Organocatalyzed Three-Component Ugi and Passerini Reactions of 4-Oxoazetidine-2-carbaldehydes and Azetidine-2,3-diones. Application to the Synthesis of γ -Lactams and γ -Lactones

Benito Alcaide,^{*,†} Pedro Almendros,[‡] Cristina Aragoncillo,[†] Ricardo Callejo,[†] and M. Pilar Ruiz[†]

[†]*Grupo de Lactamas y Heterociclos Bioactivos, Departamento de Química Orgánica I, Unidad*

Asociada al CSIC, Facultad de Química, Universidad Complutense de Madrid, 28040-Madrid, Spain,

[‡]*Instituto de Química Orgánica General, IQOG, CSIC, Juan de la Cierva 3, 28006-Madrid, Spain, and*

alcaideb@quim.ucm.es

ABSTRACT

Organocatalyzed U-3CR of 4-oxoazetidine-2-carbaldehydes has been studied. Besides, the organocatalyzed P-3CR of 4-oxoazetidine-2-carbaldehydes and azetidine-2,3-diones has been described for the first time. U-3CR and P-3CR adducts have been obtained in good yields and reasonable diastereoselectivities. Phenyl phosphinic acid has been the catalyst of choice to study the scope of both organocatalyzed multicomponent reactions using a variety of β -lactams, isocyanides and amines. A catalytic cycle explaining the formation of Ugi and Passerini adducts has been proposed. Highly

functionalized U-3CR and P-3CR adducts derived from β -lactams have proved to be useful substrates for the preparation of enantiopure γ -lactams and γ -lactones via N1–C2 β -lactam ring opening/cyclization under acidic or basic conditions.

INTRODUCTION

Multicomponent reactions (MCRs) are synthetic processes that combine three or more substrates to afford new compounds in one pot a single step.¹ This powerful methodology ~~allow~~ allows both complexity and diversity in the final substrates with high atom economy. The advantages and the applications of MCRs have been widely demonstrated in the synthesis of natural products,^{2,3} and medicinal chemistry.^{3,4} In particular, isocyanide-based MCRs (IMCRs) are especially attractive in terms of functional group tolerance and the high levels of chemo-, regio-, and stereoselectivity obtained.⁵ Among them, the Passerini three-component reaction (P-3CR) and the Ugi four-component reaction (U-4CR) are the most prominent. In this context, List has reported the first organocatalyzed three-component Ugi reaction (U-3CR) of different aldehydes, *p*-anisidine and a variety of isocyanides using phenyl phosphinic acid as catalyst.⁶

On the other hand, the β -lactam ring has been permanently associated with their potent antibacterial activity and, more recently, with enzyme inhibition, anticancer activity and gene activation.⁷ Besides, from the synthetic point of view, this four-membered ring is an excellent substrate to obtain a diverse family of nitrogenated compounds ranging from three-membered skeletons to macrocyclic structures and acyclic compounds.⁸ In particular, different methodologies which involves ring opening of the β -lactam nucleus followed by cyclization have been developed.⁹

The γ -lactam ring is present in natural and synthetic products with interesting therapeutic activities.¹⁰ For example, succinimide¹¹ and pyroglutamic acid¹² cores have significant chemical and medicinal importance as they are implicate in different relevant processes. In addition, the γ -lactone

moiety is a substructure present in natural compounds. In particular *N*-acyl homoserine lactones (AHLs) are involved in the multicellular communication network of most gram-negative bacteria,¹³ and sesquiterpene lactones exhibit a variety of biological activities.¹⁴

Following up our interest in the area of the synthesis of nitrogenated compounds,¹⁵ and the investigation of methodologies based in multicomponent processes,¹⁶ we became interested in the study of the organocatalyzed U-3CR process in β -lactam substrates.

RESULTS AND DISCUSSION

U-3CR in of 4-Oxoazetidine-2-carbaldehydes

First of all, we decided to investigate the U-3CR catalyzed by phenyl phosphinic acid in of 4-oxoazetidine-2-carbaldehydes **1**.

Starting substrates, optically pure 4-oxoazetidine-2-carbaldehydes **1a–e**, were prepared, using standard methodology, as single *cis*-enantiomers from imines of (*R*)-2,3-*O*-isopropylideneglyceraldehyde, through Staudinger reaction with the corresponding alkoxy(aryloxy)acetyl chloride in the presence of Et₃N, followed by sequential acidic acetonide hydrolysis and oxidative cleavage.¹⁷

~~Our first experiment~~ In order to show the viability of the organocatalyzed U-3CR in of β -lactam aldehydes **1**, our first experiment was the reaction of aldehyde **1a**, allylamine and benzyl isocyanide (BnNC) in presence of a catalytic amount of phenyl phosphinic acid (10% mol) ~~in catalytic amount (10% mol)~~, using the same reaction conditions previously described ~~previously~~ (toluene, 80°C).⁶ In the event, α -amino amide **2a** was obtained as a separable mixture of *syn/anti* isomers in 61:39 ratio in 83% yield (Table 1, entry 1). Compound **2a** was also obtained quantitatively within the same *syn/anti* ratio when the reaction was tested ~~using~~ under milder conditions, dichloromethane at room temperature ~~compound 2a was obtained quantitatively in the same *syn/anti* ratio~~ (Table 1, entry 2). Thus, the above

mild reaction conditions were applied to study the scope of the multicomponent process in of β -lactam aldehydes **1**. The reaction of aldehyde **1a**, allylamine and *t*-butyl isocyanide (*t*-BuNC) in presence of phenyl phosphinic acid (10% mol) afforded product **2b** with similar diastereoselectivity (63:37) and excellent yield (92%) (Table 1, entry 3). When the U-3CR was tested in aldehyde **1b**, with an aliphatic substituent in the nitrogen, compound **2c** was obtained with slightly better diastereoselectivity (72:28) in 66% yield (Table 1, entry 4). Analogously, the reaction of aldehyde **1c**, *t*-BuNC and methyl glycinate, afforded compound **2d** with a comparable diastereoselectivity (70:30) and good yield (74%) (Table 1, entry 5). Unfortunately, α -amino amide **2d** was isolated as an inseparable mixture of *syn/anti* isomers. Next, we decided to explore the multicomponent reaction using aromatic amines. The reactions were performed using aldehydes **1a** and **1d**, with benzyl isocyanide and *t*-BuNC, respectively, and an electron rich aromatic amine, *p*-anisidine. Thus, compounds **2e** and **2f** were obtained with comparable values in terms of diastereoselectivity and yield (Table 1, entries 6 and 7). However, α -(*p*-methoxyphenyl)amino amide **2e** was isolated as an inseparable mixture of *syn/anti* isomers. Compound **2g** was obtained without significant changes in terms of diastereoselectivity (68:32) and yield (67%) when the reaction was performed with aldehyde **1b**, *t*-BuNC and an electron poor aromatic amine, such as *p*-nitroaniline, compound **2g** was obtained with no significant changes in terms of diastereoselectivity (68:32) and yield (67%) (Table 1, entry 8).

Table 1. U-3CR of 4-oxoazetidin-2-carbaldehydes **1, amines, isocyanides and phenyl phosphinic acid as catalyst^a**

Entry	Aldehyde	R ¹	R ²	R ³	R ⁴	Conditions	t (h) ^b	Product	<i>syn/anti</i> ^c	Yield (%) ^d
1	(+)- 1a	PMP ^e	MeO	Bn	2-propenyl	toluene/80°C	28	2a	61:39	51:32
2	(+)- 1a	PMP ^e	MeO	Bn	2-propenyl	CH ₂ Cl ₂ /rt	28	2a	61:39	61:39
3	(+)- 1a	PMP ^e	MeO	<i>t</i> -Bu	2-propenyl	CH ₂ Cl ₂ /rt	48	2b	63:37	58:34
4	(-)- 1b	2-propenyl	PhO	Bn	2-propenyl	CH ₂ Cl ₂ /rt	39	2c	72:28	48:18
5	(-)- 1c	Bn	Ph ^f	<i>t</i> -Bu	CH ₂ CO ₂ Me ^g	CH ₂ Cl ₂ /rt	24	2d	70:30	74 ^h
6	(+)- 1a	PMP ^e	MeO	<i>t</i> -Bu	PMP ^e	CH ₂ Cl ₂ /rt	18	2e	64:36	74 ^h
7	(+)- 1d	PMP ^e	PhO	Bn	PMP ^e	CH ₂ Cl ₂ /rt	16	2f	70:30	62:28
8	(-)- 1b	2-propenyl	PhO	<i>t</i> -Bu	PNP ⁱ	CH ₂ Cl ₂ /rt	22	2g	68:32	46:21

^aAll reactions were performed by using an aldehyde/amine/isocyanide ratio of 1.0:1.1:1.1 mmol. ^bReaction progress was followed by TLC. ^cThe *syn/anti* ratio was determined by integration of well-resolved signals in the ¹H NMR spectra (300 MHz) of the crude reaction mixtures before purification. ^dYield of pure, isolated isomers with correct analytical and spectral data. ^ePMP = 4-MeOC₆H₄. ^fPh^f = Phtalimidoyl. ^gThe reaction was carried out by treatment of amine chlorhydrate with triethyl amine in the reaction conditions. ^hYield of pure, isolated mixture of isomers. ⁱPNP = 4-NO₂C₆H₄.

Scheme 1 shows the mechanistic proposal for the U-3CR of compounds **1**, which is comparable to List's proposal. Phenyl phosphinic acid **I** can be considered a Brönsted acid and, in the form of its phenylphosphonous acid tautomer **II**, a Lewis base. Both properties ~~must~~ could be involved in the catalytic process. The mechanism proposed involves protonation of the in situ generated imine, formed by reaction of aldehyde **1** and the corresponding amine. Next, addition of the isocyanide and subsequent trapping of the nitrilium ion with the phosphinate anion would take place. Finally, a molecule of water, which is released in the imine formation, reacts with intermediate **IV** to generate **V**, which fragments to the α -amino amide **2**, and the catalyst.

Scheme 1. Mechanistic proposal for the U-3CR catalyzed by phenyl phosphinic acid

P-3CR in of 4-Oxoazetidine-2-carbaldehydes and Azetidine-2,3-diones

Once the U-3CR organocatalyzed by phenyl phosphinic acid was studied, we decided to investigate the analogous process, the Passerini reaction; ~~in~~ of aldehydes **1**. In fact, to the best of our knowledge, there is no report about organocatalyzed diastereoselective Passerini reaction.¹⁸

According ~~with~~ to the mechanism previously proposed for the organocatalyzed U-3CR, a molecule of water is formed during the formation of the imine. Thus, an external addition of water would be necessary which would act as the acidic component in the Passerini reaction ~~in the Passerini reaction it would be necessary an external addition of water which would act as the acidic component~~. Taking into account this idea, we decided to study the reaction of aldehyde **1a**, *t*-BuNC, a stoichiometric amount of water and phenyl phosphinic acid (10% mol) in dichloromethane at room temperature. Fortunately, the corresponding α -hydroxy amide **3a** was obtained as a mixture of isomers (60:40) quantitatively (Table 2, entry 1). Next, we decided to test the P-3CR in aqueous media in order to minimize the amount of organic solvent employed. However, adduct **3a** was isolated in lower yield (64 and 67%) when the reaction was performed using mixtures of THF/ H_2O (1:1) and MeCN/ H_2O (1:1), respectively ~~adduct 3a~~

~~was isolated in lower yield (64 and 67%, respectively)~~ (Table 2, entries 2 and 3). In addition, the reaction times for both experiments were considerably ~~longer than~~ longer than with the use of dichloromethane as solvent. In relation with the diastereoselectivity, the use of MeCN/H₂O slightly decreased the *syn/anti* ratio (55:45) (Table 2, entry 3). Thus, we decide to study the scope of the reaction using dichloromethane ~~as solvent~~ at room temperature. When ~~we~~ the reaction was carried out ~~the reaction~~ with β -lactam **1d**, ~~with~~ containing a phenoxy ~~instead~~ instead of a methoxy group at C-3 position of the β -lactam ring, the diastereoselectivity was slightly increased (65:35) in the α -hydroxy amide **3b** (Table 2, entry 4). Next, we decided to investigate the effect of another isocyanide. Thus, the reaction of aldehyde **1a** with BnNC, water and phenyl phosphinic acid, in the above reaction conditions afforded compound **3b** with a comparable diastereoselectivity (60:40) and excellent yield (88%) (Table 2, entry 5).

