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Pyrolysis of azetidinone derivatives: a versatile route towards electron-rich alkenes, C-1 allylation and/or homologation of aldehydes†

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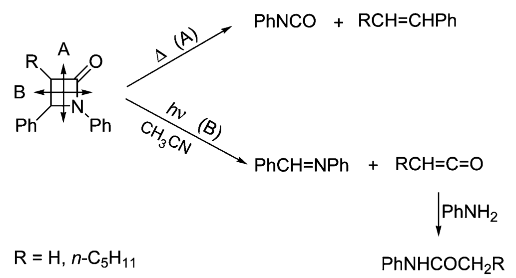
Pyrolysis of β-lactams and β-thiolactams led essentially to stereoselective synthesis of the high energy electron-rich *Z*-alkenes. Extension of this methodology to the pyrolysis of 3-allyloxy derivatives gave a simple direct route to the synthetically important 4-pentenal. These pyrolytic transformations convert aldehydes to aryloxyalkenes (a protected homologation) and 4-pentenal (a C-1 allylation and homologation). The starting 3-aryloxy and 3-allyloxy-β-lactams were synthesized by the standard Staudinger ketene-imine [2 + 2] cycloaddition. The corresponding β-thiolactams have readily been obtained in good yields by thiation of β-lactams with Lawesson's reagent.

1. Introduction

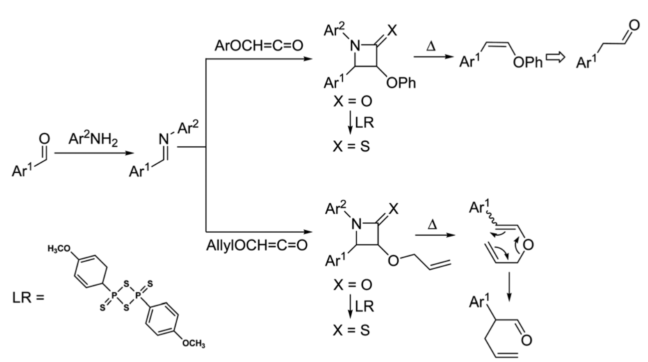
The term "β-lactam synthon method" has been introduced in 1997,[1] since then azetidin-2-ones have acquired a prominent place in organic chemistry as synthons for further elaboration. The constrained azetidinone ring has been employed successfully in synthetic methodologies towards all kinds of nitrogen-containing compounds.[2] The Staudinger [2 + 2] ketene–imine cycloaddition reaction is considered as one of the most important synthetic approaches to β-lactams (2-azetidinones) which have important application in pharmaceutical and synthetic chemistry.[1–5] Although the reaction has been discovered a hundred years ago,[4] it still attracts recent interest.[1–3,5]

Pyrolysis of these β-lactams has received little attention and was shown to give mainly alkenes with no more functional groups.[6–12] The thermal fragmentation of β-lactams occurs by two different pathways, the first one gives the starting ketene and imine (B) and the second pathway (A) gives alkene and isocyanate which could be trapped with amine to give the corresponding urea derivatives, Fischer found that the thermal fragmentation favours pathway A, while photolysis favours pathway B (Scheme 1).[11]

The present work is part of a project directed towards exploring the pyrolytic behaviour of this important ring system and its potentiality in producing useful functionalized organic reagents for further chemical elaboration. Scheme 2 illustrates our strategy to utilize such pyrolytic transformation to convert aldehydes to aryloxyalkenes (a protected homologation of the starting aldehyde) and 4-pentenal (a C-1 allylation and homologation).



Scheme 1 Routes for fragmentation of β-lactams.



Scheme 2 Strategy to convert aldehydes to aryloxyalkenes and 4-pentenal through β-lactams and thio-β-lactams pyrolysis.

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† Electronic supplementary information (ESI) available: Characterization data for all new β-lactams and β-thiolactams including ^{1}H NMR and ^{13}C NMR spectra (Tables 1 and 2) and mass spectra of some representative examples. See DOI: 10.1039/c4ra01024h

2. Results and discussion

The starting β-lactams and their corresponding 2-thioxo derivatives needed in our study were synthesized as outlined in Scheme 3. Thus, the reaction of imines **1a–g** with excess phenoxyacetyl chloride (2.5 equiv.) in dry DCM (CH_2Cl_2) in the presence of triethylamine with exception of **1d** gave the corresponding β-lactams as *cis* isomer **2a–c,e–g** respectively. In case of **1d** a mixture of *cis* and *trans* β-lactams **2d** and **3d** were formed (40 : 60) respectively. The *cis* stereochemistry of all products **2a–g** was assigned based on the coupling constants between the protons at C3 and C4, with observed *J*-values = 4.8 Hz.[13] The *trans* stereoisomer **3d** was unambiguously assigned based on the coupling constant between the protons at C3 and C4, with the observed *J*-value = 1.8 Hz (ref. 13) (see ESI Table 1†).

Moreover, it seemed worthwhile to compare the pyrolytic reaction of β-lactams **2a–g** and the corresponding thio-β-lactams **4a–g**. The later were synthesized in 65–73% yields by refluxing the corresponding β-lactams **2a–g** with Lawesson's reagent (LR) in dry toluene for 3 h (Scheme 3). All products **4a–g** retained the *cis* stereochemistry as indicated by the coupling constants between the protons at C3 and C4, with the observed *J*-values = 4.4–4.8 Hz.

We first studied the static pyrolysis (sealed-tube pyrolysis) of **2a** to optimize the condition for complete reaction for the desired pyrolysis products. The products of the reaction were analyzed directly after the thermolysis using ^{1}H and ^{13}C NMR spectroscopy. Table 1 shows the main products obtained under reduced pressure 1 × 10^{-2} Torr and at different pyrolysis temperatures (250, 270, 290, 300, 320, 350 and 400 °C). It is clear that the substrate **2a** is stable up to 250 °C and start to pyrolyze at 270 °C to 25% of the corresponding *Z*-alkene. However, at temperature lower 300 °C isomerisation of *cis*-β-lactam **2a** to *trans*-β-lactam **3a** was the main process, while by increasing the temperature and thermolysis time, fission of the β-lactam ring became the major pathway. Complete pyrolysis of **2a** occurred at 350 °C in 20 minutes with the formation of the *Z* and *E* alkene in 37% yield. Increasing the pyrolysis temperature to 400 °C and reducing the reaction time to 5 minutes increased *Z* : *E* ratio (Table 1).

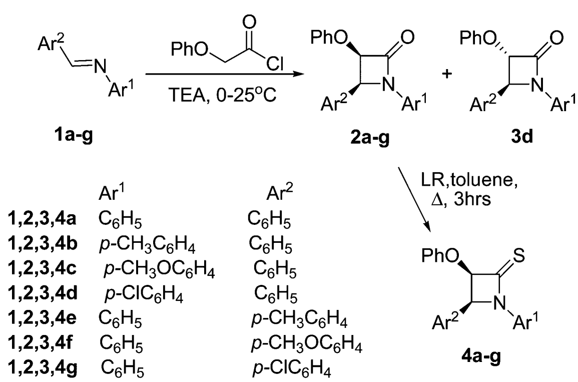
The β-lactams **2a–g** subjected to static pyrolysis at 350 °C and flash vacuum pyrolysis (FVP) at 600 °C. The pyrolytic reaction mixtures was carefully analyzed with the use of ^{1}H and ^{13}C NMR spectra, we found that, in STP at 350 °C of β-lactams **2a–g** in addition to formation of the corresponding *E* and *Z* alkenes, imines **1a–g** were formed in 6–11% yield. The main cleavage reaction is postulated to involve a retro [2 + 2] cycloreversion type fragmentation of the β-lactam ring liberating *Z*-alkene isomers together with the *E* isomers in a high diastereomeric ratio, however, under FVT the *Z* isomer is the major products in all cases (Scheme 4, Table 2). This could be explained by the fact the long residence time in static pyrolysis leads to isomerization of the *Z* isomer to the more stable *E* isomer.

Similar study revealed that the optimum temperature for the static pyrolysis of the thiolactams **4a–g** is 280 °C and 550 °C for the FVP. At 250 °C (STP) only partial isomerisation took place to give the corresponding *trans*-thio-β-lactams **6**. Thus STP (at 250 °C, 20 min) of **4a,c,f** gave a mixture of **4a,c,f** with the corresponding *trans* isomers **6a** (25%), **6c** (37%), **6f** (40%).

