

Communication

A CO₂-Mediated Conjugate Cyanide Addition to Chalcones

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Received: 30 November 2020; Accepted: 16 December 2020; Published: 18 December 2020



Abstract: Carbon dioxide is an intrinsically stable molecule; however, it can readily react with various nucleophilic reagents. In the presence of a cyanide source, CO₂ was proven to be useful to promote addition reactions. Here we report the use of CO₂ to facilitate 1,4-conjugate cyanide addition reaction to chalcones to generate organonitriles. Nitriles are key component in organic synthesis due to their utility in numerous functional group transformation, however, conjugation addition of cyanide has been a challenge in this substrate class due to side reactions. To mitigate this, we employed simple ammonium and metal cyanide sources as nucleophiles under carbon dioxide atmosphere where high selectivity toward the desired product was obtained. The presented reaction is not feasible under inert atmosphere, which highlights the important role of CO₂, as a Lewis and Brønsted acidic catalyst. Further derivatization of organonitriles compounds were performed to showcase the utility of the reaction, while an unprecedented dimerization reaction was identified and characterized, affording a cyclopentanone scaffold.

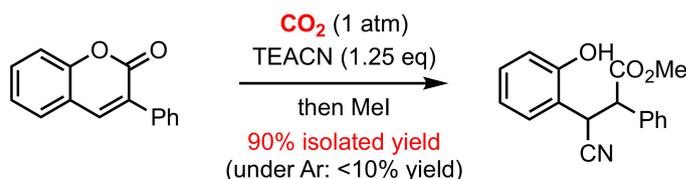
Keywords: carbon dioxide; cyanide; nitriles; catalysis; heterocycles

1. Introduction

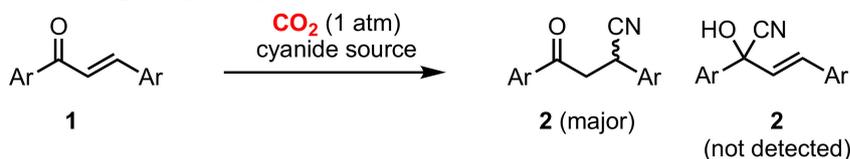
Carbon dioxide (CO₂) is a thermodynamically stable and kinetic inert molecule however utilization and functionalization of CO₂ found many unique modes of actions [1,2]. For example, CO₂ can be used as temporary protecting group, thus preventing polymerization of acrylonitriles initiated by cyanide anion [3,4]. In principle, the nucleophilicity of cyanide is sufficiently high however it requires catalytic species to enhance reaction rates under controlled manner to improve selectivity [5]. This is particularly the case with insoluble metal cyanides, such as NaCN and KCN, when reactions are performed in organic solvents. Nevertheless, the obtained organonitriles are ubiquitous functional group in organic synthesis, enabling facile synthesis of various molecular scaffolds via meta-selective C-H activation [6,7], reduction (amines) [8], hydrolysis (carbonyls) [9], radical reactions (cyanide abstraction) [10,11] and umpolung chemistry (cyanohydrins) [12]. Among many reaction pathways, hydrocyanation with gaseous HCN showed the most atom economic reaction with olefin substrates [13]. The use of solid metal cyanide sources is desirable to avoid volatile HCN, however, it often requires high reaction temperature due to the low solubility and reactivity of alkali metal cyanides [14]. Recently our group demonstrated the employment of catalytic amounts of CO₂ for 1,4-conjugate cyanide addition reaction of coumarin substrates [15]. The use of ammonium cyanide as a nucleophile was sufficient to quantitatively convert the starting materials to the desired products under 1 atm of CO₂ (Scheme 1A). In addition, we found that cyanohydrin synthesis can be facilitated under CO₂ atmosphere, implying potential catalysis mediated by CO₂. Here we expand our system to a general

Michael acceptor namely chalcones, which exhibit broad application potentials after cyanation reaction under CO₂ atmosphere. Previous studies on chalcone cyanation reactions were limited to metal catalysts, including a Ni-catalyzed cyano-borrowing process [16] a Sm-mediated reaction [17] and a Sc(OTf)₃ mediated reaction with an ammonium cyanide nucleophile [18]. Organic and inorganic bases, tetraarylphosphonium inner salts and Cs₂CO₃ were reported to catalyze addition of TMS-CN (trimethylsilyl cyanide) to chalcones [19,20]. To the best of our knowledge, the CO₂-promoted cyanation reaction of chalcones exhibit the first metal-free 1,4-cyanation reaction without generating HCN under practical reaction conditions by using cyanide salts [21–23].

