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Construction of 3-allylidene-4-vinyltetrahydrofurans and 3-allylidene-4-vinylpyrrolidines via sequential domino allylation/olefination of C–C triple bonds

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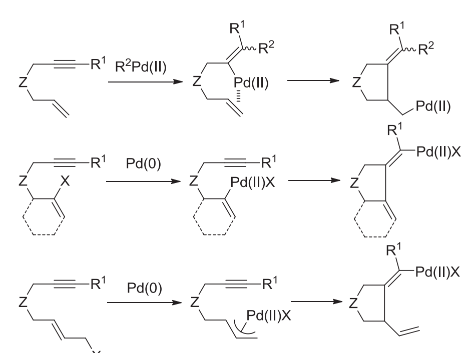
ABSTRACT

An efficient method via sequential domino allylation/olefination of C–C triple bonds for the syntheses of five-membered heterocycles was developed by treatment 1,6-enynes with alkenes in the presence of a palladium catalyst. The configurations of the 1,3-dienes of the five-membered heterocycles are stereocontrolled.

1. Introduction

One of the challenges of using organometallic chemistry is finding reactions and strategies that allow for the facile conversion of simple compounds into complex materials, medicines, or molecules of theoretical interest.[1] Palladium-catalyzed cyclization is an important method for the construction of ring systems because it offers an efficient entryway to cyclic compounds from readily available acyclic substrates.[2] Cyclization reactions of 1,6-enynes have been widely investigated with various palladium catalysts.[3] Most cyclization reactions of 1,6-enynes are initiated by hydropalladation,[4] carbopalladation,[5] acetoxypalladation,[6] halopalladation[7] or metalpalladation[8] of the triple bond to provide a vinylpalladium intermediate. Intramolecular carbopalladation of the double bond realizes the cyclization of 1,6-enynes (Eq. 1). The cyclization process involving alkenyl-,[9] or arylpalladium[10,11] halide complexes, which were generated via oxidative addition of alkenyl or aryl halides undergoing cyclic carbopalladation of alkynes affording vinylpalladium species, has also been widely studied (Eq. 2). The intramolecular insertion of the triple bond to the π-allylpalladium species has also been extensively studied (Eq. 3), but the sequential domino allylation/olefination of C–C triple bonds has been less studied. Conceptually, the installation of the electron-withdrawing functionality by means of an organometallic elementary step, such as the insertion of an alkyne into a vinyl–palladium bond[12] followed by a tandem process is required in the isomerization process. This step is more than a methodological extension of the Heck reaction as it could also provide access to heterodomino reactions.[13] We describe herein a new method via sequential domino allylation/olefination of C–C triple bonds for the syntheses of 3-allylidene-4-vinyltetrahydrofurans and 3-allylidene-4-vinylpyrrolidines.



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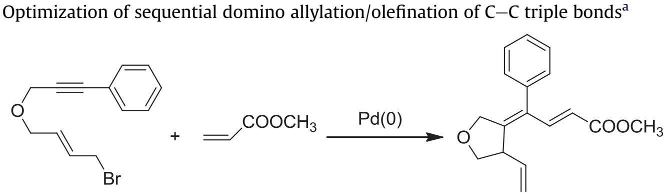
2. Results and discussion

Our initial attempts were aimed at studying the effect of the solvent on the allylation/olefination of C–C triple bonds (Table 1). In the presence of the $Pd(OAc)_2/PPh_3$ catalyst (5 mol %) and K_2CO_3 (2 equiv) as a base, the reaction of enyne (**1a**, 1 mmol) and olefin (**2a**, 3 mmol) in THF at 80 °C afforded **3aa** in 54% yield (Table 1, entry 1). Screening of various solvents revealed that the solvent played a significant role in this reaction (Table 1, entries 1–5). Only trace amount of the desired product **3aa** was obtained when acetonitrile was used as a solvent (entry 3). DCE (1,2-dichloroethane) was found to be the best of all solvents tested (Table 1, entries 1–5). Further lowering the catalyst loadings from 5 mol % to 3 mol % resulted in decreased product yields from 76% to 65% (Table 1, entries 5 and 6). The effect of temperature on the reaction was studied. No desired product could be observed when the reaction was performed at room temperature, but most of the starting materials remained unchanged (Table 1, entry 7). The reaction proceeded sluggishly at 60 °C and was not completed even after two days (Table 1, entry 8). Raising the temperature to 100 °C resulted in a decrease of the product yield to 68% (Table 1, entry 9). An examination of the importance of the bases in this reaction revealed that potassium carbonate was significantly better than sodium carbonate and triethylamine (Table 1, entries 10 and 11). Survey of a number of other palladium catalysts, such as $PdCl_2$, $Pd(PPh_3)_4$, and $Pd(PPh_3)_2Cl_2$ indicated that these catalysts were all less effective than $Pd(OAc)_2$ with regard to the product yields (Table 1, entries 12–14).

Table 1
Optimization of sequential domino allylation/olefination of C–C triple bonds[a]



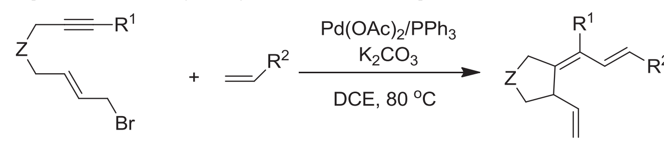
1a 2a 3aa

Entry	[Pd](mol %)/L	Base (2 equiv)	Solvent	T^b (°C)	Yield[c] (%)
1	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	THF	80	54
2	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	DMF	80	18
3	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	CH_3CN	80	Trace
4	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	Toluene	80	38
5	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	DCE	80	76
6	$Pd(OAc)_2/PPh_3$ (3:3)	K_2CO_3	DCE	80	65
7	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	DCE	rt	0
8	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	DCE	60	23
9	$Pd(OAc)_2/PPh_3$ (5:5)	K_2CO_3	DCE	100	68
10	$Pd(OAc)_2/PPh_3$ (5:5)	Na_2CO_3	DCE	80	14
11	$Pd(OAc)_2/PPh_3$ (5:5)	Et_3N	DCE	80	Trace
12	$[PdCl_2]/PPh_3$(5:5)	K_2CO_3	DCE	80	11
13	$Pd(PPh_3)_4$(5)	K_2CO_3	DCE	80	46
14	$[Pd(PPh_3)_2Cl_2]$(5)	K_2CO_3	DCE	80	Trace

[a] Reactions were run in the presence of 3 equiv **2a** in appropriate solvents (0.33 M) for 20 h.
[b] Oil bath temperature.
[c] Isolated yield.