Taking into consideration that the use of β -lactam aldehydes **1** with aliphatic substituents at nitrogen position increased the diastereoselectivity in the U-3CR, we decided to examine the behaviour of aldehydes **1c** and **1e**. In the event, ~~we observed that~~ the reaction of both compounds with *t*-BuNC and phenyl phosphinic acid (10% mol) afforded adducts **3d** and **3e** respectively. Unexpectedly, compound **3d** was isolated in a very low diastereoselectivity (55:45) in 68% yield (Table 2, entry 6). Fortunately, compound **3e**, which was isolated in excellent yield (96%), an improved diastereoselectivity was observed (70:30) (Table 2, entry 7).

The structure of adducts **2** and **3** was assigned by NMR studies. The relative stereochemistry of compounds **2** has been established in the γ -lactams (see below). However, NMR vicinal coupling constants of the H4 and H4' protons for the *syn*-**3** and *anti*-**3** adducts are very useful information to ~~determine~~ establish the relative stereochemistry (see Table S1 in Supporting information). For any pair of

diastereomers, the vicinal coupling constant between H4 and H4' is higher for *anti*-isomers ($^3J_{\text{H4,H4}'} = 5.2\text{--}1.6$ Hz) than for the *syn*-isomers ($^3J_{\text{H4,H4}'} = 3.4\text{--}1.2$ Hz). In addition, the stereochemistry of compounds **3** was finally confirmed by chemical correlation with their corresponding γ -lactones (see below). Then, by analogy, adducts *syn*-**2** are the major isomers for the previous U-3CR in aldehydes **1**. The observed *syn*-diastereoselectivity for compounds **2** and **3** might be explained by the Felkin-Anh model.¹⁹

Table 2. P-3CR of 4-oxoazetidine-2-carbaldehydes **1, isocyanides and water in presence of phenyl Phosphinic Acid^a**

Entry	Aldehyde	R ¹	R ²	R ³	Solvent	t (h) ^b	Product	<i>syn/anti</i> ^c	Yield (%) ^d
1	(+)- 1a	PMP ^e	MeO	<i>t</i> -Bu	CH ₂ Cl ₂	21	3a	60:40	60:40
2	(+)- 1a	PMP ^e	MeO	<i>t</i> -Bu	THF/H ₂ O	48	3a	60:40	38:26
3	(+)- 1a	PMP ^e	MeO	<i>t</i> -Bu	MeCN/H ₂ O	32	3a	55:45	37:30
4	(+)- 1d	PMP ^e	PhO	<i>t</i> -Bu	CH ₂ Cl ₂	19	3b	65:35	59:32
5	(+)- 1a	PMP ^e	MeO	Bn	CH ₂ Cl ₂	20	3c	60:40	55:35
6	(-)- 1c	Bn	Ph ^f	<i>t</i> -Bu	CH ₂ Cl ₂	21	3d	55:45	37:31
7	(+)- 1e	2-Propynyl	PhO	<i>t</i> -Bu	CH ₂ Cl ₂	20	3e	70:30	67:29

^aAll reactions were performed by using an aldehyde/isocyanide/water ratio of 1.0:1.1:1.1 mmol.

^bReaction progress was followed by TLC. ^cThe *syn/anti* ratio was determined by integration of well-resolved signals in the ¹H NMR spectra (300 MHz) of the crude reaction mixtures before purification.

^dYield of pure, isolated isomers with correct analytical and spectral data. ^ePMP = 4-MeOC₆H₄.

The 3-substituted 3-hydroxy β -lactam scaffold is an efficient carboxylate mimic,²⁰ showing interesting activity in acyl CoA-cholesterol acyltransferase inhibition assays. In addition, it is found in

several monobactams with interesting pharmacological activities such as sulfacezin (A) (Figure 1), and related compounds. Due to the importance of the 3-hydroxy-3-substituted β -lactam skeleton, we have reported the synthesis of these compounds using different synthetic strategies.^{16,21}

Figure 1. Sulfacezin (A), a representative example of a compound containing the 3-substituted 3-hydroxy β -lactam framework.

The results obtained with oxoazetidine-2-carbaldehydes **1** encouraged us to screen the P-3CR in azetidine-2,3-diones **4**. The starting materials, enantiopure azetidine-2,3-diones **4**, were efficiently prepared ~~in optically pure form~~ from aromatic or aliphatic (*R*)-2,3-*O*-isopropylideneglyceraldehyde-derived imines by Staudinger reaction with acetoxyacetyl chloride in the presence of Et₃N, followed by sequential transesterification and Swern oxidation, as we have previously reported.²²

First, we examined the reaction of azetidine-2,3-dione **4a** with BnNC, water and phenyl phosphinic acid (10% mol), affording α -hydroxy amide **5a** with complete *syn*-diastereoselectively (with *cis* configuration between the β -lactam H4 and the amide group on C3) and good yield (78%). Analogously, the reaction of ketene **4b** with BnNC and water, in the above reaction conditions afforded 3-substituted 3-hydroxy- β -lactam **5b** in excellent yield and total diastereoselectivity. The reaction of azetidine-2,3-diones **4a** and **4d** using *t*-BuNC afforded compounds **5c** and **5d** in total diastereoselectivity although, compound **5c** was isolated in low yield. The use of ethyl isocyanoacetate with ketone **4a** gave compound **5e** with 45% yield and total diastereoselectivity.

The diastereoselectivity ~~must be~~ is controlled by the presence of the substituent placed at C-4 position of the β -lactam ring, ~~in~~ which blocks preferentially one face of the carbonyl group ~~is blocked~~.

Thus, the nucleophilic addition takes place to the less hindered face of the carbonyl group, affording P-3CR adducts **3** as single isomers.^{16a, 23}

Table 3. P-3CR of azetidine-2,3-diones **4, isocyanides and water in presence of phenyl phosphinic acid^a**

Entry	Ketone	R ¹	R ²	t (h) ^b	Product	syn/anti ^c	Yield (%) ^d
1	(+)- 4a	PMP ^e	Bn	45	(-)- 5a	100:0	78
2	(-)- 4b	Bn	Bn	27	(-)- 5b	100:0	80
3	(+)- 4a	PMP ^e	<i>t</i> -Bu	48	(-)- 5c	100:0	48
4	(-)- 4c	2-propenyl	<i>t</i> -Bu	23	(-)- 5d	100:0	71
5	(+)- 4a	PMP ^e	CH ₂ CO ₂ Et	72	(+)- 5e	100:0	45

^aAll reactions were performed by using a ketone/isocyanide/water ratio of 1.0:1.1:1.1 mmol. ^bReaction progress was followed by TLC. ^cThe syn/anti ratio was determined by integration of well-resolved signals in the ¹H NMR spectra (300 MHz) of the crude reaction mixtures before purification. ^dYield of pure, isolated isomers with correct analytical and spectral data. ^ePMP = 4-MeOC₆H₄.

Synthesis of γ -Lactams and γ -Lactones via N1–C2 Ring Cleavage/Cyclization of U-3CR Adduct **2** and P-3CR Adduct **3**, Respectively

Taking into account the importance of γ -lactam and γ -lactone skeletons, we decide to take advantage of the highly functionalized adducts **2** and **3** to access to these 5-membered rings. In fact, rearrangement reactions of both adducts would result a stereoselective synthetic pathway to functionalized γ -lactams **6** and γ -lactones **7** (Scheme 2).

Scheme 2. Possible N1–C2 β -lactam ring cleavage/cyclization of Ugi adducts **2 and Passerini adducts **3****

N1–C2 β -lactam ring cleavage/cyclization ~~can occur~~ usually takes place in acidic or basic conditions. To explore the process, ~~we decided to study the expansion reaction of~~ compound *syn*-**2a** containing a *p*-methoxyphenyl group substituent in the nitrogen of the β -lactam, was employed. It is well known that this kind of β -lactams undergo easy N1–C2 ring cleavage due to the stabilization of the nitrogen anion, acting as a good leaving group. Treatment of adduct *syn*-**2a** under acidic conditions, using a mixture of methanol and sulphuric acid, afforded γ -lactam *syn*-**6a** in low yield (22%) (Scheme 3).

Scheme 3. Synthesis of γ -lactam *syn*-6a** via N1–C2 cleavage/cyclization in acidic conditions**

In order to improve the yield, we decided to carry out the reaction in basic conditions, using a stoichiometric amount of sodium methoxide in methanol ~~as solvent~~. Thus, reaction of compound *syn*-**2a** using one equivalent of sodium methoxide in methanol at room temperature exclusively afforded γ -lactam *syn*-**6a** in excellent yield (84%) after chromatographic purification (Table 1, entry 1). The reaction of isomer *anti*-**2a** under the same reaction conditions gave the expected γ -lactam in 60% yield (Table 1, entry 2). Fortunately, the feasible epimerization of the proton in α position of the amide group

was not observed in both experiments. ~~in both experiments it was not observed epimerization of the proton in α position of the amide group.~~ The scope of the reaction was ~~carried out~~ developed using Ugi adducts *syn*-**2b** and *anti*-**2b**, with a *t*-butyl carbamoyl group, affording γ -lactams *syn*-**6b** and *anti*-**6b** in good yields (82 and 71%, respectively). Interestingly, the expansion process took place with Ugi adducts *syn*-**2c** and *anti*-**2c** with a propenyl group substituent in the nitrogen of the β -lactam ring. γ -Lactams *syn*-**6c** and *anti*-**6c** were obtained in excellent yields (81 and 76% respectively) in longer reaction times. It seems ~~to be~~ reasonable that the expansion reaction of *N*-propenyl substituted β -lactams ~~must~~ can be slower than with *N*-PMP substituted β -lactams, because the negative charge of the nitrogen is not in resonance with the aliphatic group. Next, ~~we decided, to examine~~ the influence of an aromatic substituent in the amine group, such as *p*-methoxyphenyl, was studied. Thus, reaction of an inseparable mixture of isomers **2e** (*syn:anti* 64:36) in presence of sodium methoxide and methanol at 35°C, gave β -lactams *syn*-**6d** and *anti*-**6d** as a separable mixture of diastereoisomers by flash chromatography. Isomers *syn*-(+)-**6d** and *anti*-**6d** were isolated in good yields and in the same *syn/anti* ratio (Table 1, entry 7). γ -Lactam *syn*-**6e** was obtained in lower yield (45%) when the reaction was performed using compound *syn*-**2f** with a *p*-nitrophenyl group ~~γ -lactam *syn*-**6e** was obtained in lower yield (45%).~~ It seems reasonable that the nitrogen at this position is less nucleophile than in the rest of the examples.

Table 4. Synthesis of γ -lactams 6 via N1–C2 ring cleavage/cyclization of Ugi adducts 2^a

Entry	U-3CR adduct	R ¹	R ²	R ³	R ⁴	t(h) ^b	Product	Yield (%) ^c
1	<i>syn</i> -(+)- 2a	PMP ^d	MeO	Bn	2-propenyl	10	<i>syn</i> -(+)- 6a	84
2	<i>anti</i> -(+)- 2a	PMP ^d	MeO	Bn	2-propenyl	10	<i>anti</i> -(-)- 6a	60
3	<i>syn</i> -(+)- 2b	PMP ^d	MeO	<i>t</i> -Bu	2-propenyl	23	<i>syn</i> -(+)- 6b	82
4	<i>anti</i> -(+)- 2b	PMP ^d	MeO	<i>t</i> -Bu	2-propenyl	23	<i>anti</i> -(-)- 6b	71
5	<i>syn</i> -(+)- 2c	2-propenyl	PhO	Bn	2-propenyl	24	<i>syn</i> -(+)- 6c	81
6	<i>anti</i> -(+)- 2c	2-propenyl	PhO	Bn	2-propenyl	24	<i>anti</i> -(+)- 6c	76
7 ^e	2e^f	PMP ^d	MeO	<i>t</i> -Bu	PMP ^d	17	<i>syn</i> -(+)- 6d / <i>anti</i> -(+)- 6d	51:28
8 ^e	<i>syn</i> -(+)- 2f	2-propenyl	PhO	<i>t</i> -Bu	PNP ^g	24	<i>syn</i> -(+)- 6e	45

^aAll reactions were performed by using a substrate/MeONa ratio of 1.0:1.0 mmol. ^bReaction progress was followed by TLC. ^cYield of pure, isolated isomers with correct analytical and spectral data. ^dPMP = 4-MeOC₆H₄. ^eThe reaction was performed at 35°C. ^fThe starting material was an inseparable mixture of *syn/anti* isomers in 64:36 ratio. ^gPNP = 4-NO₂C₆H₄.