Moreover, the corresponding thiourea derivatives **13a–d** (11–16%) instead of arylisocyanates were detected in all cases. Unfortunately at higher temperature 280 °C for 15 min charring took place with formation of poor yield of the corresponding *E* and *Z* alkenes (5–14%). On the other hand, FVP of thio-β-lactams **4a–g** at 550 °C gave better yield of the corresponding alkenes (Scheme 4, Table 2) with higher *Z* diastereomeric ratio.

The **5** *E*/*Z* isomers percent were calculated depending on the integration of the *E* isomer proton (Ar^2–CH=) at δ = 6.3 ppm (*J* = 12.8 Hz) with the integration of the *Z* isomer proton (Ar^2–CH=) at δ = 5.6 ppm (*J* = 6.8 Hz), and all products percent are calculated using DCM method.[14]

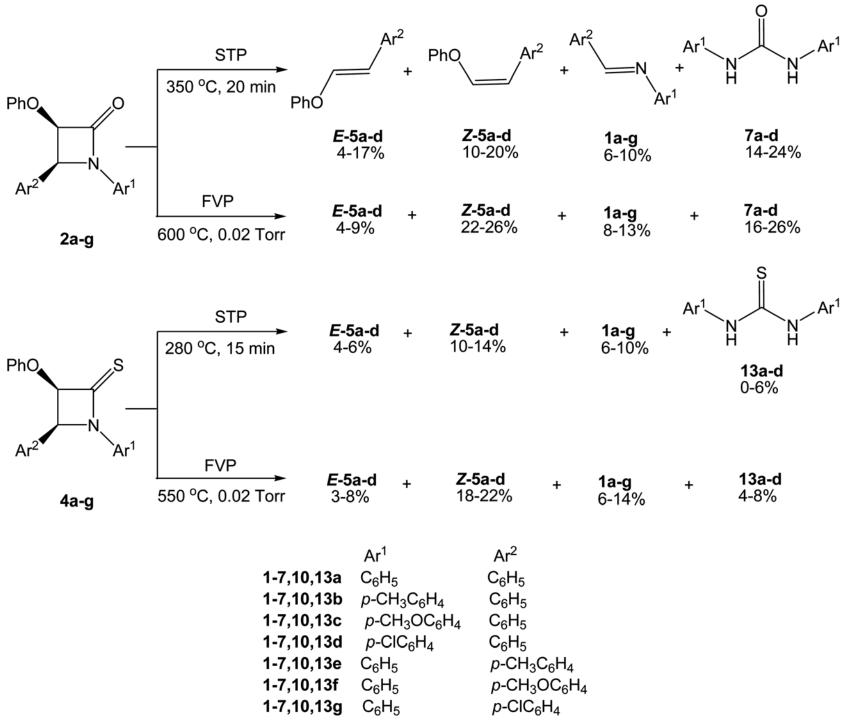
Our study was then extended to pyrolysis of the 3-allyloxy analogues of compounds **2** and **4** which are expected to undergo further Claisen rearrangement for the initially pyrolytically produced allyloxyalkene. The new 3-allyloxy-1,4-diaryl-2-



Scheme 3 Synthesis of β-lactams **2a–g** and thio-β-lactams **4a–g**.

Table 1 Products from STP of *cis*-β-lactam **2a** (yield %)

Entry	Temp.(°C)	Time (min)	*cis*-β-lactam **2a**	*trans*-β-lactam **3a**	*Z*-**5a**	*E*-**5a**
1	250	30	100	0	0	0
2	270	90	40	25	25	0
3	290	15	50	20	15	0
4	300	30	25	25	25	1
5	320	30	8	18	23	13
6	350	20	0	0	20	17
7	400	5	0	0	21	10



Scheme 4 Products of SVP and FVP of *cis* β-lactam **2a–g** and *cis*-thio-β-lactams **4a–g**.

Table 2 Products of STP and FVP of *cis*-β-lactams **2a–g** and *cis*-thio-β-lactams **4a–g**

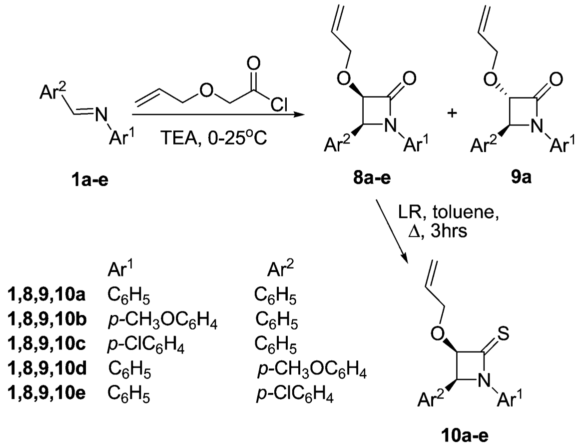
	STP[a]			FVP[b]		
Comp. no.	Alkene (*E*/*Z*)	Imine (yield %)	Urea (thiourea) (yield %)	Alkene (*E*/*Z*)	Imine (yield %)	Urea (thiourea) (yield %)
2a	**5a** (17/20)	**1a** (10)	**7a** (24)	**5a** (6/25)	**1a** (11)	**7a** (18)
2b	**5a** (11/16)	**1b** (8)	**7b** (20)	**5a** (9/22)	**1b** (10)	**7b** (16)
2c	**5a** (9/17)	**1c** (7)	**7c** (20)	**5a** (6/23)	**1c** (12)	**7c** (26)
2d	**5a** (11/17)	**1d** (11)	**7d** (16)	**5a** (7/26)	**1d** (12)	**7d** (18)
2e	**5b** (12/19)	**1e** (8)	**7a** (18)	**5b** (5/24)	**1e** (8)	**7a** (18)
2f	**5c** (9/12)	**1f** (6)	**7a** (14)	**5c** (4/25)	**1f** (13)	**7a** (20)
2g	**5d** (16/22)	**1g** (11)	**7a** (24)	**5d** (7/24)	**1g** (12)	**7a** (24)
4a	**5a** (6/10)	**1a** (8)	**13a** (4)	**5a** (4/18)	**1a** (7)	**13a** (8)
4b	**5a** (5/10)	**1b** (10)	**13b** (0)	**5a** (7/20)	**1b** (9)	**13b** (4)
4c	**5a** (6/14)	**1c** (6)	**13c** (4)	**5a** (3/22)	**1c** (11)	**13c** (8)
4d	**5a** (4/12)	**1d** (8)	**13d** (6)	**5a** (5/19)	**1d** (6)	**13d** (6)
4e	**5b** (6/12)	**1e** (8)	**13a** (4)	**5b** (3/21)	**1e** (11)	**13a** (8)
4f	**5c** (4/10)	**1f** (7)	**13a** (0)	**5c** (4/19)	**1f** (9)	**13a** (4)
4g	**5d** (4/13)	**1g** (6)	**13a** (4)	**5d** (8/21)	**1g** (14)	**13a** (6)

[a] STP, 350 °C, 0.01 Torr, 20 min. for β-lactams **2a–g**, 280 °C, 0.01 Torr, 15 min for thio-β-lactams **4a–g.** [b] FVP, 600 °C, 0.02 Torr for β-lactams **2a–g**, 550 °C, 0.02 Torr; for thio-β-lactams **4a–g.**

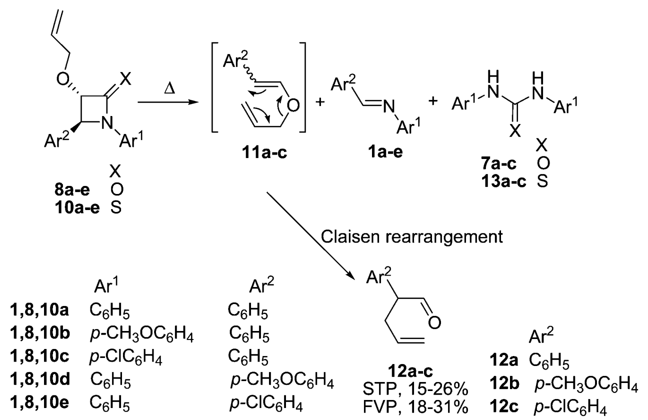
azetidinone **8a–e** were prepared by the reaction of imines **1a–e** with allyloxyacetyl chloride in the presence of triethylamine. In all cases *cis*-β-lactams **8a–e** were obtained except in case of the imine **1a** *trans*-β-lactams **9a** was formed in 4% yield. The corresponding 3-allyloxy-β-thiolactams **10a–e** were obtained by thiation of **8a–e** with Lawesson's reagent (Scheme 5) (see ESI Table 2†).