Under the optimized conditions, we extended the domino allylation/olefination of C–C triple bonds with a range of enynes and commercially available alkenes (Table 2, entries 1–4). In Table 2, enyne **1a** readily reacted with electron deficient alkenes, such as methyl acrylate **2a**, ethyl acrylate **2b**, acrylonitrile **2c**, and styrene **2d** to afford the corresponding products **3aa–ad** in moderate to good yields (Table 2, entries 1–4). Attempted allylation/olefination of C–C triple bonds of **1a** with methyl methacrylate did not produce the desired product probably due to the steric/electronic effects. To further explore the generality and scope of the allylation/olefination of C–C triple bonds, a variety of enynes **1b–f** were investigated, and the results are summarized in Table 2 (entries 5–23). It was found that 1,6-enynes with oxygen and nitrogen linkages could be used in this domino allylation/olefination of C–C triple bonds. The linkage atoms had no obvious effect on the reaction. With respect to the substituents R^1 at the alkynes terminus, substituents R^1 on 1,6-enynes not only could be aryl (phenyl, 4-chlorophenyl, and 4-methoxyphenyl), but also be butyl. But the reaction of the butyl-substituted 1,6-enyne with alkenes produced the desired products in relative low yields in comparison with other 1,6-enynes (Table 2, entries 17–19). Interestingly, the configuration of the 1,3-butadiene products **3** is exclusively in the (*E*,*Z*)-form, which was assigned by the ^1H NMR and NOSEY spectra of products **3dc** and **3dd**, indicating high regio- and high stereoselectivity for the construction of 1,3-butadiene fragments.

Table 2
Sequential domino allylation/olefination of C–C triple bonds[a]



1 2 3

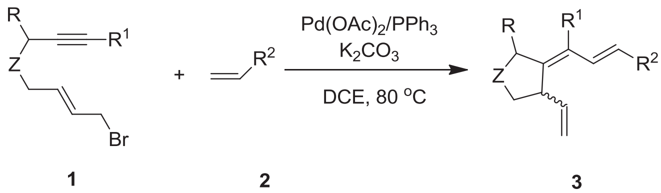
Entry	Enyne	Alkene	Product	Yield[b] (%)
1	Z=O, R^1=Ph (**1a**)	R^2=CO_2Me (**2a**)	**3aa**	76
2	**1a**	R^2=CO_2Et (**2b**)	**3ab**	73
3	**1a**	R^2=CN (**2c**)	**3ac**	78
4	**1a**	R^2=Ph (**2d**)	**3ad**	52
5	Z=O, R^1=4-Cl–Ph (**1b**)	**2a**	**3ba**	79
6	**1b**	**2b**	**3bb**	72
7	**1b**	**2c**	**3bc**	82
8	**1b**	**2d**	**3bd**	50
9	Z=O, R^1=4-MeO–Ph (**1c**)	**2a**	**3ca**	75
10	**1c**	**2b**	**3cb**	69
11	**1c**	**2c**	**3cc**	77
12	**1c**	**2d**	**3cd**	48
13	Z=TsN, R^1=Ph (**1d**)	**2a**	**3da**	77
14	**1d**	**2b**	**3db**	73
15	**1d**	**2c**	**3dc**	76
16	**1d**	**2d**	**3dd**	50
17	Z=TsN, R^1=*n*-Bu (**1e**)	**2a**	**3ea**	44
18	**1e**	**2c**	**3ec**	47
19	**1e**	**2d**	**3ed**	32
20	Z=BocN, R^1=Ph (**1f**)	**2a**	**3fa**	73
21	**1f**	**2b**	**3fb**	70
22	**1f**	**2c**	**3fc**	72
23	**1f**	**2d**	**3fd**	54

[a] General conditions: enyne (1.0 equiv), alkene (3.0 equiv), $Pd(OAc)_2$ (5 mol %), PPh_3 (5 mol %), K_2CO_3 (2 equiv), DCE (3 mL), 80 °C (oil bath temperature).
[b] Isolated yields after flash column chromatography.

On the basis of the results on the above domino allylation/olefination of C–C triple bonds, we introduced a substituting group at the 5-position of 1,6-enynes to study the relative stereochemistry of the five-membered heterocycle products. The results are summarized in Table 3. When the linked atom of 1,6-enyne is oxygen, the major products are in the trans form. However, use of 1,6-enyne with tosylamide linkage resulted in the production of cis products as major outcomes.

The stereochemistry of the products (Table 3) was confirmed by using NOE methods. In typical examples, NOE interactions were observed between the vinyl and methine protons of products **3gc** and **3gd** (Fig. 1), indicating a trans relationship between these substituents. The cis configuration of **3ic** was assigned based on strong NOE interaction between the methyl and vinyl protons (Fig. 1), and further confirmed by the X-ray crystal structure analysis (Fig. 2).[14]

Table 3
Sequential domino reactions of 5-position substituted 1,6-enynes with olefins[a]



Entry	Enyne	Alkene	Product	Yield[b] [trans/cis][c]
1	Z=O, R=Me, R^1=Ph (**1g**)	R^2=CO_2Me (**2a**)	**3ga**	70[d]
2	**1g**	R^2=CO_2Et (**2b**)	**3gb**	68 (85/15)
3	**1g**	R^2=CN (**2c**)	**3gc**	73[d]
4	**1g**	R^2=Ph (**2d**)	**3gd**	41[d]
5	Z=O, R=Et, R^1=Ph (**1h**)	**2c**	**3hc**	65[d]
6	Z=O, R=Et, R^1=Ph (**1i**)	**2c**	**3ic**	68[d]
7	**1i**	**2d**	**3id**	45 (30/70)

[a] General conditions: enyne (1.0 equiv), alkene (3.0 equiv), $Pd(OAc)_2$ (5 mol %), PPh_3 (5 mol %), K_2CO_3 (2 equiv), DCE (3 mL), 80 °C (oil bath temperature).
[b] Isolated yields after flash column chromatography.
[c] The ratio was determined by ^1H NMR.
[d] Only trans or cis products were isolated depending on heteroatoms in 1,6-enynes.

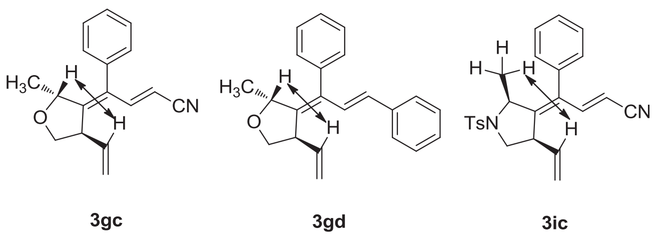


Fig. 1. NOE interactions were used to confirm the configuration of the products (see the Supplementary data).