Finally, it is important to mention remark that γ -lactams **6** with an amide group in C5 position, are structurally related to pyroglutamic acid. Thus, compounds **6** are interesting compounds from the chemical and biological point of view.

Satisfied with the above results, we set out to evaluate the N1–C2 ring cleavage/cyclization in of Passerini adducts **3**. The application of this methodology would allow access to γ -butyrolactones (Tables 5 and 6). The FeCl₃-catalyzed ring expansion reaction of 2-azetidinone-tethered allenic alcohols to give γ -lactones has been recently described in our research group ~~in our research group we have described the ring expansion reaction of 2-azetidinone-tethered allenic alcohols catalyzed by iron(III) chloride to give γ -lactones.~~²⁴ Thus, we decided to apply the same reaction conditions in to substrate *syn*-**3a**. Reaction of α -hydroxy amide *syn*-**3a**, with FeCl₃·6H₂O (10 % mol) in dichloroethane at 80 °C, selectively gave γ -lactone *syn*-**7a** ~~selectively~~ in very low yield (23%) (Table 5, entry 1). Then, we decided to try the basic conditions used for the preparation of γ -lactams **6**. Reaction of compound *syn*-**3a**

with 1 equivalent of sodium methoxide gave a mixture of γ -lactone *syn*-**7a** (32%) and hydroxyamino ester **8** (47%) (Table 5, entry 2). The use of two equivalents of sodium methoxide at room temperature or under reflux conditions, afforded hydroxyamino ester **8** exclusively (75% and 48% respectively) (Table 5, entries 3 and 4). Unfortunately, the use of excess of sodium methoxide gave compound **8** in lower yield, with partial epimerization after long reaction times. Interestingly, when the reaction was conducted in a mixture of methanol and sulphuric acid gave hydroxyamino ester **8** in good yield (73%) after chromatographic purification (Table 5, entry 5).

Table 5. Reactivity of α -hydroxy amide *syn*-3a****

Entry	Conditions	t(h) ^a	<i>syn</i> -(+)- 7a /(-)- 8 ^b	Yield (%) ^c
1	FeCl ₃ ·6H ₂ O (10% mol)/DCE/80 °C	21	100:0	23
2	MeONa (1 equiv.)/MeOH/RT	6	40:60	32:47
3	MeONa (2 equiv.)/MeOH/RT	3	0:100	75
4	MeONa (1 equiv.)/MeOH/reflux	1	0:100	48
5	MeOH (1 equiv.)/H ₂ SO ₄ (2:1)	2	0:100	73

^aReaction progress was followed by TLC. ^bThe *syn/anti* ratio was determined by integration of well-resolved signals in the ¹H NMR spectra (300 MHz) of the crude reaction mixtures before purification. ^cYield of pure, isolated isomers with correct analytical and spectral data.

Due to the difficulties to obtain γ -lactones in a one pot process from α -hydroxy amides **3**, we decided to prepare these compounds via sequential ring opening followed by lactonization of the α -hydroxy amides **3** in acidic media. Thus, reaction of compound *syn*-**3a** in MeOH/H₂SO₄ (2:1) gave α -hydroxy amide **9** **8**. ~~After neutralization and isolation of compound **9**, The cyclization step was carried out using a catalytic amount of *p*-toluenesulfonic acid in toluene at reflux temperature after~~

neutralization and isolation of compound **8** **9**. In the event, enantiomerically pure γ -butyrolactone *syn*-**7a** was isolated in good yield (73%) without epimerization of the α position of the amide group (Table 6, entry 1). However, lactone *anti*-**7a** was obtained in low yield when the reaction was performed with isomer *anti*-**3a**, ~~lactone *anti*-**7a** was obtained in low yield~~ (Table 6, entry 2). To assess scope, Passerini adducts **3b** and **3c** were tested as precursors. Gratifyingly, compounds **3b** and **3c** were completely and exclusively converted to γ -lactones **7** in moderate yield (Table 6, entries 3–5). Replacement of the *p*-methoxyphenyl group at the nitrogen, by an aliphatic substituent such as 2-propynyl group, in Passerini adduct *syn*-**3d**, also afforded γ -butyrolactone *syn*-**7d** (Table 6, entry 6). However, longer reaction time for the ring opening of the β -lactam was observed.

The structure and stereochemistry of γ -lactams **6** and γ -lactones **7** were assigned by NMR studies. The *cis*-stereochemistry of the four-membered ring was set during the cyclization step. The cyclic structures (by DEPT, ~~HETCOR~~ HMQC, and COSY) and the stereochemistry (by vicinal proton couplings) of γ -lactams **6** and γ -lactones **7** were established by NMR one- and two-dimensional techniques and NOESY-1D experiments (see Fig 1 in Supporting information). In addition, the vicinal coupling constants between H3, H4 and H4, H5 protons in compounds **6** are higher for *anti,syn*-isomers [(7.0 Hz < $^3J_{3,4}$ < 9.5 Hz); (7.9 Hz < $^3J_{4,5}$ < 9.1 Hz)] than for the *anti,anti*-isomers [(7.0 Hz < $^3J_{3,4}$ < 9.5 Hz); (7.9 Hz < $^3J_{4,5}$ < 9.1 Hz)] (see Table S3 in Supporting information). Analogously, for γ -lactones **7**, the vicinal coupling constants between H3, H4 and H5, H4 protons, are higher for *anti,syn*-isomers [(5.7 Hz < $^3J_{3,4}$ < 6.9 Hz); (4.1 Hz < $^3J_{5,4}$ < 6.7 Hz)] than for the *anti,anti*-isomers [(4.9 Hz < $^3J_{3,4}$ < 5.1 Hz); (4.7 Hz < $^3J_{5,4}$ < 5.4 Hz)] (see Table S4 in Supporting information). Taking into account that U-3CR adducts **2** and P-3CR adducts **3** are converted into γ -lactams **6** and γ -lactones **7**, respectively, the stereochemistries of the carbinolic stereogenic centers for compounds **2** and **3** were confirmed by comparison with well-established five-membered rings **6** and **7**.

Table 6. Synthesis of γ -butyrolactones **7 via sequential ring opening/lactonization of Passerini adducts **3****

Entry	P-3CR adduct	R ¹	R ²	R ³	t(h) ^[a]	Product	Yield (%) ^b
1	<i>syn</i> -(+)- 3a	PMP ^c	MeO	<i>t</i> -Bu	2	<i>syn</i> -(+)- 7a	73
2	<i>anti</i> -(+)- 3a	PMP ^c	MeO	<i>t</i> -Bu	2	<i>anti</i> -(-)- 7a	34
3	<i>syn</i> -(+)- 3b	PMP ^c	MeO	Bn	7	<i>syn</i> -(+)- 7b	47
4	<i>anti</i> -(+)- 3b	PMP ^c	MeO	Bn	7	<i>anti</i> -(-)- 7b	42
5	<i>syn</i> -(+)- 3c	PMP ^c	PhO	<i>t</i> -Bu	24	<i>syn</i> -(+)- 7c	57
6	<i>syn</i> -(+)- 3d	2-propynyl	PhO	<i>t</i> -Bu	72	<i>syn</i> -(+)- 7d	52

^aReaction progress was followed by TLC for the methanolysis step. The reaction time for the lactonization reaction was 2 hours in all cases. ^bYield of pure, isolated isomers with correct analytical and spectral data. ^cPMP = 4-MeOC₆H₄

CONCLUSION

In conclusion, firstly, organocatalyzed U-3CR between β -lactam aldehydes, amines, isocyanides and phenyl phosphinic acid has been studied affording the corresponding adducts with moderate diastereoselectivities and good yields. Secondly, organocatalyzed P-3CR between carbonyl β -lactams, isocyanides and water has been described for the first time. The scope of these multicomponent

processes has been investigated and the utility of the resulting products for the selective preparation of highly functionalized γ -lactams and γ -lactones has been demonstrated.

EXPERIMENTAL SECTION²⁵

General Methods. ^1H and ^{13}C NMR spectra were recorded in CDCl_3 except otherwise stated. Chemical shifts are given in ppm relative to TMS (^1H , 0.0 ppm) or CDCl_3 (^{13}C , 77.0 ppm). Low and high resolution mass spectra were performed on a QTOF LC/MS spectrometer using the electronic impact (EI) or electrospray modes (ES) unless otherwise stated. Specific rotation $[\alpha]_{\text{D}}$ is given in 10^{-1} deg $\text{cm}^2 \text{g}^{-1}$ at 20 °C, and the concentration (c) is expressed in grams per 100 mL. All commercially available compounds were used without further purification. Flash S-2 chromatography was performed by using silica gel 60 (230–400 mesh). Products were identified by TLC. UV light ($\lambda = 254\text{nm}$) and a solution of phosphomolibdic acid in EtOH (1 g of phosphomolybdic acid hydrate, 100 mL EtOH) was used to develop the plates.

General Procedure for the Organocatalyzed U-3CR of aldehydes **1**. Synthesis of Compounds **2**.

Method A. To a solution of aldehyde **1** (1 mmol) in anhydrous dichloromethane (5 mL), the corresponding amine (1.1 mmol), the appropriate isocyanide (1.1 mmol) and phenyl phosphinic acid (0.1 mmol) were sequentially added at room temperature under argon atmosphere. The reaction mixture was stirred until complete disappearances of the starting material (TLC). Then, the solvent was removed under reduced pressure. The residue was purified by flash chromatography eluting with *n*-hexane/ethyl acetate mixtures. **Method B.** To a solution of aldehyde **1** (1 mmol) in anhydrous dichloromethane (5 mL), methyl glycinate chlorhydrate (1.1 mmol) and triethylamine (1.1 mol) were added at room temperature. The reaction mixture was stirred at room temperature for 1 h. Then, *t*-butyl isocyanide (1.1 mmol) and phenyl phosphinic acid (0.1 mmol) were added at room temperature and under argon atmosphere. The reaction mixture was stirred at room temperature for 14h. Then, the solvent was removed under reduced pressure. The residue was purified by flash chromatography.

