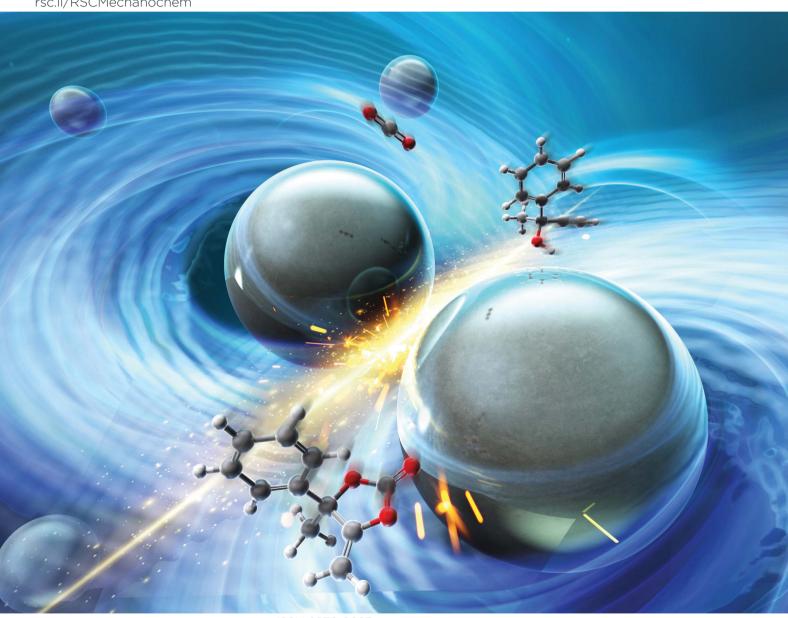
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Synthesis of cyclic carbonates via silver-catalysed fixation of CO₂ to propargyl alcohols under mechanochemical conditions

This paper describes the development of a mechanochemical method for the synthesis of cyclic carbonate

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esters via CO₂ fixation on propargyl alcohols. This solvent-free process is rapid and occurs under ambient conditions, thus offering a sustainable and efficient alternative to conventional solvent-based protocols. The mechanochemistry, which utilises the energy generated from milling, has the advantage of minimising waste, reducing reaction times, and simplifying work-up. The developed protocol demonstrates broad functional group tolerance, high yields, and the elimination of complex setups, thus highlighting its potential for application in organic and pharmaceutical synthesis.

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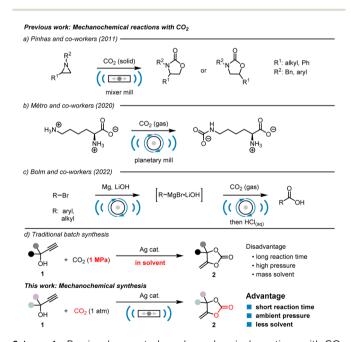
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Introduction

The introduction of CO₂ as a valuable C1 building block within the domain of organic synthesis has led to the emergence of a rapidly growing field of research. Significant research has been conducted with the aim of developing synthetic strategies for the incorporation of CO2 into high-value fine chemicals. 1-4 One of the most promising reactions is the carboxylation of propargyl alcohol, which facilitates the synthesis of α-alkylidene cyclic carbonates. This process has become a crucial step in the pharmaceutical industry and is a fundamental step in the synthesis of polycarbonates and polyurethanes.⁵⁻⁷ A variety of catalytic systems have been developed for the synthesis of cyclic carbonates,8 although most of them require high CO2 pressure and elevated temperatures. It would be highly beneficial to explore the possibility of developing processes that operate without solvents and at ambient temperature.9 However, it should be noted that all of the aforementioned systems still required a relatively long reaction time and large amounts of CO₂. Consequently, there is a necessity for further research to develop processes that operate without solvents and at ambient temperature.

Mechanochemistry denotes chemical transformations, typically conducted on solid-phase substrates, that are activated through the application of mechanical energy, most notably via grinding in ball mills.10a Well established in the fields of crystal engineering and polymorphism, mechanochemistry has recently attracted renewed attention as a method for organic synthesis.10h To further clarify, mechanochemistry, defined as the utilisation of grinding jars or balls to induce chemical reactions, is gaining increasing attention as a promising solvent-free synthesis technique.10 It is anticipated that this

method could provide practical solutions to a number of issues associated with conventional solvent-based protocols. Recent examples of mechanochemically induced Suzuki-coupling,11 Birch reductions¹² and Grignard reactions¹³ have demonstrated key advantages of mechanochemistry, such as the reduction or



Scheme 1 Previously reported mechanochemical reactions with CO₂ and silver-catalyzed synthesis of cyclic carbonate derivatives.