A) CO₂-catalyzed cyanation of coumarins (Ref 15)



B) This work: CO₂-catalyzed cyanation of chalcones



Scheme 1. (A) Previous work: CO₂-catalyzed cyanation of coumarins, TEACN: tetraethylammonium cyanide (B) cyanation of chalcone (1) under CO₂ atmosphere (1 atm).

2. Results

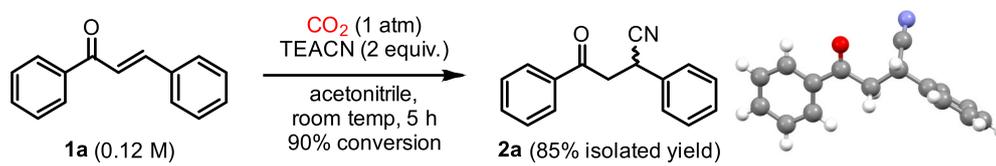
We commenced our investigation on chalcone cyanation reactions by optimizing reaction conditions under CO₂ atmosphere. It was clear that the reaction showed no product formation under inert atmosphere (N₂) although the starting material was fully consumed. This can be ascribed to the reversibility of the reaction and the decomposition of the cyanated product (2) to form the corresponding cyanohydrin (1,2-adduct), dehydration products and oligomers. We hypothesized that the presence of CO₂ diminished the polymerization of chalcone substrates by forming carboxylate intermediates on the α-position of the product [5]. It is noteworthy that the formation of cyanohydrin of 1,4-conjugate addition products 2 can occur, without the formation of 1,2-adducts (2'). The desired products can be obtained after standard work-up.

2.1. Optimization

To understand the cyanation process, we attempted to optimize reaction conditions. At the outset, we observed that the presence of CO₂ is critical to obtain the desired product (entry 1, Table 1). The structure of the cyanation product 2a was unambiguously confirmed by isolating crystalline product which was recrystallized and analyzed by X-ray crystallography. On the other hand, the crude reaction mixture, under nitrogen atmosphere, often showed complicated mixtures of byproducts and insoluble particles, indicating formation of polymeric species. Under carbon dioxide atmosphere (1 atm), it was found that 2–3 equivalents of the cyanide nucleophile were necessary to afford satisfactory yields of the desired product (up to 85% isolated yield, entries 2 and 3). Interestingly, the employment of KCN instead of tetraethylammonium cyanide (TEACN) showed a lower yield (19%) confirming the importance of solubility of cyanide nucleophile. This can be controlled by adding an additional phase-transfer reagent (NMe₄Cl) in the presence of excess amounts of KCN (3.3 equiv) as a nucleophile, affording the product in a good yield (72%). Solvent screening and temperature screening showed no further improvement of the reaction conditions (entries 6–9). However, we concluded that the positive

CO₂ effect was quite general in some of the tested organic solvents, for example, under nitrogen atmosphere, un-optimal solvents afforded lower yields of the product compared to the reactions under CO₂.

Table 1. Optimization of reaction conditions ^a.



Entry.	Deviation from the Standard Reaction Conditions	Yield (%) ^b
1	Under N ₂ instead of CO ₂	trace
2	1.1 equiv. of NEt ₄ CN	67%
3	3 equiv. of NEt ₄ CN	81%
4	KCN (2 equiv) instead of NEt ₄ CN	19%
5	KCN (3.3 equiv) instead of NEt ₄ CN + 2 equiv of NMe ₄ Cl	72%
6	DCM as a solvent	20%
7	DMF as a solvent	35%
8	DMSO as a solvent	65%
9	un-optimal solvents (EtOH, Et ₂ O, TFH, dioxane) under CO ₂ /N ₂	n.r.

^a General conditions: **1a** (0.24 mmol) was added to a solution of TEACN (2 equiv.) in a solvent (2 mL) under the corresponding atmosphere with a balloon. The reaction mixture was stirred at room temperature for 5 h. ^b Yield determined by ¹H-NMR in the presence of an internal standard (1,3,5-trimethoxybenzene).