Ugi adduct 2a. Method A. From 50 mg (1.19 mmol) of aldehyde (+)-**1a**, compound **2a** was obtained as a mixture of isomers in a *syn/anti* ratio (61:39). After flash chromatography (*n*-hexane/ethyl acetate, 1:1) 53 mg (61%) of the less polar compound *syn*-(+)-**2a** and 34 mg (39%) of the more polar compound *anti*-(+)-**2a** were obtained. ***syn*-(+)-2a**. White solid; Mp: 94–95°C (*n*-hexane/ethyl acetate); $[\alpha]_D +66.0$ (c 0.3, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.88 (t, *J* = 5.3 Hz, 1H), 7.26 (m, 5H), 7.12 (m, 2H), 6.73 (AA'XX', 2H), 5.74 (m, 1H), 5.08 (m, 2H), 5.00 (dd, *J* = 5.3 Hz, *J* = 1.3 Hz, 1H), 4.68 (d, *J* = 5.3 Hz, 1H), 4.47 (dd, *J* = 14.8, 6.3 Hz, 1H), 4.19 (dd, *J* = 14.8, 5.5 Hz, 1H), 3.74 (s, 3H), 3.65 (s, 3H), 3.40 (s, 1H), 3.29 (dd, *J* = 13.8, 6.4 Hz, 1H), 3.20 (dd, *J* = 13.7, 6.0 Hz, 1H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 172.8, 164.8, 156.7, 137.6, 135.7, 130.1, 128.6, 127.6, 127.4, 119.3, 117.0, 114.2, 83.2, 59.9, 59.2, 58.8, 55.4, 51.5, 43.3; IR (KBr): ν = 3340, 1749, 1663 cm⁻¹; HRMS (ES): calcd (%) for C₂₃H₂₈N₃O₄⁺ [*M*+*H*]⁺: 410.2074; found: 410.2068. ***anti*-(+)-2a**. Colorless oil; $[\alpha]_D +123.2$ (c 0.4, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 8.14 (t, *J* = 5.6 Hz, 1H), 7.40 (AA'XX', 2H), 7.30 (m, 5H), 6.91 (AA'XX', 2H), 5.70 (m, 1H), 5.11 (dd, *J* = 5.0, 3.7 Hz, 1H), 4.84 (m, 2H), 4.69 (d, *J* = 5.1 Hz, 1H), 4.57 (dd, *J* = 14.9, 6.7 Hz, 1H), 4.34 (dd, *J* = 15.0, 5.3 Hz, 1H), 3.90 (d, *J* = 3.6 Hz, 1H), 3.81 (s, 3H), 3.47 (s, 3H), 3.24 (dd, *J* = 13.9, 5.4 Hz, 1H), 2.89 (dd, *J* = 13.9, 7.0 Hz, 1H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 172.0, 164.4, 156.6, 138.3, 135.9, 130.6, 128.6, 127.5, 127.3, 118.4, 117.3, 114.6, 83.8, 60.0, 58.6, 57.0, 55.4, 51.2, 43.0; IR (CHCl₃): ν = 3346, 1748, 1659 cm⁻¹; HRMS (ES): calcd (%) for C₂₃H₂₈N₃O₄⁺ [*M*+*H*]⁺: 410.2074; found: 410.2076.

Ugi adduct 2b. Method A. From 60 mg (0.26 mmol) of aldehyde (+)-**1a**, compound **2b** was obtained as a mixture of isomers in a *syn/anti* ratio (63:37). After flash chromatography (*n*-hexane/ethyl acetate, 1:3) 33 mg (34%) of the less polar compound *syn*-(+)-**2b** and 55 mg (58%) of the more polar compound *anti*-(+)-**2b** were obtained. ***syn*-(+)-2b**. Colorless oil; $[\alpha]_D +85.5$ (c 0.7, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.66 (bs, 1H), 7.38 (AA'XX', 2H), 6.88 (AA'XX', 2H), 5.63 (m, 1H), 5.02

(dd, $J = 5.1, 3.6$ Hz, 1H), 4.87 (m, 2H), 4.67 (d, $J = 5.2$ Hz, 1H), 3.79 (s, 3H), 3.72 (d, $J = 3.4$ Hz, 1H), 3.55 (s, 3H), 3.23 (ddt, $J = 14.1, 5.4$ Hz, 1.5 Hz, 1H), 2.88 (dd, $J = 14.2, 6.7$ Hz, 1H), 1.34 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.1, 164.4, 156.5, 136.1, 130.7, 118.4, 116.8, 114.5, 83.8, 60.1, 58.9, 57.6, 55.4, 51.3, 50.6, 28.6$; IR (CHCl_3): $\nu = 3339, 1749, 1666\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{20}\text{H}_{30}\text{N}_3\text{O}_4^+$ $[M+H]^+$: 376.2231; found: 376.2244. **anti-(+)-2b**. Colorless oil; $[\alpha]_{\text{D}} +70.7$ (c 0.6, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.50$ (bs, 1H), 7.30 (AA'XX', 2H), 6.82 (AA'XX', 2H), 5.80 (m, 1H), 5.12 (m, 2H), 4.98 (d, $J = 5.1$ Hz, 1H), 4.66 (d, $J = 5.2$ Hz, 1H), 3.78 (3H, s), 3.65 (s, 3H), 3.36 (dd, $J = 14.0, 6.2$ Hz, 1H), 3.20 (bs, 1H), 3.17 (dd, $J = 14.3, 6.0$ Hz, 1H), 1.29 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.6, 165.1, 156.8, 136.0, 130.4, 119.6, 116.7, 114.3, 83.2, 59.9, 59.5, 58.7, 55.5, 51.4, 28.4, 50.6$; IR (CHCl_3): $\nu = 3332, 1750, 1668\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{20}\text{H}_{30}\text{N}_3\text{O}_4^+$ $[M+H]^+$: 376.2231; found: 376.2234.

Ugi adduct 2c. Method A. From 50 mg (0.22 mmol) of aldehyde (–)-**1b**, compound **2c** was obtained as a mixture of isomers in a *syn/anti* ratio (72:28). After flash chromatography (CH_2Cl_2 /ethyl acetate, 3:1) 42 mg (48%) of the less polar compound *syn*-(+)-**2c** and 16 mg (18%) of the more polar compound *anti*-(+)-**2c** were obtained. **syn-(+)-2c**. White solid. Mp: 108–109°C (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +17.4$ (c 0.6, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.74$ (bs, 1H), 7.30 (m, 7H), 7.04 (m, 3H), 5.74 (m, 2H), 5.30 (d, $J = 4.9$ Hz, 1H), 5.12 (m, 4H), 4.54 (dd, $J = 4.9, 3.0$ Hz, 1H), 4.41 (d, $J = 6.0$ Hz, 2H), 4.07 (ddt, $J = 15.4, 5.6$ Hz, 1.4 Hz, 1H), 3.60 (dd, $J = 15.4, 7.0$ Hz, 1H), 3.40 (d, $J = 2.9$ Hz, 1H), 3.25 (d, $J = 6.2$ Hz, 2H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.8, 165.6, 157.3, 137.7, 135.5, 130.7, 129.7, 128.7, 127.8, 127.6, 122.6, 119.2, 117.1, 115.4, 80.8, 60.3, 59.0, 51.4, 44.4, 43.4$; IR (CHCl_3): $\nu = 3319, 1757, 1656\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{28}\text{N}_3\text{O}_3^+$ $[M+H]^+$: 406.2125; found: 406.2106. **anti-(+)-2c**. White solid. Mp: 125–126°C (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +50.7$ (c 0.4, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.77$ (t, $J = 5.5$ Hz, 1H), 7.29 (m, 5H), 7.17 (m, 2H),

7.03 (m, 3H), 5.79 (m, 2H), 5.33 (d, $J = 4.9$ Hz, 1H), 5.21 (m, 4H), 4.61 (t, $J = 4.9$ Hz, 1H), 4.40 (dd, $J = 14.2, 6.3$ Hz, 1H), 4.25 (ddt, $J = 15.4, 5.4, 1.4$ Hz, 1H), 4.11 (dd, $J = 14.8, 5.6$ Hz, 1H), 3.65 (d, $J = 4.8$ Hz, 1H), 3.63 (dd, $J = 15.2, 7.4$ Hz, 1H), 3.38 (dd, $J = 13.9, 6.0$ Hz, 1H), 3.25 (dd, $J = 13.9, 6.2$ Hz, 1H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.0, 165.7, 157.2, 137.8, 135.7, 130.6, 129.6, 128.6, 127.7, 127.4, 122.7, 119.8, 117.3, 115.6, 81.1, 59.9, 58.9, 51.7, 43.7, 43.2$; IR (CHCl_3): $\nu = 3332, 1755, 1658\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{28}\text{N}_3\text{O}_3^+ [M+H]^+$: 406.2125; found: 406.2121.

Ugi adduct 2d. Method B. From 89 mg (0.27 mmol) of aldehyde (–)-**1c**, compound **2d** was obtained as a mixture of isomers in a *syn/anti* ratio (70:30). After flash chromatography (*n*-hexane/ethyl acetate, 1:3) 100 mg (74%) of an inseparable mixture of isomers *syn*-**2d** and *anti*-**2d** was obtained. **syn-2d.** ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.86$ (AA'BB', 2H), 7.74 (AA'BB', 2H), 7.33 (m, 5H), 6.24 (bs, 1H), 5.45 (d, $J = 5.3$ Hz, 1H), 4.73 (d, $J = 15.2$ Hz, 1H), 4.60 (d, $J = 15.2$ Hz, 1H), 4.04 (dd, $J = 7.8, 5.3$ Hz, 1H), 3.64 (s, 3H), 3.29 (d, $J = 7.9$ Hz, 1H), 3.09 (d, $J = 17.2$ Hz, 1H), 2.97 (d, $J = 17.1$ Hz, 1H), 2.03 (bs, 1H), 1.00 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.7, 169.4, 164.6, 135.8, 134.5, 131.9, 128.9, 128.2, 127.9, 123.7, 62.9, 59.6, 55.6, 51.8, 51.0, 48.0, 46.1, 28.2$; HRMS (ES): calcd (%) for $\text{C}_{27}\text{H}_{30}\text{N}_4\text{O}_6^+ [M+H]^+$: 507.2238; found: 507.2255. **anti-2d.** ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.86$ (2H, AA'BB'), 7.74 (AA'BB', 2H), 7.33 (m, 5H), 6.49 (bs, 1H), 5.37 (d, $J = 5.3$ Hz, 1H), 4.68 (d, $J = 15.2$ Hz, 1H), 4.40 (d, $J = 15.0$ Hz, 1H), 4.11 (dd, $J = 6.9, 5.4$ Hz, 1H), 3.45 (s, 3H), 3.26 (d, $J = 7.2$ Hz, 1H), 3.00 (d, $J = 17.2$ Hz, 1H), 2.85 (d, $J = 17.4$ Hz, 1H), 2.03 (bs, 1H), 1.13 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.4, 167.4, 164.3, 135.5, 134.4, 131.9, 129.0, 128.3, 128.0, 123.7, 61.8, 58.7, 56.4, 51.6, 51.1, 48.4, 45.6, 28.3$.

Ugi adduct 2e. Method A. From 50 mg (0.21 mmol) of aldehyde (+)-**1a**, compound **2e** was obtained as a mixture of isomers in a *syn/anti* ratio (64:36). After flash chromatography (*n*-hexane/ethyl acetate, 1:1) 70 mg (74%) of an inseparable mixture of isomers *syn*-**2e** and *anti*-**2e** was obtained. **syn-2e.**

^1H NMR (300 MHz, CDCl_3 , 25°C): δ = 7.12 (m, 2H), 7.09 (AA'XX', 2H), 6.68 (AA'XX', 2H), 6.58 (m, 2H), 5.19 (bs, 1H), 4.76 (d, J = 5.1 Hz, 1H), 4.44 (d, J = 2.6 Hz, 1H), 3.74 (s, 3H), 3.671 (s, 3H), 3.669 (s, 3H), 1.36 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 170.0, 163.6, 156.2, 153.1, 140.2, 130.0, 118.5, 115.9, 114.5, 113.9, 83.7, 60.3, 58.9, 57.9, 55.6, 55.3, 51.0, 28.6. HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{31}\text{N}_3\text{O}_5^+$ $[M+H]^+$: 442.2336; found: 442.2336. **anti-2e**. ^1H NMR (300 MHz, CDCl_3 , 25°C): δ = 7.38 (AA'XX', 2H), 6.85 (AA'XX', 2H), 6.77 (AA'XX', 2H), 6.58 (m, 2H), 5.09 (dd, J = 5.2, 1.7 Hz, 1H), 4.68 (d, J = 5.3 Hz, 1H), 3.79 (s, 3H), 3.76 (s, 3H), 3.67 (m, 1H), 3.43 (s, 3H), 1.28 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 171.0, 165.1, 156.8, 153.3, 140.6, 130.1, 119.5, 115.8, 114.5, 114.3, 82.9, 59.5, 58.2, 59.0, 55.5, 55.4, 51.0, 28.3.