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elimination of solvents, shorter reaction times, cleaner reaction mixtures, and simpler work-up procedures. These approaches have been shown to significantly reduce the generation of waste, particularly from solvents used in reactions or during the purification of intermediates. The integration of organic reactions with mechanochemical methods thus represents a major step forward in developing environmentally friendly synthetic strategies. To date, only three studies have reported mechanochemical CO₂ insertions: (i) the transformation of aziridine into oxazolidinone using dry ice, (ii) the addition of gaseous CO₂ to L-lysine, resulting in the formation of its ε-carbamate, and (iii) the Grignard reaction with CO₂ (Scheme 1a–c). ^{13a,14,15} Utilization of solid CO₂ surrogates, such as NaHCO₃, was also explored. ¹⁶

This communication delineates the development of a mechanochemical method for synthesising cyclic carbonate esters via CO_2 fixation on various propargyl alcohols. Compared to conventional methods that typically require solvents, long reaction times, and high CO_2 pressure (Scheme 1d), sc our solvent-free process proceeds rapidly under ambient conditions with minimal CO_2 input. Furthermore, this study was extended to bioactive substances, thereby demonstrating the efficacy of a simple mechanochemical protocol.

Results and discussion

In order to optimise CO_2 fixation under ball-milling conditions, reaction parameters were extensively investigated using 2-phenyl-3-butyn-2-ol (1a) as a model substrate (see: Tables 1 and S1 in SI). Following the optimisation process, a maximum isolated yield of 96% (99% GC yield) was achieved for the targeted carbonate 2a under a 1 atm of CO_2 atmosphere. The reaction was carried out utilising Ag_2CO_3 (2 mol%) as the catalyst for

alkyne activation, PPh3 (6 mol%) as the ligand for the silver catalyst, 9a and dichloroethane (DCE, 5.0 equiv.) as a liquidassisted grinding (LAG) agent to enhance mixing and reaction efficiency under mechanochemical conditions.10t The reaction was carried out in a 50 mL stainless-steel jar equipped with three 15 mm milling balls, operating at a frequency of 15 Hz for 60 min using a mixer mill (Entry 1). Transpositioning to a planetary mill operating at 800 rpm, as was employed in our previous ball-milling investigations,17 resulted in a marked reduction in the mass balance, yielding only 48% of 2a despite an almost complete conversion of 1a (96%) within 30 min (Entry 2). This result is attributed to decomposition of the product caused by the excessive mechanical energy.18 The size of the milling balls significantly impacted both the mass balance and substrate conversion. The utilisation of 15 mm balls resulted in a close correlation between the conversion of 1a (98% with five balls; 78% with three balls) and the yields of 2a (95% with five balls; 77% with three balls). However, notable discrepancies were observed when employing 10 mm balls (seven balls) or a single 25 mm ball (Entries 3-6). Furthermore, increasing the milling frequency from 15 Hz to 20 or 25 Hz resulted in diminished recovery yields, indicating that high-energy inputs promoted decompositions of the product (Entries 7 and 8). Attempts to replace Ag₂CO₃ and PPh₃ with alternative silver catalysts and phosphine ligands did not improve the yields (Entries 9 and 10). Control experiments, excluding Ag₂CO₃, PPh₃, or DCE, demonstrated the indispensability of all three components, as no product formation was observed in their absence (Entries 11-13). Conventional stirring conditions in a recovery flask yielded a mere 7% of the desired product 2a (Entry 14).

Table 1 Optimisation of reaction conditions for the synthesis of 2a^a

Entry	Difference from standard conditions	Conv. ^b (%)	Yield of $2a^b$ (%)
1	None	100	99 (96)
2^c	Planetary mill instead of mixer 3×15 mm mill for 30 min	96	48
3	7×10 mm instead of 3×15 mm balls for 30 min	97	89
4	5×15 mm instead of 3×15 mm balls for 30 min	98	95
5	30 min instead of 60 min	78	77
6	1×25 mm instead of 3×15 mm balls for 30 min	71	58
7	20 Hz instead of 15 Hz milling frequency for 30 min	93	80
8	25 Hz instead of 15 Hz milling frequency for 30 min	84	43
9	AgOAc instead of Ag ₂ CO ₃ for 30 min	9	1
10	(p-tol) ₃ P instead of PPh ₃ for 30 min	82	31
11	Without Ag ₂ CO ₃ for 30 min	31	0
12	Without PPh ₃ for 30 min	10	0
13	Without DCE for 30 min	1	0
14	Stir bar mixing in recovery flask for 30 min	18	7

^a Unless otherwise specified, all reactions were performed with **1a** (0.5 mmol), Ag₂CO₃ (0.02 mmol), PPh₃ (0.06 mmol), DCE (2.5 mmol) and CO₂ (1 atm) at ambient conditions. ^b Determined by GC analysis with decane as the internal standard. Yields of isolated products are given in parentheses. ^c Reaction carried out in a 20 mL ZrO₂ bowl with 50 × 5 mm ZrO₂ balls mixing at 800 rpm.