2.2. Substrate Scope

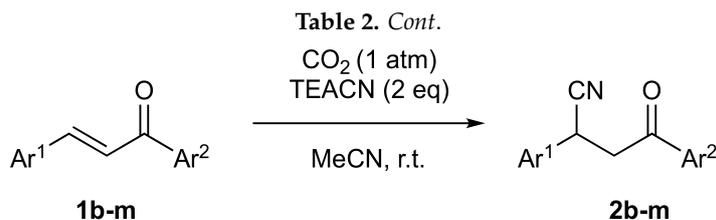
With optimized reaction conditions in our hands, we turned our attention to evaluate our methodology in electronically differentiated substrates **1b–m** to show generality of the process (Table 2). The corresponding chalcone substrates were readily prepared via condensation reactions (See Supplementary Materials). In general our reaction conditions was proven to be applicable for most of chalcones affording conjugated addition product in good yields (59–73% isolated yield) within short reaction time. When the reaction time was prolonged, the reaction proved to form various byproducts, presumably via dimerization and oligomerization. It is noteworthy here that some of cyanation product were obtained in low yields (**2d**: 13%, **2g**: 20%), however, these are unique cases with highly electron-withdrawing group (-NO₂) and a free amine (-NH₂), which are difficult to control for other types of side reactions. Further investigations with cyclic enone substrates (**1h–1l**) showed promising reactivity for cyanation under CO₂, delivering the desired products in moderate to good yields. Indanone-derived product **2h** was spontaneous crystallized (15% from the reaction mixture), which confirmed the product unambiguously by X-ray crystallography as a single diastereomer. Interestingly, chroman-4-one derived chalcones (**1k** and **1l**, entries 10 and 11) showed different reaction pathways: chalcone **1k** was converted to ring-opened form (**2k**), presumably after a cyanation-induced ring opening reaction and then double bond isomerization to afford thermodynamically stable products. For the reaction with chalcone **1l**, we tentatively assigned the main product as chromone derivative (**2l**) without the incorporation of cyanide, indicating many potential reaction pathways, which can lead to the formation of unexpected byproducts.

Table 2. Substrate scope for the cyanation of different chalcone derivatives under CO₂ ^a.

$$\text{Ar}^1\text{-CH=CH-C(=O)-Ar}^2 \xrightarrow[\text{MeCN, r.t.}]{\text{CO}_2 (1 \text{ atm}), \text{TEACN (2 eq)}} \text{Ar}^1\text{-CH(CN)-CH}_2\text{-C(=O)-Ar}^2$$

1b-m **2b-m**

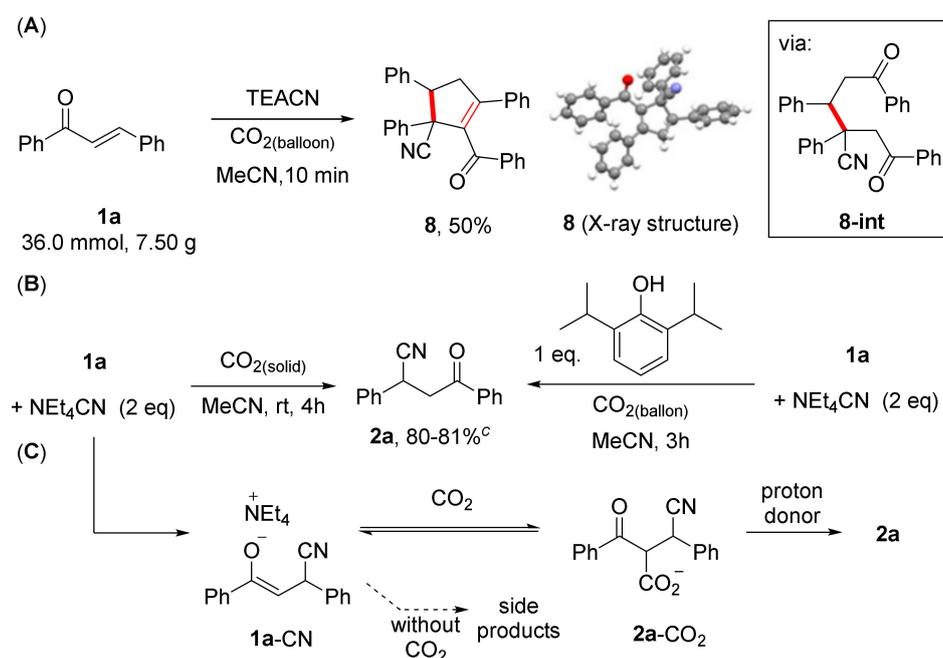
Entry	Chalcone, 1	Time/h	Product, 2	Yield/% ^c
1		7.5		73
2		2.5		63
3		2		13 ^b
4		2		59
5		7.5		64
6		2		20 ^b
7		18		15 ^d
			<i>rac</i> - 2h (single diastereomer)	
8		18		37
			2i , d.r. = 2:1	
9		18		74
			2j , d.r. = 2.4:1	



