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β-酮腈类化合物合成方法研究进展：从传统离子型策略到酰基自由基氢酰化

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摘　要

β-酮腈类化合物同时含有羰基和氰基两类重要官能团，是有机合成中极具价值的多功能中间体。文章系统综述了β-酮腈类化合物的主要合成策略，包括腈α-位酰化、酮烯醇盐或其等效体的亲电氰化、β-酮羰基化合物直接α-氰化、过渡金属催化羰基化偶联以及氧化偶联等传统非自由基方法。同时，重点总结了近年来自由基和光化学策略在β-酮腈合成中的应用，尤其是醛、苯并噻唑啉、4-酰基汉斯酯和酰氯等酰基自由基来源参与活化烯烃加氢酰化反应的研究进展。现有方法虽已取得显著发展，但仍存在局限，发展以简单易得芳香醛为直接底物、反应条件更温和简洁、无需金属或复杂前体的新型β-酮腈构建方法，仍具有重要的方法学意义和应用价值。

关键词

β-酮腈，酰基自由基，氢酰化，自由基反应，光化学合成

Recent Advances in Synthetic Methods for β-Ketonitriles: From Traditional Ionic Strategies to Acyl Radical Hydroacylation

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Abstract

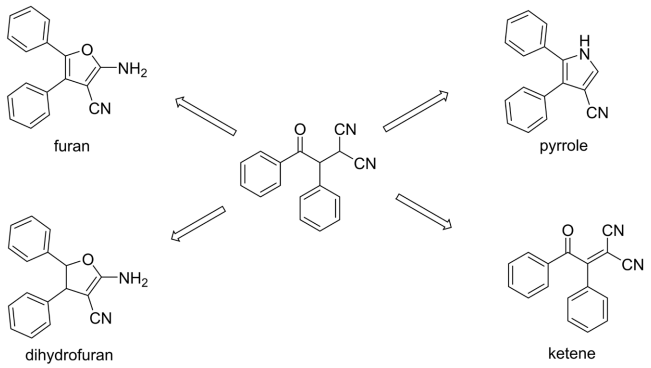
β-Ketonitriles, bearing both carbonyl and cyano functional groups, are highly valuable multifunctional intermediates in organic synthesis. This article summarizes the major synthetic strategies for β-ketonitriles, including classical non-radical approaches such as α-acylation of nitriles, electrophilic cyanation of ketone enolates or their equivalents, direct α-cyanation of β-keto carbonyl compounds, transition-metal-catalyzed carbonylative coupling, and oxidative coupling reactions. Particular attention is given to recent advances in radical and photochemical strategies, especially hydroacylation reactions of activated alkenes enabled by acyl radicals generated from aldehydes, benzothiazolines, 4-acyl Hantzsch esters, and acyl chlorides. Although significant progress has been made with existing methodologies, limitations remain. Developing novel methods for constructing β-ketonitriles using readily available aromatic aldehydes as direct substrates under milder and simpler conditions, without requiring metals or complex precursors, continues to hold important methodological significance and practical value.

Keywords

β-Ketonitriles, Acyl Radical, Hydroacylation, Radical Reaction, Photochemical Synthesis

1. β-酮腈类化合物简介

β-酮腈是兼具羰基与氰基的双官能团化合物。得益于羰基和氰基均可发生多样化的后续转化，β-酮腈既能够作为有机合成中的关键中间体参与多种官能团转化(图 1)，也可充当多功能合成砌块，用于高效搭建复杂分子骨架及多种杂环结构[1]。相关骨架常见于药物分子和生物活性化合物中，因此在基础研究和应用场景开发中均受到关注[2]-[4]。例如，β-酮腈经不对称还原可进一步转化为手性 β-羟基腈，为含手性中心分子的合成提供重要入口[5]-[9]。近些年，β-酮腈在碳环、芳香环、杂环、螺环以及稠合杂环体系的构筑中均显示出较好的适用范围，已逐步成为高附加值中间体研究中的重要对象[10]-[12]。另外，β-酮腈还可转化为吡咯及其他含氮杂环，因此在含氮骨架合成中具有特殊意义[13]-[18]。因此，建立操作简便、效率较高且底物适用性良好的 β-酮腈合成方法，依然是有机合成领域值得持续关注的问题。

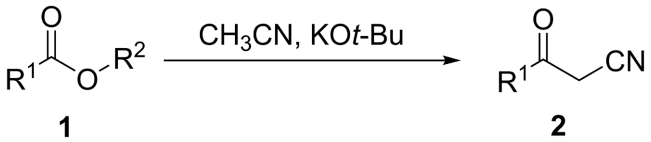


Scheme 1. Applications of β-ketonitriles in transformations
图 1. β-酮腈类化合物的转化应用

2. 传统非自由基策略合成 β-酮腈化合物

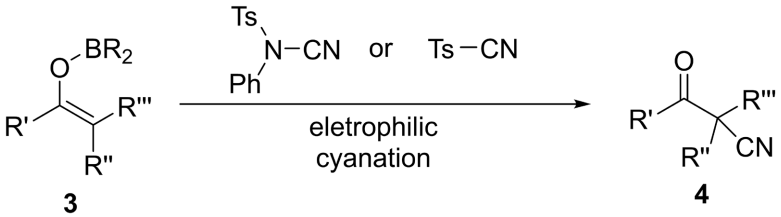
鉴于 β-酮腈同时包含羰基和氰基两类高价值官能团，其构建方法一直是合成化学研究中的重要课题。已有的离子型或非自由基路线主要涵盖腈 α-位酰化、酮烯醇盐或其等效体的亲电氰化、β-酮羰基化合物的直接 α-氰化以及过渡金属催化羰基化偶联等类型[19]。

腈 α-位酰化属于较早建立且应用场景广泛的路线。通常，该策略经由强碱夺取腈 α-位质子，形成相应的碳负离子物种，再与酯、内酯或其他酰基供体发生 Claisen 型酰基转移反应，进而构筑 β-酮腈骨架。该路线设计直观，所需原料通常较易获得，并适用于若干结构相对简单的 β-酮腈制备，因而长期被认为是该类化合物合成的基础方法[20]-[26]。基于这一思路，Pienaar 等于 2019 年发展了以酯和内酯为酰基来源、以腈为亲核组分、KO*t*-Bu 为碱制备 β-酮腈及三官能化中间体的方法[27]。该反应显示出原料成本低、操作较为直接以及一定的绿色化优势，表明传统酰化路线经条件优化后仍具有实用价值(图 2)。然而，这类方法往往仍需要较强的碱条件，这也限制了其在官能团耐受性、区域选择性和复杂分子应用场景方面的进一步拓展。



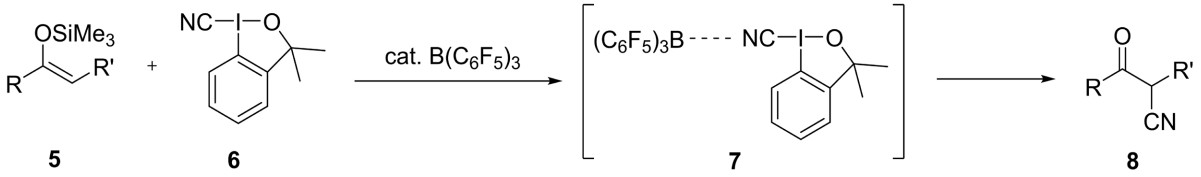
Scheme 2. Under the action of KO*t*-Bu, acetonide anion is generated and the esterification occurs with the lactone in the ether solvent
图 2. KO*t*-Bu 作用下生成乙腈阴离子与内酯在醚溶剂中的酰化

与腈 α-位酰化不同，酮烯醇盐或其等效体的亲电氰化则代表了由羰基化合物出发安装氰基单元的另一种重要方法。该方法通常先形成烯醇盐、硅烯醚或硼烯醇盐等烯醇等效体，再利用亲电氰化试剂在 α-位引入 CN 单元，最终得出 β-酮腈。1981 年，Kahne 和 Collum 发展了酮烯醇盐与对甲苯磺酰氰之间的动力学氰化反应，说明烯醇化物可经由高效氰化转化为 β-酮腈[28]。伴随亲电氰化试剂的发展，该方向在近年获得了进一步发展。2016 年，Kiyokawa、Nagata 和 Minakata 发展了硼烯醇盐的亲电氰化反应，利用 NCTS 或 TsCN 即可合成多种 β-酮腈，并可构建含季碳中心的底物[29] (图 3)。该工作展示了该策略在底物范围和合成应用场景方面的潜力。



