *J* = 8.3 Hz, 1H), 6.77 (d, *J* = 8.2 Hz, 1H), 6.55 (d, *J* = 8.4 Hz, 2H), 4.87 (dd, *J* = 9.9 Hz, 2.4 Hz, 1H), 4.51 (s, 1H), 4.35 (dd, *J* = 10.9 Hz, 2.3 Hz, 1H), 3.81 (m, 9H), 3.78 (s, 3H), 3.67 (t, *J* = 10.4 Hz, 1H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 153.0, 148.8, 148.3, 136.5, 131.9, 123.9, 118.5, 110.8, 109.2, 104.9, 79.9, 72.0, 55.8, 55.7, 55.6.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{18}H_{21}O_5$) calc.: 317.1389, found: 317.1388.
MF: $C_{18}H_{22}O_6$
MW: 334.37 g/mol

2-(3,5-Dimethoxyphenoxy)-1-(3,4-dimethoxyphenyl)ethan-1-ol (1g)[17]



Yield: step 1: 100%, step 2: 94%.

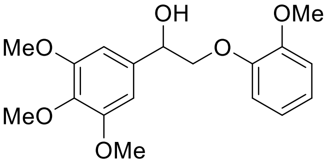
^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.03 – 6.94 (m, 2H), 6.87 (d, *J* = 8.2 Hz, 1H), 6.10 (s, 3H), 5.06 (dd, *J* = 8.7 Hz, 3.3 Hz, 1H), 4.07 – 3.95 (m, 2H), 3.91 (s, 3H), 3.89 (s, 3H), 3.76 (s, 6H), 2.74 (brs, 1H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 161.7, 160.4, 149.3, 149.0, 132.3, 118.7, 111.2, 109.4, 93.7, 93.6, 73.5, 72.5, 56.1, 56.0, 55.5.

HRMS (ESI) (m/z): [M+H]$^+$ = ($C_{18}H_{23}O_6$) calc.: 335.1495; found: 335.1493.
MF: $C_{18}H_{22}O_6$
MW: 334.37 g/mol

2-(2-Methoxyphenoxy)-1-(3,4,5-trimethoxyphenyl)ethan-1-ol (1h)[17]

2-Bromo-1-(3,4,5-trimethoxyphenyl)ethan-1-one which was necessary for the first step of the synthesis of **1h** was prepared according to a previously reported procedure (10 mmol scale, 46% yield).[20]



Yield: step 1: 52%, step 2: 88%.

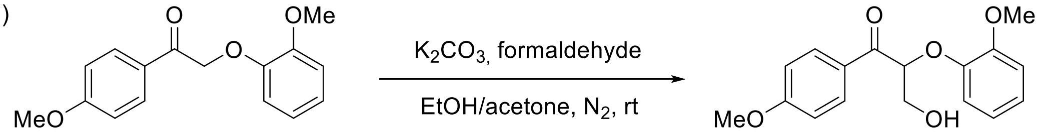
^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.05 – 6.84 (m, 4H), 6.66 (s, 2H), 5.03 (dd, *J* = 9.2 Hz, 2.9 Hz, 1H), 4.17 (dd, *J* = 10.0 Hz, 3.0 Hz, 1H), 4.02 – 3.92 (m, 1H), 3.87 (s, 3H), 3.86 (s, 6H), 3.83 (s, 3H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 153.4, 150.2, 148.0, 137.6, 135.4, 122.7, 121.2, 116.1, 112.0, 103.2, 76.4, 72.5, 60.9, 56.2, 55.9.

HRMS (APCI) (m/z): [M+H-H$_2$O]$^+$ ($C_{18}H_{21}O_5$) calc.: 317.1389, found: 317.1398.
MF: $C_{18}H_{22}O_6$
MW: 334.37 g/mol

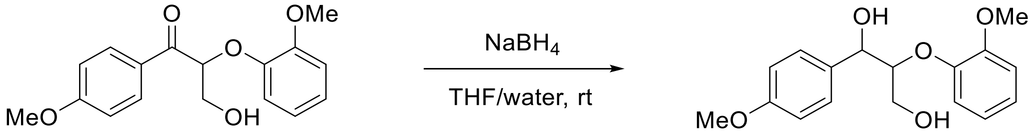
Synthesis of and characterization of branched substrate 1i[15b]

1.)



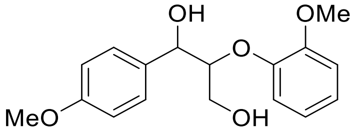
To a suspension of K_2CO_3 (0.6 g, 4.3 mmol, 1.0 equiv.) in ethanol/acetone (v/v = 1/1, 20 mL), 2-(2-methoxyphenoxy)-1-(4-methoxyphenyl)ethan-1-one (1.2 g, 4.4 mmol, 1.0 equiv.) and a solution of formaldehyde in water (37%) (0.6 mL, 7.3 mmol, 1.7 equiv.) was added. The reaction mixture was stirred for 4 h at rt under N_2 atmosphere, then it was filtered to remove K_2CO_3 and concentrated *in vacuo*. The residue was purified by column chromatography and used directly for the next step, although containing impurities.

2.)



In a 100 mL round-bottom flask, the ketone from step 1 (2.0 mmol, 1.0 equiv.) and a THF/water mixture (12 mL, v/v = 4/1) were mixed. $NaBH_4$ (2.4 mmol, 1.2 equiv.) was added in one portion and the reaction mixture was stirred at rt for 2 h. Then, an aqueous saturated NH_4Cl solution (15 mL) was added. The crude product was extracted with EA (3 × 10 mL) and the combined organic extracts were dried over anhydrous Na_2SO_4. The organic solvent was evaporated *in vacuo* and the residue was purified by automated column chromatography on flash silica gel (PE/EA = 9:1 to 1:1) to obtain the desired product.

3-Methoxy-2-(2-methoxyphenoxy)-1-(4-methoxyphenyl)propan-1-ol (1i)[17]



Yield: 73%

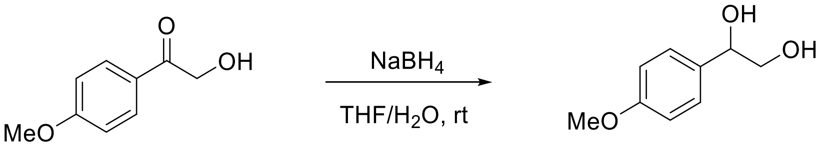
^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.40 – 7.28 (m, 2H), 7.16 – 6.86 (m, 6H), 5.03 – 4.95 (m, 1H), 4.18 – 4.07 (m, 1H), 4.07 – 3.99 (m, 1H), 3.92 – 3.86 (m, 3H), 3.81 – 3.78 (m, 3H), 3.69 – 3.57 (m, 1H), 3.50 – 3.40 (m, 1H), 2.95 (brs, 1H).

Spectral data are consistent with those reported in the literature.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{17}H_{19}O_4$) calc.: 287.1283, found: 287.1282.
MF: $C_{17}H_{20}O_5$
MW: 304.34 g/mol

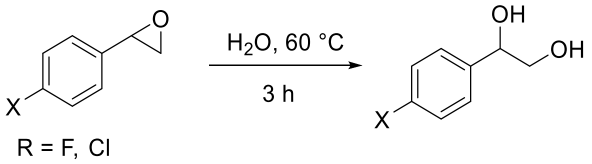
5.4.2.2. Synthesis of Acetylated Aromatic Substrates

General procedure for the synthesis of diols via reduction (step 1)



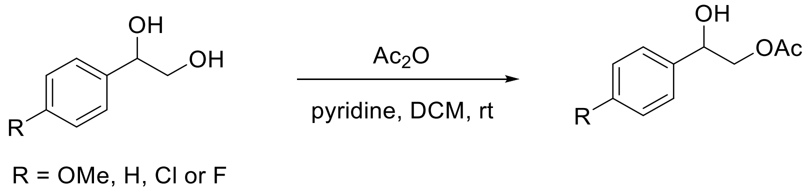
In a 100 mL round-bottom flask, the respective ketone (5.0 mmol, 1.0 equiv.) and a THF/water mixture (25 mL, v/v = 4/1) were mixed. $NaBH_4$ (6.0 mmol, 1.2 equiv.) was added in one portion and the reaction mixture was stirred at rt for 2 h. Then, an aqueous saturated NH_4Cl solution (30 mL) was added. The crude product was extracted with EA (3 × 20 mL) and the combined organic extracts were dried over anhydrous Na_2SO_4. The organic solvent was evaporated *in vacuo* and the residue was purified by automated column chromatography on flash silica gel (PE/EA = 9:1 to 1:1) to obtain the desired diol.

General procedure for the synthesis of diols via ring opening of epoxides (step 1)[21]



To the respective epoxide (5.0 mmol, 1.0 equiv.) was added distilled water (30 mL) and the reaction mixture was stirred for 3 h at 60 °C. The reaction mixture was extracted with EA (3 x 15 mL) and brine (2 x 15 mL). The combined organic phases were dried over Na_2SO_4, concentrated *in vacuo* and purified by flash column chromatography (PE/EA = 9:1 to 1:1).

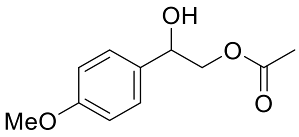
General procedure for the acetylation of diols (step 2)



To a solution of diol (3.0 mmol) in DCM (12 mL) was added Ac_2O (4.5 mmol) and pyridine (1 mL) and the mixture was stirred for 3 h at rt. Then it was diluted with DCM to 30 mL and washed with 1M HCl (2 × 15 mL), saturated $NaHCO_3$ (aq.) (15 mL) and brine (15 mL). The organic phase was dried over anhydrous Na_2SO_4 and concentrated *in vacuo*. The crude product was purified by flash column chromatography (PE/EA = 9:1 to 2:1).