Entry	Chalcone, 1	Time/h	Product, 2	Yield/% ^c
10	 1k	18	 2k	23
11	 1l	18	 2l	41
12	 1m	18	 2m	88

^a General conditions: In a vial, NEt₄CN and **1b-1m** (0.40 mmol) were stirred in 3 mL solvent at room temperature under CO₂ atmosphere via balloon. ^b Yields were determined by ¹H-NMR via internal standard (1,3,5-trimethoxy-benzene). ^c Isolated Yield. ^d isolated yield based on the precipitated crystals.

Among many possible side reaction pathways, we found out that a dimerization reaction occurred at a higher concentration (7.5 g-scale, 36.0 mmol, 0.36 M) to generate cyclopentenone scaffold **8** in 50% isolated yield. A proposed reaction mechanism includes Robinson annulation (1,4-conjugate cyanation reaction and subsequent aldol condensation reaction). We confirmed that the obtained cyclopentenone **8** showed reasonable stability in the reaction mixture. Based on our analysis of the reaction mixture, the cyclic enone (**8**) showed no reactivity in the presence of additional cyanide nucleophiles under the same reaction conditions. In 1959, R. B. Davis reported the isolation of a similar compound from a reaction of benzaldehyde, sodium cyanide and acetophenone in methanol without detailed characterization of the compound [24]. To verify this, we investigated the reaction mechanism by analyzing the reaction mixture at earlier stages and isolated dimer **8-int** (Scheme 2), which was formed after the cyanation reaction. This dimerization process can be controlled by increasing the concentration of CO₂ (dry ice, 25 g for 2.4 mmol chalcone) or in the presence of stoichiometric amounts of a proton donor (2,6-diisopropylphenol): the desired product was obtained in good yield 80% and 81% respectively. The role the additional proton source needs further investigation, however, we presumed that the formation of ammonium enolate (i.e., **1a-CN**) prohibits the selective conversion of the starting material to the product **2**. In the presence of a sterically demanding phenol, a facile protonation process of the enolate is expected affording the desired products. Higher concentration of CO₂ and water is also beneficial to render acidic reaction conditions, therefore minimizing oligomerization and polymerization reactions (Scheme 2C). We presume that the carboxylated product (**2a-CO₂**) is responsible for the successful cyanation reactions under our optimized reaction conditions despite the substrate dependency.



Scheme 2. (A) Dimerization of chalcone (**1a**) to cyclopentanone **8** and the single crystal X-ray structure of dimer **8** (B) large scale cyanation reactions with dry ice and a proton donor. (C) a plausible reaction mechanism with CO_2 and without CO_2 (oligomerization and other side products formation reactions).

2.3. Functionalization of Cyanated Chalcones

We further demonstrated the utility of the CO_2 -mediated conjugate cyanation reaction by functionalizing the β -cyanoketone product **2a**. The racemic cyanated product was prepared in a larger scale reaction based on the above-mentioned studies (Scheme 2B,C) and then subjected to various types of organic transformation as illustrated in Figure 1. Reduction of the ketone functional group was performed with NaBH_4 in methanol to give selectively β -nitrile alcohol albeit low isolate yield of the product presumably due to the high acidity of the α -proton. Nevertheless, this reduction reaction shows an interesting synthetic route toward functionalized alcohols with a nitrile group untouched. We also performed transformation of nitrile group to tetrazole in the presence of ZnCl_2 promoter, smoothly affording the desired product in 39% yield [25]. For hydrolysis, we found out that with the choice of a strong Brønsted acid directed to different hydrolysis products, amide product **4a** was obtained in good yield (71%) in concentrated sulfuric acid at room temperature. On the other hand, carboxylic acid product **5a** was obtained under reflux conditions with concentrated HCl under CO_2 atmosphere to prevent a potential decarboxylation reaction.