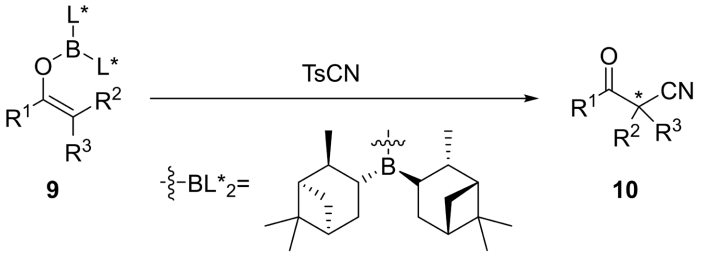
Scheme 3. Electrophilic cyanation of boron enolates
图 3. 硼烯醇酸盐的亲电氰化

2017 年，Nagata 等又提出 $B(C_6F_5)_3$ 活化苯并噁唑型氰化试剂的策略，完成了硅烯醚的催化亲电氰化[30]。在该体系中，路易斯酸 $B(C_6F_5)_3$ 经由与氰化试剂的氰基配位增强其亲电性，继而硅烯醚进攻氰基，并经加成－消除了过程生成目标产物(图 4)。该研究从试剂活化角度为温和构建 β-酮腈提供了新的设计思路。



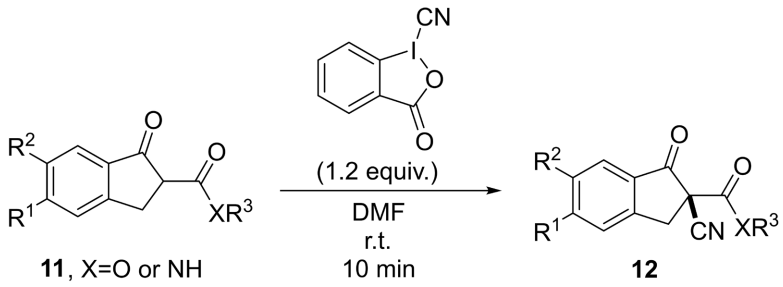
Scheme 4. Catalytic electrophilic cyanation of silane ethers
图 4. 硅烯醚的催化亲电氰化

继而，Nagata、Tamaki 和 Kiyokawa 等又将硼烯醇盐亲电氰化进一步应用于不对称反应，完成了手性 *β*-酮腈的高对映选择性合成[31] (图 5)。这表明亲电氰化路线不仅可以实现高效成键，而且具备进一步发展立体选择性控制的潜力。



Scheme 5. Asymmetric electrophilic cyanation of boron enolates
图 5. 硼烯醇盐的不对称亲电氰化

除了一般酮类底物外，*β*-酮酯和 *β*-酮酰胺等 *β*-酮羰基化合物也可经由直接 *α*-氰化获得高官能化腈类产物。鉴于这类底物更易形成烯醇或烯醇盐，因此通常可以在较温和条件下反应。2015 年，陈甫雪课题组以氰基苯并噁唑为氰化试剂，对 *β*-酮酯和 *β*-酮酰胺进行直接亲电 *α*-氰化[32]。该反应在 DMF、室温且无催化剂条件下即可快速完成，并可高效构建含季碳中心的 *β*-酮腈衍生物(图 6)。该策略降低了 *β*-酮羰基底物 *α*-氰化的操作流程，也为复杂 *β*-酮腈骨架的快速制备提供了便捷途径。

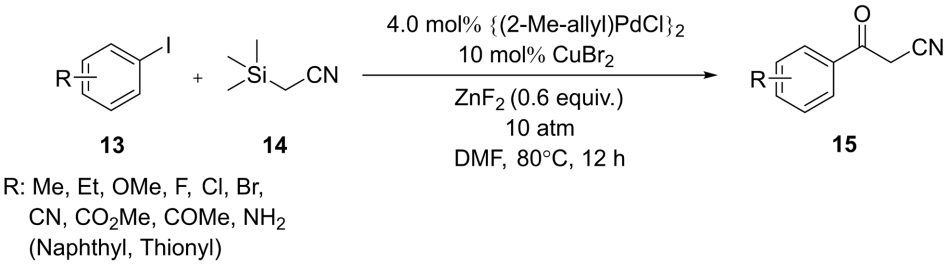


Scheme 6. Direct electrophilic cyanation of *β*-ketones and amides with cyano-benzoxazole
图 6. *β*-酮酯和酰胺与氰基苯并噁唑的直接亲电氰化

总体而言，亲电氰化方法在效率和选择性方面表现出优势，但往往需要预先制备烯醇盐、硅烯醚或硼烯醇盐，并依赖专门的亲电氰化试剂。因此，在操作简便性、底物普适性和规模化应用场景方面仍有一定局限。

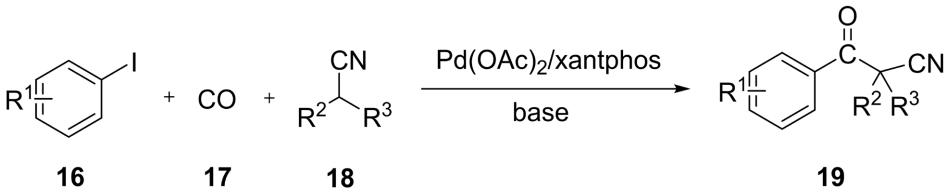
过渡金属催化羰基化偶联则为该骨架构建提供了另一类构建 *β*-酮腈的模块化策略。与“先生成烯醇等效体、再引入氰基”的路线不同，羰基化偶联通常以 CO 为羰基来源，在过渡金属催化下将卤代芳烃、

腈组分与羰基源组装为 β-酮腈。2012 年，Park 和 Lee 发展了芳基碘化物与三甲基硅乙腈的 Pd 催化羰基化反[33]。该方法以 $Mo(CO)_6$ 为 CO 来源，在无需额外配体的条件下一锅合成苯甲酰乙腈类化合物，显示出较好的官能团兼容性和应用场景价值(图 7)。



Scheme 7. Pd-catalyzed carbonylation of aryl iodides and trimethylsilyl ethanone
图 7. 芳基碘化物和三甲基硅乙腈的 Pd 催化羰基化

2014 年，Schranck、Burhardt 和 Bornschein 等进一步建立了未活化腈参与的 Pd 催化羰基化 α-芳基化反应，首次完成了未预官能团化腈底物的羰基化 α-芳基化[34]，且能够较方便地引入 ^{13}CO 标记羰基(图 8)。该类方法在分子片段模块化组装和同位素标记方面具有独特价值，但该类体系通常需要 CO 或 CO 替代源、贵金属催化剂以及相应反应装置，因此在绿色性和操作便利性方面仍存在优化空间。



Scheme 8. Pd-catalyzed carbonylation of α-arylation to β-ketonitriles
图 8. Pd 催化的羰基化 α-芳基化转化为 β-酮腈

需要指出的是，上述传统非自由基策略虽然各有特点且已在特定场景中得到应用，但它们共同面临着一些难以回避的瓶颈问题：1) 腈 α-位酰化依赖强碱条件，不仅对湿气和空气敏感，而且强碱环境限制了多种敏感官能团的共存；2) 亲电氰化路线通常需要预先制备烯醇盐、硅烯醚或硼烯醇盐等中间体，增加了操作步骤和试剂成本，同时专用氰化试剂(如 NCTS)的制备和储存也存在一定挑战；3) 过渡金属催化羰基化偶联虽然实现了模块化组装的优势，但对贵金属(Pd、Ir 等)的依赖以及 CO 气体的使用带来了显著的绿色性和安全性顾虑，同时也增加了工业化生产的设备投入和安全管控成本。正是基于对这些局限性的认识，近年来研究者开始探索能够避免上述问题的替代方案——即通过自由基途径实现 β-酮腈的高效构建。自由基策略的核心优势在于：反应条件更为温和(常可在室温附近进行)、无需使用强碱或贵重金属催化剂、对官能团具有更好的兼容性，并且原子经济性往往更高。以下将分别讨论由醛直接产生酰基自由基以及由预制前体释放酰基自由基的两条主要自由基路径。