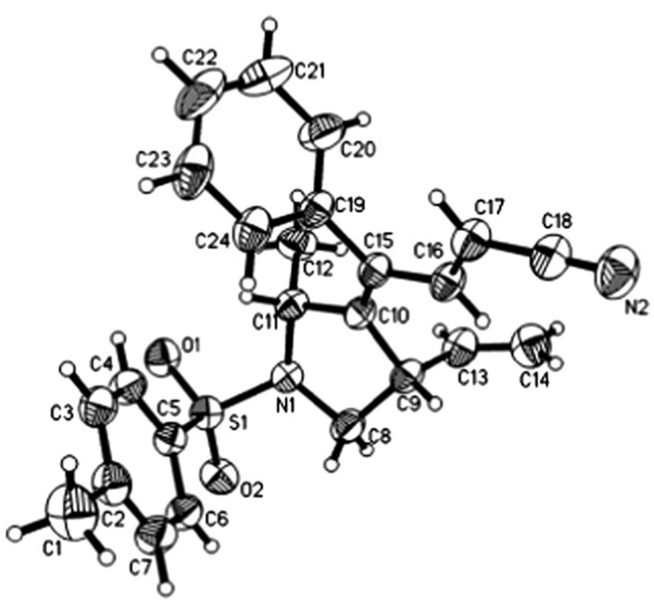
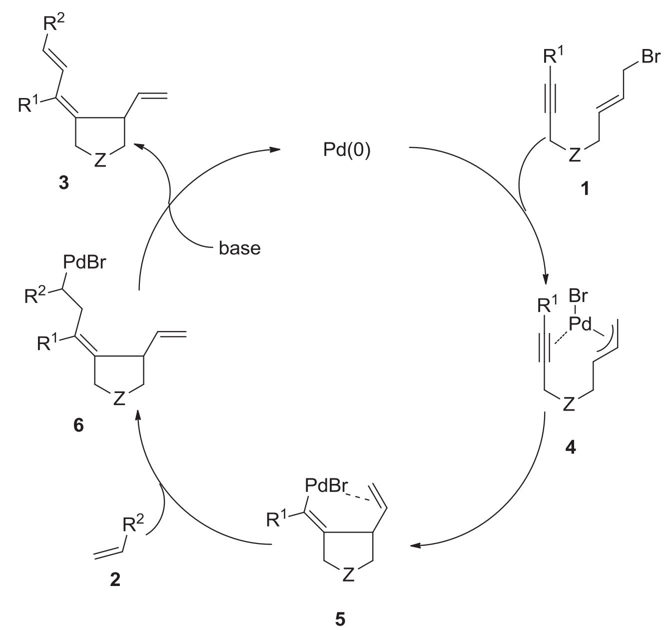


Fig. 2. Molecular structure of compound **3ic**. Ellipsiods are drawn at 30% probability. Selected bond lengths (Å) and angles (°) C9–C10 1.521(3), C9–C13 1.510(3), C13–C14 1.286(3), C10–C15 1.338(3), C15–C16 1.451(3), C16–C17 1.328(3), C8–C9–C10 102.2(2), C10–C9–C13 112.0(2), C11–C10–C15 122.4(2), C9–C10–C15 127.2(2), C10–C15–C16 121.4(2), C15–C16–C17 125.7(2).

A possible reaction mechanism that accounts for the formation of products **3** is shown in Scheme 1. Oxidative addition of allyl bromide to palladium(0) results in the π-allylpalladium species that subsequently coordinates with the triple bond of 1,6-enyne to give intermediate **4**. The *syn* carbopalladation affords the vinyl-palladium intermediate **5**. The insertion of alkene **2** to the vinyl–palladium bond led to alkylpalladium intermediate **6**, which liberates **3** and HPdBr after classical β-hydrogen elimination. A reductive elimination assisted by potassium carbonate regenerates palladium(0).[15]



Scheme 1. Proposed mechanism of synthesis of **3**.

3. Conclusions

In summary, we have developed a sequential domino allylation/olefination of C–C triple bonds method for the syntheses of 3-allylidene-4-vinyltetrahydrofurans and 3-allylidene-4-vinylpyrrolidines system by treatment of easily available 1,6-enynes with commercially available alkenes in the presence of a palladium catalyst. Interestingly, the 1,3-diene units could be constructed in high regio- and stereoselectivity. Studies addressing the synthetic scope of the domino reaction and the photophysical and pharmacological properties of these new allylidene-vinyl(hetero)cyclic units are currently underway.

4. Experimental

4.1. General experiment

All the catalytic reactions were performed under an argon atmosphere using the oven-dried Schlenk flask. The chemicals were purchased from Alfa Aesar and Acros Chemicals. All solvents and materials were pre-dried, redistilled or recrystallized before use. ^1H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were recorded on a Bruker Avance 300 spectrometer with $CDCl_3$ as the solvent. Chemical shifts are reported in parts per million by assigning TMS resonance in the ^1H NMR spectra as 0.00 ppm and $CDCl_3$ resonance in the ^{13}C spectra as 77.0 ppm. All coupling constants (*J* values) were reported in hertz (Hz). Column chromatography was performed on silica gel 300–400 mesh. Melting points were determined using a Gallenkamp melting point apparatus and are uncorrected. The FT-IR spectra were recorded from KBr pellets in the 4000–400 cm^{-1} ranges on a Nicolet 5DX spectrometer. Mass spectra were performed on Micromass GCT-MS. X-ray Crystallography diffraction data of **3ic** was collected at room temperature with a Bruker SMART Apex CCD diffractometer with Mo Kα radiation (λ=0.71073 Å) with a graphite monochromator using the ω-scan mode. Data reductions and absorption corrections were performed with SAINT and SADABS software, respectively. The structure was solved by direct methods and refined on F^2 by full-matrix least squares using SHELXTL.[16] All non-hydrogen atoms were treated anisotropically. The positions of hydrogen atoms were generated geometrically. 1,6-Enynes **1a**–**i** were prepared by published procedures.[17]

4.2. Synthesis

Enyne **1a**–**i** (1.0 equiv), K_2CO_3 (2.0 equiv), $Pd(OAc)_2$ (5 mol %), and PPh_3 (5 mol %) were added to a degassed solution of alkene **2a**–**d** (3.0 equiv) in DCE (3 mL), and the mixture was stirred at room temperature for half an hour and then heated at 80 °C for 20 h. The reaction mixture was cooled, and then quenched with water and extracted with EtOAc (3×5 mL). The combined organic layers were washed with hydrochloric acid (5%), sodium carbonate (5%), and saturated sodium chloride solution. After separation, the organic layer was dried over $MgSO_4$ and then concentrated. The residue was purified by flash chromatography column (8:1 petroleum ether/EtOAc) to give the corresponding product **3**.

*4.2.1. Compound **3aa**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, J=15.3 Hz, 1H; C–CH–CH), 7.38–7.35 (m, 3H; Ar–H), 7.10–7.08 (m, 2H; Ar–H), 5.99–5.90 (m, 1H; CH–CH–CH_2), 5.40 (d, J=15.3 Hz, 1H; CH–CH–CO), 5.31–5.20 (m, 2H; CH–CH_2), 4.26 (d, J=15.3 Hz, 1H; O–C*H*H–C), 4.08–4.03 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.91–3.84 (m, 2H; O–CH*H*–CH, CH_2–C*H*–CH), 3.69 (s, 1H; O–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 167.6, 150.3, 143.2 137.6, 131.8, 128.7, 128.5, 127.7, 119.8, 116.2, 74.2, 71.2, 51.5, 46.6; FT-IR (neat): ν_{max} 3080, 3028, 1714, 1633, 1288, 1170, 1103, 1064, 736, 704 cm^{-1}; HRMS: calcd for $C_{17}H_{19}O_3$ [M+H]$^+$ 271.1329; found 271.1326.