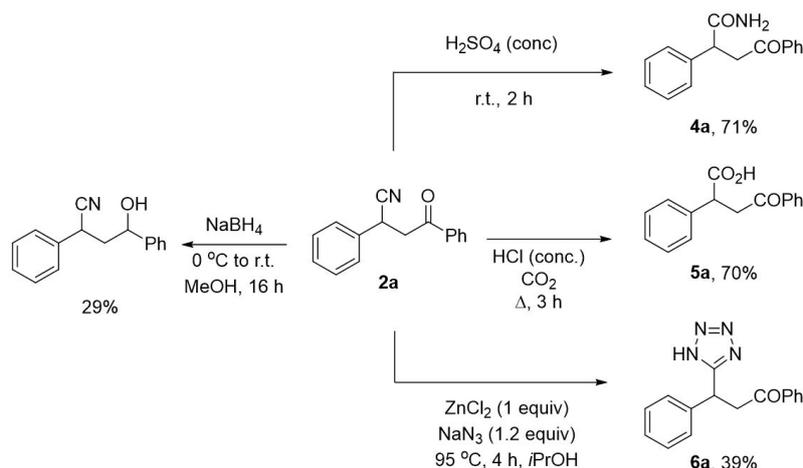


Figure 1. Functionalization of cyanation product **2a** via hydrolysis, tetrazole formation, reduction and amide bond formation reactions.

3. Discussion

The use of CO_2 for organic synthesis is appealing for many reasons [26] (1) as a cheap and non-innocent inert gas, (2) often accelerate and control reactions, (3) enabling chemistry with insoluble metal cyanide reagents in organic solvents. However, it is important to note that the employment of CO_2 can complicate the outcome of reactions due to undesired binding of nucleophiles therefore reducing the reactivity. Based on our investigation and previous studies [15,27,28], we presumed that the positive effects of CO_2 in catalyzing chemical reactions can be general, particularly in reactions involving reversible steps. In the current investigation with chalcones, the reaction is highly controlled by thermodynamics that allowed us to access various products in high yield. The importance of CO_2 , however, cannot be neglected due to the severe side products' formation in the absence of CO_2 . This phenomenon—a cleaner reaction mixture under CO_2 —has been sporadically revealed in synthetic chemistry [29,30]. Further investigation will pave the way to understand the true capacity of CO_2 in organic synthesis, potentially providing new ways of mitigating anthropogenic CO_2 via CO_2 capture and sequestration in a catalytic manner.

4. Materials and Methods

All the chemicals, unless stated otherwise were purchased from commercial suppliers in the highest purity and used without further purification. Solvents used were HPLC (high performance liquid chromatography) grade either as it is or dried on molecular sieves (4 Å) prior to use. The water concentrations of all the solvents used in the present study were measured on a Karl Fischer titrator (831 KF Coulometer). Analytical thin layer chromatography was done on Merck DC-Alufolien SIO2 60 F254 0.2 mm thick pre-coated TLC plates. Column chromatography was performed using SiO_2 (SI 1721, 60 Å, 40–63 μm). ^1H NMR and ^{13}C NMR spectra were recorded with 500 MHz Ultrashield Plus 500 spectrometer and 126 MHz on a Bruker instrument. All chemical shifts (d) are given in ppm using the solvent residual peak as reference. X-ray crystallography was performed by the crystallography service of the Department of Chemistry, University of Copenhagen, Denmark on a Bruker/Nonius Kappa CCD 4-circle diffractometer.

5. Conclusions

In conclusion, we have demonstrated a facile cyanation reaction of chalcone electrophiles under atmospheric CO_2 pressure at ambient reaction temperature. This is a unique system considering the reversibility of the reaction and competition reaction pathways. We ascribed the observed selectivity to the active role of non-inert gas CO_2 , which can interact with substrates (cyanide and chalcones),

intermediates, transition states and products. Further applications of CO₂-mediated organic synthesis are underway in our laboratory to expand the concept to various organic transformation.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4344/10/12/1481/s1>, Synthetic procedures for substrates, reaction conditions and ¹H and ¹³C NMR spectra.

Author Contributions: Conceptualization, J.-W.L. and S.D.; investigation, S.D., G.B.H., F.S.K.; Crystallography A.K.; writing—original draft preparation, J.-W.L.; writing—review and editing, S.D., J.-W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Novo Nordisk Fonden, grant number NNF17OC0027598 and Villum Fonden (00019062). S.D. was funded by ERASMUS Program.