3. 自由基策略合成 β-酮腈化合物

值得注意的是，在自由基策略内部同样存在一个方法论演进的过程。早期的研究主要依赖过氧化物引发剂和传统热自由基条件(如 NHPI 介导的链式反应)，这些方法虽然证明了醛直接转化为酰基自由基的可行性，但仍存在选择性差、副反应多等问题。随着光化学和氢原子转移(HAT)催化的发展，醛的选择性

C-H 活化逐渐成为可能——光催化剂或 HAT 催化剂能够在温和条件下特异性地攫取甲酰基 C-H 键，从而大幅提升了反应的区域选择性和官能团兼容性。这一演进过程清晰地展示了催化手段创新如何推动自由基合成方法从“可行”走向“实用”。

近些年，β-酮腈合成已由传统离子型反应延伸至自由基和光化学体系。在这类反应中，一般首先形成酰基自由基，继而其对活化烯烃发生加成，再经氢转移、单电子转移或其他终止过程得到目标 β-酮腈[35]-[39]。与传统非自由基策略相较而言，自由基路径通常能够在较温和的条件下完成高活性双键受体的转化，并降低对底物预官能团化的依赖[40]-[45]，因此成为该领域近年来的重要研究方向。

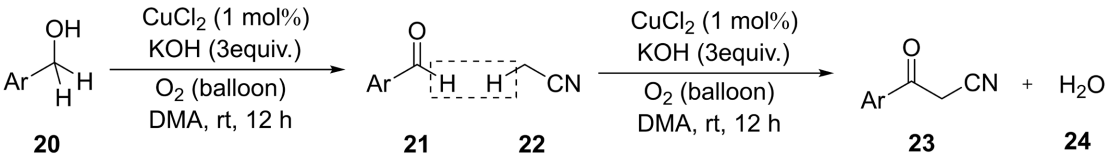
3.1. 由醛直接产生酰基自由基

酰基自由基可参与烯烃加成、交叉偶联和多种串联转化，是自由基化学中非常重要的活性中间体[46]-[49]。直接由醛生成酰基自由基尤其受到关注，因为醛类原料具有来源丰富、成本较低和结构类型多样等特点；若能够直接转化甲酰基 C-H 键，则可避免额外前体制备，由此提高步骤经济性和原子经济性[50]-[52]。

早期研究已经说明醛可在自由基条件下直接参与后续成键反应。2001 年，Tsujimoto、Iwahama 和 Sakaguchi 等以 N-羟基二甲酰亚胺(NHPI)为极性反转催化剂，完成了醛对烯烃的自由基链式加成[53]。尽管该方法仍需过氧化物引发，但该结果清楚说明醛的甲酰基 C-H 键能够在适当条件下转化为酰基自由基。

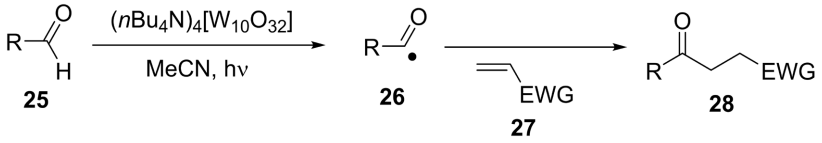
除了醛直接自由基加成外，氧化偶联也为 β-酮腈构建提供了区别于传统酰化和氰化的新途径。2014 年，刘仁华课题组发展了铜催化芳香醇与乙腈的有氧氧化偶联反应，以氧气为终端氧化剂直接获得 β-酮腈[54]。在该体系中，苯甲醇首先被氧化为苯甲醛，继而醛与乙腈发生氰甲基化并进一步氧化生成目标产物。作者认为，铜中心与乙腈作用可降低乙腈 pKa，并在氧气参与下形成活性氧化物种，进而推动醛中间体向 β-酮腈转化(图 9)。该工作经由脱氢 C-C 偶联直接搭建 β-酮腈骨架，减少了预制烯醇等效体的步骤，体现了不同的成键设计理念。

从底物范围角度考察(图 9)，该反应展现了较好的芳香醇适应性：无论是带有给电子基团(如甲基、甲氧基)的苯甲醇衍生物，还是带有吸电子基团(如氯、溴、氟、三氟甲基)的对位取代苯甲醇，均可顺利参与反应并以中等至良好的收率获得相应 β-酮腈产物。特别值得关注的是，萘甲醇和杂环甲醇(如呋喃甲醇、噻吩甲醇)同样可以作为有效的底物，这表明该方法在药物分子骨架构建中可能具有广泛的应用潜力。然而，该方法目前主要局限于芳香醇与乙腈的组合，脂肪族醇类和取代乙腈的适用性尚未得到充分验证。



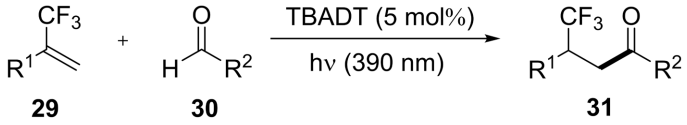
Scheme 9. Copper-catalyzed aerobic oxidation coupling of aromatic alcohols and acetonitrile to form β-ketonitriles
图 9. 铜催化芳香醇和乙腈的需氧氧化偶联为 β-酮腈

伴随光化学和氢原子转移(HAT)化学的发展，醛的直接光活化已成为酰基自由基生成的重要途径[55]-[60]。2007 年，Esposti、Dondi 和 Fagnoni 等利用十钨酸盐光催化剂完成了醛对亲电烯烃的酰化反应[61]。激发态 TBADT 从醛中攫取氢原子生成酰基自由基，继而该自由基被缺电子烯烃捕获，并经反向氢转移得到目标产物(图 10)。该研究将醛直接获得酰基自由基的概念从传统热自由基体系拓展至条件更温和且可调控的光化学平台。



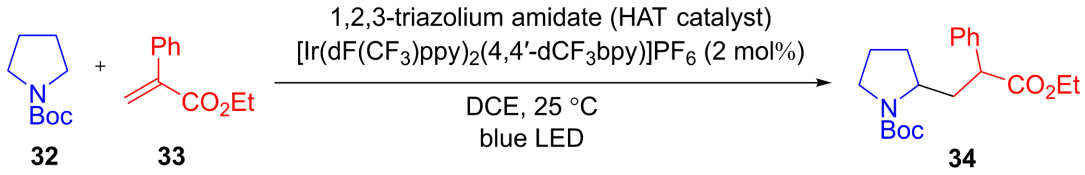
Scheme 10. Acetylation of electrophilic alkenes by ten tungstate-photocatalytic activation of aldehydes
图 10. 通过十钨酸盐－光催化活化醛对亲电烯烃的酰化

此后，醛直接产生酰基自由基的受体范围持续拓展。2019 年，王川课题组发展了三氟甲基烯烃的光催化加氢酰化反应[62]。在 TBADT 作用下，醛被转化为酰基自由基，并与三氟甲基烯烃发生加成，同时有效抑制 β-F 消除，从而得到一系列 β-CF_3 酮产物(图 11)。该研究表明，经过合理设计的 HAT 光催化体系有助于提高醛直接酰基化反应的效率和区域选择性。



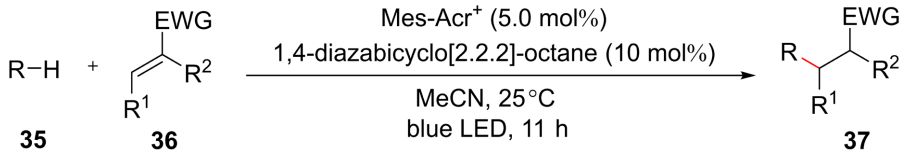
Scheme 11. Photocatalytic hydrogenation acylation of trifluoromethyl alkenes
图 11. 三氟甲基烯烃的光催化加氢酰化

HAT 催化剂的设计也促进了该方向的发展。2020 年，Ohmatsu、Suzuki 和 Furukawa 等发展了两性离子 1,2,3-三唑鎓酰胺催化剂，并说明其可在可见光氧化还原条件下高效介导 HAT 过程[63]。该体系经由光氧化还原过程生成酰胺基自由基，继而从 C-H 底物中夺氢形成碳自由基，再与缺电子烯烃加成，最终经 SET 和质子化得到烷基化产物(图 12)。虽然该反应并非直接用于构筑 β-酮腈，但从催化剂设计角度表明，稳定且可单电子氧化的酰胺结构能够作为有效 HAT 平台。



Scheme 12. Zwitterionic 1,2,3-triazolium amide acts as a catalyst for photo-induced hydrogen atom transfer radical alkylation
图 12. 两性离子 1,2,3-三唑鎓酰胺为催化剂光诱导氢原子转移自由基烷基化