*4.2.2. Compound **3ab**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, J=15.6 Hz, 1H; C–CH–CH), 7.37–7.31 (m, 3H; Ar–H), 7.09–7.07 (m, 2H; Ar–H), 5.97–5.89 (m, 1H; CH–CH–CH_2), 5.37 (d, J=15.6 Hz, 1H; CH–CH–CO), 5.30–5.19 (m, 2H; CH–CH_2), 4.25 (d, J=15.9 Hz, 1H; O–CH*H*–C), 4.18–4.02 (m, 4H; O–C*H*H–C, O–CH*H*–CH, O–CH_2–CH_3), 3.89–3.83 (m, 2H; O–CH*H*–CH, CH_2–C*H*–CH), 1.23 (t, J=6.6 Hz, 3H; CH_2–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 167.3, 150.2, 143.0, 137.7, 137.6, 131.9, 128.8, 128.6, 127.7, 120.3, 116.3, 74.2, 71.3, 60.3, 14.2; FT-IR (neat): ν_{max} 3080, 3028, 1714, 1633, 1286, 1172, 1101, 1064, 734, 702 cm^{-1}; HRMS: calcd for $C_{18}H_{21}O_3$ [M+H]$^+$ 285.1485; found 285.1479.

*4.2.3. Compound **3ac**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.53 (d, J=15.9 Hz, 1H; C–CH–CH), 7.38 (m, 3H; Ar–H), 7.08 (m, 2H; Ar–H), 5.95–5.87 (m, 1H; CH–CH–CH_2), 5.27–5.22 (m, 2H; CH–CH_2), 4.83 (d, J=15.9 Hz, 1H; CH–CH–CN), 4.24 (d, J=15.9 Hz, 1H; O–CH*H*–C), 4.08–4.03 (m, 2H; O–C*H*H–C, O–CH*H*–CH), 3.88–3.86 (m, 1H; O–C*H*H–CH), 3.74 (m, 1H; CH_2–C*H*–CH); ^{13}C NMR (75 MHz, $CDCl_3$): 151.5, 148.5, 137.2, 135.9, 131.6, 129.1, 128.6, 128.3, 118.6, 116.8, 98.3, 74.4, 71.5, 46.9; FT-IR (neat): ν_{max} 3080, 3028, 2214, 1633, 1593, 1105, 1064, 707 cm^{-1}; HRMS: calcd for $C_{16}H_{16}NO$ [M+H]$^+$ 238.1226; found 238.1222.

*4.2.4. Compound **3ad**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.46–7.19 (m, 11H; C–CH–CH, Ar–H), 6.07–5.99 (m, 2H; CH–CH–CH_2, CH–CH–C), 5.37–5.22 (m, 2H; CH–CH_2), 4.27 (d, J=15.0 Hz, 1H; O–CH*H*–C), 4.13–4.07 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.90–3.84 (m, 2H; O–C*H*H–CH, CH_2–C*H*–CH); ^{13}C NMR (75 MHz, $CDCl_3$): 141.7, 139.0, 138.6, 137.5, 133.5, 130.9, 128.9, 128.6, 128.2, 127.5, 127.3, 126.4, 115.7, 74.4, 71.4, 46.7. FT-IR (neat): ν_{max} 3078, 3028, 1633, 1597, 1101, 1064, 734, 702 cm^{-1}; HRMS: calcd for $C_{21}H_{21}O$ [M+H]$^+$ 289.1587; found 289.1590.

*4.2.5. Compound **3ba**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.79 (d, J=15.6 Hz, 1H; C–CH–CH), 7.35 (d, J=8.3 Hz, 2H; Ar–H), 7.03 (m, J=8.3 Hz, 2H; Ar–H), 5.95–5.87 (m, 1H; CH–CH–CH_2), 5.35 (d, J=15.6 Hz, 1H; CH–CH–CO), 5.29–5.19 (m, 2H; CH–CH_2), 4.24 (d, J=15.9 Hz, 1H; O–CH*H*–C), 4.06–4.01 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.89–3.81 (m, 2H; O–CH*H*–CH, CH_2–C*H*–CH), 3.69 (s, 3H; O–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 167.5, 150.9, 142.8, 137.4, 135.9, 133.7, 130.7, 130.0, 129.1, 119.9, 116.4, 74.2, 71.2, 51.6, 46.7; FT-IR (neat): ν_{max} 3082, 3028, 1714, 1633, 1288, 1170, 1101, 1062, 839 cm^{-1}; HRMS: calcd for $C_{17}H_{18}ClO_3$ [M+H]$^+$ 305.0939; found 305.0940.

*4.2.6. Compound **3bb**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.80 (d, J=15.6 Hz, 1H; C–CH–CH), 7.35 (d, J=8.1 Hz, 2H; Ar–H), 7.03 (m, J=8.1 Hz, 2H; Ar–H), 5.94–5.86 (m, 1H; CH–CH–CH_2), 5.34 (d, J=15.3 Hz, 1H; CH–CH–CO), 5.29–5.19 (m, 2H; CH–CH_2), 4.26–4.01 (m, 5H; O–CH_2–C, O–CH_2–CH_3, O–CH*H*–CH), 3.89–3.81 (m, 2H; O–CH*H*–CH, CH_2–C*H*–CH), 1.24 (t, J=6.6 Hz, 3H; CH_2CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 167.0, 150.7, 142.6, 137.5, 135.9, 133.7, 130.7, 130.0, 129.1, 120.4, 116.4, 74.2, 71.2, 60.4, 46.8, 14.2; FT-IR (neat): ν_{max} 3082, 3028, 1714, 1633, 1286, 1172, 1101, 1062, 833 cm^{-1}; HRMS: calcd for $C_{18}H_{20}ClO_3$ [M+H]$^+$ 319.1095; found 319.1128.

*4.2.7. Compound **3bc**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.51 (d, J=15.9 Hz, 1H; C–CH–CH), 7.40 (d, J=7.5 Hz, 2H; Ar–H), 7.03 (d, J=7.5 Hz, 2H; Ar–H), 5.96–5.85 (m, 1H; CH–CH–CH_2), 5.30–5.21 (m, 2H; CH–CH_2), 4.82 (d, J=15.9 Hz, 1H; CH–CH–CN), 4.23 (d, J=15.9 Hz, 1H; O–C*H*H–C), 4.09–4.01 (m, 2H; O–C*H*H–C, O–C*H*H–CH), 3.88–3.85 (m, 1H; O–C*H*H–CH), 3.74 (m, 1H; CH_2–C*H*–CH); ^{13}C NMR (75 MHz, $CDCl_3$): 152.1, 148.1, 136.9, 134.4, 134.3, 130.4, 130.1, 129.5, 118.3, 116.9, 98.2, 74.3, 71.4, 46.9; FT-IR (neat): ν_{max} 3082, 3028, 2216, 1635, 1593, 1105, 1062, 839 cm^{-1}; HRMS: calcd for $C_{16}H_{15}ClNO$ [M+H]$^+$ 272.0837; found 272.0839.