Characterization of acetylated aromatic substrates

2-Hydroxy-2-(4-methoxyphenyl)ethyl acetate (1j)[18]



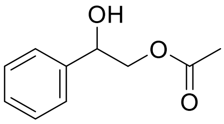
Yield: step 1 (reduction): 56%, step 2: 61%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.32 – 7.25 (m, 2H), 6.91 – 6.84 (m, 2H), 4.88 (dd, *J* = 8.4 Hz, 3.5 Hz, 1H), 4.26 – 4.07 (m, 2H), 3.79 (s, 3H), 2.67 (brs, 1H), 2.08 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 171.3 (C_q), 159.6 (C_q), 132.0 (C_q), 127.5 (+), 114.0 (+), 72.0 (+), 69.4 (–), 55.4 (+), 21.0 (+).

HRMS (APCI) (m/z): $[M+NH_4]^+$ = ($C_{11}NH_{18}O_4$) calc.: 228.1230, found: 228.1230.
MF: $C_{11}H_{14}O_4$
MW: 210.23 g/mol

2-Hydroxy-2-phenylethyl acetate (1k)[22]



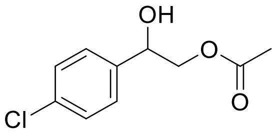
Yield: 52%

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.37 – 7.25 (m, 5H), 4.89 (dd, *J* = 8.3 Hz, 3.5 Hz, 1H), 4.26 – 4.06 (m, 2H), 3.09 (brs, 1H), 2.05 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 171.3, 140.0, 128.5, 128.1, 126.2, 72.2, 69.3, 20.9.

HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_{10}H_{11}O_2$) calc.: 163.0759, found: 163.0755.
MF: $C_{10}H_{12}O_3$
MW: 180.20 g/mol

2-(4-Chlorophenyl)-2-hydroxyethyl acetate (1l)[22]



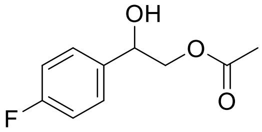
Yield: step 1 (epoxide opening): 95%, step 2: 45%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] 7.40 – 7.14 (m, 4H), 4.98 – 4.76 (m, 1H), 4.29 – 3.95 (m, 2H), 3.07 (brs, 1H), 2.07 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 171.4, 138.5, 133.9, 128.7, 127.6, 71.6, 69.1, 20.9.

HRMS (APCI) (m/z): $[M+H]^+$ ($C_{10}H_{12}ClO_3$) calc.: 215.0475, found: 215.0469.
MF: $C_{10}H_{11}ClO_3$
MW: 214.65 g/mol

2-(4-Fluorophenyl)-2-hydroxyethyl acetate (1m)[22]



Yield: step 1 (epoxide opening): 68%, step 2: 38%.

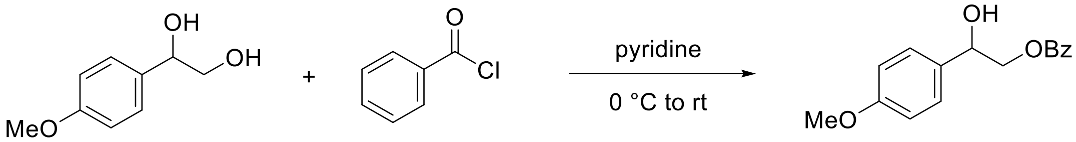
^{1}**H NMR** (300 MHz, $CDCl_3$): δ [ppm] = 7.38 – 7.21 (m, 2H), 7.00 (td, *J* = 8.6 Hz, 1.9 Hz, 2H), 4.92 – 4.78 (m, 1H), 4.23 – 3.99 (m, 2H), 3.09 (brs, 1H), 2.03 (s, 3H).

^{13}**C NMR** (75 MHz, $CDCl_3$): δ [ppm] = 171.4, 162.5 (d, *J* = 246.1 Hz), 135.8, 127.9 (d, *J* = 8.2 Hz), 115.4 (d, *J* = 21.5 Hz), 71.5, 69.2, 20.8.

HRMS (APCI) (m/z): $[M+H]^+$ ($C_{10}H_{12}FO_3$) calc.: 199.0770, found: 199.0766.
MF: $C_{10}H_{11}FO_3$
MW: 198.19 g/mol

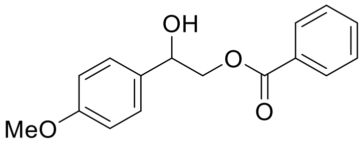
5.4.2.3. Synthesis of Aromatic Substrates with Other Leaving Groups

Synthesis and characterization of substrate with benzyl leaving group (1n)[23]



To a stirred solution of 1-(4-methoxyphenyl)-1,2-ethandiol (0.34 g, 2.0 mmol, 1.0 equiv.) in pyridine (4 mL) at 0 °C, benzoylchloride (0.25 mL, 2.2 mmol, 1.1 equiv.) was added dropwise. The mixture was allowed to warm to rt over night before ice water (4 mL) was added. After stirring for 30 minutes, the mixture was extracted with DCM (3 x 15 mL) and the combined organic phase was dried over sodium sulfate. Purification by column chromatography (PE/EA = 7:3) gave the product as colorless solid.

2-Hydroxy-2-(4-methoxyphenyl)ethyl benzoate (1n)[24]

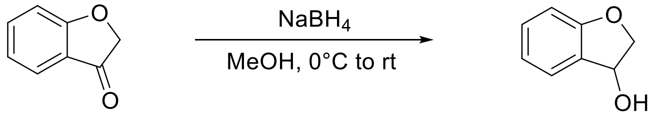


Yield: 73%

^{1}**H NMR** (300 MHz, $CDCl_3$): δ [ppm] = 7.29 (m, 2H), 7.78 – 7.51 (m, 2H), 7.48 – 7.27 (m, 4H), 6.97 – 6.83 (m, 2H), 5.06 (dd, J = 3.6 Hz, 1H), 4.55 – 4.24 (m, 2H), 3.81 (s, 3H).

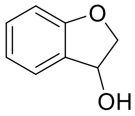
HRMS (ES) (m/z): $[M+NH_4]^+$ ($C_{16}NH_{20}O_4$) calc.: 290.1392, found: 290.1388.
MF: $C_{16}H_{16}O_4$
MW: 272.30 g/mol

Synthesis and characterization of intramolecular substrate (1o)[25]



To a stirred solution of 3-coumaranone (0.50 g, 3.7 mmol, 1.0 equiv.) in methanol (10 mL) at 0°C, sodium borohydride (1.6 g, 42 mmol, 11.4 equiv.) was added in portions within 1 hour. The reaction mixture was stirred for additional 30 minutes at 0 °C to complete conversion, monitored by TLC. The mixture was allowed to warm to rt and HCl (15 mL, 0.2 M) was added. After extraction with chloroform (3 x 15 mL), the combined organic phases were dried over sodium sulfate. The crude product was purified by column chromatography with *tert*-butyl methyl ether.

2,3-Dihydrobenzofuran-3-ol (1o)[25]



Yield: 99%

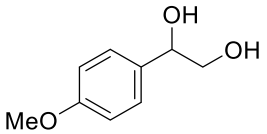
^{1}H NMR (300 MHz, CDCl$_3$): δ [ppm] = 7.40 (dd, *J* = 7.4 Hz, 0.6 Hz, 1H), 7.26 (td, *J* = 7.6 Hz, 1.3 Hz, 1H), 6.94 (td, *J* = 7.4 Hz, 0.9 Hz, 1H), 6.87 (d, *J* = 8.1 Hz, 1H), 5.29 (brs, 1H), 4.50 (dd, *J* = 10.7 Hz, 6.5 Hz, 1H), 4.39 (dd, *J* = 10.7 Hz, 2.2 Hz, 1H), 2.42 – 2.24 (m, 1H).

^{13}C NMR (75 MHz, CDCl$_3$): δ [ppm] = 160.3, 130.9, 128.3, 125.6, 121.1, 110.7, 79.2, 72.2.

HRMS (EI) (m/z): [M$^•$]$^+$ ($C_8H_8O_2$) calc.: 136.0524, found: 136.0515.
MF: $C_8H_8O_2$
MW: 136.15 g/mol

5.4.2.4. Synthesis of Unprotected and Full-protected Diol Derivatives

1-(4-Methoxyphenyl)ethane-1,2-diol (4)[26]

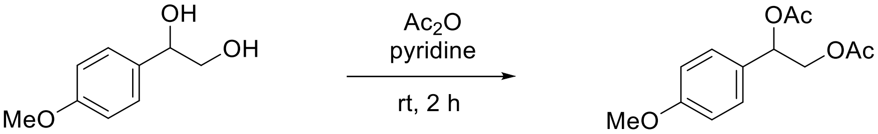


Yield: (by reduction with $NaBH_4$, see 2.4, step 1) 56%.

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.34 – 7.26 (m, 2H), 6.93 – 6.87 (m, 2H), 4.78 (dd, *J* = 8.0 Hz, 3.8 Hz, 1H), 3.81 (s, 3H), 3.76 – 3.62 (m, 2H), 2.01 (brs, 2H).