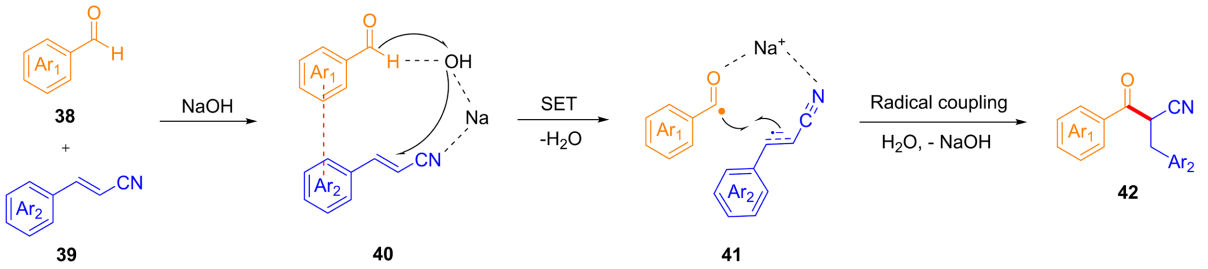
2022 年，Matsumoto、Yamamoto 和 Maruoka 发展了阳离子 DABCO 型 HAT 催化剂，完成了位点选择性 C-H 烷基化反应[64]。该催化体系经由吖啶鎓光催化剂激发态引发单电子氧化，并经分子内电子转移生成活性胺自由基物种，从而选择性攫取底物 C-H 键氢原子，生成的碳自由基再与缺电子烯烃偶联(图 13)。这些研究为醛及其他 C-H 底物经 HAT 过程生成自由基中间体提供了重要催化基础。



Scheme 13. Cationic DABCO catalyst achieves site-selective C-H alkylation through photo-induced hydrogen atom transfer
图 13. 阳离子 DABCO 催化剂通过光诱导氢原子转移实现位点选择性 C-H 烷基化

需要指出的是，酰基自由基的形成并非一定依赖外部光照。2025 年，刘伟和欧伟课题组发展了芳基丙烯腈的直接加氢酰化反应，该反应在碱促进和 EDA 复合物协助下可于无光条件中进行[65]。作者认为，醛、芳基丙烯腈和 NaOH 形成有色 EDA 复合物后，可发生分子间 SET 和 HAT 过程，生成酰基自由基和 α-氰基自由基接触对，继而经自由基偶联和质子化得到 β-酮腈产物(图 14)。这一结果表明，β-酮腈构建已从传统光氧化还原体系扩展到自由基与电子给受体协同的新模式。

整个催化循环可分为以下几个关键步骤：1) EDA 复合物形成：在 NaOH 条件下，醛去质子化生成烯醇负离子(电子供体)，与缺电子的芳基丙烯腈(电子受体)相互作用，形成 EDA 复合物。2) 单电子转移(SET)：EDA 复合物经可见光或热促进，发生分子间 SET，从烯醇负离子向芳基丙烯腈转移一个电子，生成自由基阴/阳离子对。3) PCET/HAT：SET 中间体迅速经质子或氢原子转移，释放出酰基自由基与 α-氰基碳自由基两个关键活性物种。4) 自由基–自由基偶联：两种自由基在溶剂笼内高效偶联，形成新 C-C 键，构建 β-酮腈骨架。5) 质子化：烷氧负离子质子化得到最终产物。该机理无需任何外加光催化剂、过渡金属或氧化还原剂，仅依靠反应组分自身形成的 EDA 复合物驱动，是目前最简洁的 β-酮腈合成策略之一。



Scheme 14. EDA complex facilitates the direct hydrogenation of aryl acrylates
图 14. EDA 复合物协助芳基丙烯腈直接氢酰化

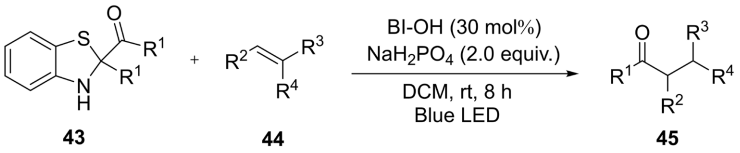
总体而言，醛直接获得酰基自由基具有原料易得、步骤经济性好以及原子利用率较高等优点。不过，该策略仍面临一些问题：甲酰基 C-H 键的选择性活化通常需要合适的 HAT 催化剂、光敏剂或激发态过程调控；同时，酰基自由基在部分体系中可能发生脱羰、副反应或选择性下降。因此，发展更简洁、更可控的醛直接酰基自由基反应仍具有重要研究价值。

3.2. 由预制酰基自由基前体产生酰基自由基

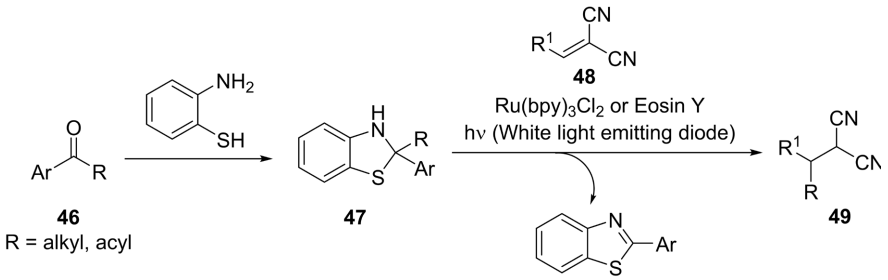
与醛直接活化相较而言，将醛或其他羰基来源预先转化为更活泼的酰基自由基前体，再在光、热或氧化还原条件下释放酰基自由基，也是一类应用场景较多且相对易于调控的策略[66]-[76]。该方法的其优势主要体现在，自由基活性被前体化后，可在较稳定、可预测的状态下储存，并在需要时释放，因此在反应可控性和自由基生成效率方面更具可操作性[77]-[82]。

苯并噻唑啉类化合物是近年较具代表性的酰基自由基前体。2019 年，朱进课题组发展了以 C2-酰基取代苯并噻唑啉为酰基自由基来源的策略[83]。该体系在可见光照射下，经由芳构化驱动的 C-C 键均裂生成酰基自由基，并进一步用于自由基烷基化、烯基化和炔基化反应(图 15)。该工作拓展了苯并噻唑啉在自由基化学中的应用场景，也为温和条件下酰基自由基参与的 C-C 键构建提供了新思路。

同年，Uchikura、Moriyama 和 Toda 等发展了 2-酰基取代苯并噻唑啉作为自由基转移试剂，在光照条件下实现烯烃的加氢酰化和加氢烷基化[84]。在该体系中，苯并噻唑啉经光氧化还原催化剂 SET 氧化后释放酰基或烷基自由基，自由基加成至烯烃后再经 SET 还原和质子化得到产物(图 16)。该方法利用结构可调的苯并噻唑啉温和释放自由基，减少了高毒性试剂和大量金属的使用。

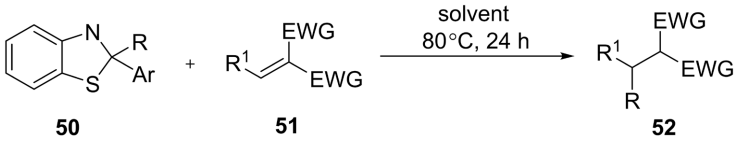


Scheme 15. C2-acyl-substituted benzothiazolinol generates an acyl radical
图 15. C2-酰基取代苯并噻唑啉生成酰基自由基



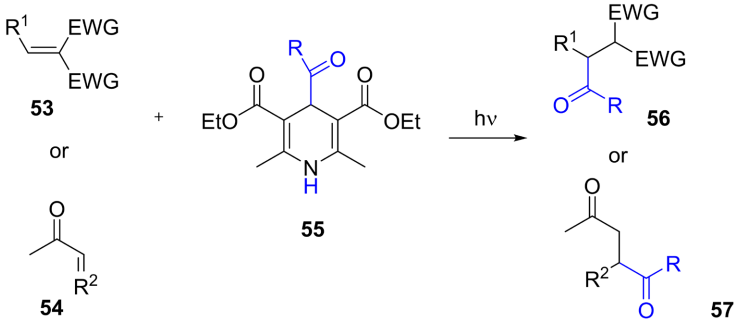
Scheme 16. Benzothiazolin as an acyl radical transfer reagent
图 16. 苯并噻唑啉作为酰基自由基转移试剂