*4.2.8. Compound **3bd**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.39 (d, J=7.8 Hz, 2H; Ar–H), 7.30–7.14 (m, 6H; Ar–H; C–CH–CH), 7.13 (d, J=7.5 Hz, 2H; Ar–H), 6.01–5.96 (m, 2H; CH–CH–CH_2, C–CH–C), 5.34–5.21 (m, 2H; CH–CH_2), 4.23 (d, J=15.0 Hz, 1H; O–CH*H*–C), 4.11–4.03 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.88–3.81 (m, 2H; O–CH*H*–CH, CH_2–C*H*–CH); ^{13}C NMR (75 MHz, $CDCl_3$): 142.2, 138.4, 137.4, 137.3, 133.2, 132.4, 131.1, 130.4, 128.9, 128.6, 127.8, 127.6, 126.4, 115.8, 74.4, 71.2, 46.8; FT-IR (neat): ν_{max} 3078, 3030, 1639, 1593, 1105, 829, 746, 700 cm^{-1}; HRMS: calcd for $C_{21}H_{20}ClO$ [M+H]$^+$ 323.1197; found 323.1181.

*4.2.9. Compound **3ca**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.81 (d, J=15.6 Hz, 1H; C–CH–CH), 7.01 (d, J=8.4 Hz, 2H; Ar–H), 6.90 (d, J=8.1 Hz, 2H; Ar–H), 5.97–5.89 (m, 1H; CH–CH–CH_2), 5.43 (d, J=15.3 Hz, 1H; CH–CH–CO), 5.29–5.19 (m, 2H; CH–CH_2), 4.28 (d, J=16.2 Hz, 1H; O–CH*H*–C), 4.10–4.02 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.89–3.83 (m, 5H; O–CH*H*–CH, CH_2–C*H*–CH, O–CH_3), 3.70 (s, 3H; O–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 167.7, 158.9, 150.3, 143.6, 137.7, 131.5, 129.8, 119.7, 116.2, 114.1, 74.2, 71.4, 55.3, 51.6, 46.7; FT-IR (neat): ν_{max} 3078, 3034, 1714, 1633, 1288, 1246, 1170, 1101, 1064, 837 cm^{-1}; HRMS: calcd for $C_{18}H_{21}O_4$ [M+H]$^+$ 301.1434; found 301.1426.

*4.2.10. Compound **3cb**.* Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, J=15.6 Hz, 1H; CCH), 7.01 (d, J=7.8 Hz, 2H; Ar–H), 6.90 (d, J=8.1 Hz, 2H; Ar–H), 5.99–5.88 (m, 1H; CH–CH–CH_2), 5.42 (d, J=15.3 Hz, 1H; CH–CH–CO), 5.30–5.19 (m, 2H; CH–CH_2), 4.28 (d, J=15.6 Hz, 1H; O–CH*H*–C), 4.19–4.03 (m, 4H; O–CH*H*–C, O–CH*H*–CH, O–CH_2–CH_3), 3.89–3.83 (m, 5H; O–CH*H*–CH, CH_2–C*H*–CH, O–CH_3), 1.25 (t, *J*=6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): 167.3, 158.9, 150.2, 143.4, 137.7, 131.5, 129.8, 120.2, 116.2, 114.1, 74.2, 71.4, 60.3, 55.2, 46.7, 14.2; FT-IR (neat): ν_{max} 3078, 3034, 1714, 1633, 1286, 1246, 1174, 1101, 1064, 837 cm^{-1}; HRMS: calcd for $C_{19}H_{23}O_4$ [M+H]$^+$ 315.1591; found 315.1580.

4.2.11. Compound ***3cc***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.52 (d, *J*=15.9 Hz, 1H; C–CH–CH), 7.00 (d, *J*=8.1 Hz, 2H; Ar–H), 6.92 (d, *J*=9.0 Hz, 2H; Ar–H), 5.97–5.86 (m, 1H; CH–CH–CH_2), 5.26–5.21 (m, 2H; CH–C*H*$_2$), 4.87 (d, *J*=15.9 Hz, 1H; CH–CH–CN), 4.25 (d, *J*=16.2 Hz, 1H; O–CH*H*–C), 4.09–4.04 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.88–3.83 (m, 4H; O–CH*H*–CH, O–CH_3), 3.78–3.73 (m, 1H; CH_2–C*H*–CH); ^{13}C NMR (75 MHz, $CDCl_3$): 159.3, 151.4, 148.8, 137.3, 131.2, 129.8, 128.1, 118.7, 116.7, 114.4, 97.8, 74.3, 71.5, 55.3, 46.9; FT-IR (neat): ν_{max} 3078, 3034, 2214, 1633, 1593, 1247, 1105, 1064, 839 cm^{-1}; HRMS: calcd for $C_{17}H_{18}NO_2$ [M+H]$^+$ 268.1332; found 268.1332.

4.2.12. Compound ***3cd***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.31–7.20 (m, 6H; C–CH–CH, Ar–H), 7.11 (d, *J*=7.8 Hz, 2H; Ar–H), 6.95 (d, *J*=6.9 Hz, 2H; Ar–H), 6.09–5.95 (m, 2H; CH–CH–CH_2, CH–CH–C), 5.35–5.21 (m, 2H; CH–C*H*$_2$), 4.28 (d, *J*=15.0 Hz, 1H; O–CH*H*–C), 4.13–4.08 (m, 2H; O–CH*H*–C, O–CH*H*–CH), 3.86–3.82 (m, 5H; O–CH*H*–CH, CH_2–C*H*–CH, O–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 158.6, 141.8, 138.7, 137.6, 133.1, 131.3, 130.8, 130.1, 128.6, 128.5, 127.4, 126.4, 115.6, 113.9, 74.4, 71.4, 55.2, 46.7; FT-IR (neat): ν_{max} 3078, 3032, 1635, 1608, 1246, 1031, 1107, 756, 694 cm^{-1}; HRMS: calcd for $C_{22}H_{23}O_2$ [M+H]$^+$ 319.1693; found 319.1681.