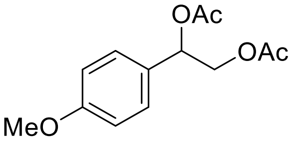
HRMS (APCI) (m/z): $[M+H-H_2O]^+$ ($C_9H_{11}O_2$) calc.: 151.0759, found: 151.0785.
MF: $C_9H_{12}O_3$
MW: 168.19 g/mol

Synthesis and characterization of compound 5[27]



A solution of 1-(4-methoxyphenyl)ethane-1,2-diol (5 mmol, 1.0 equiv.) in 2 mL pyridine/acetic anhydride (1:1, v/v) was stirred at rt for 2 h. Then, the reaction mixture was diluted with EA (5 mL) and washed with a solution of $NaHCO_3$ (5%, 5 mL), water and brine. The organic phases were dried over anhydrous Na_2SO_4 and concentrated *in vacuo*. The resulting crude product was purified by flash column chromatography (PE/EA = 9:1) to give compound **5**.

1-(4-Methoxyphenyl)ethane-1,2-diyl diacetate (5)



Yield: 58%

^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.33 – 7.26 (m, 2H), 6.92 – 6.85 (m, 2H), 5.96 (t, *J* = 6.1 Hz, 1H), 4.29 (d, *J* = 6.0 Hz, 2H), 3.80 (s, 3H), 2.09 (s, 3H), 2.05 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 170.8 (C_q), 170.2 (C_q), 159.9 (C_q), 128.7 (C_q), 128.3 (+), 114.1 (+), 73.1 (+), 66.2 (–), 55.4 (+), 21.3 (+), 21.0 (+).

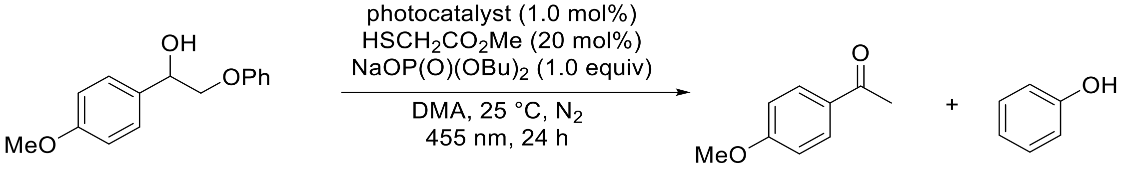
HRMS (APCI) (m/z): $[M+H]^+$ ($C_{13}H_{17}O_5$) calc.: 253.1071, found: 253.1068.
MF: $C_{13}H_{16}O_5$
MW: 252.27 g/mol

5.4.2.5. Procedure for the Preparation of $NaOP(O)(OBu)_2$

To a solution of dibutylphosphate (10 mmol, 2.102 g) in 10 mL deionized water, $NaHCO_3$ (10 mmol, 0.840 g) was added in portions. After the addition was completed, the reaction mixture was stirred at rt for another 1 h. Then water was removed under reduced pressure. The resulting residue was further dried under vacuum for one week to afford the desired product in quantitative yield.

5.4.3. Optimization of Reaction Conditions for the Photocatalytic Fragmentation

Table S5-1: Screening of photocatalysts.

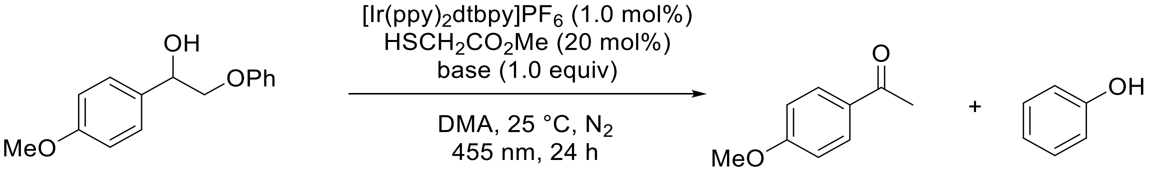


Entry	Photocatalyst	Yield of ketone[a]	Yield of phenol[a]
1	Ru(ppy)$_3$*6H$_2$O	nd	nd
2	*fac*-Ir(ppy)$_3$	nd	nd
3	Ir[dFCF$_3$(ppy)$_2$dtbpy]PF$_6$	3%	4%
4	Ir[FCF$_3$(ppy)$_2$dtbpy]PF$_6$	72%	57%
5	**[Ir(ppy)$_2$dtbpy]PF$_6$**	91%	81%
6	Eosin Y (5 mol%)	nd	nd
7	Perylene (5 mol%)	nd	nd
8	4CzIPN (5 mol%)	26%	26%
9	4CzIPN (5 mol%), air	59%	48%

[a] Determined by GC analysis using naphthalene as an internal standard.

Optimization for [Ir(ppy)$_2$dtbpy]PF$_6$ system

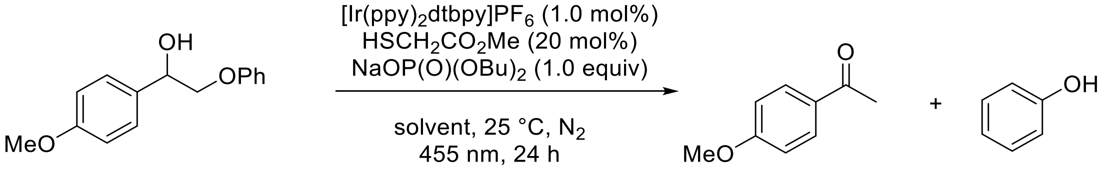
Table S5-2: Screening of bases for the iridium system.



Entry	Base	Yield of ketone[a]	Yield of phenol[a]
1	K$_2$CO$_3$	21%	14%
2	NaOAc	53%	54%
3	NaOPiv	23%	9%
4	NaHCO$_3$	29%	24%
5	NaHPO$_4$	nd	nd
6	2,4,6-collidine	traces	traces
7	**NaOP(O)(OBu)$_2$**	91%	81%
8	NaOP(O)(OBu)$_2$ (50 mol%)	40%	30%

[a] Determined by GC analysis using naphthalene as an internal standard.

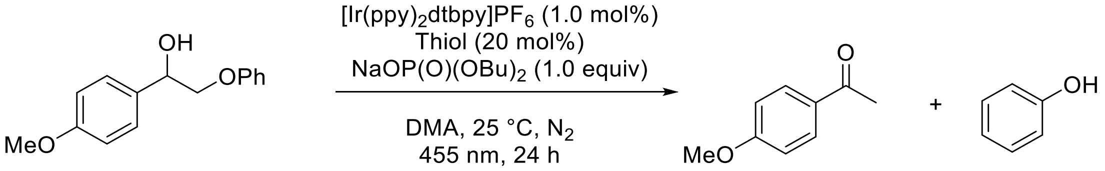
Table S5-3: Screening of solvents for the iridium system.



Entry	Solvent	Yield of ketone[a]	Yield of phenol[a]
1	DCM	28%	traces
2	DCE	9%	traces
3	1,4-Dioxane	12%	traces
4	Acetone	16%	13%
5	MeCN	11%	0%
6	EA	7%	22%
7	DMSO	46%	45%
8	DMF	23%	24%

[a] Determined by GC analysis using naphthalene as an internal standard.

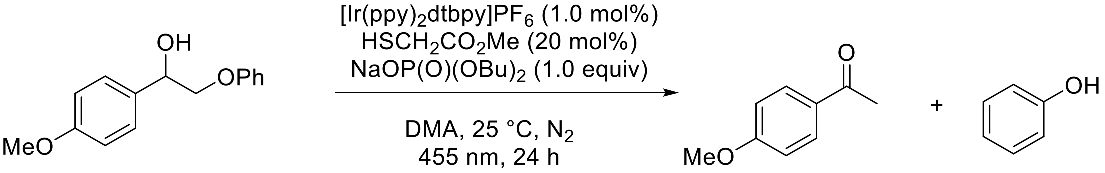
Table S5-4: Screening of thiols for the iridium system.



Entry	Thiol	Yield of ketone[a]	Yield of phenol[a]
1	PhSH	22%	13%
2	PhSSPh	17%	8%
3	BnSH	58%	52%
4	$CH_3CH(SH)COCH_3$	71%	49%
5	$CH_3CH(SH)CO_2Et$	40%	33%

[a] Determined by GC analysis using naphthalene as an internal standard.

Table S5-5: Control reactions for the iridium system.

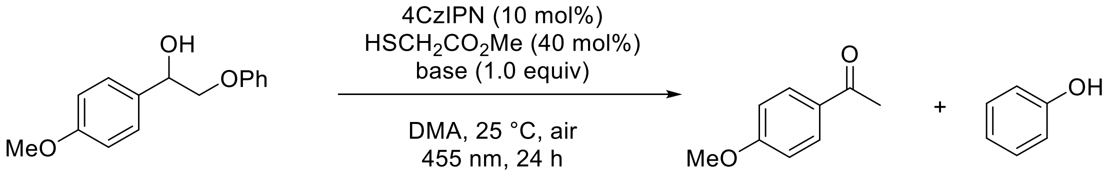


Entry	Deviation from standard conditions	Yield of ketone[a]	Yield of phenol[a]
1	no light	nd	nd
2	no photocatalyst	nd	nd
3	no thiol	nd	nd
4	no base	nd	nd
5	under air	16%	trace

[a] Determined by GC analysis using naphthalene as an internal standard.

Optimization for 4CzIPN system

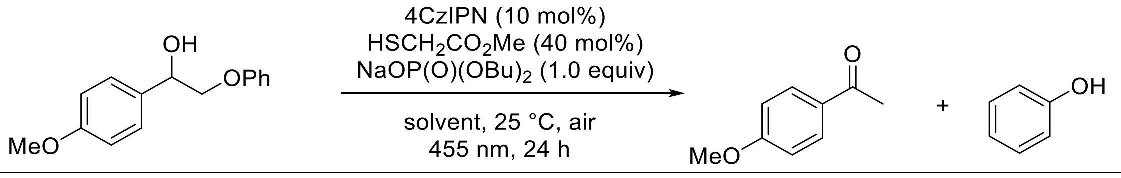
Table S5-6: Screening of bases for the 4CzIPN system.