The optimum temperature for pyrolysis of allyloxy-1,4-diaryl-2-azetidinone **8a–e** is 300 °C (STP) and 600 °C (FVP). The ^{1}H and ^{13}C NMR spectroscopic analysis of the pyrolysate showed the formation of urea derivatives **7a–c** and imines **1a–c**, but the methylene protons signal at δ 4.3 corresponding to the olefinic ether intermediate **11a**[15,16] was not detected in the pyrolysate, while the spectroscopic properties were identical with those reported for the corresponding 4-pentenal **12a–c** (a Claisen rearrangement of aldehydes)[17,18] (Scheme 6).

FVP of allyloxy-1,4-diaryl-2-azetidinone **8a–d** at 600 °C gave the 4-pentenals **12a–c** together with the other by-products **7a–c**,



Scheme 5 Synthesis of β-lactams **8a–e** and thio-β-lactams **10a-e**.



Scheme 6 Products of SVP and FVP of *cis*-β-lactam **8a–e** and thio-β-lactams **10a–e**.

1a–c but with a higher yields of aldehydes **12a–c**. On the other hand, pyrolysis of thio-β-lactams **10a–e** gave poor yields in both STP and FVP even on decreasing the pyrolysis temperature (270 °C, STP), (550 °C, FVP). The aldehydes **12a–c** and imines **1a–c** have been detected in the pyrolysate in addition to traces of thiourea derivatives **13a–c** (Table 3).

The percent yield of the products in pyrolysate mixture based on the characteristic protons, aldehydes based on the characteristic aldehyde proton at 9.7 ppm (d, $J = 1.6$ Hz),[17,18] imines based on the characteristic CH=N proton at 8.4 ppm, and urea derivatives on the exchangeable NH proton at 8.5–8.8 (ref. 19) or based on the characteristic MeO proton at 3.8 ppm.

3. Conclusion

The present work offers an interesting application of synthetic transformation of a new 2-azetidinones into valuable intermediates in synthetic chemistry including electron-rich *Z*-olefins and 4-pentenal derivatives. The latter have important applications in synthetic chemistry and were prepared recently by multi step reaction.[20,21] Moreover, the reported synthesized aryl vinyl ethers found applications in the synthesis of biologically active molecules and natural product analogues,[22] and because of its importance various methods for their synthesis have been reported.[23] Also, the reported pyrolytic transformations convert aldehydes to aryloxyalkenes (a protected homologation) and 4-pentenal (a C-1 allylation and homologation).

4. Experimental

4.1 General

All reactions were carried out in oven-dried glassware under N_2, using commercially supplied solvents and reagents unless otherwise stated. THF and CH_2Cl_2 were redistilled from Na–Ph_2CO and CaH_2 respectively. Column chromatography was carried out on silica gel using flash techniques (eluants are given in parentheses). Analytical thin-layer chromatography was performed on precoated silica gel F254 aluminum plates with visualization under UV light.

Melting points were obtained using a melting point apparatus and are uncorrected. IR spectra were recorded on FT-IR

Table 3 Products of SVP and FVP of *cis*-β-lactams **8a–e** and thio-β-lactams **10a–e**

	STP[a]			FVP[b]		
Comp. no.	Alde. no. (yield %)	Imine no. (yield %)	Urea(thiourea) no. (yield %)	Alde. no. (yield %)	Imine no. (yield %)	Urea(thiourea) no. (yield %)
8a	**12a** (26)	**1a** (18)	**7a** (18)	**12a** (31)	**1a** (15)	**7a** (14)
8b	**12a** (20)	**1b** (12)	**7b** (24)	**12a** (28)	**1b** (14)	**7b** (16)
8c	**12a** (22)	**1c** (25)	**7c** (17)	**12a** (26)	**1c** (19)	**7c** (15)
8d	**12b** (21)	**1d** (17)	**7a** (21)	**12b** (27)	**1d** (22)	**7a** (15)
8e	**12c** (24)	**1e** (12)	**7a** (9)	**12c** (27)	**1e** (18)	**7a** (13)
10a	**12a** (18)	**1a** (20)	**13a** (3)	**12a** (22)	**1a** (20)	**13a** (5)
10b	**12a** (15)	**1b** (19)	**13b** (2)	**12a** (18)	**1b** (18)	**13b** (3)
10c	**12a** (18)	**1c** (19)	**13c** (4)	**12a** (21)	**1c** (16)	**13c** (3)
10d	**12b** (16)	**1d** (22)	**13a** (0)	**12b** (21)	**1d** (19)	**13a** (4)
10e	**12c** (15)	**1e** (13)	**13a** (2)	**12c** (23)	**1e** (17)	**13a** (2)

[a] STP, 300 °C, 0.01 Torr, 15 min. for β-lactams **8a–e**, 270 °C, 0.01 Torr, 15 min for thio-β-lactams **10a–e**. [b] FVP, 600 °C, 0.02 Torr for β-lactams **8a–e**, 550 °C, 0.02 Torr; for thio-β-lactams **10a–e**.

spectrophotometer as neat thin films between NaCl plates in the case of liquid substances or as KBr pellets in the case of solids, with adsorptions reported in wavenumbers (cm^{-1}). ^{1}H NMR spectra were recorded at 400 or 600 MHz with chemical shifts (δ) quoted in parts per million (ppm) and coupling constants (J) recorded in hertz (Hz). ^{13}C NMR spectra were recorded at 100 or 150 MHz with chemical shifts (δ) quoted in ppm. Mass spectral data were measured with EI positive ion mode. Microanalyses were performed on LECO CH NS-932 Elemental Analyzer.

4.2 Synthesis of β-lactams 2a–g: general procedure

To a stirred cold (0 °C) solution of appropriate imines **1a–g** (40 mmol, 1 equiv.) and triethylamine (25 mmol, 2.5 equiv.) in dry CH_2Cl_2 (15 mL) under nitrogen atmosphere was added drop-wise with a syringe a solution of phenoxyacetyl chloride (100 mmol, 2.5 equiv.) in dry CH_2Cl_2 (5 mL). The mixture was stirred at 0 °C for 30 min, and then left stirring at room temperature overnight. The reaction mixture washed with water, $NaHCO_3$ solution and brine. The organic layer was then dried over anhydrous Na_2SO_4 and the solvent was removed *in vacuo*. The remaining solid was recrystallized from ethanol to give corresponding β-lactams **2a–g** as colourless solid in 57–74% yield.

(±)-*cis*-3-Phenoxy-1,4-diphenyl-2-azetindione (2a). Colorless crystals, yield 8.4 g (67%), mp 193–195 °C (194 °C);[24] ν_{max}(KBr)/cm^{-1} 3003, 2916, 1744, 1588, 1558, 1455, 1419, 1210, 749, 701. δ_H(400 MHz, $CDCl_3$) 7.38–7.26 (m, 9H), 7.16 (t, 2H, J 8.4), 7.09 (t, 1H, J 7.2), 6.93 (t, 1H, J 8.0), 6.78 (d, 2H, J 8.0), 5.57 (d, 1H, J 4.8), 5.40 (d, 1H, J 4.8); δ_C(100 MHz, $CDCl_3$) 163.3, 157.1, 137.1, 132.7, 129.49, 129.40, 128.9, 128.6, 128.3, 124.8, 122.4, 117.8, 115.9, 81.3, 62.2; HR-MS (EI) m/z $[M]^+$ calcd for $C_{21}H_{17}NO_2$ 315.1259, found 315.1256.

(±)-*cis*-3-Phenoxy-4-phenyl-1-(*p*-tolyl)-2-azetidione (2b). Colorless crystals, yield 7.9 g (60%), mp 175–177 °C; ν_{max}(KBr)/cm^{-1} 3029, 2947, 2856, 1743, 1598, 1494, 1253, 864, 825, 746, 684; δ_H(400 MHz, $CDCl_3$) 7.36 (d, 2H, J 8.4), 7.26 (m, 4H), 7.17 (t, 2H, J 8.4), 7.08 (d, 3H, J 7.6), 6.92 (t, 1H, J 7.6), 6.79 (d, 2H, J 8.4), 5.53 (d, 1H, J 4.8), 5.36 (d, 1H, J 4.8), 2.29 (s, 3H); δ_C(100 MHz, $CDCl_3$) 163.4, 157.2, 138.7, 137.2, 129.6, 129.4, 129.3, 128.2, 124.7, 122.3, 117.8, 116.0, 81.4, 61.1, 21.4; HR-MS (EI) m/z $[M]^+$ calcd for $C_{22}H_{19}NO_2$ 329.1416, found 329.1411.