4.2.13. Compound ***3da***. White solid. Mp 151–152 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.69–7.58 (m, 3H; C–CH–CH, Ar–H), 7.36–7.26 (m, 5H; Ar–H), 6.98 (m, 2H; Ar–H), 5.85–5.79 (m, 1H; CH–CH–CH_2), 5.34 (d, *J*=15.0 Hz, 1H; CH–CH–CO), 5.23–5.13 (m, 2H; CH–C*H*$_2$), 3.85–3.79 (m, 2H; CH_2–C*H*–CH, N–C*H*H–C), 3.67 (s, 3H; O–CH_3), 3.47–3.41 (m, 2H; N–C*H*H–C, N–C*H*H–CH), 3.33–3.30 (m, 1H; N–C*H*H–CH), 2.43 (s, 3H; C–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 167.4, 145.4, 143.9, 141.9, 136.9, 134.1, 132.1, 129.7, 128.9, 128.4, 128.0, 127.8, 120.8, 116.5, 53.6, 51.8, 51.6, 44.9, 21.6; FT-IR (KBr): ν_{max} 3084, 3034, 1712, 1633, 1598, 1344, 1284, 1157, 1089, 816 cm^{-1}; HRMS: calcd for $C_{24}H_{26}NO_4S$ [M+H]$^+$ 424.1577; found 424.1574.

4.2.14. Compound ***3db***. White solid. Mp 134–135 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.67 (d, *J*=15.6 Hz, 1H; C–CH–CH), 7.60 (d, *J*=7.2 Hz, 2H; Ar–H), 7.36–7.26 (m, 5H; Ar–H), 6.98 (d, *J*=5.1 Hz, 2H; Ar–H), 5.85–5.79 (m, 1H; CH–CH–CH_2), 5.33 (d, *J*=15.6 Hz, 1H; CH–CH–CO), 5.23–5.13 (m, 2H; CH–C*H*$_2$), 4.12 (d, *J*=7.2 Hz, 2H; O–CH_2–CH_3), 3.85–3.79 (m, 2H; CH_2–C*H*–CH, N–C*H*H–C), 3.47–3.40 (m, 2H; N–C*H*H–C, N–C*H*H–CH), 3.34–3.29 (m, 1H; N–C*H*H–CH), 2.43 (s, 3H; C–CH_3), 1.22 (d, *J*=6.6 Hz, 3H; CH_2–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 166.9, 145.2, 143.9, 141.8, 137.0, 134.2, 132.1, 129.7, 128.9, 128.5, 127.9, 127.8, 121.3, 116.5, 64.4, 53.6, 51.8, 44.9, 21.6, 14.2; FT-IR (KBr): ν_{max} 3076, 3026, 1712, 1340, 1284, 1176, 1157, 1091, 816, 705 cm^{-1}; HRMS: calcd for $C_{25}H_{28}NO_4S$ [M+H]$^+$ 438.1734; found 438.1702.

4.2.15. Compound ***3dc***. White solid. Mp 150–151 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.60 (d, *J*=7.5 Hz, 2H; Ar–H), 7.39–7.26 (m, 6H; Ar–H, C–CH–CH), 6.97 (d, *J*=6.4 Hz, 2H; Ar–H), 5.84–5.75 (m, 1H; CH–CH–CH_2), 5.20–5.15 (m, 2H; CH–C*H*$_2$), 4.78 (d, *J*=15.9 Hz, 1H; CH–CH–CN), 3.82–3.69 (m, 2H; CH_2–C*H*–CH, N–C*H*H–C), 3.47–3.30 (m, 3H; N–C*H*H–C, N–CH_2–CH,), 2.44 (s, 3H; C–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 147.3, 146.6, 144.1, 136.6, 135.4, 133.8, 131.9, 129.8, 129.3, 128.6, 128.5, 127.9, 118.2, 117.1, 99.1, 53.8, 51.9, 45.1, 21.6; FT-IR (KBr): ν_{max} 3084, 3034, 2214, 1597, 1344, 1157, 812 cm^{-1}; HRMS: calcd for $C_{23}H_{23}N_2O_2S$ [M+H]$^+$ 391.1475; found 391.1461.

4.2.16. Compound ***3dd***. White solid. Mp 135–137 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.62 (d, *J*=7.5 Hz, 2H; Ar–H), 7.42–7.06 (m, 13H; Ar–H, C–CH–CH), 5.97 (d, *J*=15.9 Hz, 1H; CH–CH–C), 5.90–5.82 (m, 1H; CH–CH–CH_2), 5.27–5.14 (m, 2H; CH–C*H*$_2$), 3.82–3.77 (m, 2H; CH_2–C*H*–CH, N–C*H*H–C), 3.50–3.38 (m, 3H; N–C*H*H–C, N–CH_2–CH), 2.44 (s, 3H; C–CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): 143.7, 138.5, 137.8, 137.2, 136.9, 135.8, 132.2, 131.9, 129.7, 128.8, 128.7, 128.6, 127.9, 127.7, 127.5, 127.1, 126.4, 115.9, 53.9, 51.7, 44.8, 21.6; FT-IR (KBr): ν_{max} 3076, 3027, 1597, 1336, 1153, 817, 750, 700 cm^{-1}; HRMS: calcd for $C_{28}H_{28}NO_2S$ [M+H]$^+$ 442.1835; found 442.1792.

4.2.17. Compound ***3ea***. White solid. Mp 122–124 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.71 (d, *J*=7.5 Hz, 2H; Ar–H), 7.43 (d, *J*=15.9 Hz, 1H; C–CH–CH), 7.34 (d, *J*=7.5 Hz, 2H; Ar–H), 5.83 (d, *J*=15.9 Hz, 1H; CH–CH–CO), 5.77–5.69 (m, 1H; CH–C*H*–CH_2), 5.08–5.03 (m, 2H; CH–C*H*$_2$), 4.09 (d, *J*=15.9 Hz, 1H; N–C*H*H–C), 3.77–3.66 (m, 5H; N–C*H*H–C, CH_2–C*H*–CH, O–CH_3), 3.45–3.41 (m, 1H; N–C*H*H–CH), 3.19–3.14 (m, 1H; N–C*H*H–CH), 2.44 (s, 3H; C–CH_3), 2.08–2.04 (m, 2H; C–C*H*$_2$–CH_2), 1.31–1.30 (m, 4H; CH_2–C*H*$_2$–C*H*$_2$–CH_3), 0.90 (m, 3H; CH_2–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 167.6, 144.1, 143.9, 141.4, 137.2, 132.0, 131.4, 129.7, 127.9, 117.2, 116.1, 53.5, 51.6, 50.8, 44.8, 30.4, 29.5, 22.9, 21.6, 13.9; FT-IR (KBr): ν_{max} 3076, 3026, 1710, 1344, 1286, 1168, 1091, 817 cm^{-1}; HRMS: calcd for $C_{22}H_{30}NO_4S$ [M+H]$^+$ 404.1890; found 404.1873.