Entry	Base	Yield of ketone[a]	Yield of phenol[a]
1	K_2CO_3	20%	28%
2	NaOAc	31%	42%
3	$NaHCO_3$	32%	72%
4	**$NaOP(O)(OBu)_2$**	72%	44%

[a] Determined by GC analysis using naphthalene as an internal standard.

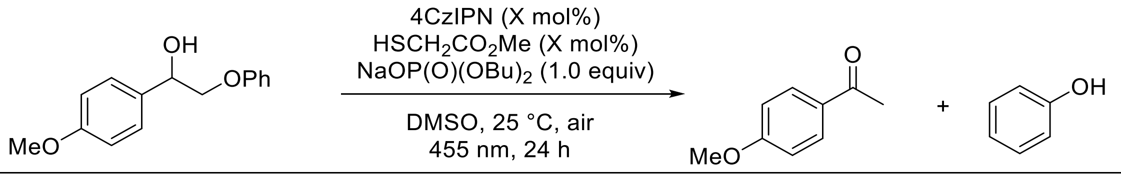
Table S5-7: Screening of solvents for the 4CzIPN system.



Entry	Solvent	Yield of ketone[a]	Yield of phenol[a]
1	DCM	63%	traces
2	DCE	62%	traces
3	1,4-Dioxane	21%	15%
4	Acetone	35%	traces
5	MeCN	39%	7%
6	**DMSO**	73%	54%
7	DMF	71%	41%
8	THF	50%	25%

[a] Determined by GC analysis using naphthalene as an internal standard.

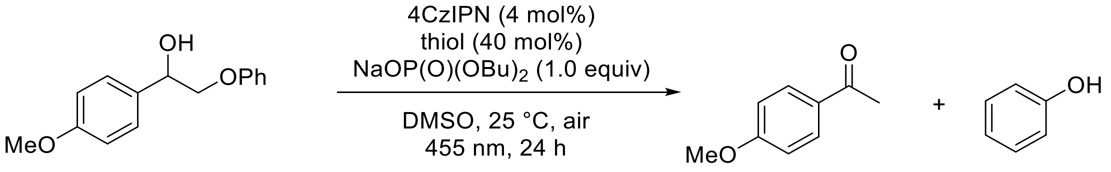
Table S5-8: Screening of different amounts of catalyst and thiol.



Entry	Solvent	Yield of ketone[a]	Yield of phenol[a]
1	8 mol% 4CzIPN, 20 mol% thiol	80%	41%
2	8 mol% 4CzIPN, **40 mol% thiol**	76%	58%
3	8 mol% 4CzIPN, 60 mol% thiol	71%	58%
4	8 mol% 4CzIPN, 80 mol% thiol	57%	55%
5	**4 mol% 4CzIPN, 40 mol% thiol**	82%	57%
6	3 mol% 4CzIPN, 40 mol% thiol	69%	46%
7	2 mol% 4CzIPN, 40 mol% thiol	31%	20%
8	1 mol% 4CzIPN, 40 mol% thiol	18%	13%
9	10 mol % 4CzIPN, 40 mol% thiol	73%	54%

[a] Determined by GC analysis using naphthalene as an internal standard.

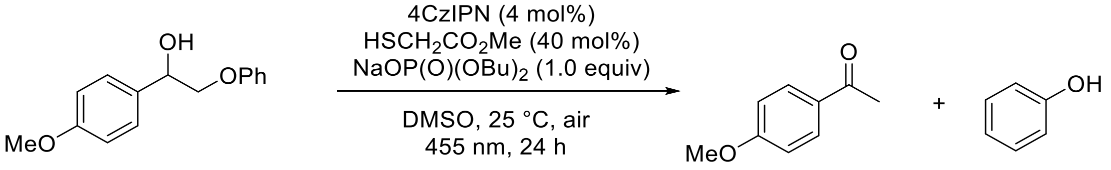
Table S5-9: Screening of thiols for the 4CzIPN system.



Entry	Thiol	Yield of ketone[a]	Yield of phenol[a]
1	PhSH	40%	19%
2	PhSSPh	41%	19%
3	BnSH	56%	32%
4	$CH_3CH(SH)COCH_3$	80%	36%
5	$CH_3CH(SH)CO_2Et$	77%	38%
6	(*i*Pr)$_3$SiSH	81%	52%

[a] Determined by GC analysis using naphthalene as an internal standard.

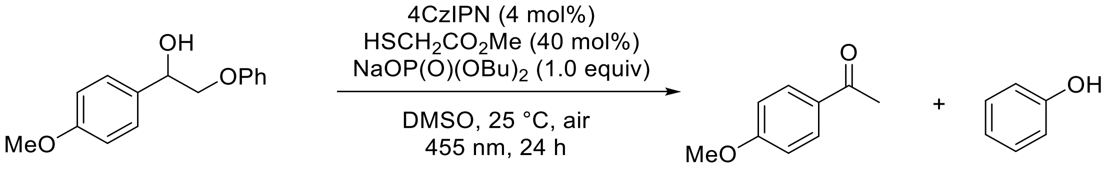
Table S5-10: Control reactions for the 4CzIPN system.



Entry	Deviation from standard conditions	Yield of ketone[a]	Yield of phenol[a]
1	no light	nd	nd
2	no photocatalyst	nd	nd
3	no thiol	23%	11%
4	no base	25%	0%
5	N_2 atmosphere	26%	26%
6	O_2-balloon	traces	nd

[a] Determined by GC analysis using naphthalene as an internal standard.

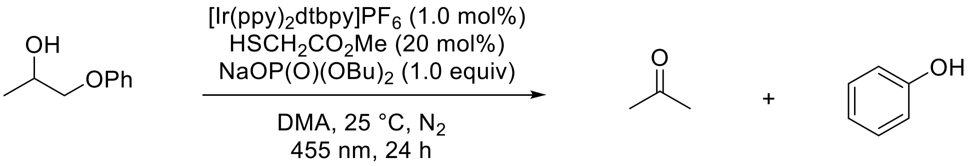
Table S5-11: Further screening reactions for the 4CzIPN system.



Entry	Deviation from standard conditions	Yield of ketone[a]	Yield of phenol[a]
1	0.2 mmol in 1 mL DMSO	64%	58%
2	0.2 mmol in 2 mL DMSO	56%	54%
3	0.1 mmol in 2 mL DMSO	67%	32%
4	**0.5 equiv. base**	80%	57%

[a] Determined by GC analysis using naphthalene as an internal standard. Standard conditions: 0.1 mmol substrate in 1 mL DMSO.

Table S5-12: Screening of C–O cleavage of alkyl substrates.



Entry	Deviation from standard conditions	Conversion	Yield of phenol[a]
1	no change	44%	39%
2	72 h	62%	49%
3	**2.0 mol% Ir-cat, 40 mol% thiol, 72 h**	80%	72%
4	same as entry 3, 0.2 mmol in 1 mL DMA	79%	66%
5	4.0 mol% 4CzIPN, 40 mol% thiol, 48 h, under air	41%	nd

[a] Determined by GC analysis using naphthalene as an internal standard.

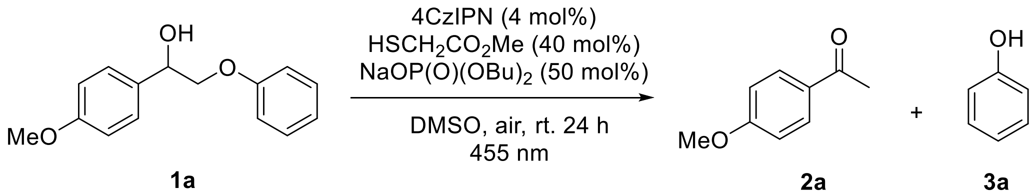
5.4.4. General Procedures for Photocatalytic Reactions

Visible light-induced C–O cleavage of benzylic diol derivatives via 4CzIPN catalysis

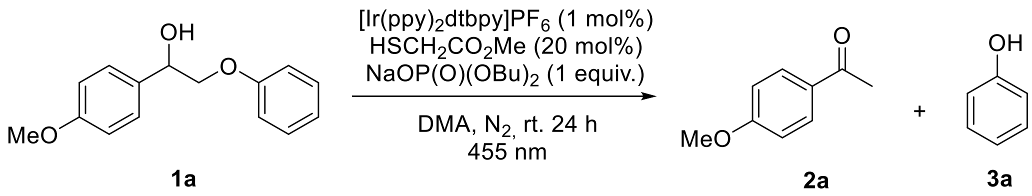
The substrate (0.1 mmol, 1.0 equiv.), 4CzIPN (3.2 mg, 0.004 mmol, 4 mol%) and $NaOP(O)(OBu)_2$ (11.6 mg, 0.05 mmol, 0.5 equiv.) were weighed into a 5 mL crimp cap vial equipped with a stirring bar. Dry DMSO (1.0 mL) and methyl thioglycolate (4 µL, 0.04 mmol, 40 mol%) were added *via* syringe and the vial was capped. The yellow reaction mixture was irradiated using a blue LED for 24 h at 25 °C. Then four vials with the same content were combined and the reaction mixture was diluted with EA (40 mL) and washed with water (2 x 15 mL). The organic layer was dried over Na_2SO_4 and the solvent was removed under reduced pressure. Purification of the crude product was performed by flash column chromatography (PE/EA = 9:1 up to 1:1).