2020 年，Uchikura 等进一步建立了热促进版本，在无光、无添加剂条件下实现电子缺陷烯烃的加氢烷基化和加氢酰化[85] (图 17)。这表明苯并噻唑啉既能够作为光化学自由基前体，也可在热条件下表现出较高自由基转移活性，显示出该类前体的可调控性和实用潜力。



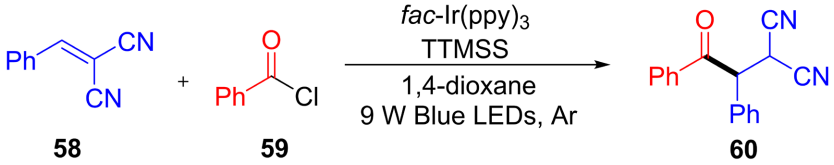
Scheme 17. Radical hydrogen alkylation and hydrogen acylation of benzothiazolin under thermal conditions
图 17. 苯并噻唑啉在热条件下的自由基氢烷基化和氢酰化

除了苯并噻唑啉外，4-酰基汉斯酯也是一类重要的酰基自由基储库。2022 年，Pálvölgyi、Ehrschwendtner 和 Schnürch 等以 4-酰基汉斯酯为自由基来源，在无光催化剂和无添加剂条件下实现缺电子烯烃和烯酮的加氢酰化[86]。作者认为该反应可能经直接光激发进行：4-酰基汉斯酯吸收可见光后生成酰基自由基，继而对苄烯丙二腈发生共轭加成，生成的自由基中间体再从基态汉斯酯获得氢原子，形成加氢酰化产物(图 18)。该策略将自由基来源和氢源功能整合于同一分子中，体系相对简洁。



Scheme 18. 4-Acyl Hantzsch ester generates an acyl radical
图 18. 4-酰基汉斯酯生成酰基自由基

近些年，酰氯也被用于酰基自由基前体。2024 年，官智、何延红课题组发展了酰氯与苄烯丙二腈的可见光诱导加氢酰化反应[87]。该体系以三(三甲基硅基)硅烷(TTMSS)同时作为氢原子供体和电子供体，并在 Ir 光催化剂作用下生成酰基自由基。酰基自由基加成至苄烯丙二腈后，所得自由基中间体从 TTMSS 获得氢原子形成 *β*-酮腈产物，同时硅自由基还原 Ir(IV)完成催化循环(图 19)。



Scheme 19. Acyl chloride generates acyl free radicals
图 19. 酰氯生成酰基自由基

1) 不对称自由基合成方法的开发：利用手性 HAT 催化剂或手性光催化剂实现 *β*-酮腈的不对称合成，结合有机小分子光催化剂与手性布朗斯特酸/碱协同催化策略，有望取得重要突破。

2) 底物范围的拓展：开发适用于非共轭烯烃或炔烃的加氢酰化策略，构建 *γ*、*δ*-位官能化羰基化合物；同时借助新型 HAT 催化剂活化惰性 C-H 键(如烷烃、醚类)，将进一步扩展方法适用范围。

3) 流动化学与连续流工艺的应用：针对光化学反应放大中光穿透深度受限及自由基反应对传质传热敏感等问题，引入流动化学体系是实现高效、安全、可控合成的理想途径。

4) 绿色催化体系的持续创新：探索新型有机电子供体–受体组合、机械力化学驱动的酰基自由基生成及生物酶催化酰基化等新兴策略，为 *β*-酮腈绿色合成提供全新思路。

总体来看，现有 *β*-酮腈合成方法已经较为多样，但不同策略仍存在自身限制[88]。因此，从简单易得底物出发，在更简洁、温和且少依赖外加催化体系的条件下发展新的 *β*-酮腈构建方法，仍具有明确的方法学意义和潜在应用场景价值。

4. 总结

β-酮腈因同时含有羰基和氰基而具有较高合成价值，可进一步转化为吡咯及其他含氮杂环结构，在药物化学、天然产物合成和功能分子构建中均具有重要意义。

围绕 *β*-酮腈骨架的构建，已有研究发展了腈 *α*-位酰化、亲电氰化、*β*-酮羰基化合物直接 *α*-氰化、过渡金属催化羰基化偶联、氧化偶联以及自由基/光化学加氢酰化等多种策略。这些方法在反应设计、成键效率和底物拓展方面取得了明显进展，但也不同程度依赖强碱、专用氰化试剂、CO 或 CO 替代源、贵金属催化剂、复杂 HAT 催化体系以及预制酰基自由基前体。因此，在反应条件简洁性、底物普适性和实际应用场景便利性方面仍存在提升空间。

同时，酰基自由基生成方式和芳香醛参与光促进偶联反应的研究表明，酰基自由基既可由醛直接活化产生，也可由苯并噻唑啉、4-酰基汉斯酯、酰氯等前体释放，并进一步与活化烯烃发生加成偶联，为 *β*-酮腈骨架构建提供了重要方法学基础。然而，以简单芳香醛为直接底物，在不依赖金属试剂、复杂 HAT 试剂和预制酰基自由基前体的条件下实现活化烯烃偶联构建 *β*-酮腈的研究仍相对有限，仍有必要进一步探索更简洁、更绿色的新反应体系。

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参考文献

[1] Elnagdi, M.H., Elmoghayar, M.R.H. and Elgemeie, G.E.H. (1984) The Chemistry of 3-Oxoalkanenitriles. *Synthesis*, **1984**, 1-26. https://doi.org/10.1055/s-1984-30717

[2] Khidre, R.E., Abdelwahab, B.F. and Badria, F.A.-R. (2011) New Quinoline-Based Compounds for Analgesic and Anti-Inflammatory Evaluation. *Letters in Drug Design & Discovery*, **8**, 640-648. https://doi.org/10.2174/157018011796235194

[3] Khidre, R.E. and Abdelwahab, B.F. (2013) Synthesis of 5-Membered Heterocycles Using Benzoylacetonitriles as Synthon. *Turkish Journal of Chemistry*, **37**, 685-712. https://doi.org/10.3906/kim-1211-31

[4] Hauser, C.R. and Eby, C.J. (1957) Cyclization of *β*-Ketonitriles or *β*-Ketoamides with Ketones by Polyphosphoric Acid to Form Substituted 2-Pyridones. *Journal of the American Chemical Society*, **79**, 728-731. https://doi.org/10.1021/ja01560a062

[5] Florey, P., Smallridge, A.J., Ten, A. and Trewhella, M.A. (1999) Chemo- and Stereoselective Reduction of an *α*-Cyanoketone by Bakers' Yeast at Low Temperature. *Organic Letters*, **1**, 1879-1880. https://doi.org/10.1021/ol990833y

[6] Watanabe, M., Murata, K. and Ikariya, T. (2002) Practical Synthesis of Optically Active Amino Alcohols via Asymmetric Transfer Hydrogenation of Functionalized Aromatic Ketones. *The Journal of Organic Chemistry*, **67**, 1712-1715. https://doi.org/10.1021/jo011076w

[7] Zhu, D., Ankati, H., Mukherjee, C., Yang, Y., Biehl, E.R. and Hua, L. (2007) Asymmetric Reduction of *β*-Ketonitriles with a Recombinant Carbonyl Reductase and Enzymatic Transformation to Optically Pure *B*-Hydroxy Carboxylic Acids. *Organic Letters*, **9**, 2561-2563. https://doi.org/10.1021/ol070962b

[8] Ankati, H., Zhu, D., Yang, Y., Biehl, E.R. and Hua, L. (2009) Asymmetric Synthesis of Both Antipodes of *β*-Hydroxy Nitriles and *β*-Hydroxy Carboxylic Acids via Enzymatic Reduction or Sequential Reduction/Hydrolysis. *The Journal of Organic Chemistry*, **74**, 1658-1662. https://doi.org/10.1021/jo802495f

[9] Soltani, O., Ariger, M.A., Vázquez-Villa, H. and Carreira, E.M. (2010) Transfer Hydrogenation in Water: Enantioselective, Catalytic Reduction of *α*-Cyano and *α*-Nitro Substituted Acetophenones. *Organic Letters*, **12**, 2893-2895. https://doi.org/10.1021/ol1008894

[10] Robinson, J.M., Ahmed, M., Alaniz, N.J., Boyles, T.R., Brasher, C.D., Floyd, K.A., *et al*. (1998) Pyridine Syntheses. II. Condensation Routes toward Streptonigrin Ring C. *Journal of Heterocyclic Chemistry*, **35**, 65-69. https://doi.org/10.1002/jhet.5570350113