Propargyl alcohols 1b-v were subjected to the reaction under the optimised conditions (Scheme 2). The reaction yielded cyclic carbonates 2b-l in isolated yields ranging from 57% to 95%, irrespective of the position or nature of the substituents (methyl, methoxy, fluorine, chlorine, bromine, nitro, methoxycarbonyl, and trifluoromethyl groups) on the benzene rings. These functional groups did not adversely impact the reaction outcome. The presence of a pyridyl group at the propargyl position in 1m had no detrimental effect, and resulted in an excellent 98% isolated yield of 2m. Sterically more hindered propargylic alcohols such as 1n, were also efficiently converted into their corresponding cyclic carbonates (2n) in yields of 87%. The reaction of gem-diphenyl propargyl alcohol 10 yielded the desired product 20 in an 86% yield, while gem-dimethyl propargylic alcohol 1p produced 2p in an isolated yield of 37%, which was comparatively lower. Conversely, internal propargyl alcohols (1q and 1r) were effectively transformed into Z-vinylidene cyclic carbonates, yielding 2q and 2r in 58% and 76% isolated yields, respectively. Spirocyclic compounds 2s-v were obtained in moderate to good yields (70-93%) when cyclic propargylic alcohols 1s-v were employed. Importantly, this methodology was effective when applied to the estrogenic active pharmaceutical ingredient, ethinylestradiol (1v), bearing both a phenolic hydroxyl group and a steroid skeleton. The reaction proceeded efficiently, furnishing the corresponding cyclic carbonate 2v in a commendable 70% isolated yield.

In this study, a novel one-pot process combining the synthesis of cyclic carbonates and subsequent transformation utilising a ball-milling apparatus was explored (Scheme 3). Following the fixation of CO₂ to propargyl alcohol 1a under optimised ball-milling conditions, pyrrolidine was introduced directly into the reaction mixture within the milling jar, and

Reaction conditions: propargyl alcohol (0.5 mmol), DCE (5 eq.), Ag₂CO₃ (2 mol%) and PPh₃ (6 mol%) were in a stainless-steel jar (50 mL) with a stainless-steel ball (15 m and PPh₃ (3 mol%). ^b Using Ag₂CO₃ (4 mol%) and PPh₃ (12 mol%).

Scheme 2 Substrate scope.

Scheme 3 One-pot transformation to carbamates.

additional milling at 15 Hz was conducted for 30 min. This integrated procedure efficiently yielded β-oxopropylcarbamates 3a19 in 86%, without requiring any intermediate operation

Conclusions

A novel mechanochemical strategy for the synthesis of cyclic carbonate esters via the fixation of CO2 onto propargylic alcohols has been developed. This protocol facilitates the rapid production of cyclic carbonates without the need for complex reaction setups or sophisticated synthetic techniques, thus offering a more streamlined and efficient alternative to conventional methods. The process is highly effective in producing a wide range of cyclic carbonate derivatives, demonstrating excellent functional group tolerance, short reaction times, and high yields. This streamlined approach is expected to hold significant relevance in the domains of organic synthesis and pharmaceutical development. We further anticipate that the mechanochemical processes could be adapted for large-scale chemical production in the near future.

Author contributions

N. T., H. S., and T. I. contributed to the preparation of the manuscript and SI. H. S. and T. I. contributed to research design. All authors have approved the version of the manuscript for publication.

Conflicts of interest

There are no conflicts to declare.

Data availability

All data of this study are documented within the manuscript and its SI. Supplementary information: experimental details, ¹H and ¹³C NMR spectra, and other spectra data. See DOI: https:// doi.org/10.1039/d5mr00072f.