Visible light-induced C–O cleavage of benzylic diol derivatives via $[Ir(ppy)_2(dtbpy)]PF_6$ catalysis

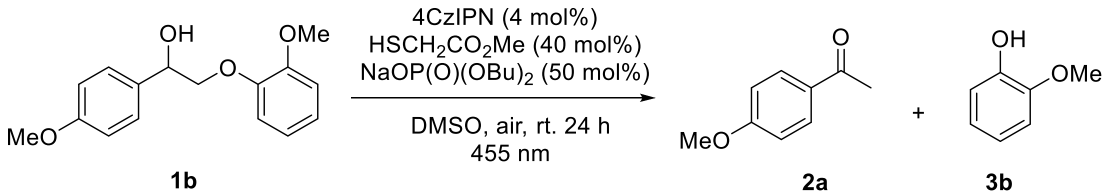
The substrate (0.2 mmol, 1.0 equiv.), $[Ir(ppy)_2(dtbpy)]PF_6$ (1.8 mg, 0.002 mmol, 1 mol%) and $NaOP(O)(OBu)_2$ (46.4 mg, 0.2 mmol, 1.0 equiv.) were weighed into a 5 mL crimp cap vial equipped with a stirring bar. Dry DMA (2.0 mL) and methyl thioglycolate (4 µL, 0.04 mmol, 20 mol%) were added *via* syringe. Nitrogen atmosphere was then introduced *via* three cycles of freeze-pump-thaw (10 minutes vacuum at 1 mbar). The yellow reaction mixture was irradiated using a blue LED for 24 h at 25 °C. Then two vials with the same content were combined and the reaction mixture was diluted with EA (40 mL) and extracted with water (2 x 15 mL). The organic layer was dried over Na_2SO_4 and the solvent was removed under reduced pressure. Purification of the crude product was performed by flash column chromatography (PE/EA = 9:1 up to 1:1).



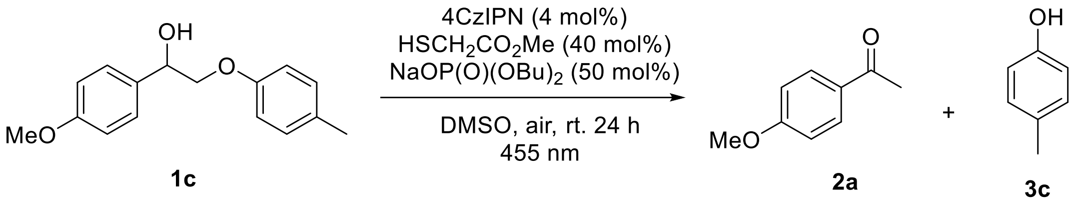
Following the general procedure 4.1. with substrate **1a** (24.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2a** (47.6 mg, 79%) and phenol **3a** (23.9 mg, 63%).



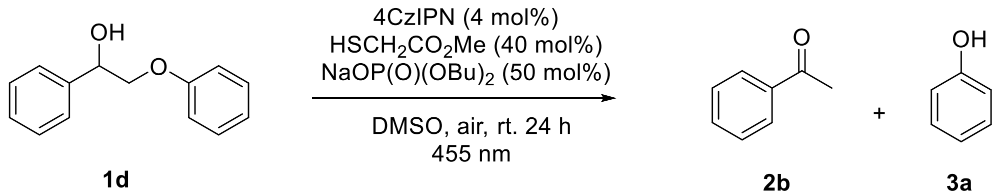
Following the general procedure 4.2. with substrate **1a** (48.9 mg, 0.2 mmol) and 1 mol% Ir catalyst. Two reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2a** (51.8 mg, 86%) and phenol **3a** (26.8 mg, 71%).



Following the general procedure 4.1. with substrate **1b** (27.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2a** (41.3 mg, 69%) and phenol **3b** (25.4 mg, 51%).



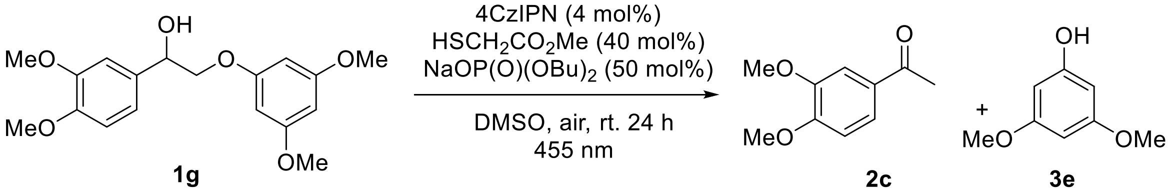
Following the general procedure 4.1. with substrate **1c** (25.8 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2a** (54.2 mg, 90%) and phenol **3c** (26.4 mg, 61%).



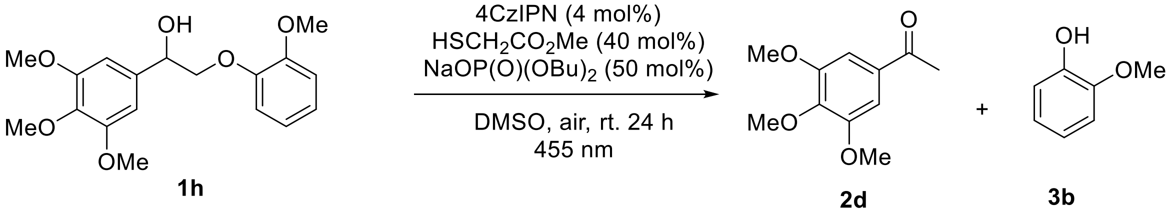
Following the general procedure 4.1. with substrate **1d** (21.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2b** (33.0 mg, 69%) and phenol **3a** (18.9 mg, 50%).

Following the general procedure 4.1. with substrate **1e** (30.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2c** (54.0 mg, 75%) and phenol **3b** (30.1 mg, 61%).

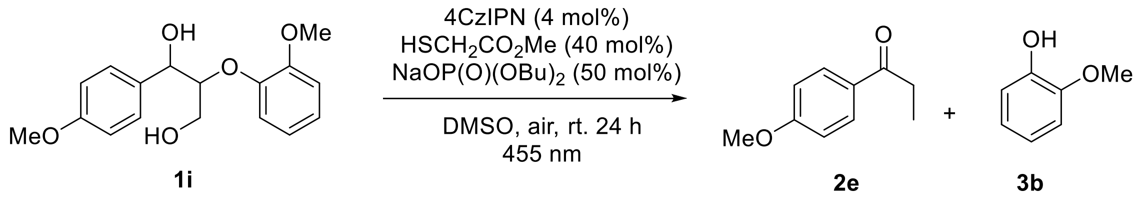
Following the general procedure 4.1. with substrate **1f** (33.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2c** (60.1 mg, 83%) and phenol **3d** (46.6 mg, 76%).



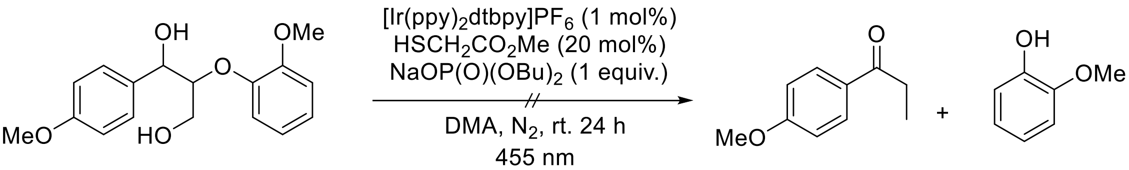
Following the general procedure 4.1. with substrate **1g** (33.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2c** (72.0 mg, 100%) and phenol **3e** (51.8 mg, 84%).



Following the general procedure 4.1. with substrate **1h** (33.4 mg, 0.1 mmol) and 4CzIPN. Two reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2d** (28.6 mg, 68%) and phenol **3b** (8.3 mg, 33%).

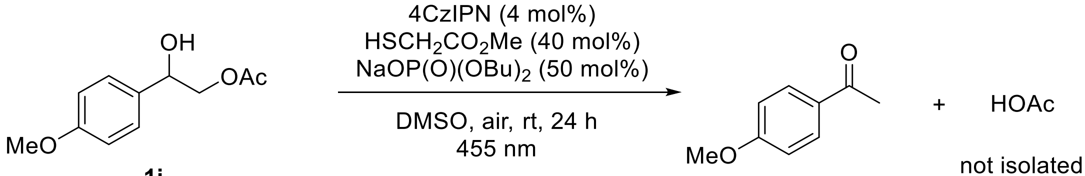


Following the general procedure 4.1. with substrate **1i** (30.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain phenol **3b** (10.0 mg, 20%), but no ketone could be isolated. Ketone **2e** was detected by GC-MS analysis.



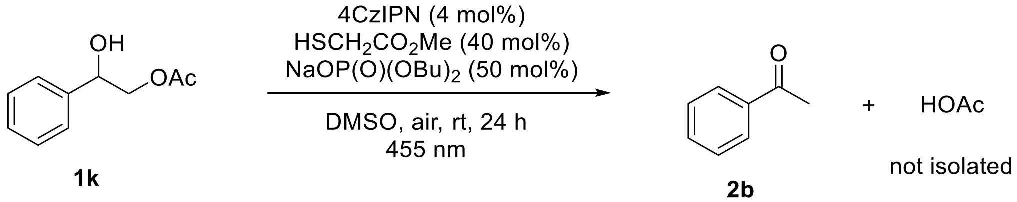
1i **2e** **3b**

Following the general procedure 4.2. with substrate **1i** (60.9 mg, 0.2 mmol) and 1 mol% Ir catalyst. Two reactions were carried out in parallel and then combined for isolation by column chromatography, but no ketone **2e** nor phenol **3b** could be isolated. Ketone **2e** was detected by GC-MS analysis.