Ugi adduct 2f. Method A. From 53 mg (0.14 mmol) of aldehyde (+)-**1d**, compound **2f** was obtained as a mixture of isomers in a *syn/anti* ratio (70:30). After flash chromatography (*n*-hexane/ethyl acetate, 1:1) 21 mg (28%) of the less polar compound *anti*-(+)-**2f** and 50 mg (64%) of the more polar compound *syn*-(+)-**2f** were obtained. **syn**-(+)-**2f**. White solid. Mp: 141–143°C (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +82.7$ (c 0.6, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): δ = 7.55 (t, J = 5.6 Hz, 1H), 7.30 (m, 5H), 7.08 (m, 7H), 6.69 (AA'XX', 2H), 6.51 (AA'XX', 2H), 6.47 (AA'XX', 2H), 5.51 (d, J = 5.0 Hz, 1H), 5.40 (dd, J = 4.8, 3.5 Hz, 1H), 4.72 (d, J = 3.4 Hz, 1H), 4.34 (dd, J = 14.5, 5.6 Hz, 1H), 4.34 (dd, J = 14.5, 5.6 Hz, 1H), 4.20 (dd, J = 14.6, 6.0 Hz, 1H), 3.65 (s, 3H), 3.74 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 170.6, 162.2, 157.2, 156.6, 153.4, 140.1, 137.6, 129.7, 129.6, 128.7, 127.8, 127.5, 123.1, 118.8, 116.2, 116.1, 114.6, 114.2, 81.1, 58.2, 59.0, 55.6, 55.4, 43.4; IR (KBr): ν = 3374, 1750, 1661 cm^{-1} ; HRMS (ES): calcd (%) for $\text{C}_{32}\text{H}_{32}\text{N}_3\text{O}_5^+$ $[M+H]^+$: 538.2336; found: 538.2311. **anti**-(+)-**2f**. White solid. Mp: 150–151°C (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +66.2$ (c 0.2, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): δ = 7.59 (t, J = 5.6 Hz, 1H), 7.36 (AA'XX', 2H), 7.25 (m, 3H), 7.19 (t, J = 8.0 Hz, 2H), 7.08 (m, 2H), 6.96 (t, J = 7.3 Hz, 1H), 6.77 (d, J = 8.8 Hz, 2H), 6.74 (AA'XX', 2H), 6.65 (AA'XX', 2H), 6.57 (AA'XX', 2H),

5.53 (d, $J = 5.1$ Hz, 1H), 5.43 (d, $J = 5.3$ Hz, 1H), 4.44 (dd, $J = 14.8, 6.3$ Hz, 1H), 4.36 (dd, $J = 14.9, 5.7$ Hz, 1H), 4.08 (s, 1H), 3.77 (s, 3H), 3.75 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 172.1, 163.4, 157.1, 156.8, 153.7, 140.5, 137.4, 129.9, 129.5, 128.6, 127.8, 127.5, 122.3, 119.3, 116.1, 115.1, 114.8, 114.6, 79.3, 58.44, 58.42, 55.8, 55.5, 43.6$; IR (KBr): $\nu = 3350, 1754, 1664\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{32}\text{H}_{32}\text{N}_3\text{O}_5^+ [M+H]^+$: 538.2336; found: 538.2317.

Ugi adduct 2g. Method A. From 58 mg (0.25 mmol) of aldehyde (–)-**1b**, compound **2g** was obtained as a mixture of isomers in a *syn/anti* ratio (68:32). After flash chromatography (diethyl ether) 24 mg (21%) of the less polar compound *anti*-(+)-**2g** and 52 mg (46%) of the more polar compound *syn*-(+)-**2g** were obtained. ***syn*-(+)-2g**. Yellowish solid. Mp: $193\text{--}194^\circ\text{C}$ (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +5.8$ (c 1.0, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 8.11$ (AA'XX', 2H), 7.25 (m, 2H), 7.02 (m, 1H), 6.88 (m, 2H), 6.67 (AA'XX', 2H), 6.51 (bs, 1H), 5.77 (m, 1H), 5.39 (d, $J = 5.1$ Hz, 1H), 5.25 (m, 3H), 4.56 (t, $J = 5.0$ Hz, 1H), 4.21 (dd, $J = 6.3, 5.3$ Hz, 1H), 4.15 (ddt, $J = 15.3, 5.6, 1.2$ Hz, 1H), 3.51 (dd, $J = 15.3, 7.2$ Hz, 1H), 1.32 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 168.1, 165.9, 156.5, 152.0, 139.8, 130.4, 129.7, 126.1, 122.8, 120.1, 115.1, 112.8, 80.1, 58.0, 57.1, 51.8, 44.5, 28.5$; IR (KBr): $\nu = 3301, 1755\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{28}\text{N}_4\text{O}_5^+ [M+H]^+$: 453.2132; found: 453.2133.

***anti*-(+)-2g**. Yellowish solid. Mp: $189\text{--}190^\circ\text{C}$ (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +63.4$ (c 0.1, CHCl_3) ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 8.15$ (AA'XX', 2H), 7.39 (m, 2H), 7.14 (m, 3H), 6.62 (AA'XX', 2H), 6.58 (bs, 1H), 5.60 (m, 2H), 5.43 (d, $J = 5.0$ Hz, 1H), 5.19 (m, 2H), 4.59 (dd, $J = 5.0, 2.6$ Hz, 1H), 4.43 (dd, $J = 7.8, 2.6$ Hz, 1H), 4.03 (ddt, $J = 15.4, 5.7, 1.3$ Hz, 1H), 3.55 (dd, $J = 15.3, 7.2$ Hz, 1H), 1.29 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 166.7, 165.0, 156.6, 151.2, 139.8, 130.4, 130.0, 126.5, 123.6, 120.2, 115.8, 112.2, 81.0, 58.3, 56.3, 51.8, 43.8, 28.5$; IR (KBr): $\nu = 3300, 1761\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{28}\text{N}_4\text{O}_5^+ [M+H]^+$: 453.2132; found: 453.2126.

General Procedure for the Organocatalyzed P-3CR of aldehydes **1**. Synthesis of Compounds **3**.

To a solution of aldehyde **1** (1 mmol) in anhydrous dichloromethane (5 mL), water (1.1 mmol), the appropriate isocyanide (1.1 mmol) and phenyl phosphinic acid (0.1 mmol) were sequentially added at room temperature under argon atmosphere. The reaction mixture was stirred until complete disappearances of the starting material (TLC). Then, the solvent was removed under reduced pressure. The residue was purified by flash chromatography eluting with n-hexane/ethyl acetate mixtures.

Passerini adduct 3a. From 100 mg (0.42 mmol) of aldehyde (+)-**1a**, compound **3a** was obtained as a mixture of isomers in a *syn/anti* ratio (60:40). After flash chromatography (*n*-hexane/ethyl acetate, 1:2) 57 mg (40%) of the less polar compound *anti*-(+)-**3a** and 86 mg (60%) of the more polar compound *syn*-(+)-**3a** were obtained. ***syn*-(+)-3a**. White solid. Mp: 116–117°C (*n*-hexane/ethyl acetate); $[\alpha]_D +45.2$ (c 0.2, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.40 (AA'XX, 2H, s), 6.80 (AA'XX', 2H, s), 6.59 (bs, 1H), 4.94 (dd, *J* = 5.2, 1.2 Hz, 1H), 4.71 (d, *J* = 5.2 Hz, 1H), 4.27 (d, *J* = 1.2 Hz, 1H), 3.76 (s, 3H), 3.70 (s, 3H), 1.22 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 169.2, 164.2, 156.7, 130.2, 120.0, 114.2, 82.8, 69.2, 60.0, 58.2, 55.4, 50.9, 28.4; IR (KBr): ν = 3394, 1747 cm⁻¹; HRMS (ES): calcd (%) for C₁₇H₂₅N₂O₅⁺ [*M*+*H*]⁺: 337.1758; found: 337.1765. ***anti*-(+)-3a**. White solid. Mp: 158–159°C (*n*-hexane/ethyl acetate); $[\alpha]_D +83.9$ (c 0.4, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.41 (AA'XX', 2H, s), 6.83 (m, 1H), 6.85 (AA'XX', 2H, s), 4.80 (dd, *J* = 5.2, 1.6 Hz, 1H), 4.73 (d, *J* = 5.2 Hz, 1H), 4.48 (d, *J* = 1.1 Hz, 1H), 3.87 (bs, 1H), 3.78 (s, 3H), 3.69 (s, 3H), 1.33 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 169.4, 163.5, 156.6, 130.2, 118.9, 114.4, 83.2, 68.8, 60.0, 59.5, 55.4, 51.4, 28.6; IR (KBr): ν = 3393, 1747, 1664 cm⁻¹; HRMS (ES): calcd (%) for C₁₇H₂₅N₂O₅⁺ [*M*+*H*]⁺: 337.1758; found: 337.1757.

Passerini adduct 3b. From 67 mg (0.22 mmol) of aldehyde (+)-**1a**, compound **3b** was obtained as a mixture of isomers in a *syn/anti* ratio (65:35). After flash chromatography (*n*-hexane/ethyl acetate, 1:1) 53 mg (59%) of the less polar compound *syn*-(+)-**3b** and 29 mg (32%) of the more polar compound

anti-(+)-**3b** were obtained. *syn*-(+)-**3b**. White solid; Mp: 167–169°C (*n*-hexane/ethyl acetate); $[\alpha]_D +72.5$ (c 1.4, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.45 (AA'XX', 2H), 7.34 (m, 2H), 7.06 (m, 3H), 6.83 (AA'XX', 2H), 6.64 (bs, 1H), 5.45 (d, *J* = 5.1 Hz, 1H), 5.20 (d, *J* = 5.6 Hz, 1H), 4.41 (d, *J* = 4.0 Hz, 1H), 3.78 (s, 3H), 3.13 (d, *J* = 4.2 Hz, 1H), 1.25 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 169.2, 162.7, 156.9, 156.8, 130.2, 129.9, 123.2, 120.0, 115.9, 114.3, 80.1, 68.8, 58.5, 55.4, 51.0, 28.4; IR (KBr): ν = 3390, 1751, 1664 cm⁻¹; HRMS (ES): calcd (%) for C₂₂H₂₇N₂O₅⁺ [*M*+*H*]⁺: 399.1914; found: 399.1927. *anti*-(+)-**3b**. White solid; Mp: 127–128°C (*n*-hexane/ethyl acetate); $[\alpha]_D +108.2$ (c 0.6, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.47 (AA'XX', 2H), 7.35 (m, 2H), 7.12 (m, 3H), 6.88 (AA'XX', 2H), 6.76 (bs, 1H), 5.48 (d, *J* = 5.3 Hz, 1H), 5.00 (dd, *J* = 5.3, 1.8 Hz, 1H), 4.61 (s, 1H), 3.79 (s, 3H), 1.26 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 168.8, 162.2, 156.8, 156.7, 130.0, 129.9, 123.5, 119.0, 116.0, 114.4, 80.4, 68.8, 59.9, 55.4, 51.5, 28.5; IR (KBr): ν = 3384, 1752, 1656 cm⁻¹; HRMS (ES): calcd (%) for C₂₂H₂₇N₂O₅⁺ [*M*+*H*]⁺: 399.1914; found: 399.1897.

Passerini adduct 3c. From 103 mg (0.44 mmol) of aldehyde (+)-**1a**, compound **3c** was obtained as a mixture of isomers in a *syn/anti* ratio (60:40). After flash chromatography (*n*-hexane/ethyl acetate, 1:2) 57 mg (35%) of the less polar compound *anti*-(+)-**3c** and 86 mg (53%) of the more polar compound *syn*-(+)-**3c** were obtained. *syn*-(+)-**3c**. White solid; Mp: 157–159°C (*n*-hexane/ethyl acetate); $[\alpha]_D +67.3$ (c 0.5, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.45 (AA'XX', 2H), 7.34 (m, 2H), 7.06 (m, 3H), 6.83 (AA'XX', 2H), 6.64 (bs, 1H), 5.45 (d, *J* = 5.1 Hz, 1H), 5.20 (d, *J* = 5.6 Hz, 1H), 4.41 (d, *J* = 4.0 Hz, 1H), 3.78 (s, 3H), 3.13 (d, *J* = 4.2 Hz, 1H), 1.25 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 169.2, 162.7, 156.9, 156.8, 130.2, 129.9, 123.2, 120.0, 115.9, 114.3, 68.8, 58.5, 55.4, 51.0, 28.4; IR (KBr): ν = 3295, 1732, 1652 cm⁻¹; HRMS (ES): calcd (%) for C₂₀H₂₃N₂O₅⁺ [*M*+*H*]⁺: 371.1601; found: 371.1608. *anti*-(+)-**3c**. White solid; Mp: 135–136°C (*n*-hexane/ethyl acetate); $[\alpha]_D +107.6$ (c 0.5, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.39 (AA'XX', 2H), 7.30 (m, 5H), 7.20 (t, *J* = 5.6 Hz, 1H), 6.88

(AA'XX', 2H), 4.95 (dd, $J = 5.0, 2.6$ Hz, 1H), 4.75 (d, $J = 5.1$ Hz, 1H), 4.69 (s, 1H), 4.58 (dd, $J = 14.8, 6.4$ Hz, 1H), 4.38 (dd, $J = 14.8, 5.4$ Hz, 1H), 3.79 (s, 3H), 3.56 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.0, 163.5, 156.7, 137.7, 129.8, 128.6, 127.7, 127.6, 118.9, 114.5, 83.7, 68.8, 60.0, 58.3, 55.4, 43.2$; IR (KBr): $\nu = 3354, 1746, 1656\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{20}\text{H}_{23}\text{N}_2\text{O}_5^+ [M+H]^+$: 371.1601; found: 371.1583.