(±)-*cis*-3-Phenoxy-1-(*p*-methoxyphenyl)-4-phenyl-2-azetidinone (2c). Colorless crystals, yield 8.1 g (60%), mp 190–191 °C (186 °C);[25] ν_{max}(KBr)/cm^{-1} 3035, 2956, 2831, 1742, 1588, 1455, 1441, 882, 750, 696; δ_H(600 MHz, $CDCl_3$) 7.30–7.25 (m, 7H), 7.14 (m, 2H), 6.90 (t, 1H, J 7.6), 6.80–6.76 (m, 4H), 5.55 (d, 1H, J 4.8), 5.35 (d, 1H, J 4.8), 3.74 (s, 3H); δ_C(125 MHz, $CDCl_3$) 162.2, 157.1, 156.7, 132.8, 130.6, 129.4, 128.9, 128.5, 128.3, 122.3, 119.1, 115.9, 114.6, 81.4, 62.3, 55.6; HR-MS (EI) m/z $[M]^+$ calcd for $C_{22}H_{19}NO_3$ 345.1365, found 345.1362.

(±)-*cis*-3-Phenoxy-1-(*p*-chlorophenyl)-4-phenyl-2-azetidinone (2d). Colorless crystals, yield 3.4 g (30%), mp 272–273 °C; ν_{max}(KBr)/cm^{-1} 3048, 1745, 1598, 1492, 1350, 1251, 866, 837, 746, 684; δ_H(400 MHz, DMSO-d_6) 7.39–7.32 (m, 6H), 7.27 (m, 3H), 7.18 (t, 2H, J 7.2), 6.91 (t, 1H, J 7.2), 6.80 (d, 2H, J 7.8), 5.78 (d, 1H, J 4.0), 5.70 (d, 1H, J 4.0); δ_C(100 MHz, DMSO-d_6) 162.6, 156.2, 135.2, 132.5, 129.1, 128.8, 128.7, 127.9, 127.7, 127.6, 121.5, 118.4, 115.0, 80.6, 60.8; HR-MS (EI) m/z $[M]^+$ calcd for $C_{21}H_{16}{}^{35}ClNO_2$ 349.0870,found 349.0865.

(±)-*cis*-3-Phenoxy-4-(*p*-tolyl)-1-phenyl-2-azetidinone (2e).[26] Colorless crystals, yield 9.7 g (74%), mp 172–173 °C; ν_{max}(KBr)/cm^{-1} 3029, 2947, 2856, 1922, 1746, 1598, 1473, 1388, 746, 684; δ_H(600 MHz, $CDCl_3$) 7.36 (d, 2H, J 7.8), 7.26–7.23 (m, 4H), 7.15 (t, 2H, J 8.4), 7.06 (d, 3H, J 7.8), 6.90 (t, 1H, J 7.2),6.78 (d, 2H, J 7.8), 5.52 (d, 1H, J 4.8), 5.34 (d, 1H, J 4.8), 2.27 (s, 3H); δ_C(125 MHz, $CDCl_3$) 163.4, 157.2, 138.7, 137.1, 129.6, 129.4, 129.3, 128.2, 124.7, 122.3, 117.8, 116.0, 81.4, 62.1, 21.4; HR-MS (EI) m/z $[M]^+$ calcd for $C_{22}H_{19}NO_2$ 329.1416, found 329.1410.

(±)-*cis*-3-Phenoxy-4-(*p*-methoxyphenyl)-1-phenyl-2-azetidinone (2f). Colorless crystals, yield 8.4 g (61%), mp 152–155 °C (150 °C);[25] ν_{max}(KBr)/cm^{-1} 3041, 2957, 2872, 1758, 1597, 1458, 1384, 1362, 1251, 895, 754, 690; δ_H(400 MHz, $CDCl_3$) 7.36 (d, 2H, J 7.6), 7.36–7.25 (m, 4H), 7.17 (t, 2H, J 7.6), 7.08 (t, 1H, J 7.6), 6.92 (t, 1H, J 7.2), 6.80 (m, 4H), 5.53 (d, 1H, J 4.8), 5.35 (d, 1H, J 4.8), 3.75 (s, 3H); δ_C(100 MHz, $CDCl_3$) 163.3, 160.0, 157.2, 137.3, 129.6, 129.4, 129.3, 124.7, 124.5, 122.3, 117.8, 115.9, 114.1, 81.4, 61.9, 55.4; HR-MS (EI) m/z $[M]^+$ calcd for $C_{22}H_{19}NO_3$ 345.1365, found 345.1361.

(±)-*cis*-3-Phenoxy-4-(*p*-chlorophenyl)-1-phenyl-2-azetidinone (2g).[27] Colorless crystals, yield 6.5 g (58%), mp 193–196 °C; ν_{max}(KBr)/cm^{-1} 3047, 1743, 1598, 1490, 1350, 1251, 865, 837, 744 and 684; δ_H(400 MHz, $CDCl_3$) 7.26–7.11 (m, 8H), 7.08 (t, 2H, J 8.0), 7.01 (t, 1H, J 7.6), 6.84 (t, 1H, J 7.2), 6.68 (d, 2H, J 8.0), 5.47 (d, 1H, J 4.8), 5.28 (d, 1H, J 4.8); δ_C(100 MHz, $CDCl_3$) 163.0, 156.9, 136.9, 134.8, 131.4, 129.65, 129.60, 129.4, 128.9, 125.0, 122.6, 117.7, 115.8, 81.2, 61.5; HR-MS (EI) m/z $[M]^+$ calcd for $C_{21}H_{16}{}^{35}ClNO_2$ 349.0870, found 349.0867.

(±)-*trans*-3-Phenoxy-1-(*p*-chlorophenyl)-4-phenyl-2-azetidinone (3d). Colorless crystals, yield 5.1 g (45%), mp 149–150 °C; ν_{max}(KBr)/cm^{-1} 3050, 1745, 1599, 1490, 1353, 1250, 866, 838, 746, 685; δ_H(600 MHz, $CDCl_3$) 7.39–7.19 (m, 11H), 7.00 (t, 1H, J 7.2), 6.87 (d, 2H, J 7.8), 5.11 (d, 1H, J 1.8), 5.00 (d, 1H, J 1.8); δ_C(125 MHz, $CDCl_3$) 162.7, 157.0, 135.5, 135.2, 129.9, 129.8, 129.6, 129.5, 129.4, 126.5, 122.5, 118.9, 115.5, 87.6, 64.3; HR-MS (EI) m/z $[M]^+$ calcd for $C_{21}H_{16}{}^{35}ClNO_2$ 349.0870, found 349.0870.

4.3 Synthesis of thio-β-lactams 4a–g: general procedure

A mixture of appropriate β-lactams **2a–g** (4 mmol) and Lawesson's reagent (1.6 g, 4 mmol) in dry toluene (15 mL) was refluxed for 3 h. The solvent was then removed *in vacuo* and the resulting solid was recrystallised from ethanol to give the corresponding thio-β-lactams **4a–g** in 65–77% yield.

(±)-*cis*-3-Phenoxy-1,4-diphenyazetidin-2-thione (4a). Colorless crystals, 0.88 g (67%), mp 170–175 °C; ν_{max}(KBr)/cm^{-1} 3026, 3006, 2927, 1589, 1494, 1427, 1228, 1205, 1074, 765, 746, 686; δ_H(400 MHz, $CDCl_3$) 7.92 (d, 2H, J 8.4), 7.36–7.13 (m, 10H), 6.93 (t, 1H, J 6.7), 6.78 (d, 2H, J 8.0), 5.89 (d, 1H, J 4.8), 5.35 (d, 1H, J 4.8); δ_C(100 MHz, $CDCl_3$) 195.2, 157.2, 138.0, 132.0, 129.4, 129.2, 128.7, 128.3, 126.6, 122.5, 118.5, 116.3, 79.5, 70.4; HR-MS (EI) m/z $[M]^+$ calcd for $C_{21}H_{17}NOS$ 331.1031, found 331.1028.