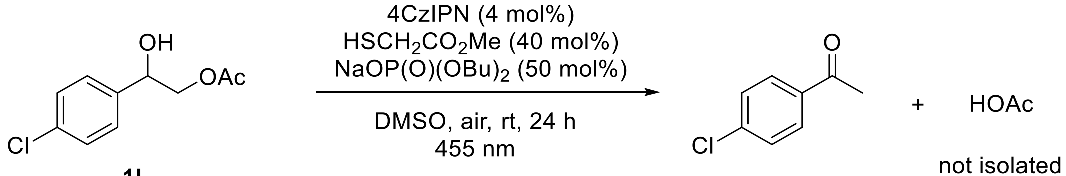
1j **2a**

Following the general procedure 4.1. with substrate **1j** (21.0 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2a** (41.9 mg, 70%).



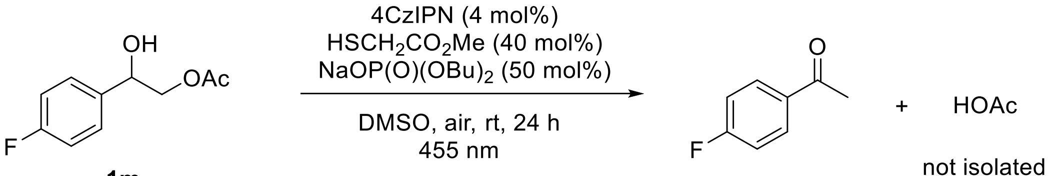
1k **2b**

Following the general procedure 4.1. with substrate **1k** (18.0 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2b** (35.6 mg, 74%).



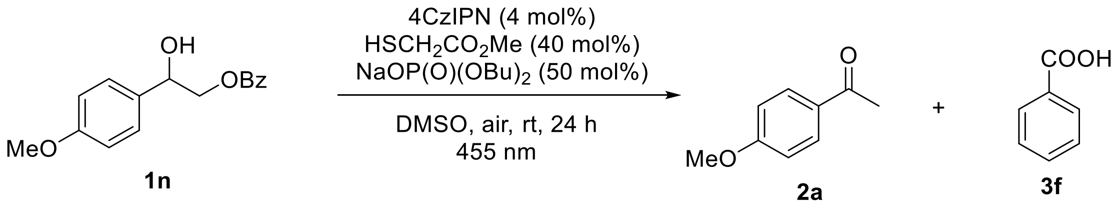
1l **2f**

Following the general procedure 4.1. with substrate **1l** (21.5 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2f** (37.6 mg, 61%).

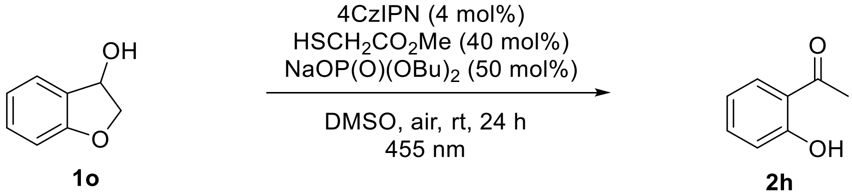


1m **2g**

Following the general procedure 4.1. with substrate **1m** (19.8 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2g** (41.6 mg, 75%).

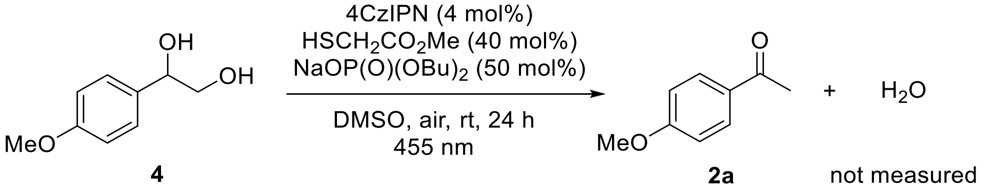


Following the general procedure 4.1. with substrate **1n** (27.2 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2a** (43.8 mg, 73%) and benzoic acid **3f** (34.1 mg, 70%).

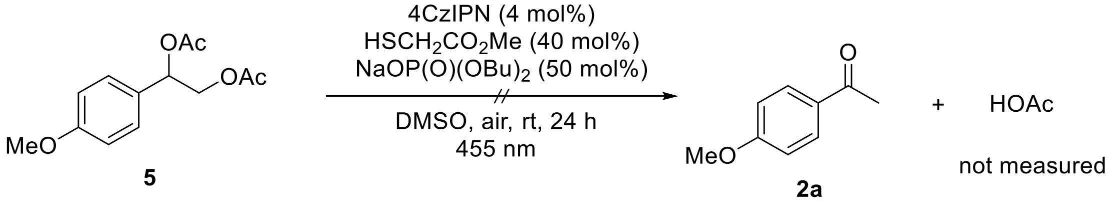


Following the general procedure 4.1. with substrate **1o** (13.4 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography to obtain ketone **2h** (24.5 mg, 45%).

5.4.5. Control Experiments for Clarification of the Mechanism



Following the general procedure 4.1. with substrate **4** (16.8 mg, 0.1 mmol) and 4CzIPN. The yield of ketone **2a** (5%) was determined by GC-analysis with the internal standard naphthalene.

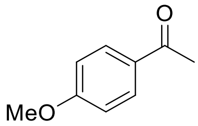


Following the general procedure 4.1. with substrate **5** (25.2 mg, 0.1 mmol) and 4CzIPN. Four reactions were carried out in parallel and then combined for isolation by column chromatography, but ketone **2a** could not be obtained and no conversion was observed.

5.4.6. Characterization of Isolated Products

Characterization of ketones

1-(4-Methoxyphenyl)ethan-1-one (2a)[28]

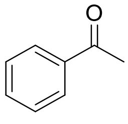


^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.97 – 7.88 (m, 2H), 6.97 – 6.87 (m, 2H), 3.85 (s, 3H), 2.54 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 196.9 (C_q), 163.6 (C_q), 130.7 (+), 130.4 (C_q), 113.8 (+), 55.6 (+), 26.5 (+).

HRMS (APCI) (m/z): $[M+H]^+$ ($C_9H_{11}O_2$) calc.: 151.0759, 151.0762.
MF: $C_9H_{10}O_2$
MW: 150.18 g/mol

Acetophenone (2b)[29]

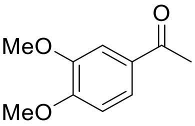


^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 8.02 – 7.91 (m, 2H), 7.60 – 7.53 (m, 1H), 7.49 – 7.43 (m, 2H), 2.61 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 198.5 (C_q), 137.2 (C_q), 133.3 (+), 128.7 (+), 128.5 (+), 26.7 (+).

HRMS (EI) (m/z): $[M^•]^+$ (C_8H_8O) calc.: 120.0570, found: 120.0572.
MF: C_8H_8O
MW: 120.15 g/mol

1-(3,4-Dimethoxyphenyl)ethan-1-one (2c)[30]

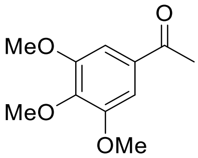


^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.54 (dd, *J* = 8.3 Hz, 2.0 Hz, 1H), 7.49 (d, *J* = 2.0 Hz, 1H), 6.85 (d, *J* = 8.3 Hz, 1H), 3.91 (s, 3H), 3.90 (s, 3H), 2.53 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 196.9 (C_q), 153.3 (C_q), 149.0 (C_q), 130.5 (C_q), 123.3 (+), 110.04 (+), 109.96 (+), 56.1 (+), 56.0 (+), 26.3 (+).

HRMS (EI) (m/z): $[M^•]^+$ ($C_{10}H_{12}O_3$) calc.: 180.0781, found: 180.0776.
MF: $C_{10}H_{12}O_3$
MW: 180.20 g/mol

1-(3,4,5-Trimethoxyphenyl)ethan-1-one (2d)[31]

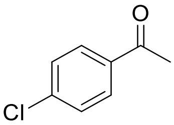


^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.21 (s, 2H), 3.92 (s, 6H), 3.92 (s, 3H), 2.59 (s, 3H).

^{13}C NMR (101 MHz, $CDCl_3$): δ [ppm] = 197.0 (C_q), 153.2 (C_q), 142.8 (C_q), 132.6 (C_q), 106.0 (+), 61.1 (+), 56.5 (+), 26.6 (+).

HRMS (EI) (m/z): $[M^•]^+$ ($C_{11}H_{14}O_4$) calc.: 210.0887, found: 210.0884.
MF: $C_{11}H_{14}O_4$
MW: 210.23 g/mol

1-(4-Chlorophenyl)ethan-1-one (2f)[32]

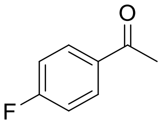


^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.92 – 7.85 (m, 2H), 7.46 – 7.39 (m, 2H), 2.58 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 197.1 (C_q), 139.7 (C_q), 135.5 (C_q), 129.9 (+), 129.0 (+), 26.7 (+).

HRMS (EI) (m/z): $[M^•]^+$ (C_8H_7ClO) calc.: 154.0180, found: 154.0180.
MF: C_8H_7ClO
MW: 154.59 g/mol

1-(4-Fluorophenyl)ethan-1-one (2g)[33]

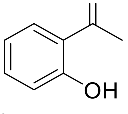


^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 8.02 – 7.91 (m, 2H), 7.17 – 7.05 (m, 2H), 2.58 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 196.7 (C_q), 165.9 (C_q, d, J = 254.7 Hz), 133.6 (C_q, d, J = 3.0 Hz), 131.1 (+, d, J = 9.3 Hz), 115.8 (+, d, J = 21.9 Hz), 26.6 (+).