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Notes and references

- 1 W. Liang, V. S. Ilchenko, D. Eliyahu, A. A. Savchenkov, A. B. Matsko, D. Seidel and L. Maleki, *Nat. Commun.*, 2015, **6**, 7371.
- 2 T. Niemi and T. Repo, Eur. J. Org Chem., 2019, 2019, 1180.
- 3 A. Cherubini-Celli, J. Mateos, M. Bonchio, L. Dell'Amico and X. Companyó, *ChemSusChem*, 2018, **11**, 3056.
- 4 J. Artz, T. E. Müller, K. Thenert, J. Kleinekorte, R. Meys, A. Sternberg, A. Bardow and W. Leitner, *Chem. Rev.*, 2018, 118, 434.
- 5 R. R. Shaikh, S. Pornpraprom and V. D'Elia, *ACS Catal.*, 2018, 8, 419.
- 6 A. J. Kamphuis, F. Picchioni and P. P. Pescarmona, *Green Chem.*, 2019, 21, 406.
- 7 B. Grignard, S. Gennen, C. Jérôme, A. W. Kleij and C. Detrembleur, *Chem. Soc. Rev.*, 2019, **48**, 4466.
- 8 (a) Y. Sugawara, W. Yamada, S. Yoshida, T. Ikeno and T. Yamada, J. Am. Chem. Soc., 2007, 129, 12902; (b) W. Yamada, Y. Sugawara, H. M. Cheng, T. Ikeno and T. Yamada, Eur. J. Org Chem., 2007, 2604; (c) Z. Z. Yang, Y. F. Zhao, H. Y. Zhang, B. Yu, Z. S. Ma, G. P. Ji and Z. M. Liu, Chem. Commun., 2014, 50, 13910; (d) Y. L. Gu, F. Shi and Y. Q. Deng, J. Org. Chem., 2004, 69, 391; (e) Y. Kayaki, M. Yamamoto and T. Ikariya, Angew. Chem., Int. Ed., 2009, 48, 4194; (f) Y. B. Wang, Y. M. Wang, W. Z. Zhang and X. B. Lu, J. Am. Chem. Soc., 2013, 135, 11996; (g) Y. B. Wang, D. S. Sun, H. Zhou, W. Z. Zhang and X. B. Lu, Green Chem., 2014, 16, 2266; (h) Y. Kayaki, M. Yamamoto and T. Ikariya, J. Org. Chem., 2007, 72, 647; (i) T. Kimura, K. Kamata and N. Mizuno, Angew. Chem., Int. Ed., 2012, 51, 6700; (j) Q.-W. Song, B. Yu, X.-D. Li, R. Ma, Z.-F. Diao, R.-G. Li, W. Li and L.-N. He, Green Chem., 2014, 16, 1633; (k) Q.-W. Song and L.-N. He, Adv. Synth. Catal., 2016, 358, 1251; (1) M. Li, S. Abdolmohammadi, M. S. Hoseininezhad-Namin, F. Behmagham and E. Vessally, J. CO₂ Util., 2020, 38, 220; (m) B. Grignard, C. Ngassamtounzoua, S. Gennen, B. Gilbert, R. Méreau, C. Jerome, T. Tassaing and C. Detrembleur, ChemCatChem, 2018, 10, 2584; (n) R. Méreau, B. Grignard, A. Boyaval, C. Detrembleur, C. Jerome and T. Tassaing, ChemCatChem, 2018, 10, 956; (o) H. Zhou, G.-X. Wang and X.-B. Lu, Asian J. Org. Chem., 2017, 6, 1264; (p) N. Della Ca', B. Gabriele, G. Ruffolo, L. Veltri, T. Zanetta and M. Costa, Adv. Synth. Catal., 2011, 353, 133.
- 9 (a) Q.-W. Song, W.-Q. Chen, R. Ma, A. Yu, Q.-Y. Li, Y. Chang and L.-N. He, *ChemSusChem*, 2015, **8**, 821; (b) G. Bresciani, M. Bortoluzzi, C. Ghelarducci, F. Marchetti and G. Pampaloni, *New J. Chem.*, 2021, **45**, 4340.
- 10 For selected reviews on the use of ball-milling for organic synthesis: (a) S. L. James, C. J. Adams, C. Bolm, D. Braga, P. Collier, T. Friščić, F. Grepioni, K. D. M. Harris, G. Hyett, W. Jones, A. Krebs, J. Mack, L. Maini, A. G. Orpen, I. P. Parkin, W. C. Shearouse, J. W. Steed and D. C. Waddell, Chem. Soc. Rev., 2012, 41, 413; (b) G.-W. Wang, Chem. Soc. Rev., 2013, 42, 7668; (c) J.-L. Do and T. Friščić, ACS Cent. Sci., 2017, 3, 13; (d)