[11] Ryabukhin, S.V., Plaskon, A.S., Ostapchuk, E.N., Volochnyuk, D.M., Shishkin, O.V., Shivanyuk, A.N., *et al*. (2007) A One-Step Fusion of 1,3-Thiazine and Pyrimidine Cycles. *Organic Letters*, **9**, 4215-4218. https://doi.org/10.1021/ol701782v

[12] Reddy, P.S.N. and Reddy, P. (2004) Synthesis of Pyrazolo[5',1':2,3]Pyrimido[4,5-b][1,4]-Benzoxazines, a NEW Heterocyclic Ring System from 5(3)-Aminopyrazoles. *Heterocyclic Communications*, **10**, 163-166. https://doi.org/10.1515/hc.2004.10.2-3.163

[13] Rostampoor, A. and Alizadeh, A. (2025) Recent Advances in the Application of *β*-Ketonitriles as Multifunctional Intermediates in Organic Chemistry. *RSC Advances*, **15**, 14558-14586. https://doi.org/10.1039/d4ra07788a

[14] Shi, T., Yin, G., Wang, X., Xiong, Y., Peng, Y., Li, S., *et al*. (2023) Recent Advances in the Syntheses of Pyrroles. *Green Synthesis and Catalysis*, **4**, 20-34. https://doi.org/10.1016/j.gresc.2022.06.004

[15] Bhardwaj, V., Gumber, D., Abbot, V., Dhiman, S. and Sharma, P. (2015) Pyrrole: A Resourceful Small Molecule in Key Medicinal Hetero-Aromatics. *RSC Advances*, **5**, 15233-15266. https://doi.org/10.1039/c4ra15710a

[16] Jeelan, B.N., Basavarajaiah, S.M. and Shyamsunder, K. (2022) Therapeutic Potential of Pyrrole and Pyrrolidine Analogs: An Update. *Molecular Diversity*, **26**, 2915-2937. https://doi.org/10.1007/s11030-022-10387-8

[17] Singh, N., Singh, S., Kohli, S., Singh, A., Asiki, H., Rathee, G., *et al*. (2021) Recent Progress in the Total Synthesis of Pyrrole-Containing Natural Products (2011-2020). *Organic Chemistry Frontiers*, **8**, 5550-5573. https://doi.org/10.1039/d0qo01574a

[18] Seipp, K., Geske, L. and Opatz, T. (2021) Marine Pyrrole Alkaloids. *Marine Drugs*, **19**, Article 514. https://doi.org/10.3390/md19090514

[19] Kiyokawa, K., Minakata, S. and Nagata, T. (2018) Recent Advances in the Synthesis of *β*-Ketonitriles. *Synthesis*, **50**, 485-498. https://doi.org/10.1055/s-0036-1589128

[20] Dorsch, J.B. and McElvain, S.M. (1932) The Preparation of Benzoylacetic Ester and Some of Its Homologs. *Journal of the American Chemical Society*, **54**, 2960-2964. https://doi.org/10.1021/ja01346a047

[21] Blake, J., Willson, C.D. and Rapoport, H. (1964) 3-Pyrrolidinones by Intramolecular Condensation. *Journal of the American Chemical Society*, **86**, 5293-5299. https://doi.org/10.1021/ja01077a049

[22] Eby, C.J. and Hauser, C.R. (1957) Acylations of Nitriles with Esters by Sodium Amide in Liquid Ammonia to Form *β*-Ketonitriles. Consideration of Amidine Formation[1]. *Journal of the American Chemical Society*, **79**, 723-725. https://doi.org/10.1021/ja01560a060

[23] Barhdadi, R., Gal, J., Heintz, M. and Troupel, M. (1992) Aryl Halides as Convenient Precursors of Electrogenerated Bases. Efficient Syntheses of *β*-Oxo Nitriles or Esters by Coupling Active-Hydrogen Groups with Esters. *Journal of the Chemical Society*, *Chemical Communications*, **28**, 50-51. https://doi.org/10.1039/c39920000050

[24] Hébri, H., Duñach, E. and Périchon, J. (1992) Samarium-Catalyzed Electrochemical Cyanomethylation of Esters. *Synlett*, **1992**, 293-294. https://doi.org/10.1055/s-1992-21343

[25] Kayaleh, N.E., Gupta, R.C. and Johnson, F. (2000) Enolate Ions as *β*-Activators of Ortho-Metalation: Direct Synthesis of 3-Aminoindenones. *The Journal of Organic Chemistry*, **65**, 4515-4522. https://doi.org/10.1021/jo991968k

[26] Ji, Y., Trenkle, W.C. and Vowles, J.V. (2006) A High-Yielding Preparation of *β*-Ketonitriles. *Organic Letters*, **8**, 1161-1163. https://doi.org/10.1021/ol053164z

[27] Pienaar, D.P., Butsi, K.R., Rousseau, A.L. and Brady, D. (2019) A Green, Economical Synthesis of *β*-Ketonitriles and Trifunctionalized Building Blocks from Esters and Lactones. *Beilstein Journal of Organic Chemistry*, **15**, 2930-2935. https://doi.org/10.3762/bjoc.15.287

[28] Kahne, D. and Collum, D.B. (1981) Kinetic Cyanations of Ketone Enolates. *Tetrahedron Letters*, **22**, 5011-5014. https://doi.org/10.1016/s0040-4039(01)92406-2

[29] Kiyokawa, K., Nagata, T. and Minakata, S. (2016) Electrophilic Cyanation of Boron Enolates: Efficient Access to Various *β*-Ketonitrile Derivatives. *Angewandte Chemie International Edition*, **55**, 10458-10462. https://doi.org/10.1002/anie.201605445

[30] Nagata, T., Matsubara, H., Kiyokawa, K. and Minakata, S. (2017) Catalytic Activation of 1-Cyano-3,3-Dimethyl-3-(1*H*)-1,2-Benziodoxole with $B(C_6F_5)_3$ Enabling the Electrophilic Cyanation of Silyl Enol Ethers. *Organic Letters*, **19**, 4672-4675. https://doi.org/10.1021/acs.orglett.7b02313

[31] Nagata, T., Tamaki, A., Kiyokawa, K., Tsutsumi, R., Yamanaka, M. and Minakata, S. (2018) Enantioselective Electrophilic Cyanation of Boron Enolates: Scope and Mechanistic Studies. *Chemistry—A European Journal*, **24**, 17027-17032. https://doi.org/10.1002/chem.201804455

[32] Wang, Y.-F., Qiu, J.S., Kong, D.J., Gao, Y.T., Lu, F.P., Karmaker, P.G. and Chen, F.X. (2015) The Direct Electrophilic Cyanation of *β*-Keto Esters and Amides with Cyano Benziodoxole. *Organic & Biomolecular Chemistry*, **13**, 365-368. https://doi.org/10.1039/c4ob02032d

[33] Park, A. and Lee, S. (2012) Synthesis of Benzoylacetonitriles from Pd-Catalyzed Carbonylation of Aryl Iodides and Trimethylsilylacetonitrile. *Organic Letters*, **14**, 1118-1121. https://doi.org/10.1021/ol300035u

[34] Schranck, J., Burhardt, M., Bornschein, C., Neumann, H., Skrydstrup, T. and Beller, M. (2014) Palladium-Catalyzed Carbonylative *α*-Arylation to *β*-Ketonitriles. *Chemistry—A European Journal*, **20**, 9534-9538. https://doi.org/10.1002/chem.201402893

[35] Ruan, L., Chen, C., Zhang, X. and Sun, J. (2018) Recent Advances on the Photo-Induced Reactions of Acyl Radical. *Chinese Journal of Organic Chemistry*, **38**, 3155-3164. https://doi.org/10.6023/cjoc201806009

[36] Chatgilialoglu, C., Crich, D., Komatsu, M. and Ryu, I. (1999) Chemistry of Acyl Radicals. *Chemical Reviews*, **99**, 1991-2070. https://doi.org/10.1021/cr9601425

[37] Banerjee, A., Lei, Z. and Ngai, M.Y. (2018) Acyl Radical Chemistry via Visible-Light Photoredox Catalysis. *Synthesis*, **51**, 303-333. https://doi.org/10.1055/s-0037-1610329