Passerini adduct 3d. From 51 mg (0.15 mmol) of aldehyde (–)-**1c**, compound **3d** was obtained as a mixture of isomers in a *syn/anti* ratio (55:45). After flash chromatography (diethyl ether) 25 mg (37%) of the less polar compound *syn*-(+)-**3d** and 20 mg (31%) of the more polar compound *anti*-(+)-**3d** were obtained. ***syn*-(–)-3d.** Colorless oil; $[\alpha]_{\text{D}} -6.5$ (c 0.9, CHCl_3). ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.88$ (AA'BB', 2H), 7.77 (AA'BB', 2H), 7.35 (m, 5H), 6.54 (bs, 1H), 5.50 (d, $J = 5.4$ Hz, 1H), 4.72 (d, $J = 15.2$ Hz, 1H), 4.64 (dd, $J = 5.5, 3.4$ Hz, 1H), 4.31 (d, $J = 15.1$ Hz, 1H), 4.03 (t, $J = 3.9$ Hz, 1H), 3.81 (d, $J = 4.5$ Hz, 1H), 1.27 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 169.3, 167.9, 164.1, 135.5, 134.7, 131.5, 129.0, 128.2, 128.0, 124.0, 68.9, 59.3, 56.0, 51.0, 46.4, 28.5$; IR (CHCl_3): $\nu = 3384, 1760, 1720, 1670\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{26}\text{N}_3\text{O}_5^+ [M+H]^+$: 436.1867; found: 436.1867. ***anti*-(+)-3d.** Colorless oil; $[\alpha]_{\text{D}} +18.2$ (c 0.6, CHCl_3). ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.87$ (AA'BB', 2H), 7.78 (AA'BB', 2H), 7.36 (m, 5H), 6.21 (bs, 1H), 5.50 (d, $J = 5.3$ Hz, 1H), 4.75 (d, $J = 14.9$ Hz, 1H), 4.40 (t, $J = 5.2$ Hz, 1H), 4.39 (d, $J = 15.3$ Hz, 1H), 4.17 (dd, $J = 7.8, 5.5$ Hz, 1H), 3.76 (d, $J = 7.8$ Hz, 1H), 0.95 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 169.3, 163.7, 134.8, 134.7, 131.6, 129.2, 128.3, 128.3, 123.9, 68.5, 58.6, 55.5, 50.8, 45.7, 28.1$; IR (CHCl_3): $\nu = 3382, 1761, 1722, 1668\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{26}\text{N}_3\text{O}_5^+ [M+H]^+$: 436.1867; found: 436.1872.

Passerini adduct 3e. From 81 mg (0.36 mmol) of aldehyde (+)-**1e**, compound **3e** was obtained as a mixture of isomers in a *syn/anti* ratio (70:30). After flash chromatography (*n*-hexane/ethyl acetate, 3:2) 78 mg (67%) of the less polar compound *syn*-(+)-**3e** and 34 mg (29%) of the more polar compound *anti*-

(+)-**3e** were obtained. **syn-(+)-3e**. White solid; Mp: 137–138°C (*n*-hexane/ethyl acetate); $[\alpha]_D +39.6$ (c 0.5, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.34 (m, 2H), 7.10 (m, 3H), 6.70 (bs, 1H), 5.35 (d, *J* = 5.0 Hz, 1H), 4.59 (dd, *J* = 5.0, 3.1 Hz, 1H), 4.40 (d, *J* = 3.1 Hz, 1H), 4.36 (dd, *J* = 17.8, 2.6 Hz, 1H), 3.85 (dd, *J* = 17.7, *J* = 2.5 Hz, 1H), 2.31 (t, *J* = 2.5 Hz, 1H), 1.40 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 168.7, 164.7, 156.6, 129.9, 123.3, 115.8, 80.8, 76.1, 73.1, 69.4, 58.6, 51.3, 30.9, 28.6; IR (KBr): ν = 3297, 3384, 1763, 1666 cm⁻¹; HRMS (ES): calcd (%) for C₁₈H₂₃N₂O₄⁺ [*M*+*H*]⁺: 331.1652; found: 331.1652. **anti-(+)-3e**. White solid; Mp: 88–90°C (*n*-hexane/ethyl acetate); $[\alpha]_D +86.4$ (c 0.8, CHCl₃). ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.33 (m, 2H), 7.09 (m, 3H), 6.72 (bs, 1H), 5.37 (d, *J* = 5.0 Hz, 1H), 4.60 (dd, *J* = 4.8, 3.4 Hz, 1H), 4.50 (d, *J* = 3.1 Hz, 1H), 4.36 (dd, *J* = 17.8, 2.6 Hz, 1H), 4.01 (dd, *J* = 17.7, 2.5 Hz, 1H), 2.33 (t, *J* = 2.5 Hz, 1H), 1.32 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 169.2, 164.8, 156.7, 129.8, 123.3, 115.9, 81.5, 75.9, 73.3, 69.7, 59.1, 51.4, 30.4, 28.5; IR (KBr): ν = 3295, 3388, 1761, 1660 cm⁻¹; HRMS (ES): calcd (%) for C₁₈H₂₃N₂O₄⁺ [*M*+*H*]⁺: 331.1652; found: 331.1665.

General Procedure for the Organocatalyzed P-3CR of ketones **4**. Synthesis of Compounds **5**.

To a solution of ketone **4** (1 mmol) in anhydrous dichloromethane (5 mL), water (1.1 mmol), the appropriate isocyanide (1.1 mmol) and phenyl phosphinic acid (0.1 mmol) were sequentially added at room temperature under argon atmosphere. The reaction mixture was stirred until complete disappearances of the starting material (TLC). Then, the solvent was removed under reduced pressure. The residue was purified by flash chromatography eluting with *n*-hexane/ethyl acetate mixtures.

Passerini adduct syn-(-)-5a. From 44 mg (0.15 mmol) of azetidine-2,3-dione (+)-**4a**, 50 mg (78%) of compound **syn-(-)-5a** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 2:1).²⁶

Passerini adduct *syn*-(-)-5b. From 60 mg (0.22 mmol) of azetidine-2,3-dione (-)-**4b**, 66 mg (80%) of compound *syn*-(-)-**5b** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1). Mp: 148–149°C (*n*-hexane/ethyl acetate); $[\alpha]_D -79.7$ (c 2.0, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.44 (m, 2H), 7.30 (m, 8H), 6.89 (t, J = 5.8 Hz, 1H), 5.47 (bs, 1H), 5.02 (d, J = 15.2 Hz, 1H), 4.48 (dd, J = 14.8, 6.1 Hz, 1H), 4.36 (m, 2H), 4.24 (d, J = 15.1 Hz, 1H), 4.10 (dd, J = 9.1, 7.2 Hz, 1H), 3.94 (d, J = 5.3 Hz, 1H), 3.64 (dd, J = 9.1, 4.4 Hz, 1H), 1.41 (s, 3H), 1.34 (s, 3H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 167.4, 167.3, 137.4, 134.3, 128.74, 128.69, 128.4, 127.8, 127.6, 127.5, 110.3, 85.2, 75.1, 66.3, 63.6, 45.5, 43.3, 26.3, 24.9; IR (KBr): ν = 3315, 1745, 1671 cm⁻¹; HRMS (ES): calcd (%) for C₂₃H₂₇N₂O₅⁺ [$M+H$]⁺: 411.1914; found: 411.1930.

Passerini adduct *syn*-(-)-5c. From 32 mg (0.11 mmol) of azetidine-2,3-dione (+)-**4a**, 21 mg (48%) of compound *syn*-(-)-**5c** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1). Mp: 154–156°C (*n*-hexane/ethyl acetate); $[\alpha]_D -7.0$ (c 0.6, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.49 (AA'XX', 2H), 6.86 (AA'XX', 2H), 6.56 (bs, 1H), 5.08 (bs, 1H), 4.60 (d, J = 4.8 Hz, 1H), 4.43 (td, J = 6.7, 4.9 Hz, 1H), 4.20 (dd, J = 8.9, 6.7 Hz, 1H), 3.79 (s, 3H), 3.80 (dd, J = 8.8, 6.9 Hz, 1H), 1.41 (s, 3H), 1.39 (s, 9H), 1.37 (s, 3H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 166.0, 164.7, 157.1, 130.0, 120.6, 114.0, 110.2, 84.9, 75.7, 66.5, 64.9, 55.4, 51.7, 28.6, 26.3, 25.2; IR (KBr): ν = 3243, 1759, 1658 cm⁻¹; HRMS (ES): calcd (%) for C₂₀H₂₉N₂O₆⁺ [$M+H$]⁺: 393.2020; found: 393.2034.

Passerini adduct *syn*-(-)-5d. From 55 mg (0.24 mmol) of azetidine-2,3-dione (-)-**4c**, 56 mg (71%) of compound *syn*-(-)-**5d** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1). Mp: 130–132°C (*n*-hexane/ethyl acetate) $[\alpha]_D -106.8$ (c 0.3, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 6.57 (bs, 1H), 5.85 (m, 1H), 5.36 (m, 2H), 4.96 (bs, 1H), 4.34 (m, 2H), 4.17 (dd, J = 8.9, 7.2 Hz, 1H), 4.05 (d, J = 4.5 Hz, 1H), 3.82 (dd, J = 9.1, 4.5 Hz, 1H), 3.70 (dd, J

=15.7, 7.5 Hz, 1H), 1.39 (s, 9H), 1.38 (s, 3H), 1.36 (s, 3H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 167.4, 166.1, 130.9, 119.1, 110.2, 85.3, 75.2, 66.4, 63.7, 51.4, 44.1, 28.6, 26.5, 25.0; IR (KBr): ν = 3403, 1746, 1679 cm^{-1} ; HRMS (ES): calcd (%) for $\text{C}_{16}\text{H}_{27}\text{N}_2\text{O}_5^+$ $[M+H]^+$: 327.1914; found: 327.1914.

Passerini adduct *syn*-(+)-5e. From 42 mg (0.14 mmol) of azetidine-2,3-dione (+)-**4a**, 27 mg (45%) of compound *syn*-(+)-**5e** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1). Mp: 123–124°C (*n*-hexane/ethyl acetate); $[\alpha]_{\text{D}} +5.8$ (c 0.2, CHCl_3). ^1H NMR (300 MHz, CDCl_3 , 25°C): δ = 7.57 (AA'XX', 2H), 6.87 (AA'XX', 2H), 6.37 (bs, 1H), 4.56 (d, J = 6.6 Hz, 1H), 4.45 (q, J = 6.6 Hz, 1H), 4.20 (q, J = 7.0 Hz, 2H), 4.22 (m, 2H), 3.96 (dd, J = 18.0, 5.0 Hz, 1H), 3.80 (s, 3H), 3.79 (m, 1H), 1.46 (s, 3H), 1.38 (s, 3H), 1.28 (t, J = 7.2 Hz, 3H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 170.1, 167.9, 164.5, 157.2, 130.0, 120.7, 114.0, 110.1, 84.1, 76.3, 66.7, 66.3, 61.7, 55.4, 41.1, 26.5, 25.1, 14.0; IR (KBr): ν = 3346, 1750, 1680 cm^{-1} ; HRMS (ES): calcd (%) for $\text{C}_{20}\text{H}_{30}\text{N}_3\text{O}_8^+$ $[M+H]^+$: 440.2027; found: 440.2045.