- J. G. Hernández and C. Bolm, J. Org. Chem., 2017, 82, 4007; (e) T.-X. Métro, J. Martinez and F. Lamaty, ACS Sustainable Chem. Eng., 2017, 5, 9599; (f) T. K. Achar, A. Bose and P. Mal, Beilstein J. Org. Chem., 2017, 13, 1907; (g) O. Eguaogie, J. S. Vyle, P. F. Conlon, M. A. Gîlea and Y. Liang, Beilstein J. Org. Chem., 2018, 14, 955; (h) J. L. Howard, Q. Cao and D. L. Browne, Chem. Sci., 2018, 9, 3080; (i) J. Andersen and J. Mack, Green Chem., 2018, 20, 1435; (j) C. Bolm and J. G. Hernández, Angew. Chem., Int. Ed., 2019, 58, 3285; (k) T. Friščić, C. Mottillo and H. M. Titi, Angew. Chem., Int. Ed., 2020, 59, 1018; (l) K. Kubota and H. Ito, Trends Chem., 2020, 2, 1066; (m) A. Porcheddu, E. Colacino, L. De Luca and F. Delogu, ACS Catal., 2020, 10, 8344; (n) J. A. Leitch and D. L. Browne, Chem.-Eur. J., 2021, 27, 9721; (o) P. Ying, J. Yu and W. Su, Adv. Synth. Catal., 2021, 363, 1246; (p) K. J. Ardila-Fierro and J. G. Hernández, ChemSusChem, 2021, 14, 2145; (q) V. Martinez, T. Stolar, B. Karadeniz, I. Brekalo and K. Užarević, Nat. Rev. Chem., 2023, 7, 51; (r) K. Kubota, Bull. Chem. Soc. Ipn., 2023, 96, 913; (s) N. Fantozzi, J.-N. Volle, A. Porcheddu, D. Virieux, F. García and E. Colacino, Chem. Soc. Rev., 2023, 52, 6680; (t) G. A. Bowmaker, Chem. Commun., 2013, 49, 334.
- 11 T. Seo, N. Toyoshima, K. Kubota and H. Ito, *J. Am. Chem. Soc.*, 2021, **143**, 6165.
- 12 (a) Y. Gao, K. Kubota and H. Ito, Angew. Chem., Int. Ed., 2023,
 62, e202217723; (b) J. V. Nallaparaju, R. Satsi,
 D. Merzhyievskyi, T. Jarg, R. Aav and D. G. Kananovich,
 Angew. Chem., Int. Ed., 2024, 63, e202319449.
- 13 (a) V. S. Pfennig, R. C. Villella, J. Nikodemus and C. Bolm, Angew. Chem., Int. Ed., 2022, 61, e202116514; (b)
 R. Takahashi, A. Hu, P. Gao, Y. Gao, Y. Pang, T. Seo,
 S. Maeda, J. Jiang, H. Takaya, K. Kubota and H. Ito, Nat. Commun., 2021, 12, 6691.
- 14 C. Phung, R. M. Ulrich, M. Ibrahim, N. T. G. Tighe, D. L. Lieberman and A. R. Pinhas, *Green Chem.*, 2011, 13, 3224.
- 15 A.-A. Al-Terkawi, F. Lamaty and T.-X. Métro, ACS Sustainable Chem. Eng., 2020, 8, 13159.
- 16 During the preparation of this manuscript, a mechanochemical synthesis of cyclic carbamatesvia silver-catalysed fixation of CO₂ generated from NaHCO₃ with propargyl amines was reported; see: F. Mele, A. Aquilini, A. M. Constantin, F. Pancrazzi, L. Righi, A. Porcheddu, R. Maggi, D. A. Cauzzi, G. Maestri, E. Motti, L. Capaldo and N. Della Ca', *ChemSusChem*, 2025, e202500461.
- 17 Y. Sawama, M. Niikawa, K. Ban, K. Park, S. Aibara, M. Itoh and H. Sajiki, *Bull. Chem. Soc. Jpn.*, 2020, 93, 1074.
- 18 We conducted an experiment to evaluate the stability of the product 2a under the conditions: 2a (0.5 mmol) was subjected to planetary ball milling with 50×5 mm zirconia balls in a 20 mL zirconia bowl at 800 rpm for 15 minutes. The recovery yield of 2a was 83%, suggesting partial decomposition of the product under such conditions.
- 19 Z. Z. Yang, L. N. He, J. Gao, A. H. Liu and B. Yu, *Energy Environ. Sci.*, 2012, 5, 6602.