[38] Raviola, C., Protti, S., Ravelli, D. and Fagnoni, M. (2019) Photogenerated Acyl/Alkoxycarbonyl/Carbamoyl Radicals for Sustainable Synthesis. *Green Chemistry*, **21**, 748-764. https://doi.org/10.1039/c8gc03810d

[39] Cho, S.H., Kim, J.Y., Kwak, J. and Chang, S. (2011) Recent Advances in the Transition Metal-Catalyzed Twofold Oxidative C-H Bond Activation Strategy for C-C and C-N Bond Formation. *Chemical Society Reviews*, **40**, 5068-5083. https://doi.org/10.1039/c1cs15082k

[40] Liu, W., Li, Y., Liu, K. and Li, Z. (2011) Iron-Catalyzed Carbonylation-Peroxidation of Alkenes with Aldehydes and Hydroperoxides. *Journal of the American Chemical Society*, **133**, 10756-10759. https://doi.org/10.1021/ja204226n

[41] Benati, L., Calestani, G., Leardini, R., Minozzi, M., Nanni, D., Spagnolo, P., *et al*. (2003) Generation and Intramolecular Reactivity of Acyl Radicals from Alkynylthiol Esters under Reducing Tin-Free Conditions. *Organic Letters*, **5**, 1313-1316. https://doi.org/10.1021/ol034252r

[42] Bath, S., Laso, N.M., Lopez-Ruiz, H., Quiclet-Sire, B. and Zard, S.Z. (2003) A Practical Access to Acyl Radicals from Acyl Hydrazides. *Chemical Communications*, **39**, 204-205. https://doi.org/10.1039/b210764c

[43] Boger, D.L. and Mathvink, R.J. (1989) Phenyl Selenoesters as Effective Precursors of Acyl Radicals for Use in Intermolecular Alkene Addition Reactions. *The Journal of Organic Chemistry*, **54**, 1777-1779. https://doi.org/10.1021/jo00269a001

[44] Chen, C., Crich, D. and Papadatos, A. (1992) The Chemistry of Acyl Tellurides: Generation and Trapping of Acyl Radicals, Including Aryltellurium Group Transfer. *Journal of the American Chemical Society*, **114**, 8313-8314. https://doi.org/10.1021/ja00047a066

[45] Crich, D., Chen, C., Hwang, J., Yuan, H., Papadatos, A. and Walter, R.I. (1994) Photoinduced Free Radical Chemistry of the Acyl Tellurides: Generation, Inter- and Intramolecular Trapping, and ESR Spectroscopic Identification of Acyl Radicals. *Journal of the American Chemical Society*, **116**, 8937-8951. https://doi.org/10.1021/ja00099a011

[46] Bugaut, X. and Glorius, F. (2012) Organocatalytic Umpolung: N-Heterocyclic Carbenes and Beyond. *Chemical Society Reviews*, **41**, 3511-3522. https://doi.org/10.1039/c2cs15333e

[47] Enders, D., Niemeier, O. and Henseler, A. (2007) Organocatalysis by N-Heterocyclic Carbenes. *Chemical Reviews*, **107**, 5606-5655. https://doi.org/10.1021/cr068372z

[48] Duncton, M.A.J. (2011) Minisci Reactions: Versatile CH-Functionalizations for Medicinal Chemists. *MedChemComm*, **2**, 1135-1161. https://doi.org/10.1039/c1md00134e

[49] Boger, D.L. and Mathvink, R.J. (1992) Acyl Radicals: Intermolecular and Intramolecular Alkene Addition Reactions. *The Journal of Organic Chemistry*, **57**, 1429-1443. https://doi.org/10.1021/jo00031a021

[50] Capaldo, L. and Ravelli, D. (2017) Hydrogen Atom Transfer (HAT): A Versatile Strategy for Substrate Activation in Photocatalyzed Organic Synthesis. *European Journal of Organic Chemistry*, **2017**, 2056-2071. https://doi.org/10.1002/ejoc.201601485

[51] Shi, Z. and Glorius, F. (2013) Synthesis of Fluorenones Viaquaternary Ammonium Salt-Promoted Intramolecular Dehydrogenative Arylation of Aldehydes. *Chemical Science*, **4**, 829-833. https://doi.org/10.1039/c2sc21823b

[52] Jhuang, H., Reddy, D.M., Chen, T. and Lee, C. (2016) DTBP/TBHP-Promoted Hydroacylation of Unactivated Alkenes. *Asian Journal of Organic Chemistry*, **5**, 1452-1456. https://doi.org/10.1002/ajoc.201600423

[53] Tsujimoto, S., Iwahama, T., Sakaguchi, S. and Ishii, Y. (2001) The Radical-Chain Addition of Aldehydes to Alkenes by the Use of N-Hydroxyphthalimide (NHPI) as a Polarity-Reversal Catalyst. *Chemical Communications*, **37**, 2352-2353. https://doi.org/10.1039/b107548a

[54] Shen, J., Yang, D., Liu, Y., Qin, S., Zhang, J., Sun, J., *et al*. (2014) Copper-Catalyzed Aerobic Oxidative Coupling of Aromatic Alcohols and Acetonitrile to *β*-Ketonitriles. *Organic Letters*, **16**, 350-353. https://doi.org/10.1021/ol403555n

[55] Li, J. and Wang, D.Z. (2015) Visible-Light-Promoted Photoredox Syntheses of *α*,*β*-Epoxy Ketones from Styrenes and Benzaldehydes under Alkaline Conditions. *Organic Letters*, **17**, 5260-5263. https://doi.org/10.1021/acs.orglett.5b02629

[56] Jung, S., Kim, J. and Hong, S. (2017) Visible Light-Promoted Synthesis of Spiroepoxy Chromanone Derivatives via a Tandem Oxidation/Radical Cyclization/Epoxidation Process. *Advanced Synthesis & Catalysis*, **359**, 3945-3949. https://doi.org/10.1002/adsc.201701072

[57] Iqbal, N. and Cho, E.J. (2016) Visible-Light-Mediated Synthesis of Amides from Aldehydes and Amines via in Situ Acid Chloride Formation. *The Journal of Organic Chemistry*, **81**, 1905-1911. https://doi.org/10.1021/acs.joc.5b02726

[58] Mukherjee, S., Garza-Sanchez, R.A., Tlahuext-Aca, A. and Glorius, F. (2017) Alkynylation of C(O)-H Bonds Enabled by Photoredox-Mediated Hydrogen-Atom Transfer. *Angewandte Chemie International Edition*, **56**, 14723-14726. https://doi.org/10.1002/anie.201708037

[59] Zhang, X. and MacMillan, D.W.C. (2017) Direct Aldehyde C-H Arylation and Alkylation via the Combination of Nickel, Hydrogen Atom Transfer, and Photoredox Catalysis. *Journal of the American Chemical Society*, **139**, 11353-11356. https://doi.org/10.1021/jacs.7b07078

[60] Vu, M.D., Das, M. and Liu, X. (2017) Direct Aldehyde Csp^2-H Functionalization through Visible-Light-Mediated Photoredox Catalysis. *Chemistry—A European Journal*, **23**, 15899-15902. https://doi.org/10.1002/chem.201704224

[61] Esposti, S., Dondi, D., Fagnoni, M. and Albini, A. (2007) Acylation of Electrophilic Olefins through Decatungstate-Photocatalyzed Activation of Aldehydes. *Angewandte Chemie International Edition*, **46**, 2531-2534. https://doi.org/10.1002/anie.200604820

[62] Fan, P., Zhang, C., Lan, Y., Lin, Z., Zhang, L. and Wang, C. (2019) Photocatalytic Hydroacylation of Trifluoromethyl Alkenes. *Chemical Communications*, **55**, 12691-12694. https://doi.org/10.1039/c9cc07285c

[63] Ohmatsu, K., Suzuki, R., Furukawa, Y., Sato, M. and Ooi, T. (2020) Zwitterionic 1,2,3-Triazolium Amidate as a Catalyst for Photoinduced Hydrogen-Atom Transfer Radical Alkylation. *ACS Catalysis*, **10**, 2627-2632. https://doi.org/10.1021/acscatal.9b04491

[64] Matsumoto, A., Yamamoto, M. and Maruoka, K. (2022) Cationic DABCO-Based Catalyst for Site-Selective C-H Alkylation via Photoinduced Hydrogen-Atom Transfer. *ACS Catalysis*, **12**, 2045-2051. https://doi.org/10.1021/acscatal.1c05484