4.2.18. Compound ***3ec***. White solid. Mp 105–106 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.70 (d, *J*=6.6 Hz, 2H; Ar–H), 7.34 (d, *J*=6.6 Hz, 2H; Ar–H), 7.11 (d, *J*=16.8 Hz, 1H; C–CH–CH), 5.77–5.66 (m, 1H; CH–CH–CH_2), 5.27 (d, *J*=16.8 Hz, 1H; CH–CH–CN), 5.09–4.96 (m, 2H; CH–C*H*$_2$), 4.07 (d, *J*=16.8 Hz, 1H; N–C*H*H–C), 3.73 (d, *J*=16.5 Hz, 1H; N–C*H*H–C), 3.55 (m, 1H; CH_2–C*H*–CH), 3.41–3.38 (m, 1H; N–C*H*H–CH), 3.19–3.14 (m, 1H; N–C*H*H–CH), 2.43 (s, 3H; C–CH_3), 2.04 (m, 2H; C–CH_2–CH_2), 1.29 (m, 4H; CH_2–C*H*$_2$–C*H*$_2$–CH_3), 0.90 (m, 3H; CH_2–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 146.9, 145.4, 144.2, 136.9, 131.8, 131.1, 129.8, 127.9, 118.5, 116.7, 95.7, 53.7, 51.0, 44.9, 30.2, 28.8, 22.9, 21.6, 13.9; FT-IR (KBr): ν_{max} 3084, 3034, 2210, 1631, 1595, 1346, 1157, 817 cm^{-1}; HRMS: calcd for $C_{21}H_{27}N_2O_2S$ [M+H]$^+$ 371.1788; found 371.1778.

4.2.19. Compound ***3ed***. White solid. Mp 90–91 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.73 (d, *J*=6.6 Hz, 2H; Ar–H), 7.36–7.17 (m, 7H; Ar–H), 6.85 (d, *J*=16.2 Hz, 1H; C–CH–CH), 6.49 (d, *J*=16.2 Hz, 1H; CH–CH–C), 5.84–5.72 (m, 1H; CH–C*H*–CH_2), 5.12–5.04 (m, 2H; CH–C*H*$_2$), 4.08 (d, *J*=15.0 Hz, 1H; N–C*H*H–C), 3.78 (d, *J*=15.0 Hz, 1H; N–C*H*H–C), 3.66–3.61 (m, 1H; CH_2–C*H*–CH), 3.42–3.37 (m, 1H; N–C*H*H–CH), 3.23–3.17 (m, 1H; N–C*H*H–CH), 2.43 (s, 3H; C–CH_3), 2.23–2.15 (m, 2H; C–CH_2–CH_2), 1.41–1.32 (m, 4H; CH_2–C*H*$_2$–C*H*$_2$–CH_3), 0.93 (m, 3H; CH_2–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 143.8, 138.1, 137.6, 135.8, 132.9, 132.3, 129.7, 128.7, 127.9, 127.5, 126.3, 126.1, 115.5, 53.8, 50.8, 44.8, 30.8, 29.6, 23.0, 21.6, 14.0; FT-IR (KBr): ν_{max} 3084, 3034, 2210, 1631, 1597, 1344, 1157, 707 cm^{-1}. HRMS: calcd for $C_{26}H_{32}NO_2S$ [M+H]$^+$ 422.2148; found 422.2145.

4.2.20. Compound ***3fa***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.78 (d, *J*=15.9 Hz, 1H; C–CH–CH), 7.35–7.27 (m, 3H; Ar–H), 7.09 (m, 2H; Ar–H), 5.98–5.87 (m, 1H; CH–CH–CH_2), 5.42 (d, *J*=15.9 Hz, 1H; CH–CH–CO), 5.24–5.16 (m, 2H; CH–C*H*$_2$), 4.05–3.92 (m, 2H; N–CH_2–C), 3.70–3.54 (m, 6H; N–CH_2–CH, CH_2–C*H*–CH, O–CH_3), 1.42 (s, 9H; C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 167.6, 154.4, 147.1, 142.4, 137.9, 137.3, 133.4, 128.8, 128.7, 127.8, 120.4, 115.5, 79.8, 51.5, 49.9, 44.8, 43.8, 28.4; FT-IR (neat): ν_{max} 3093, 3062, 2978, 1714, 1697, 1400, 1288, 1166, 702 cm^{-1}; HRMS: calcd for $C_{22}H_{28}NO_4$ [M+H]$^+$ 370.1974; found 370.1968.

*4.2.21. Compound **3fb***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.79 (d, *J*=15.6 Hz, 1H; C–CH–CH), 7.35–7.27 (m, 3H; Ar–H), 7.09 (m, 2H; Ar–H), 5.98–5.87 (m, 1H; CH–CH–CH_2), 5.41 (d, *J*=15.6 Hz, 1H; CH–CH–CO), 5.24–5.15 (m, 2H; CH–C*H*$_2$), 4.15 (q, *J*=6.9 Hz, 2H; O–CH_2–CH_3), 4.04–3.92 (m, 2H; N–CH_2–C), 3.69–3.54 (m, 3H; N–CH_2–CH, CH_2–C*H*–CH), 1.42 (s, 9H; C(CH_3)$_3$), 1.24 (t, *J*=6.9 Hz, 3H; CH_2–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 167.3, 154.4, 146.9, 142.2, 137.9, 137.4, 133.6, 128.8, 128.6, 127.7, 120.8, 115.4, 79.7, 60.3, 51.5, 49.9, 44.6, 28.4, 14.2; FT-IR (neat): ν_{max} 3093, 3062, 2978, 1712, 1695, 1404, 1288, 1163, 705 cm^{-1}; HRMS: calcd for $C_{23}H_{30}NO_4$ [M+H]$^+$ 384.2130; found 384.2124.

*4.2.22. Compound **3fc***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50 (d, *J*=16.2 Hz, 1H; C–CH–CH), 7.40–7.38 (m, 3H; Ar–H), 7.08–7.06 (m, 2H; Ar–H), 5.97–5.88 (m, 1H; CH–CH–CH_2), 5.22–5.17 (m, 2H; CH–C*H*$_2$), 4.86 (d, *J*=16.2 Hz, 1H; CH–CH–CN), 4.03–3.97 (m, 1H; N–C*H*H–C), 3.81 (m, 1H; CH_2–C*H*–CH), 3.69–3.61 (m, 3H; N–C*H*H–C;; N–CH_2–CH), 1.42 (s, 9H; C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 154.3, 147.8, 137.5, 135.8, 133.2, 129.2, 128.7, 128.3, 118.5, 115.9, 98.6, 79.9, 51.6, 50.0, 44.9, 28.4; FT-IR (neat): ν_{max} 3084, 3057, 2989, 2214, 1697, 1392, 1163, 707 cm^{-1}; HRMS: calcd for $C_{21}H_{25}N_2O_2$ [M+H]$^+$ 337.1871; found 337.1867.

*4.2.23. Compound **3fd***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.40–7.19 (m, 11H; Ar–H, C–CH–CH), 6.08–5.98 (m, 2H; CH–CH–C, CH–CH–CH_2), 5.29–5.16 (m, 2H; CH–C*H*$_2$), 4.03–3.91 (m, 2H; N–CH_2–C), 3.70–3.62 (m, 3H; N–CH_2–CH, CH_2–C*H*–CH), 1.44 (s, 9H; C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 154.5, 138.8, 138.6, 137.5, 135.1, 131.5, 129.0, 128.6, 128.3, 127.5, 127.3, 126.4, 114.9, 79.5, 51.7, 49.7, 44.7, 28.5; FT-IR (neat): ν_{max} 3080, 3039, 2974, 1689, 1400, 1163, 696 cm^{-1}; HRMS: calcd for $C_{26}H_{30}NO_2$ [M+H]$^+$ 388.2232; found 388.2225.