HRMS (EI) (m/z): $[M^•]^+$ (C_8H_7FO) calc.: 138.0475, found: 138.0486.
MF: C_8H_7FO
MW: 138.14 g/mol

1-(2-Hydroxyphenyl)ethan-1-one (2h)[29]



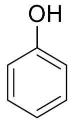
^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 12.26 (s, 1H), 7.74 (dd, J = 8.0 Hz, 1.7 Hz, 1H), 7.48 (ddd, J = 8.5 Hz, 7.2 Hz, 1.7 Hz, 1H), 6.98 (dd, J = 8.4 Hz, 1.1 Hz, 1H), 6.90 (ddd, J = 8.3 Hz, 7.2 Hz, 1.2 Hz, 1H), 2.64 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 204.7 (C_q), 162.5 (C_q), 136.6 (+), 130.9 (+), 119.8 (C_q), 119.1 (+), 118.6 (+), 26.8 (+).

MF: $C_8H_8O_2$
MW: 136.15 g/mol

Characterization of phenols and other leaving fragments

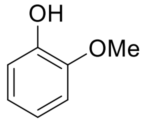
Phenol (3a)[34]



^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.29 – 7.22 (m, 2H), 6.98 – 6.90 (m, 1H), 6.90 – 6.77 (m, 2H), 5.31 (brs, 1H).
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 155.7 (C_q), 129.8 (+), 120.8 (+), 115.4 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ (C_6H_6O) calc.: 94.0413, found: 94.0422.
MF: C_6H_6O
MW: 94.11 g/mol

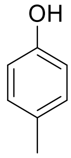
2-Methoxyphenol (3b)[18]



^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 6.99 – 6.81 (m, 4H), 3.89 (s, 3H).
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 146.7 (C_q), 145.8 (C_q), 121.6 (+), 120.3 (+), 114.7 (+), 110.8 (+), 56.0 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ (C_7H_8O2) calc.: 124.0524, found: 124.0534.
MF: $C_7H_8O_2$
MW: 124.14 g/mol

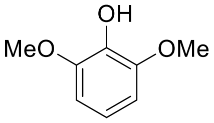
p-Cresol (3c)[18]



^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 7.10 – 6.99 (m, 2H), 6.81 – 6.70 (m, 2H), 5.07 (brs, 1H), 2.28 (s, 3H).
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 153.3 (C_q), 130.2 (+), 130.1 (C_q), 115.2 (+), 20.6 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ (C_7H_8O) calc.: 108.0570, found: 108.0566.
MF: C_7H_8O
MW: 108.14 g/mol

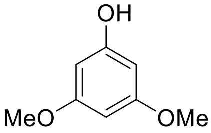
2,6-Dimethoxyphenol (3d)[17]



^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 6.80 (dd, *J* = 8.8 Hz, 7.8 Hz, 1H), 6.61 - 6.54 (m, 2H), 3.88 (s, 6H).
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 149.0 (C_q), 130.5 (C_q), 123.4 (+), 110.1 (+), 56.1 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_8H_{10}O_3$) calc.: 154.0630, found: 154.0638.
MF: $C_8H_{10}O_3$
MW: 154.17 g/mol

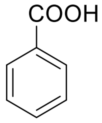
3,5-Dimethoxyphenol (3e)[17]



^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 6.09 – 6.05 (m, 1H), 6.04 (d, *J* = 2.1 Hz, 2H), 3.74 (s, 6H).
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 161.7 (C_q), 157.6 (C_q), 94.4 (+), 93.2 (+), 55.5 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_8H_{10}O_3$) calc.: 154.0630, found: 154.0638.
MF: $C_8H_{10}O_3$
MW: 154.17 g/mol

Benzoic acid (3f)[35]



^{1}H NMR (300 MHz, $CDCl_3$): δ [ppm] = 12.45 (brs, 1H), 8.19 – 8.10 (m, 2H), 7.68 – 7.58 (m, 1H), 7.54 – 7.44 (m, 2H).
^{13}C NMR (75 MHz, $CDCl_3$): δ [ppm] = 172.7 (C_q), 134.0 (+), 130.4 (+), 129.5 (C_q), 128.6 (+).

HRMS (EI) (m/z): $[M^\bullet]^+$ ($C_7H_6O_2$) calc.: 122.0368, found: 122.0357.
MF: $C_7H_6O_2$
MW: 122.12 g/mol

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6. Summary

This thesis presents different methods for the photocatalytic activation of carboxylic acid and diol derivatives. Visible light-mediated cross-couplings or cleavage of these biomass-derived substrates have been achieved and mechanistic investigations are described.

As carboxylic acids are abundant, non-toxic and inexpensive compounds with high structural diversity, they are ideal starting materials for modern, sustainable organic synthesis. Extrusion of CO_2 from different classes of carboxylic acids gives radical intermediates that react in various cross-coupling reactions. **Chapter 1** summarizes recent developments in the field of photocatalytic decarboxylative reactions and compares different methods regarding scope, product yields, atom economy, reaction time and toxicity.

Chapter 2 and **Chapter 3** present the decarboxylative cross-coupling of natural carboxylic acids with a green light-mediated, environmentally friendly method. In both cases, amino acids, α-oxy acids and fatty acids from renewable resources are activated by esterification to *N*-(acyloxy)phthalimides. The decarboxylation takes place upon reductive quenching of the excited organic dye eosin Y to its radical anion by DIPEA and subsequent reduction of the *N*-(acyloxy)phthalimide. An alkyl radical is formed which can undergo C–C bond formation reactions.

Chapter 2 describes the trapping of these alkyl radicals with electron-deficient alkenes. After cross-coupling, alkylated products without double-bonds are obtained. Although especially substrates with α-hetero atoms give good yields, even simple fatty acids are suitable, albeit giving lower yields.

In **Chapter 3**, alkyl radicals which are formed upon decarboxylation react with acetylenic sulfones under elimination of a sulfonyl radical. Starting from easily available natural carboxylic acid derivatives, this method enables the synthesis of building blocks with an alkyne moiety which are important for organic synthesis. With this method, even complex starting materials like protected sugar acids, gemfibrozil or cholic acid can be alkynylated in good yields.

Another important and abundant class of natural compounds are diols. **Chapter 4** presents a photocatalytic method for the C–C bond cleavage of vicinal diols to aldehydes and ketones. This reaction proceeds *via* ligand-to-metal-charge-transfer (LMCT) with a cerium-catalyst and under irradiation with blue light. The scope includes aryl as well as alkyl substituted diols and the protocol for the valorization of diols is operationally simple as it works under air and at room temperature.

The selective, visible light-induced fragmentation of 1,2-diol derivatives with one protected and one unprotected hydroxyl group is described in **Chapter 5**. The most abundant biomass-derived representatives of this class of compounds are lignin β-O-4 model compounds, a type of aromatic backbone diol derivative. Redox neutral cleavage of the β C(sp^3)–O bond within one step is achieved with two different homogeneous photocatalysts, in the presence of a thiol co-catalyst and blue light. Different leaving groups are compatible with the system. With the metal-free catalyst 4CzIPN, the reaction proceeds under more robust conditions but is limited to benzylic diol derivatives. With

[Ir(ppy)$_2$dtbpy]PF$_6$, the photoreactions have to be carried out under nitrogen atmosphere, but on the other side, even C–O cleavage of aliphatic diol derivatives is possible. A mechanistic pathway including reductive quenching of the excited photocatalyst and HAT of the α-hydrogen atom of the benzylic alcohol to the generated thiyl radical is postulated.

7. Zusammenfassung

In dieser Arbeit werden verschiedene Methoden zur photokatalytischen Aktivierung von Carbonsäuren und Diolderivaten vorgestellt. Durch sichtbares Licht vermittelte Kreuzkupplungen oder Spaltung der aus Biomasse gewonnenen Substrate wurde erreicht und mechanistische Untersuchungen werden beschrieben.

Da es sich bei Carbonsäuren um häufig vorkommende, nicht toxische und kostengünstige Verbindungen mit hoher struktureller Vielfalt handelt, sind sie ideale Ausgangsmaterialien für eine moderne, nachhaltige organische Synthese. Durch Abspaltung von CO_2 aus verschiedenen Carbonsäureklassen entstehen radikalische Intermediate, die in verschiedenen Kreuzkupplungen reagieren. **Kapitel 1** fasst die jüngsten Entwicklungen auf dem Gebiet der photokatalytischen Decarboxylierungsreaktionen zusammen und vergleicht verschiedene Methoden hinsichtlich Anwendungsbreite, Produktausbeute, Atomökonomie, Reaktionszeit und Toxizität.

Kapitel 2 und **Kapitel 3** beschreiben die decarboxylierende Kreuzkupplung von natürlichen Carbonsäuren mit einer umweltfreundlichen Methode, die durch grünes Licht induziert wird. In beiden Fällen werden Aminosäuren, α–Oxy- und Fettsäuren aus nachwachsenden Rohstoffen durch Veresterung zu *N*-(Acyloxy)phthalimiden aktiviert. Die Decarboxylierung erfolgt durch reduktives Löschen des angeregten organischen Farbstoffs Eosin Y zu seinem Radikalanion mittels DIPEA und anschließende Reduktion des *N*-(Acyloxy)phthalimids. Es entsteht ein Alkylradikal, das C–C-Bindungsreaktionen eingehen kann.