(±)-*cis*-3-Phenoxy-1-(*p*-tolyl)-4-phenylazetidin-2-thione (4b). Colorless crystals, 0.95 g (69%), 157–159 °C; ν_{max}(KBr)/cm^{-1} 2916, 2831, 2360, 1579, 1404, 1346, 1207, 750, 688; δ_H(400 MHz,

$CDCl_3$) 7.92 (d, 2H, *J* 8.4), 7.32 (t, 2H *J* 8.4), 7.26–7.14 (m, 5H), 7.07 (d, 2H *J* 8.0), 6.92 (t, 1H *J* 7.6), 6.81 (d, 2H *J* 8.0), 5.86 (d, 1H, *J* 4.4), 5.32 (d, 1H, *J* 4.4), 2.28 (s, 3H); δ_C(100 MHz, $CDCl_3$) 195.3, 157.3, 139.1, 138.0, 129.45, 129.41, 129.2, 128.9, 128.2, 126.6, 122.4, 118.6, 116.3, 79.7, 70.5, 21.4; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{22}H_{19}NOS$ 345.1187, found 345.1181.

(±)-*cis*-3-Phenoxy-1-(*p*-methoxyphenyl)-4-phenylazetidin-2-thione (4c). Colorless crystals, 1.03 g (71%), mp 148–150 °C; ν_{max}(KBr)/cm^{-1} 3031, 2954, 2923, 2835, 1585, 1446, 1438, 1259, 1176, 1101, 850, 748, 723, 684; δ_H(400 MHz, $CDCl_3$) 7.88 (d, 2H, *J* 8.0), 7.35–7.26 (m, 5H), 7.14 (t, 2H, *J* 7.2), 6.92 (t, 1H, *J* 7.2), 6.84 (d, 2H, *J* 7.4), 6.79 (d, 2H, *J* 8.0), 5.84 (d, 1H, *J* 4.4), 5.35 (d, 1H, *J* 4.4), 3.77 (s, 3H); δ_C(100 MHz, $CDCl_3$) 193.3, 157.9, 157.2, 132.0, 131.5, 129.3, 129.2, 128.6, 128.3, 122.4, 120.2, 116.2, 114.3, 79.5, 70.6, 55.6; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{22}H_{19}NO_2S$ 361.1136, found 361.1133.

(±)-*cis*-3-Phenoxy-1-(*p*-chlorophenyl)-4-phenyl-2-azetidin-2-thione (4d). Colorless crystals, 1.12 g (77%), mp 217–218 °C; ν_{max}(KBr)/cm^{-1} 3030, 2927, 1582, 1494, 1427, 1230, 1200, 1077, 765, 750, 686; δ_H(600 MHz, DMSO-d_6) 7.93 (d, 2H, *J* 7.8), 7.49 (d, 2H, *J* 7.8),7.31–7.16 (m, 7H) 6.90 (t, 1H, *J* 7.8), 6.80 (d, 2H, *J* 7.8), 6.36 (d, 1H, *J* 4.2), 5.64 (d, 1H, *J* 4.2); δ_C(125 MHz, DMSO-d_6) 195.2, 156.3, 136.0, 131.8130.1, 129.3, 129.2, 128.7, 128.3, 125.3, 121.9, 119.8, 115.2, 78.8, 69.5; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{21}H_{16}{}^{35}ClNOS$ 365.0641, found 365.0635.

(±)-*cis*-3-Phenoxy-4-(*p*-tolyl)-1-phenyl-2-azetidin-2-thione (4e). Colorless crystals, 0.89 g (65%), 152–153 °C; ν_{max}(KBr)/cm^{-1} 2916, 2831, 2360, 2343, 1589, 1404, 1346, 1207, 750, 688; δ_H(600 MHz, $CDCl_3$) 7.90 (d, 2H, *J* 7.8), 7.28 (t, 2H, *J* 7.8), 7.20 (d, 2H, *J* 7.4), 7.15 (m, 3H), 7.03 (d, 2H, *J* 7.8), 6.88 (t, 1H, *J* 7.8), 6.79 (d, 2H, *J* 7.8), 5.83 (d, 1H, *J* 4.2), 5.28 (d, 1H, *J* 4.2), 2.25 (s, 3H); δ_C(125 MHz, $CDCl_3$) 195.2, 157.3, 139.0, 138.0, 129.38, 129.36, 129.1, 128.8, 128.2, 126.5, 122.4, 118.5, 116.3, 79.6, 70.4, 21.3; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{22}H_{19}NOS$ 345.1187, found 345.1184.

(±)-*cis*-3-Phenoxy-4-(*p*-methoxyphenyl)-1-phenyl-2-azetidin-2-thione (4f). Colorless crystals, 1.05 g (73%), mp 148–150 °C; ν_{max}(KBr)/cm^{-1} 3030, 2953, 2923, 2835, 1586, 1446, 1438, 1259, 1176, 1101, 851, 750, 725, 683; δ_H(600 MHz, $CDCl_3$) 7.93 (d, 2H, *J* 8.0), 7.34–7.14 (m, 7H), 6.92 (t, 1H, *J* 7.6), 6.81 (t, 4H, *J* 7.6), 5.85 (d, 1H, *J* 4.4), 5.30 (d, 1H, *J* 4.4), 3.73 (s, 3H); δ_C(125 MHz, $CDCl_3$) 195.1, 160.2, 157.2, 137.9, 129.6, 129.3, 129.1, 126.5, 123.7, 122.3, 118.6, 116.2, 114.0, 79.6, 70.1, 55.3; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{22}H_{19}NO_2S$ 361.1136, found 361.1130.

(±)-*cis*-3-Phenoxy-4-(*p*-chlorophenyl)-1-phenyl-2-azetidin-2-thione (4g). Colorless crystals, 1.05 g (72%), mp 166–167 °C; ν_{max}(KBr)/cm^{-1} 3033, 2927, 1587, 1494, 1425, 1230, 1212, 1077, 765, 749, 686; δ_H(400 MHz, $CDCl_3$) 7.90 (d, 2H, *J* 8.4), 7.35–7.15 (m, 9H), 6.94 (t, 1H, *J* 7.6), 6.80 (d, 2H, *J* 8.0), 5.87 (d, 1H, *J* 4.8), 5.33 (d, 1H, *J* 4.8); δ_C(100 MHz, $CDCl_3$) 195.0, 157.0, 137.7, 135.1, 130.6, 129.6, 129.5, 129.3, 128.9, 126.8, 122.6, 118.4, 116.1, 79.3, 69.6; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{21}H_{16}{}^{35}ClNOS$ 365.0641, found 365.0635.

4.4 Synthesis of β-lactams 8a–e: general procedure

To a stirred cold (0 °C) solution of appropriate imines **1a–e** (10 mmol, 1 equiv.) and triethylamine (25 mmol, 2.5 equiv.) in dry CH_2Cl_2 (15 mL) under nitrogen atmosphere was added dropwise with a syringe a solution of allyloxyacetyl chloride (25 mmol, 2.5 equiv.) in dry CH_2Cl_2 (5 mL). The mixture was stirred at 0 °C for 30 min, and then left stirring at room temperature overnight. The reaction mixture was washed with water, $NaHCO_3$ solution and brine. The organic layer was then dried over anhydrous Na_2SO_4 and the solvent was removed *in vacuo*. The remaining solid was recrystallized from ethanol to give corresponding β-lactams **8a–e** as colourless solid in 69–84% yield.

(±)-*cis*-3-Allyloxy-1,4-diphenyl-2-azetidinone (8a). Colorless crystals, yield 2.10 g (75%), mp 131–133 °C; ν_{max}(KBr)/cm^{-1} 3036, 2910, 2857, 1741, 1595, 1497, 1389, 1184, 1132, 926, 752; δ_H(400 MHz, $CDCl_3$) 7.42–7.23 (m, 7H), 7.26 (t, 2H, *J* 7.6), 7.05 (t, 1H, *J* 7.6), 5.57 (m, 1H), 5.19 (d, 1H, *J* 4.8, H-4), 5.08 (dd, 1H, *J* 8.8, 1.2), 5.00 (dd, 1H, *J* 18.2, 1.2), 4.96 (d, 1H, *J* 4.8, H-3), 3.89 (dd, 1H, *J* 12.4, 5.6), 3.74 (dd, 1H, *J* 12.4, 5.6); δ_C(100 MHz, $CDCl_3$) 164.6, 137.2, 133.6, 133.3, 129.2, 128.7, 128.6, 128.2, 124.5, 118.2, 117.6, 82.7, 71.6, 62.1; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{17}NO_2$ 279.1259, found 279.1253; anal. calcd: C 77.40, H 6.13, N 5.01. Found C 77.20, H 6.08, N 4.90.