General Procedure for the Ring Expansion of Ugi Adducts 2. Synthesis of functionalized γ -lactams 6. Method A. To a solution of Ugi adduct **2** (1 mmol) in methanol (23 mL), sodium methoxide (1 mmol), was added in small portions at room temperature under argon atmosphere. The reaction mixture was stirred until complete disappearances of the starting material (TLC). Then, the solvent was removed under reduced pressure. The residue was purified by flash chromatography eluting with *n*-hexane/ethyl acetate mixtures. **Method B.** To a solution of Ugi adduct *syn*-(+)-**2a** (1 mmol) in methanol (2 mL), sulfuric acid (cc.) (12 mL) was added at room temperature. The reaction mixture was stirred for 54 h. Then, the mixture was neutralized with NaHCO_3 (sat.) (50 mL). The methanol was removed under reduced pressure and the mixture was extracted with ethyl acetate (5 x 100 mL). The organic layer was dried (MgSO_4) and concentrated under reduced pressure. The residue was purified by flash chromatography eluting with *n*-hexane/ethyl acetate mixtures.

Functionalized γ -lactam *syn*-(+)-6a**. Method A.** From 46 mg (0.11 mmol) of compound *syn*-(+)-**2a**, 39 mg (84%) of compound *syn*-(+)-**6a** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:3). **Method B.** From 51 mg (0.12 mmol) of compound *syn*-(+)-**2a**, 11 mg (22%) of compound *syn*-(+)-**6a** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:3). $[\alpha]_D +155.8$ (c 0.3, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.82 (bs, 1H), 7.22 (m, 3H), 7.11 (m, 2H), 6.79 (AA'BB', 2H), 6.75 (AA'BB', 2H), 5.78 (m, 1H), 5.20 (m, 2H), 4.58 (d, J = 7.4 Hz, 1H), 4.44 (dd, J = 15.2, 6.4 Hz, 1H), 4.32 (d, J = 9.1 Hz, 1H), 4.27 (dd, J = 15.2, 5.3 Hz, 1H), 4.18 (dd, J = 9.0, 7.3 Hz, 1H), 4.15 (m, 1H), 3.73 (s, 3H), 3.63 (s, 3H), 3.58 (dd J = 15.7, 6.9 Hz, 1H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.3, 168.3, 152.8, 140.2, 136.9, 131.7, 128.7, 127.8, 127.7, 119.3, 115.1, 114.4, 81.1, 61.1, 59.2, 57.5, 55.6, 45.0, 43.9; IR (CHCl₃): ν = 3317, 1689 cm⁻¹; HRMS (ES): calcd (%) for C₂₃H₂₈N₃O₄⁺ $[M+H]^+$: 410.2074; found: 410.2067.

Functionalized γ -lactam *anti*-(-)-6a**. Method A.** From 44 mg (0.11 mmol) of compound *anti*-(-)-**2a**, 27 mg (60%) of compound *anti*-(-)-**6a** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:3). Mp: 163–165°C (*n*-hexane/ethyl acetate); $[\alpha]_D -9.2$ (c 0.3, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 8.01 (bs, 1H), 7.26 (m, 5H), 6.78 (AA'BB', 2H), 6.73 (AA'BB', 2H), 5.74 (m, 1H), 5.15 (m, 2H), 4.49 (dd, J = 14.9, 6.1 Hz, 1H), 4.39 (m, 1H), 4.36 (dd, J = 14.8, 5.9 Hz, 1H), 4.09 (t, J = 5.7 Hz, 1H), 4.03 (d, J = 5.4 Hz, 1H), 3.94 (d, J = 6.1 Hz, 1H), 3.74 (s, 3H), 3.56 (s, 3H), 3.44 (dd, J = 15.5, 7.4 Hz, 1H), 2.91 (bs, 1H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.1, 168.9, 153.5, 138.9, 137.4, 130.8, 128.7, 127.8, 127.7, 119.9, 115.8, 115.0, 83.1, 65.9, 58.7, 58.3, 55.6, 44.5, 43.7; IR (KBr): ν = 3364, 3277, 1699, 1657 cm⁻¹; HRMS (ES): calcd (%) for C₂₃H₂₈N₃O₄⁺ $[M+H]^+$: 410.2074; found: 410.2077.

Functionalized γ -lactam *syn*-(+)-6b**. Method A.** From 31 mg (0.08 mmol) of compound *syn*-(+)-**2b**, 25 mg (82%) of compound *syn*-(+)-**6b** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:3). $[\alpha]_D +139.6$ (c 0.2, CHCl_3); ^1H NMR (300 MHz, d^6 -acetone, 25°C): δ = 6.80 (AA'BB', 2H), 6.74 (AA'BB', 2H), 5.77 (m, 1H), 5.21 (m, 2H), 4.45 (d, J = 7.3 Hz, 1H), 4.25 (d, J = 8.8 Hz, 1H), 4.11 (m, 1H), 4.07 (ddt, J = 15.2, 5.5 Hz, 1.5 Hz, 1H), 3.72 (s, 3H), 3.62 (s, 3H), 3.59 (dd, J = 15.6, 6.4 Hz, 1H), 1.19 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 171.3, 167.3, 152.8, 140.3, 132.1, 119.2, 115.2, 114.4, 81.0, 61.5, 59.2, 57.2, 55.8, 52.0, 45.0, 28.3; IR (CHCl_3): ν = 3337, 1689 cm^{-1} ; HRMS (ES): calcd (%) for $\text{C}_{20}\text{H}_{29}\text{N}_3\text{O}_4^+$ $[M+H]^+$: 376.2231; found: 376.2235.

Functionalized γ -lactam *anti*-(-)-6b**.** From 21 mg (0.06 mmol) of compound *anti*-(-)-**2b**, 15 mg (71%) of compound *anti*-(-)-**6b** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:3); $[\alpha]_D -14.1$ (c 1.2, CHCl_3); ^1H NMR (300 MHz, CD_3OD , 25°C): δ = 6.77 (AA'BB', 2H), 6.68 (AA'BB', 2H), 5.76 (m, 1H), 5.23 (m, 2H), 4.38 (ddt, J = 15.4, 4.8 Hz, 1.5 Hz, 1H), 4.04 (m, 2H), 3.84 (d, J = 6.0 Hz, 1H), 3.72 (s, 3H), 3.59 (s, 3H), 3.39 (dd, J = 15.3, 7.7 Hz, 1H), 1.24 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): δ = 171.0, 168.1, 153.2, 139.7, 131.2, 119.7, 115.6, 115.0, 83.1, 66.6, 58.52, 58.48, 55.7, 51.6, 44.5, 28.4; IR (CHCl_3): ν = 3334, 1693 cm^{-1} ; HRMS (ES): calcd (%) for $\text{C}_{20}\text{H}_{29}\text{N}_3\text{O}_4^+$ $[M+H]^+$: 376.2231; found: 376.2234.

Functionalized γ -lactam *syn*-(+)-6c**.** From 32 mg (0.08 mmol) of compound *syn*-(+)-**2c**, 26 mg (81%) of compound *syn*-(+)-**6c** was obtained as a colorless oil after purification by flash chromatography (dichloromethane/ethyl acetate, 5:1); $[\alpha]_D +149.7$ (c 0.5, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): δ = 7.32 (m, 7H), 7.14 (dd, J = 8.7, 1.0 Hz, 2H), 7.01 (tt, J = 7.2, 1.0 Hz, 1H), 6.52 (t, J = 5.3 Hz, 1H), 5.74 (m, 2H), 5.12 (d, J = 9.1 Hz, 1H), 5.13 (m, 4H), 4.49 (d, J = 5.8 Hz, 2H), 4.31 (ddt, J = 15.1, 5.3, 1.4 Hz, 1H), 4.04 (d, J = 7.9 Hz, 1H), 3.74 (dd, J = 8.6, 8.0 Hz, 1H), 3.58 (dd, J = 15.3, 7.9

Hz, 1H), 3.37 (ddt, $J = 14.0, 5.7, 1.4$ Hz, 1H), 3.30 (ddt, $J = 14.0, 5.7, 1.4$ Hz, 1H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.0, 168.7, 158.4, 137.4, 135.8, 131.6, 129.4, 128.8, 127.9, 127.8, 122.0, 119.3, 116.5, 80.9, 61.4, 60.7, 50.6, 45.0, 43.8$; IR (CHCl_3): $\nu = 3308, 1688\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{28}\text{N}_3\text{O}_3^+ [M+H]^+$: 406.2125; found: 406.2125.

Functionalized γ -lactam *anti*-(+)-6c**.** From 15 mg (0.04 mmol) of compound *anti*-(+)-**2c**, 11 mg (76%) of compound *anti*-(+)-**6c** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:2); $[\alpha]_D +10.2$ (c 0.4, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.30$ (m, 7H), 7.01 (m, 3H), 6.66 (bs, 1H), 5.75 (m, 2H), 5.16 (m, 4H), 4.62 (d, $J = 4.3$ Hz, 1H), 4.47 (d, $J = 5.9$ Hz, 2H), 4.43 (m, 1H), 3.87 (d, $J = 4.5$ Hz, 1H), 3.68 (dd, $J = 15.2, 7.8$ Hz, 1H), 3.58 (t, $J = 4.3$ Hz, 1H), 3.31 (d, $J = 5.9$ Hz, 2H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 170.7, 169.0, 157.6, 137.5, 135.2, 130.8, 129.5, 128.8, 127.9, 127.8, 122.3, 119.9, 117.1, 116.2, 81.2, 64.6, 61.4, 49.8, 44.9, 43.6$; IR (CHCl_3): $\nu = 3285, 1700, 1660\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{28}\text{N}_3\text{O}_3^+ [M+H]^+$: 406.2125; found: 406.2138.

Functionalized γ -lactams *syn*-(+)-6d** and *anti*-(+)-**6d**. Method B.** From 72 mg (0.16 mmol) of an inseparable mixture (64:36) of compound **2e**, compound **6d** was obtained as a mixture of isomers in a *syn/anti* ratio (64:36). After flash chromatography (dichloromethane/ethyl acetate, 2:1) 31 mg (51%) of the less polar compound *syn*-(+)-**6d** and 21 mg (28%) of the more polar compound *anti*-(+)-**6d** were obtained. ***syn*-(+)-**6d****. Colorless oil; $[\alpha]_D +91.9$ (c 0.3, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 7.29$ (AA'XX', 2H), 6.86 (AA'XX', 2H), 6.81 (AA'BB', 2H), 6.65 (AA'BB', 2H), 5.29 (bs, 1H), 4.42 (d, $J = 7.0$ Hz, 1H), 4.39 (d, $J = 8.3$ Hz, 1H), 4.30 (m, 1H), 3.78 (s, 3H), 3.75 (s, 3H), 3.72 (s, 3H), 1.15 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 170.8, 167.5, 158.0, 152.8, 140.1, 130.7, 124.8, 115.2, 114.4, 114.3, 80.9, 64.5, 59.4, 57.2, 55.8, 55.4, 52.0, 28.2$; IR (CHCl_3): $\nu = 3340, 1692\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{24}\text{H}_{31}\text{N}_3\text{O}_5^+ [M+H]^+$: 442.2336; found: 442.2332. ***anti*-(+)-**6d****. Brown solid; Mp:

85–87°C (*n*-hexane/ethyl acetate); $[\alpha]_D + 22.1$ (c 1.0, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.38 (AA'XX', 2H), 6.85 (AA'XX', 2H), 6.79 (bs, 4H), 6.06 (bs, 1H), 4.30 (d, *J* = 3.2 Hz, 1H), 4.09 (bs, 1H), 3.90 (d, *J* = 3.6 Hz, 1H), 3.76 (s, 3H), 3.75 (s, 3H), 3.62 (s, 3H), 1.19 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 170.3, 168.0, 157.7, 153.3, 139.2, 130.0, 123.6, 115.7, 115.0, 114.2, 83.6, 68.4, 58.7, 58.1, 55.6, 55.4, 51.5, 28.3; IR (KBr): ν = 3340, 1696 cm⁻¹; HRMS (ES): calcd (%) for C₂₄H₃₁N₃O₅⁺ [*M*+*H*]⁺: 442.2336; found: 442.2341.