Kapitel 2 beschreibt das Abfangen dieser Alkylradikale mit elektronenarmen Alkenen. Nach der Kreuzkupplung werden alkylierte Produkte ohne Doppelbindungen erhalten. Obwohl insbesondere mit Substraten mit α-Heteroatomen gute Ausbeuten erzielt werden, sind auch einfache Fettsäuren geeignet, auch wenn diese niedrigere Ausbeuten liefern.

In **Kapitel 3** reagieren die bei der Decarboxylierung entstehenden Alkylradikale mit Acetylensulfonen unter Abspaltung eines Sulfonylradikals. Ausgehend von leicht verfügbaren, natürlichen Carbonsäurederivaten, ermöglicht diese Methode die Herstellung von Bausteinen mit einer Alkineinheit, welche für die Synthesechemie sehr wichtig sind. Mit dieser Methode können auch komplexe Ausgangsstoffe wie geschützte Zuckersäuren, Gemfibrozil oder Cholsäure in guten Ausbeuten alkinyliert werden.

Eine weitere wichtige und häufig vorkommende Klasse von Naturstoffen sind Diole. In **Kapitel 4** wird eine photokatalytische Methode zur C–C-Bindungsspaltung von vicinalen Diolen zu Aldehyden und Ketonen vorgestellt. Diese Reaktion läuft über einen Ligand-zu-Metall-Ladungstransfer (LMCT) mit einem Cer-Katalysator und unter Bestrahlung mit blauem Licht ab. Die Substratbreite umfasst sowohl Aryl- als auch Alkyl-substituierte Diole. Das Verfahren zur Aufwertung von Diolen ist einfach anzuwenden, da es unter Luft und bei Raumtemperatur abläuft.

Die selektive, durch sichtbares Licht induzierte Fragmentierung von 1,2-Diolderivaten mit einer geschützten und einer ungeschützten Hydroxylgruppe wird in **Kapitel 5** beschrieben. Die am häufigsten vorkommenden Vertreter dieser natürlichen Verbindungsklasse sind Lignin β-O-4-Modellverbindungen, eine Art aromatisches Grundgerüst-Diolderivat. Die redoxneutrale Spaltung der β-C(sp^3)–O-Bindung in einem Schritt wird mit zwei verschiedenen homogenen Photokatalysatoren in Gegenwart eines Thiol-Cokatalysators und blauem Licht erreicht. Verschiedene Abgangsgruppen sind mit dem System kompatibel. Mit dem metallfreien Katalysator 4CzIPN verläuft die Reaktion unter robusteren Bedingungen, ist jedoch auf benzylische Diolderivate beschränkt. Mit $[Ir(ppy)_2dtbpy]PF_6$ müssen die Photoreaktionen unter Stickstoffatmosphäre durchgeführt werden, andererseits ist sogar die C–O-Spaltung von aliphatischen Diolderivaten möglich. Ein mechanistischer Weg, der das reduktive Löschen des angeregten Photokatalysators und den HAT des α-Wasserstoffatoms des Benzylalkohols zum erzeugten Thiylradikal einschließt, wird postuliert.

8. Abbreviations

A	Ampere
Å	Ångström
Acr$^+$-Mes	9-mesityl-10-methylacridinium
AES	atomic emission spectroscopy
AIBN	azobisisobutyronitrile
APCI	atmospheric pressure chemical ionization
BDE	bond-dissociation energy
BI	benziodoxole
Boc	*tert*-butyloxycarbonyl protecting group
bpy	2,2´-bipyridine
Bu	butyl
Bzl	benzyl
°C	degree celsius
CAN	ceric ammonium nitrate, $(NH_4)_2Ce(NO_3)_6$
calc.	calculated
CBX	cyanobenziodoxone
CI	chemical ionization
CV	cyclic voltammetry
d_x	deuterated (x times)
DCA	9,10-dicyanoanthracene
DCC	*N*,*N*´-dicyclohexylcarbodiimide
DCE	1,2-dichloroethane
DCM	dichloromethane
DEPT	distortionless enhancement by polarization transfer
DIPEA	*N*,*N*-diisopropylethylamine
DMA	*N*,*N*-dimethylacetamide
DMAP	4-dimethylaminopyridine
DMF	*N*,*N*-dimethylformamide
DMSO	dimethyl sulfoxide
dtbpy	di-*tert*-butyl-2,2´-dipyridyl
EA	ethyl acetate
EBX	ethynylbenziodoxolone
ee	enantiomeric excess
EI	electron ionization
equiv.	equivalent
ESI	electrospray ionization
ET	electron transfer
Et	ethyl
eV	electron volts
EWG	electron-withdrawing group
Fc	ferrocene

FID	flame ionization detector
GC	gas chromatography
h	hour(s)
HAT	hydrogen atom transfer
HPLC	high-performance/pressure liquid chromatography
HRMS	high resolution mass spectrometry
ICP	inductively coupled plasma
ISC	intersystem crossing
J	coupling constant
K	Kelvin
LC	liquid chromatography
LED	light emitting diode
LG	leaving group
LMCT	ligand-to-metal-charge-transfer
LRMS	low resolution mass spectrometry
λ	wavelength
M	molar
mA	milli Ampere
Me	methyl
MF	molecular formula
mg	milligram
MHz	Megahertz
min	minute(s)
mL	milli liter
µL	micro liter
mmol	millimole
mol%	mole percent
MS	molecular sieve
MW	molecular weight
NHE	normal hydrogen electrode
NIR	near-infrared
NPhth	*N*-(acyloxy)phthalimide
nm	nanometer
NMR	nuclear magnetic resonance
OTf	triflate
p.a.	per analysis
PC	photocatalyst
PE	petroleum ether (hexanes)
PET	photoinduced electron transfer
Ph	phenyl

phen	phenanthroline
ppm	parts per million
ppy	2-phenylpyridine
Pr	propyl
QD	quantum dots
R	alkyl/aryl/functional group
rt	room temperature
SCE	saturated calomel electrode
SET	single electron transfer
SI	supporting information
TBACl	tetrabutyl ammonium chloride
TBATFB	tetrabutyl ammonium tetrafluoroborate
TEMPO	(2,2,6,6-tetramethylpiperidin-1-yl)oxyl
THF	tetrahydrofurane
TLC	thin layer chromatography
TMS	trimethylsilyl group
Tol	*p*-toluyl
UV	ultraviolet
V	Volt
vis	visible
vs	versus
W	Watt

9. Curriculum Vitae

PERSONAL DATA

Name:	Johanna Schwarz
Date of birth:	01.10.1990
Place of birth:	Regensburg
Nationality:	German
Marital status:	Married, one child

WORK EXPERIENCE

Since 07/2019	**Patent manager** at Carl Schlenk AG, Roth

EDUCATION

11/2015 – 10/2019	**Ph.D. Thesis** at the Institute of Organic Chemistry, University of Regensburg (Supervisor: Prof. Dr. B. König)
10/2013 – 09/2015	**Master of Science** in Chemistry, University of Regensburg **Master thesis:** *“Photocatalytic, decarboxylative arylation and alkylation of biomass-derived compounds”* (Supervisor: Prof. Dr. B. König)
10/2010 – 07/2013	**Bachelor of Science** in Chemistry, University of Regensburg **Bachelor thesis:** *“Photocatalytic, oxidative C–C bond formation with phenol derivatives”* (Supervisor: Prof. Dr. B. König)
08/2001 – 06/2010	**Allgemeine Hochschulreife** (A-Levels) at the Regental-Gymnasium Nittenau

AWARDS, SCHOLAR- AND MEMBERSHIPS

07/2016 – 09/2019	Scholarship of the “Deutsche Bundesstiftung Umwelt“
Since 12/2018	Personal mentor of a female, MINT-interested student as part of the program “CyberMentor Plus“
11/2015 – 03/2019	Member of the DFG-Graduate Training Group GRK 1626 “Chemical Photocatalysis”
Since 12/2015	Member of the GDCh (Gesellschaft Deutscher Chemiker)
Since 06/2010	Online-scholarship of e-fellows.net
2009/2010	Participation in the support program „Jugend Aktiv“ for very talented students

CONFERENCES UND WORKSHOPS

09/2018	26th Lecture Conference on Photochemistry, Garching/Munich, poster
07/2017	28th International Conference on Photochemistry (ICP), Strasbourg, poster
03/2017	Workshop “Electron Transfer, Radical Ions and Radical Chemistry”, Lyon
01/2017	“Green Chemistry Horizon” (Kármán Conference) and 1st BioSC Spotlight “Enzymes and processes for biomass degradation”, Aachen
08/2016	252nd ACS National Meeting & Exposition, Philadelphia, oral presentation
11/2015 – 03/2019	Several seminar days of the GRK 1626 (“Chemical Photocatalysis“) in Bavaria, oral presentations and posters

PUBLICATIONS

Paper	“Visible Light Induced Redox Neutral Fragmentation of 1,2-Diol Derivatives”, K.Chen, J. Schwarz, T. Karl and B. König, **2019**, manuscript submitted.
	“Visible-light mediated C–C bond cleavage of 1,2-diols to carbonyls by cerium-photocatalysis”, J. Schwarz and B. König, *Chem. Comm.*, **2019**, *55*, 486-488.
	“Decarboxylative alkynylation of biomass-derived compounds by metal-free visible light photocatalysis”, J. Schwarz and B. König, *ChemPhotoChem*, **2017**, *1*, 237-242.
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Review	“Decarboxylative reactions with and without light – a comparison”, J. Schwarz and B. König, *Green Chem.*, **2018**, *20*, 323-361.
Book chapter	“Photocatalytic decarboxylations”, J. Schwarz, in *Physical Science Reviews* (De Gruyter), **2018**, vol.3, issue 7.

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