(±)-*trans*-3-Allyloxy-1,4-diphenyl-2-azetidinone (9a). Colorless crystals, yield 0.2 g (4%), mp 94–96 °C; ν_{max}(KBr)/cm^{-1} 3035, 2910, 2857, 1740, 1595, 1497, 1390, 1184, 1133, 926, 752; δ_H(400 MHz, $CDCl_3$) 7.41–7.24 (m, 9H), 7.07 (t, 1H, *J* 7.8), 5.95 (m, 1H), 5.32 (dd, 1H, *J* 15.6, 1.6), 5.23 (dd, 1H, *J* 10.4, 1.2), 4.95 (d, 1H, *J* 2.4, H-4), 4.45 (d, 1H, *J* 2.4, H-3), 4.30 (dd, 1H, *J* 12.4, 5.6), 4.24 (dd, 1H, *J* 12.4, 5.6); HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{17}NO_2$ 279.1259, found 279.1254; anal. calcd: C 77.40, H 6.13, N 5.01. Found C 77.18, H 6.09, N 4.93.

(±)-*cis*-3-Allyloxy-1-(*p*-methoxyphenyl)-4-phenyl-2-azetidinone (8b). Colorless crystals, yield 2.60 g (84%), mp 120–121 °C; ν_{max}(KBr)/cm^{-1} 3036, 2977, 2837, 1741, 1595, 1690, 1514, 1243, 1185, 1115, 993, 829, 694; δ_H(400 MHz, $CDCl_3$) 7.39–7.28 (m, 7H), 6.80–6.78 (m, 2H) 5.59 (m, 1H), 5.17 (d, 1H, *J* 4.8, H-4), 5.08 (dd, 1H, *J* 8.8, 1.2), 5.04 (dd, 1H, *J* 18.2, 1.2), 4.97 (d, 1H, *J* 4.8, H-3), 3.89 (dd, 1H, *J* 12.2, 5.6), 3.76 (dd, 1H, *J* 12.2, 5.6), 3.73 (s, 3H, OCH_3); δ_C(100 MHz, $CDCl_3$) 164.0, 156.5, 133.7, 133.4, 130.8, 128.7, 128.6, 128.3, 118.9, 118.1, 114.5, 82.9, 71.6, 62.2, 55.6; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{19}H_{19}NO_3$ 309.1365, found 309.1359; anal. calcd: C 73.77, H 6.19, N 4.53. Found C 73.49, H 6.00, N 4.34.

(±)-*cis*-3-Allyloxy-1-(*p*-chlorophenyl)-4-phenyl-2-azetidinone (8c). Colorless crystals, yield 2.15 g (69%), mp 98–100 °C; ν_{max}(KBr)/cm^{-1} 3065, 3037, 2961, 2903, 2857, 1741, 1595, 1496, 1385, 1176, 1131, 839, 814; δ_H(400 MHz, $CDCl_3$) 7.37–7.18 (m, 9H), 5.55 (m, 1H), 5.17 (d, 1H, *J* 4.8, H-4), 5.07 (dd, 1H, *J* 9.6, 1.2), 5.03 (dd, 1H, *J* 18.4, 1.2), 4.97 (d, 1H, *J* 4.8, H-3), 3.88 (dd, 1H, *J* 12.4, 5.6), 3.74 (dd, 1H, *J* 12.4, 5.6); δ_C(100 MHz, $CDCl_3$) 164.5, 135.8, 133.3, 133.1, 129.6, 129.3, 129.0, 128.8, 128.2, 118.9, 118.4, 83.0, 71.8, 62.3; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{16}ClNO_2$ 313.0870, found 313.0864; anal. calcd: C 68.90, H 5.14, N 4.46. Found C 68.71, H 5.08, N 4.32.

(±)-*cis*-3-Allyloxy-4-(*p*-methoxyphenyl)-1-phenyl-2-azetidinone (8d). Colorless crystals, yield 2.55 g (82%), mp 90–91 °C; ν_{max}(KBr)/cm^{-1} 3037, 2960, 2898, 1749, 1615, 1510, 1393, 1247, 1176, 1131, 833, 752; δ_H(400 MHz, $CDCl_3$) 7.33 (d, 4H, *J* 6.8), 7.24

(t, 2H, *J* 7.2), 7.05 (t, 1H, *J* 7.2), 6.89 (d, 2H, *J* 6.8), 5.59 (m, 1H), 5.14 (d, 1H, *J* 4.8, H-4), 5.11 (dd, 1H, *J* 8.8, 1.2), 5.07 (dd, 1H, *J* 18.2, 1.2), 4.92 (d, 1H, *J* 4.8, H-3), 3.89 (dd, 1H, *J* 12.4, 5.6), 3.80 (s, 3H, OCH_3), 3.76 (dd, 1H, *J* 12.4, 5.6); δ_C(100 MHz, $CDCl_3$) 164.7, 160.0, 137.3, 133.5, 129.5, 129.2, 125.4, 124.4, 118.2, 117.7, 114.1, 82.7, 71.7, 61.7, 55.4; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{19}H_{19}NO_3$ 309.1365, found 309.1359; anal. calcd: C 73.77, H 6.19, N 4.53. Found C 73.40, H 6.05, N 4.54.

(±)-*cis*-3-Allyloxy-4-(*p*-chlorophenyl)-1-phenyl-2-azetidinone (8e). Colorless crystals, yield 2.19 g (70%), mp 109–110 °C; ν_{max}(KBr)/cm^{-1} 3062, 3030, 2983, 2905, 1756, 1597, 1497, 1387, 1125, 1087, 929, 750, 685; δ_H(400 MHz, $CDCl_3$) 7.37–7.23 (m, 8H), 7.07 (t, 1H, *J* 7.8), 5.60 (m, 1H), 5.17 (d, 1H, *J* 4.8,H-4), 5.08 (dd, 1H, *J* 9.6, 1.2), 5.06 (dd, 1H, *J* 18.4, 1.2), 4.95 (d, 1H, *J* 4.8, H-3), 3.93 (dd, 1H, *J* 12.4, 5.6), 3.78 (dd, 1H, *J* 12.4, 5.6); δ_C(100 MHz, $CDCl_3$) 164.5, 137.0, 134.7, 133.2, 132.3, 129.6, 129.3, 129.0, 124.7, 118.4, 117.5, 82.7, 71.9, 61.4; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{16}{}^{35}ClNO_2$ 313.0870, found 313.0863; anal. calcd: C 68.90, H 5.14, N 4.46. Found C 68.69, H 5.04, N 4.38.

4.5 Synthesis of thio-β-lactams 10a–e: general procedure

A mixture of appropriate β-lactams **1a–e** (2 mmol) and Lawesson's reagent (0.8 g, 2 mmol, 2 equiv.) in dry toluene (15 mL) was refluxed for 3 h. Then the solvent evaporated at reduced pressure. Finally, the resulting solid was recrystallised in ethanol to give thio-β-lactams **10a–e** in 65–76% yield.

(±)-*cis*-3-Allyloxy-1,4-diphenylazetidin-2-thione (10a). Colorless crystals, yield 0.40 g (70%), mp 70–72 °C; ν_{max}(KBr)/cm^{-1} 3067, 3036, 2981, 2920, 1586, 1495, 1497, 1389, 1184, 1132, 926, 752; δ_H(400 MHz, $CDCl_3$) 7.88 (d, 2H, *J* 8.0), 7.40-7.26 (m, 7H), 7.17 (t, 1H, *J* 7.8), 5.71 (d, 1H, *J* 4.4, H-4),5.58 (m, 1H), 5.10–5.05 (m, 2H), 4.68 (d, 1H, *J* 4.4, H-3), 4.05 (dd, 1H, *J* 12.8, 5.6), 3.85 (dd, 1H, *J* 12.8, 5.6); δ_C(100 MHz, $CDCl_3$) 197.5, 138.1, 133.5, 132.8, 129.1, 128.7, 128.3, 126.4, 118.5, 118.1, 80.6, 71.3, 70.4; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{17}NOS$ 295.1031, found 295.1024; anal. calcd: C 73.19, H 5.80, N 4.74, S 10.85. Found C 72.89, H 5.57, N 4.61, S 10.64.