Acknowledgments: The generous support from the Department of Chemistry, University of Copenhagen and the analytic department are gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Liu, Q.; Wu, L.; Jackstell, R.; Beller, M. Using carbon dioxide as a building block in organic synthesis. *Nat. Commun.* **2015**, *6*, 5933. [[CrossRef](#)] [[PubMed](#)]
2. Yang, Y.; Lee, J.-W. Toward ideal carbon dioxide functionalization. *Chem. Sci.* **2019**, *10*, 3905–3926. [[CrossRef](#)] [[PubMed](#)]
3. Kapoor, M.; Chand-Thakuri, P.; Young, M.C. Carbon Dioxide-Mediated C(sp²)-H Arylation of Primary and Secondary Benzylamines. *J. Am. Chem. Soc.* **2019**, *141*, 7980–7989. [[CrossRef](#)] [[PubMed](#)]
4. Kapoor, M.; Liu, D.; Young, M.C. Carbon Dioxide-Mediated C(sp³)-H Arylation of Amine Substrates. *J. Am. Chem. Soc.* **2018**, *140*, 6818–6822. [[CrossRef](#)]
5. White, D.A. Cyanocarboxylation of activated olefins. *J. Chem. Soc. Perkin Trans.* **1976**, *1*, 1926–1930. [[CrossRef](#)]
6. Leow, D.; Li, G.; Mei, T.-S.; Yu, J.-Q. Activation of remote meta-C-H bonds assisted by an end-on template. *Nature* **2012**, *486*, 518–522. [[CrossRef](#)]
7. Dai, H.-X.; Li, G.; Zhang, X.-G.; Stepan, A.F.; Yu, J.-Q. Pd(II)-Catalyzed ortho- or meta-C-H Olefination of Phenol Derivatives. *J. Am. Chem. Soc.* **2013**, *135*, 7567–7571. [[CrossRef](#)]
8. Bornschein, C.; Werkmeister, S.; Wendt, B.; Jiao, H.; Alberico, E.; Baumann, W.; Junge, H.; Junge, K.; Beller, M. Mild and selective hydrogenation of aromatic and aliphatic (di)nitriles with a well-defined iron pincer complex. *Nat. Commun.* **2014**, *5*, 4111. [[CrossRef](#)]
9. Ahmed, T.J.; Knapp, S.M.M.; Tyler, D.R. Frontiers in catalytic nitrile hydration: Nitrile and cyanohydrin hydration catalyzed by homogeneous organometallic complexes. *Coord. Chem. Rev.* **2011**, *255*, 949–974. [[CrossRef](#)]
10. Chu, X.-Q.; Ge, D.; Shen, Z.-L.; Loh, T.-P. Recent Advances in Radical-Initiated C(sp³)-H Bond Oxidative Functionalization of Alkyl Nitriles. *ACS Catal.* **2018**, *8*, 258–271. [[CrossRef](#)]
11. Mattalia, J.-M.R. The reductive decyanation reaction: An overview and recent developments. *Beilstein J. Org. Chem.* **2017**, *13*, 267–284. [[CrossRef](#)] [[PubMed](#)]
12. Seebach, D. Methods of Reactivity Umpolung. *Angew. Chem. Int. Ed.* **1979**, *18*, 239–258. [[CrossRef](#)]
13. Tolman, C.A.; McKinney, R.J.; Seidel, W.C.; Druliner, J.D.; Stevens, W.R. Homogeneous Nickel-Catalyzed Olefin Hydrocyanation. In *Advances in Catalysis*; Eley, D.D., Pines, H., Weisz, P.B., Eds.; Academic Press Inc.: Cambridge, MA, USA, 1985; Volume 33, pp. 1–46.
14. Friedman, L.; Shechter, H. Preparation of Nitriles from Halides and Sodium Cyanide. An Advantageous Nucleophilic Displacement in Dimethyl Sulfoxide. *J. Org. Chem.* **1960**, *25*, 877–879. [[CrossRef](#)]
15. Roy, T.; Kim, M.J.; Yang, Y.; Kim, S.; Kang, G.; Ren, X.; Kadziola, A.; Lee, H.-Y.; Baik, M.-H.; Lee, J.-W. Carbon Dioxide-Catalyzed Stereoselective Cyanation Reaction. *ACS Catal.* **2019**, *9*, 6006–6011. [[CrossRef](#)]
16. Li, Z.-F.; Li, Q.; Ren, L.-Q.; Li, Q.-H.; Peng, Y.-G.; Liu, T.-L. Cyano-borrowing reaction: Nickel-catalyzed direct conversion of cyanohydrins and aldehydes/ketones to β-cyano ketone. *Chem. Sci.* **2019**, *10*, 5787–5792. [[CrossRef](#)]
17. Kawasaki, Y.; Fujii, A.; Nakano, Y.; Sakaguchi, S.; Ishii, Y. Acetylcyanation of Aldehydes with Acetone Cyanohydrin and Isopropenyl Acetate by Cp*2Sm(thf)₂. *J. Org. Chem.* **1999**, *64*, 4214–4216. [[CrossRef](#)]