[65] Wang, Z., Huang, S., Hou, H., Liu, W. and Ou, W. (2025) Direct Hydroacylation of Arylacrylonitriles toward *β*-Ketonitriles Assisted by an EDA Complex. *Chemical Communications*, **61**, 7510-7513. https://doi.org/10.1039/d5cc00867k

[66] Liu, J., Liu, Q., Yi, H., Qin, C., Bai, R., Qi, X., *et al*. (2014) Visible-Light-Mediated Decarboxylation/Oxidative Amidation of *α*-Keto Acids with Amines under Mild Reaction Conditions Using O_2. *Angewandte Chemie International Edition*, **53**, 502-506. https://doi.org/10.1002/anie.201308614

[67] Chu, L., Lipshultz, J.M. and MacMillan, D.W.C. (2015) Merging Photoredox and Nickel Catalysis: The Direct Synthesis of Ketones by the Decarboxylative Arylation of *α*-Oxo Acids. *Angewandte Chemie International Edition*, **54**, 7929-7933. https://doi.org/10.1002/anie.201501908

[68] Cheng, W., Shang, R., Yu, H. and Fu, Y. (2015) Room-Temperature Decarboxylative Couplings of *α*-Oxocarboxylates with Aryl Halides by Merging Photoredox with Palladium Catalysis. *Chemistry—A European Journal*, **21**, 13191-13195. https://doi.org/10.1002/chem.201502286

[69] Zhou, C., Li, P., Zhu, X. and Wang, L. (2015) Merging Photoredox with Palladium Catalysis: Decarboxylative *Ortho*-Acylation of Acetanilides with *α*-Oxocarboxylic Acids under Mild Reaction Conditions. *Organic Letters*, **17**, 6198-6201. https://doi.org/10.1021/acs.orglett.5b03192

[70] Zhou, Q., Guo, W., Ding, W., Wu, X., Chen, X., Lu, L., *et al*. (2015) Decarboxylative Alkynylation and Carbonylative Alkynylation of Carboxylic Acids Enabled by Visible-Light Photoredox Catalysis. *Angewandte Chemie International Edition*, **54**, 11196-11199. https://doi.org/10.1002/anie.201504559

[71] Bergonzini, G., Cassani, C. and Wallentin, C.-J. (2015) Acyl Radicals from Aromatic Carboxylic Acids by Means of Visible-Light Photoredox Catalysis. *Angewandte Chemie International Edition*, **54**, 14066-14069.

[72] Pettersson, F., Bergonzini, G., Cassani, C. and Wallentin, C. (2017) Redox-Neutral Dual Functionalization of Electron-deficient Alkenes. *Chemistry—A European Journal*, **23**, 7444-7447. https://doi.org/10.1002/chem.201701589

[73] Zhang, M., Ruzi, R., Xi, J., Li, N., Wu, Z., Li, W., *et al*. (2017) Photoredox-Catalyzed Hydroacylation of Olefins Employing Carboxylic Acids and Hydrosilanes. *Organic Letters*, **19**, 3430-3433. https://doi.org/10.1021/acs.orglett.7b01391

[74] Zhang, M., Li, N., Tao, X., Ruzi, R., Yu, S. and Zhu, C. (2017) Selective Reduction of Carboxylic Acids to Aldehydes with Hydrosilane via Photoredox Catalysis. *Chemical Communications*, **53**, 10228-10231. https://doi.org/10.1039/c7cc05570f

[75] Bergonzini, G., Cassani, C., Lorimer-Olsson, H., Hörberg, J. and Wallentin, C. (2016) Visible-Light-Mediated Photocatalytic Difunctionalization of Olefins by Radical Acylarylation and Tandem Acylation/Semipinacol Rearrangement. *Chemistry—A European Journal*, **22**, 3292-3295. https://doi.org/10.1002/chem.201504985

[76] Dong, S., Wu, G., Yuan, X., Zou, C. and Ye, J. (2017) Visible-Light Photoredox Catalyzed Hydroacylation of Electron-Deficient Alkenes: Carboxylic Anhydride as an Acyl Radical Source. *Organic Chemistry Frontiers*, **4**, 2230-2234. https://doi.org/10.1039/c7qo00453b

[77] Ociepa, M., Baka, O., Narodowiec, J. and Gryko, D. (2017) Light-Driven Vitamin B_{12}-Catalysed Generation of Acyl Radicals from 2-*S*-Pyridyl Thioesters. *Advanced Synthesis & Catalysis*, **359**, 3560-3565. https://doi.org/10.1002/adsc.201700913

[78] Norman, A.R., Yousif, M.N. and McErlean, C.S.P. (2018) Photoredox-Catalyzed Indirect Acyl Radical Generation from Thioesters. *Organic Chemistry Frontiers*, **5**, 3267-3298. https://doi.org/10.1039/c8qo00867a

[79] Ravelli, D., Protti, S. and Fagnoni, M. (2016) Decatungstate Anion for Photocatalyzed "Window Ledge" Reactions. *Accounts of Chemical Research*, **49**, 2232-2242. https://doi.org/10.1021/acs.accounts.6b00339

[80] Li, C.-G., Xu, G.-Q. and Xu, P.-F. (2017) Synthesis of Fused Pyran Derivatives via Visible-Light-Induced Cascade Cyclization of 1,7-Enynes with Acyl Chlorides. *Organic Letters*, **19**, 512-515. https://doi.org/10.1021/acs.orglett.6b03684

[81] Liu, Y., Wang, Q., Zhou, C., Xiong, B., Zhang, P., Yang, C., *et al*. (2018) Visible-Light-Mediated *Ipso*-Carboacylation of Alkynes: Synthesis of 3-Acylspiro[4,5]Trienones from *N*-(*p*-Methoxyaryl)Propiolamides and Acyl Chlorides. *The Journal of Organic Chemistry*, **83**, 2210-2218. https://doi.org/10.1021/acs.joc.7b03104

[82] Liu, Y., Wang, Q., Zhou, C., Xiong, B., Zhang, P., Kang, S., *et al*. (2018) Visible-Light-Mediated Cascade Difunctionalization/Cyclization of Alkynoates with Acyl Chlorides for Synthesis of 3-Acylcoumarins. *Tetrahedron Letters*, **59**, 2038-2041. https://doi.org/10.1016/j.tetlet.2018.04.033

[83] Li, L., Guo, S., Wang, Q. and Zhu, J. (2019) Acyl Radicals from Benzothiazolines: Synthons for Alkylation, Alkenylation, and Alkynylation Reactions. *Organic Letters*, **21**, 5462-5466. https://doi.org/10.1021/acs.orglett.9b01717

[84] Uchikura, T., Moriyama, K., Toda, M., Mouri, T., Ibáñez, I. and Akiyama, T. (2019) Benzothiazolines as Radical Transfer Reagents: Hydroalkylation and Hydroacylation of Alkenes by Radical Generation under Photoirradiation Conditions. *Chemical Communications*, **55**, 11171-11174. https://doi.org/10.1039/c9cc05336k

[85] Uchikura, T., Toda, M., Mouri, T., Fujii, T., Moriyama, K., Ibáñez, I., *et al*. (2020) Radical Hydroalkylation and Hydroacylation of Alkenes by the Use of Benzothiazoline under Thermal Conditions. *The Journal of Organic Chemistry*, **85**, 12715-12723. https://doi.org/10.1021/acs.joc.0c01872

[86] Pálvölgyi, Á.M., Ehrschwendtner, F., Schnürch, M. and Bica-Schröder, K. (2022) Photocatalyst-Free Hydroacylations of Electron-Poor Alkenes and Enones under Visible-Light Irradiation. *Organic & Biomolecular Chemistry*, **20**, 7245-7249. https://doi.org/10.1039/d2ob01364a

[87] Yang, M.L., Dong, C.L., Guan, Z. and He, Y. (2024) Visible Light-Induced Hydroacylation of Benzylidenemalononitriles with Aroyl Chlorides Using Silane as a Hydrogen Donor. *The Journal of Organic Chemistry*, **89**, 1285-1295. https://doi.org/10.1021/acs.joc.3c02616

[88] Liu, Y.L., Ouyang, Y.J., Zheng, H.X., Liu, H. and Wei, W. (2021) Recent Advances in Acyl Radical Enabled Reactions between Aldehydes and Alkenes. *Chemical Communications*, **57**, 6111-6120. https://doi.org/10.1039/d1cc02112e