(±)-*cis*-3-Allyloxy-1-(*p*-methoxyphenyl)-4-phenylazetidin-2-thione (10b). Colorless crystals, yield 0.49 g (76%), mp 93–94 °C; ν_{max}(KBr)/cm^{-1} 3066, 3031, 2955, 2836, 1597, 1510, 1449, 1267, 1175, 1062, 830, 699; δ_H(400 MHz, $CDCl_3$) 7.83 (d, 2H, *J* 7.6), 7.37–7.33 (m, 5H), 6.78 (d, 2H, *J* 7.2), 5.67 (d, 1H, *J* 4.4, H-4), 5.56 (m, 1H), 5.07–5.03 (m, 2H), 4.68(d, 1H, *J* 4.4, H-3), 4.00 (dd, 1H, *J* 12.8, 5.6), 3.83 (dd, 1H, *J* 12.8, 5.6), 3.73 (s, 3H, OCH_3); δ_C(100 MHz, $CDCl_3$) 195.5, 157.6, 133.4, 132.7, 131.6, 129.0, 128.7, 128.3, 120.1, 118.0, 114.1, 80.6, 71.2, 70.5, 55.5; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{19}H_{19}NO_2S$ 325.1136, found 325.1132; anal. calcd: C 70.12, H 5.88, N 4.30, S 9.85. Found C 69.97, H 5.52, N 4.21, S 9.70.

(±)-*cis*-3-Allyloxy-1-(*p*-chlorophenyl)-4-phenylazetidin-2-thione (10c). Colorless crystals, yield 0.42 g (65%), mp 34–35 °C; ν_{max}(KBr)/cm^{-1} 3067, 3031, 2981, 2903, 2864, 1576, 1493, 1399, 1266, 1166, 989, 827; δ_H(400 MHz, $CDCl_3$) 7.83 (d, 2H, *J* 7.6), 7.36 (m, 5H), 7.22 (d, 2H, *J* 8.8), 5.69 (d, 1H, *J* 4.4, H-4), 5.57 (m, 1H), 5.09–5.05 (m, 2H), 4.69 (d, 1H, *J* 4.4, H-3), 4.03 (dd, 1H, *J* 12.8, 5.6), 3.84 (dd, 1H, *J* 12.8, 5.6); δ_C(100 MHz, $CDCl_3$) 197.6, 136.5, 133.3, 132.3, 131.2, 129.2, 129.1, 128.8, 128.2, 119.7, 118.2, 80.7, 71.3, 70.5; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{16}{}^{35}ClNOS$ 329.0641, found 329.0633; anal. calcd: C 65.45, H 4.89, N 4.25, S 9.72. Found C 65.19, H 4.69, N 4.11, S 9.62.

(±)-*cis*-3-Allyloxy-4-(*p*-methoxyphenyl)-1-phenylazetidin-2-thione (10d). Colorless crystals, yield 0.47 g (72%), mp 90–91 °C; ν_{max}(KBr)/cm^{-1} 3066, 3032, 2955, 2836, 1594, 1517, 1449, 1267, 1175, 1062, 979, 699; δ_H(400 MHz, $CDCl_3$) 7.88 (d, 2H, *J* 8.8), 7.32–7.26 (m, 4H), 7.15 (t, 1H, *J* 7.2), 6.88 (d, 2H, *J* 8.8), 5.67 (d, 1H, *J* 4.4, H-4),5.63 (m, 1H), 5.14–5.07 (m, 2H), 4.65 (d, 1H, *J* 4.4, H-3), 4.04 (dd, 1H, *J* 12.8, 5.6), 3.88 (dd, 1H, *J* 12.8, 5.6), 3.79 (s, 3H, OCH_3); δ_C(100 MHz, $CDCl_3$) 197.5, 160.2, 138.1, 133.5, 129.7, 129.0, 126.3, 124.5, 118.6, 118.1, 114.2, 80.6, 71.3, 70.1, 55.4; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{19}H_{19}NO_2S$ 325.1136, found 325.1132; anal. calcd: C 70.12, H 5.88, N 4.30, S 9.85. Found C 69.89, H 5.58, N 4.23, S 9.69.

(±)-*cis*-3-Allyloxy-4-(*p*-chlorophenyl)-1-phenylazetidin-2-thione (10e). Colorless crystals, yield 0.45 g (68%), mp 58–59 °C; ν_{max}(KBr)/cm^{-1} 3069, 3047, 2923, 2857, 1595, 1494, 1426, 1266, 1164, 934, 834; δ_H(400 MHz, $CDCl_3$) 7.83 (d, 2H, *J* 8.8), 7.36–7.26 (m, 6H), 7.18 (t, 1H, *J* 7.2), 5.69 (d, 1H, *J* 4.4,H-4), 5.60 (m, 1H), 5.14–5.09 (m, 2H), 4.67 (d, 1H, *J* 4.4, H-3), 4.09 (dd, 1H, *J* 12.8, 5.6), 3.89 (dd, 1H, *J* 12.8, 5.6); δ_C(100 MHz, $CDCl_3$) 197.5, 137.8, 135.0, 133.3, 131.5, 129.7, 129.1, 129.0, 126.5, 118.4, 118.3, 80.4, 71.5, 69.6; HR-MS (EI) *m/z* $[M]^+$ calcd for $C_{18}H_{16}{}^{35}ClNOS$ 329.0641, found 329.0636; anal. calcd: C 65.45, H 4.89, N 4.25, S 9.72. Found C 65.21, H 4.76, N 4.14, S 9.53.

4.6 Pyrolysis product

(A) Flash vacuum pyrolysis. The apparatus used was similar to the one which has been described in our recent publications.[28–30] The sample of the substrate was volatilized from a tube in a Büchi Kugelrohr oven through a 30 × 2.5 cm horizontal fused quartz tube. This was heated externally by a Carbolite Eurotherm tube furnace MTF-12/38A to a temperature of 550 or 600 °C, the temperature being monitored by Pt/Pt-13% Rh thermocouple situated at the center of the furnace. The products were collected in a U-shaped trap cooled in liquid nitrogen. The whole system was maintained at a pressure of 10^{-2} Torr by an Edwards Model E2M5 high capacity rotary oil pump, the pressure being measured by a Pirani gauge situated between the cold trap and pump. Under these conditions the contact time in the hot zone was estimated to be *ca.* 10 ms. The different fractions of the product collected in the U-shaped trap were analyzed by ^1H, ^{13}C NMR, IR and LC-MS. Relative and percent yields were determined from NMR.

(B) Static pyrolysis. A sample of the substrate (1 mmol), was introduced in the reaction tube (1.5 × 12 cm Pyrex), cooled in liquid nitrogen, sealed under vacuum (0.01 Torr) and placed in the pyrolyzer for 15 minutes at 320 and 270 °C, a temperature that is required for complete pyrolysis of the substrate. The static sealed-tube (STP) pyrolysis was conducted in a custom-made Chemical Data System (CDS) pyrolyser consisting of an aluminum block with a groove to accommodate the Pyrex sealed-tube reactor, and fitted with a platinum-resistance thermometer and thermocouple connected to a Comark microprocessor thermometer. The block temperature was controlled by a Eurothem 093 precision temperature regulator. Aluminum was chosen for its low temperature gradient and resistance to elevated temperatures.

All the identified products in the STP and FVP gave satisfactory NMR (^{1}H, ^{13}C) and MS., compounds (*E*/*Z*) **5a–d**,[31–35] yield 3–25%; compounds **7**, **13a–d**,[19,36,37] yield 0–24%; compounds **12a–c**,[17,18] yield 12–31%.

*(E)-2-Phenyl-1-phenoxyethene (**5a**).*[31] Colorless oil, δ_H(400 MHz, $CDCl_3$) 7.38–7.21 (m, 9H), 7.09 (d, 2H, *J* 8.0), 6.35 (d, 1H, *J* 12.4); δ_C(100 MHz, $CDCl_3$) 157.1, 143.4, 135.1, 129.7, 128.7, 126.7, 125.6, 123.2, 116.9, 113.6; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{14}H_{12}O$ 196.0888, found 196.0882.

*(Z)-2-Phenyl-1-phenoxyethene (**5a**).*[34] Colorless oil, δ_H(400 MHz, $CDCl_3$) 7.40–7.10 (m, 10H), 6.63 (d, 1H, *J* 6.6), 5.64 (d, 1H, *J* 6.6); δ_C(100 MHz, $CDCl_3$) 157.7, 142.1, 135.4, 130.2, 129.1, 128.7, 127.1, 123.8, 117.4, 110.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{14}H_{12}O$ 196.0888, found 196.0885.