18. Ramesh, S.; Lalitha, A. Scandium(III) Triflate Catalyzed 1,4-Addition of Cyano Group to Enones Using Tetraethylammonium Cyanide as the Cyanide Source. *Acta Chim. Slov.* **2013**, *60*, 689–694.
19. Guo, S.; Mi, X. Tetraarylphosphonium inner-salts (TAPIS) as both Lewis base catalyst and phase tag. *Tetrahedron Lett.* **2017**, *58*, 2881–2884. [[CrossRef](#)]
20. Yang, J.; Shen, Y.; Chen, F.-X. Highly Efficient Cs₂CO₃-Catalyzed 1,4-Addition of Me₃SiCN to Enones with Water as the Additive. *Synthesis* **2010**, *2010*, 1325–1333. [[CrossRef](#)]
21. Ciller, J.A.; Seoane, C.; Soto, J.L. Synthesis of Heterocyclic Compounds, XXXVIII. Five-membered Heterocycles by Cyclization of 3-Benzoyl-4-oxobutanenitriles. *Liebigs Ann. Chem.* **1985**, *1985*, 51–57. [[CrossRef](#)]
22. Allen, C.F.H.; Kimball, R.K. α -Phenyl- β -Benzoylpropionitrile. *Org. Synth.* **1930**, *10*, 80.
23. Bellinger, T.J.; Harvin, T.; Pickens-Flynn, T.B.; Austin, N.; Whitaker, S.H.; Tang Yuk Tutein, M.L.C.; Hukins, D.T.; Deese, N.; Guo, F. Conjugate Addition of Grignard Reagents to Thiochromones Catalyzed by Copper Salts: A Unified Approach to Both 2-Alkylthiochroman-4-One and Thioflavanone. *Molecules* **2020**, *25*, 2128. [[CrossRef](#)] [[PubMed](#)]
24. Davis, R. Notes: Condensation of Aromatic Aldehydes with Methyl Aryl Ketones and Sodium Cyanide. *J. Org. Chem.* **1959**, *24*, 880–882. [[CrossRef](#)]
25. Vorona, S.; Artamonova, T.; Zevatskii, Y.; Myznikov, L. An Improved Protocol for the Preparation of 5-Substituted Tetrazoles from Organic Thiocyanates and Nitriles. *Synthesis* **2014**, *46*, 781–786. [[CrossRef](#)]
26. Schilling, W.; Das, S. CO₂-catalyzed/promoted transformation of organic functional groups. *Tetrahedron Lett.* **2018**, *59*, 3821–3828. [[CrossRef](#)]
27. Lee, J.-W.; Juhl, M.; Petersen, A.R. CO₂-Enabled Cyanohydrin Synthesis and Facile Iterative Homologation Reactions. *Chem. Eur. J.* **2020**. [[CrossRef](#)]
28. Yang, Y.; Liu, J.; Lee, J.-W. A CO₂-Catalyzed Transamidation Reaction. *ChemRxiv* **2020**. [[CrossRef](#)]
29. Chiang, P.-C.; Bode, J.W. On the Role of CO₂ in NHC-Catalyzed Oxidation of Aldehydes. *Org. Lett.* **2011**, *13*, 2422–2425. [[CrossRef](#)]
30. Li, H.; Wu, H.; Yu, Z.; Zhang, H.; Yang, S. CO₂-Enabled Biomass Fractionation/Depolymerization: A Highly Versatile Pre-Step for Downstream Processing. *ChemSusChem* **2020**, *13*, 3565–3582. [[CrossRef](#)]

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