*4.2.24. Compound **3ga***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.83 (d, *J*=15.3 Hz, 1H; C–CH–CH), 7.37–7.32 (m, 3H; Ar–H), 7.10–7.08 (m, 2H; Ar–H), 6.02–5.90 (m, 1H; CH–CH–CH_2), 5.35 (d, *J*=15.6 Hz, 1H; CH–CH–CO), 5.28–5.17 (m, 2H; CH–C*H*$_2$), 4.72 (m, 1H; O–C*H*(CH_3)–C), 4.13–4.09 (m, 1H; CH_2–C*H*–CH), 3.85–3.79 (m, 2H; O–CH_2–CH), 3.69 (s, 3H; O–CH_3), 0.80 (d, *J*=6.3 Hz, 3H; CH–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 167.7, 154.8, 144.5, 138.5, 137.4, 132.3, 129.3, 128.7, 127.7, 119.9, 115.8, 76.9, 71.1, 51.5, 47.5, 18.0; FT-IR (neat): ν_{max} 3080, 3028, 1714, 1278, 1114, 1068, 704 cm^{-1}; HRMS: calcd for $C_{18}H_{21}O_3$ [M+H]$^+$ 285.1485; found 285.1476.

*4.2.25. Compound **3gc***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.54 (d, *J*=16.2 Hz, 1H; C–CH–CH), 7.39–7.36 (m, 3H; Ar–H), 7.08–7.06 (m, 2H; Ar–H), 5.96–5.87 (m, 1H; CH–CH–CH_2), 5.29–5.19 (m, 2H; CH–C*H*$_2$), 4.85 (d, *J*=15.9 Hz, 1H; CH–CH–CN), 4.68 (d, *J*=6.3 Hz, 1H; O–C*H*(CH_3)–C), 4.13–4.08 (m, 1H; CH_2–C*H*–CH), 3.78–3.76 (m, 2H; O–CH_2–CH), 0.80 (d, *J*=6.3 Hz, 3H; CH–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 155.8, 149.6, 138.1, 135.8, 132.0, 129.3, 128.9, 128.2, 118.5, 116.4, 98.1, 77.1, 71.2, 47.6, 17.9; FT-IR (neat): ν_{max} 3078, 3028, 2214, 1633, 1593, 1114, 1068, 705 cm^{-1};. HRMS: calcd for $C_{17}H_{18}NO$ [M+H]$^+$ 252.1383; found 252.1369.

*4.2.26. Compound **3gd***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.41–7.19 (m, 11H; C–CH–CH, Ar–H), 6.08–5.97 (m, 2H; CH–CH–CH_2, CH–CH–C), 5.33–5.18 (m, 2H; CH–C*H*$_2$), 4.73 (d, *J*=5.7 Hz, 1H; O–C*H*(CH_3)–C), 4.17–4.13 (m, 1H; CH_2–C*H*–CH), 3.85–3.79 (m, 2H; O–CH_2–CH), 0.81 (d, *J*=6.3 Hz, 3H; CH–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 146.4, 139.6, 138.8, 137.6, 133.9, 130.9, 129.7, 129.4, 128.6, 128.4, 127.4, 127.2, 126.3, 115.2, 77.0, 71.3, 47.5, 18.6; FT-IR (neat): ν_{max} 3078, 3026, 1635, 1597, 1112, 1070, 754, 700 cm^{-1}; HRMS: calcd for $C_{22}H_{23}O$ [M+H]$^+$ 303.1743; found 303.1712.

*4.2.27. Compound **3hc***. Yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.57 (d, *J*=15.9 Hz, 1H; C–CH–CH), 7.39–7.32 (m, 3H; Ar–H), 7.09–7.07 (m, 2H; Ar–H), 5.96–5.88 (m, 1H; CH–CH–CH_2), 5.29–5.19 (m, 2H; CH–C*H*$_2$), 4.80 (d, *J*=16.2 Hz, 1H; CH–C*H*–CN), 4.52–4.50 (m, 1H; O–C*H*(C_2H_5)–C), 4.09–4.04 (m, 1H; CH_2–C*H*–CH), 3.78–3.73 (m, 2H; O–CH_2–CH), 1.11–1.04 (m, 2H; CH–CH_2–CH_3), 0.69–0.65 (m, 3H; CH_2–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 154.8, 149.7, 138.3, 135.9, 132.0, 129.2, 128.9, 128.2, 118.6, 116.4, 97.9, 82.2, 71.4, 47.8, 24.2, 9.9; FT-IR (neat): ν_{max} 3078, 3030, 2214, 1633, 1591, 1120, 1056, 707 cm^{-1}; HRMS: calcd for $C_{18}H_{20}NO$ [M+H]$^+$ 266.1539; found 266.1538.

*4.2.28. Compound **3ic***. White solid. Mp 166–167 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.64 (d, *J*=7.5 Hz, 2H; Ar–H), 7.40–7.28 (m, 6H; Ar–H, C–CH–CH), 6.86 (d, *J*=4.5 Hz, 2H; Ar–H), 5.93–5.85 (m, 1H; CH–CH–CH_2), 5.24–5.18 (m, 2H; CH–C*H*$_2$), 4.70 (d, *J*=16.2 Hz, 1H; CH–CH–CN), 4.13 (d, *J*=6.0 Hz, 1H; N–C*H*(CH_3)–C), 3.55 (m, 3H; N–CH_2–CH, CH_2–C*H*–CH), 2.47 (s, 3H; C–CH_3), 1.13 (d, *J*=6.3 Hz, 3H; CH–C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$): 151.5, 147.9, 143.9, 137.3, 134.9, 133.8, 133.2, 129.7, 129.2, 129.0, 128.5, 127.7, 118.2, 117.3, 99.4, 59.1, 52.6, 44.5, 21.6, 21.5; FT-IR (KBr): ν_{max} 3084, 3034, 2220, 1635, 1591, 1344, 1159, 813 cm^{-1}; HRMS: calcd for $C_{24}H_{25}N_2O_2S$ [M+H]$^+$ 405.1631; found 405.1627.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tet.2011.09.026. These data include MOL files and InChIKeys of the most important compounds described in this article.

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14. Crystal structure determination: $C_{24}H_{24}N_2O_2S$ **3ic**, M=404.51, triclinic, space group $P(-1)$, a=37.200(8), b=7.0923(16), c=17.560(4) Å, U=4484.6(2) $Å^3$, T=293(2) K, Z=4, 2943 reflections measured, 5174 unique (R_{int}=0.0914), which were used in all calculations. The final $wR(F^2)$ was 0.1097 (all data). CCDC 792044 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
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