*(E)-2-p-Tolyl-1-phenoxyethene (**5b**).*[31] Colorless oil, δ_H(400 MHz, $CDCl_3$) 7.41–7.06 (m, 10H), 6.40 (d, 1H, *J* 12.4), 2.34 (s, 3H); δ_C(100 MHz, $CDCl_3$) 157.0, 142.3, 135.8, 132.0, 128.7, 128.6, 125.7, 123.3, 116.8, 113.6, 21.1; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{14}O$ 210.1045, found. 210.1040.

*(E)-2-(p-Methoxyphenyl)-1-phenoxyethene (**5c**).*[35] Pale yellow oil, δ_H(400 MHz, $CDCl_3$) 7.61–7.34 (m, 6H), 7.13 (m, 2H), 6.89 (d, 2H, *J* 8.4), 6.45 (d, 1H, *J* 12.4), 3.93 (s, 3H); δ_C(100 MHz, $CDCl_3$) 156.0, 156.4, 133.0, 132.7, 129.3, 128.7, 123.6, 118.4, 114.8, 113.9, 55.4; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{14}O_2$ 226.0994, found 226.0990.

*(Z)-2-(p-Methoxyphenyl)-1-phenoxyethene (**5c**).*[33] Pale yellow oil: δ_H(400 MHz, $CDCl_3$) 7.61–7.34 (m, 5H), 7.12 (m, 2H), 6.87 (d, 2H, *J* 8.4), 6.48 (d, 1H, *J* 6.8), 5.50 (d, 1H, *J* 6.8), 3.91 (s, 3H); δ_C(100 MHz, $CDCl_3$) 156.9, 156.2, 133.1, 132.7, 129.2, 128.7, 123.7, 118.3, 114.8, 113.6, 55.4; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{14}O_2$ 226.0994, found 226.0991.

*(E)-2-(p-Chlorophenyl)-1-phenoxyethene (**5d**).*[32] Colorless oil, δ_H(400 MHz, $CDCl_3$): 7.36 (t, 2H, *J* 8.0), 7.26–7.10 (m, 6H), 7.03 (d, 2H, *J* 8.0), 6.32 (d, 1H, *J* 12.4); δ_C(100 MHz, $CDCl_3$): 157.1, 144.0, 133.5, 132.0, 129.9, 128.8, 126.6, 123.1, 117.1, 112.0; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{14}H_{11}{}^{35}ClO$ 230.0498, found 230.0498.

*1,3-Diphenylurea (**7a**).*[19] Colorless solid, mp 241–242 °C (240 °C):[19] δ_H(400 MHz, DMSO-d_6): 8.70 (s, 2H), 7.51–7.22 (m, 8H), 7.00–6.89 (m, 2H); δ_C(100 MHz, DMSO-d_6): 152.3, 139.6, 128.3, 121.9, 118.0; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{13}H_{12}N_2O$ 212.0950, found 212.0950.

*1,3-Bis-(p-tolyl)urea (**7b**).*[19] Colorless solid, mp 262–264 °C (268 °C):[19] δ_H(400 MHz, DMSO-d_6): 8.56 (s, 2H), 7.33 (d, 4H, *J* 8.0), 7.05 (d, 4H, *J* 8.0), 2.24 (s, 6H); δ_C(100 MHz, DMSO-d_6): 157.3, 142.6, 135.3, 134.9, 123.0, 24.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{16}N_2O$ 240.1263, found 240.1260.

*1,3-Bis-(p-methoxyphenyl)urea (**7c**).*[19] Colorless solid, mp 241–242 °C (242 °C):[19] δ_H(400 MHz, DMSO-d_6): 8.65 (s, 2H), 7.43 (d, 4H, *J* 8.6), 6.85 (d, 4H, *J* 8.6), 3.73 (s, 6H); δ_C(100 MHz, DMSO-d_6): 159.3, 158.6, 138.3, 125.9, 119.0, 59.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{16}N_2O_3$ 272.1161, found 272.1169.

*1,3-Bis-(p-chlorophenyl)urea (**7d**).*[19] Colorless solid, mp 297–299 °C (301 °C):[19] δ_H(400 MHz, DMSO-d_6): 8.85 (s, 2H), 7.41 (d, 4H, *J* 8.6), 7.34 (d, 4H, *J* 8.6); δ_C(100 MHz, DMSO-d_6): 157.3, 143.6, 133.3, 130.5, 125.3; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{13}H_{10}{}^{35}Cl_2N_2O$ 280.0170, found 280.0167.

*1,3-Diphenylthiourea (**13a**).*[36] Colorless solid, mp 150–151 °C (154 °C): δ_H(400 MHz, $CDCl_3$): 8.30 (s, 2H), 7.41–7.27 (m, 10H); δ_C(100 MHz, $CDCl_3$): 180.1, 137.6, 129.5, 127.1, 125.5; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{13}H_{12}N_2S$ 228.0721, found 228.0718.

*1,3-Bis-(p-tolyl)thiourea (**13b**).*[36] Colorless solid, mp 178–180 °C (179 °C): δ_H(400 MHz, DMSO-d_6): 9.56 (s, 2H), 7.34–7.14 (m, 8H), 2.31 (s, 6H); δ_C(100 MHz, DMSO-d_6): 181.2, 137.6, 134.3, 130.7, 125.8, 21.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{16}N_2S$ 256.1034, found 256.1031.

*1,3-Bis-(p-methoxyphenyl)thiourea (**13c**).*[37] Colorless solid, mp 184–185 °C (200 °C): δ_H(400 MHz, DMSO-d_6): 9.54 (s, 2H), 7.31 (d, 4H, *J* 8.8), 6.85 (d, 4H, *J* 8.8), 3.72 (s, 6H); δ_C(100 MHz, DMSO-d_6): 185.7, 162.6, 137.0, 131.9, 119.0, 60.2; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{15}H_{16}N_2O_2S$ 288.0932, found 288.0928.

*1,3-Bis-(p-chlorophenyl)thiourea (**13d**).*[36] Colorless solid, mp 167–169 °C (172 °C): δ_H(400 MHz, $CDCl_3$): 7.92 (s, 2H), 7.41–7.32 (m, 8H); δ_C(100 MHz, $CDCl_3$): 180.2, 135.6, 132.3, 129.5, 125.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{13}H_{10}{}^{35}Cl_2N_2S$ 295.9942, found 295.9940.

*2-Phenylpent-4-enal (**12a**).*[17,18] Colorless oil, δ_H(400 MHz, $CDCl_3$) 9.69 (d, 1H, *J* 1.6), 7.41–7.18 (m, 5H), 5.70 (m, 1H), 5.07–4.99 (m, 2H), 3.61 (t, 1H, *J* 7.2), 2.84 (q, 1H, *J* 6.8), 2.50 (q, 1H, *J* 6.8); δ_C(100 MHz, $CDCl_3$) 201.8, 136.6, 135.7, 129.0, 128.8, 127.6, 117.1, 58.7, 33.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{11}H_{12}O$ 160.0888, found. 160.0885.

*2-p-Methoxyphenylpent-4-enal (**12b**).*[17] Pale yellow oil, δ_H(400 MHz, $CDCl_3$) 9.62 (d, 1H, *J* 1.6), 7.14 (m, 2H), 6.88 (m, 2H), 5.71 (m, 1H), 5.03 (m, 2H), 3.78 (s, 3H), 3.56 (m, 1H), 2.85 (m, 1H), 2.46 (m, 1H); δ_C(100 MHz, $CDCl_3$) 200.2, 159.1, 135.3, 129.9, 127.5, 117.1, 114.4, 57.7, 55.3, 33.9; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{12}H_{14}O_2$ 190.0994, found. 190.0988.

*2-p-Chlorophenylpent-4-enal (**12c**).*[18] Colorless oil, δ_H(400 MHz, $CDCl_3$) 9.60 (d, 1H, *J* 1.6), 7.31–7.18 (m, 4H), 5.71 (m, 1H), 5.00 (m, 2H), 3.62 (m, 1H), 2.84 (m, 1H), 2.49 (m, 1H); δ_C(100 MHz, $CDCl_3$) 200.1, 134.7, 134.5, 134.0, 130.8, 129.6, 118.1, 58.5, 34.5; HR-MS (EI) *m/z* [M]$^+$ calcd for $C_{11}H_{11}{}^{35}ClO$ 194.0498, found. 194.0491.

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