Functionalized γ -lactam *syn*-(+)-6e. From 38 mg (0.08 mmol) of compound *syn*-(+)-2f, 17 mg (45%) of compound *syn*-(+)-6e was obtained as a yellow oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1); $[\alpha]_D + 151.1$ (c 2.0, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 8.24 (AA'XX', 2H), 7.78 (AA'XX', 2H), 7.32 (m, 2H), 7.16 (d, *J* = 7.8 Hz, 2H), 7.05 (t, *J* = 7.3 Hz, 1H), 6.04 (bs, 1H), 5.88 (m, 1H), 5.23 (d, *J* = 9.5 Hz, 1H), 5.21 (m, 2H), 4.46 (d, *J* = 7.9 Hz, 1H), 3.86 (dd, *J* = 9.4, 7.9 Hz, 1H), 3.50 (dd, *J* = 14.3, 5.7 Hz, 1H), 3.41 (dd, *J* = 14.3, 5.7 Hz, 1H), 1.40 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.1, 167.0, 158.2, 144.2, 143.7, 135.7, 129.5, 124.7, 122.4, 120.2, 116.6, 116.3, 80.6, 63.4, 60.2, 52.6, 50.7, 28.6; IR (CHCl₃): ν = 3347, 1718 cm⁻¹; HRMS (ES): calcd (%) for C₂₄H₂₈N₄O₅⁺ [*M*+*H*]⁺: 453.2132; found: 453.2149.

Reaction of α -hydroxy amide *syn*-(+)-3a with FeCl₃·6H₂O. To a solution of α -hydroxy amide *syn*-(+)-3a (51 mg, 0.15 mmol) in anhydrous 1,2-dichloroethane (1.5 mL), FeCl₃ (0.10 mmol) was added. The resulting mixture was heated at 85°C for 21 h. The reaction mixture was allowed to cool to room temperature, and then quenched with NH₄Cl sat. (0.15 mL). The mixture was extracted with ethyl acetate (3 x 4 mL), and the combined extracts were washed with brine. The organic layer was dried (MgSO₄) and concentrated under reduced pressure. The residue was purified by flash chromatography eluting with *n*-hexane/ethyl acetate (1:1) affording 12 mg (23%) of γ -lactone *syn*-(+)-7a as a colorless solid.

Reaction of α -hydroxy amide *syn*-(+)-3a** in acidic conditions.** To a solution of α -hydroxy amide *syn*-(+)-**3a** (39 mg, 0.12 mmol) in methanol (2.7 mL), sulphuric acid cc. (1.4 mL) was slowly added. The resulting mixture was stirred at room temperature for 2 hours. Then, NaHCO₃ (cc.) (6 mL) was added until pH = 7. The methanol was removed under reduced pressure and the mixture was extracted with ethyl acetate (5 x 12 mL). The organic layer was dried (MgSO₄) and concentrated under reduced pressure. Chromatography of the residue eluting with *n*-hexane/ethyl acetate (1:1) gave analytically pure amino ester (–)-**8** (32 mg, 73%).

Reaction of α -hydroxy amide *syn*-(+)-3a** in basic conditions.** To a solution of α -hydroxy amide *syn*-(+)-**3a** (21 mg, 0.06 mmol) in methanol (1.43 mL), sodium methoxide (3 mg, 0.06 mmol) was added in small portions at room temperature and under argon atmosphere. The reaction mixture was stirred for 6h. After disappearance of the starting material (TLC) the solvent was removed under reduced pressure. Chromatography of the residue gave analytically eluting with *n*-hexane/ethyl acetate (1:1) gave analytically pure amino ester (–)-**8** (11 mg, 47%) and γ -lactone *syn*-(+)-**7a** (7 mg, 32%).

General Procedure for the Synthesis of functionalized γ -lactones **7.** To a solution of α -hydroxy amide **3** (1 mmol) in methanol (23 mL), sulphuric acid cc (12 mL) was slowly added. The resulting mixture was stirred at room temperature until complete disappearance (TLC) of the starting material. Then, NaHCO₃ (cc.) (50 mL) was added until pH = 7. The methanol was removed under reduced pressure and the mixture was extracted with ethyl acetate (5 x 100 mL). The organic layer was dried (MgSO₄) and concentrated under reduced pressure. To a stirred solution of the crude mixture in anhydrous toluene (25 mL), *p*-toluensulfonic acid (0.2 mmol) was added. The reaction mixture was stirred at reflux temperature for 2h. Then, NaHCO₃ (cc.) (10 mL) was added and was extracted with ethyl acetate (3 x 20 mL). The organic layer was dried (MgSO₄) and concentrated under reduced pressure. Chromatography of the residue gave analytically pure compounds **7**.

Functionalized γ -lactone, *syn*-(+)-7a**.** From 31 mg (0.09 mmol) of compound *syn*-(+)-**3a**, 23 mg (73%) of compound *syn*-(+)-**7a** was obtained as a colorless solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1); Mp: 143–145°C (*n*-hexane/ethyl acetate); $[\alpha]_D^{25} +51.1$ (c 0.4, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 6.84 (AA'XX', 2H), 6.75 (AA'XX', 2H), 5.92 (bs, 1H), 4.95 (d, *J* = 6.7 Hz, 1H), 4.30 (t, *J* = 6.5 Hz, 1H), 4.20 (d, *J* = 6.4 Hz, 1H), 3.77 (s, 3H), 3.63 (s, 3H), 1.35 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 172.1, 165.8, 153.5, 139.6, 115.6, 115.0, 79.2, 77.2, 59.1, 58.8, 55.7, 52.3, 28.5; IR (KBr): ν = 3363, 1790, 1679 cm⁻¹; HRMS (ES): calcd (%) for C₁₇H₂₅N₂O₅⁺ [*M*+*H*]⁺: 337.1758; found: 337.1752.

Functionalized γ -lactone, *anti*-(+)-7a**.** From 29 mg (0.09 mmol) of compound *anti*-(+)-**3a**, 10 mg (34%) of compound *anti*-(+)-**7a** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1); $[\alpha]_D^{25} +20.6$ (c 0.4, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 6.87 (AA'XX', 2H), 6.82 (AA'XX', 2H), 6.10 (bs, 1H), 4.55 (d, *J* = 5.4 Hz, 1H), 4.15 (t, *J* = 5.1 Hz, 1H), 3.93 (d, *J* = 5.1 Hz, 1H), 3.77 (s, 3H), 3.62 (s, 3H), 1.37 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.9, 166.6, 154.0, 139.0, 117.0, 114.8, 81.3, 78.2, 61.0, 58.9, 55.6, 51.8, 28.6; IR (CHCl₃): ν = 3344, 1792, 1672 cm⁻¹; HRMS (ES): calcd (%) for C₁₇H₂₅N₂O₅⁺ [*M*+*H*]⁺: 337.1758; found: 337.1758.

Functionalized γ -lactone, *syn*-(+)-7b**.** From 28 mg (0.08 mmol) of compound *syn*-(+)-**3b**, 13 mg (47%) of compound *syn*-(+)-**7b** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:2); $[\alpha]_D^{25} +70.5$ (c 0.4, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.33 (m, 3H), 7.19 (m, 2H), 6.79 (AA'XX', 2H), 6.62 (AA'XX', 2H), 6.54 (t, *J* = 5.6 Hz, 1H), 5.06 (d, *J* = 6.6 Hz, 1H), 4.46 (d, *J* = 5.8 Hz, 2H), 4.33 (t, *J* = 6.3 Hz, 1H), 4.12 (d, *J* = 6.0 Hz, 1H), 3.76 (s, 3H), 3.63 (s, 3H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.9, 166.5, 153.5, 139.3, 136.8, 128.9,

127.9, 127.8, 115.7, 115.0, 79.2, 77.3, 59.1, 58.9, 55.6, 43.6; IR (CHCl₃): ν = 3358, 1790, 1673 cm⁻¹; HRMS (ES): calcd (%) for C₂₀H₂₃N₂O₅⁺ [*M*+*H*]⁺: 371.1601; found: 371.1598.

Functionalized γ -lactone, *anti*-(-)-7b**.** From 40 mg (0.11 mmol) of compound *anti*-(+)-**3b**, 17 mg (42%) of compound *anti*-(-)-**7b** was obtained as a white solid after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1); Mp: 161–163°C (*n*-hexane/ethyl acetate); [α]_D –10.6 (c 0.5, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.31 (m, 5H), 6.86 (AA'XX', 2H), 6.83 (AA'XX', 2H), 6.70 (t, *J* = 5.4 Hz, 1H), 4.71 (d, *J* = 4.9 Hz, 1H), 4.55 (dd, *J* = 14.8, 6.2 Hz, 1H), 4.42 (dd, *J* = 14.7, 5.7 Hz, 1H), 4.24 (t, *J* = 4.7 Hz, 1H), 3.90 (d, *J* = 4.7 Hz, 1H), 3.77 (s, 3H), 3.57 (s, 3H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.8, 167.4, 154.0, 138.9, 137.0, 128.8, 127.81, 127.77, 116.9, 114.9, 81.0, 78.8, 60.9, 58.9, 55.6, 43.2; IR (KBr): ν = 3341, 1793, 1667 cm⁻¹; HRMS (ES): calcd (%) for C₂₀H₂₃N₂O₅⁺ [*M*+*H*]⁺: 371.1601; found: 371.1598.

Functionalized γ -lactone, *syn*-(+)-7c**.** From 26 mg (0.07 mmol) of compound *syn*-(+)-**3c**, 15 mg (57%) of compound *syn*-(+)-**7c** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1); [α]_D +87.1 (c 0.7, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.30 (m, 2H), 7.06 (m, 3H), 6.80 (AA'XX', 2H), 6.67 (AA'XX', 2H), 5.86 (bs, 1H), 5.11 (d, *J* = 6.9 Hz, 1H), 5.03 (d, *J* = 6.6 Hz, 1H), 4.57 (t, *J* = 6.7 Hz, 1H), 4.06 (bs, 1H), 3.76 (s, 3H), 1.34 (s, 9H); ¹³C NMR (75 MHz, CDCl₃, 25°C): δ = 171.2, 165.7, 157.6, 153.6, 139.3, 129.6, 122.9, 116.6, 115.7, 115.0, 77.2, 77.3, 59.0, 55.7, 52.4, 28.4; IR (CHCl₃): ν = 3371, 1791, 1680 cm⁻¹; HRMS (ES): calcd (%) for C₂₂H₂₇N₂O₅⁺ [*M*+*H*]⁺: 399.1914; found: 399.1922.

Functionalized γ -lactone, *syn*-(+)-7d**.** From 35 mg (0.11 mmol) of compound *syn*-(+)-**3d**, 18 mg (52%) of compound *syn*-(+)-**7d** was obtained as a colorless oil after purification by flash chromatography (*n*-hexane/ethyl acetate, 1:1); [α]_D +73.3 (c 0.6, CHCl₃); ¹H NMR (300 MHz, CDCl₃, 25°C): δ = 7.32 (m, 2H), 7.08 (m, 3H), 6.22 (bs, 1H), 5.05 (d, *J* = 5.7 Hz, 1H), 4.95 (d, *J* = 4.1 Hz, 1H),

4.12 (dd, $J = 5.7, 4.1$ Hz, 1H), 3.60 (dd, $J = 17.5, 2.4$ Hz, 1H), 3.46 (dd, $J = 17.5, 2.4$ Hz, 1H), 2.28 (t, $J = 2.4$ Hz, 1H), 1.41 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 171.1, 165.6, 157.1, 129.6, 116.2, 80.7, 78.8, 77.0, 73.0, 60.5, 52.3, 36.5, 28.6$; IR (CHCl_3): $\nu = 3301, 1789, 1674\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{18}\text{H}_{23}\text{N}_2\text{O}_4^+$ $[M+H]^+$: 331.1652; found: 331.1643.

Hydroxy amino ester (–)-8. Colorless oil. $[\alpha]_{\text{D}} -6.0$ (c 2.0, CHCl_3); ^1H NMR (300 MHz, CDCl_3 , 25°C): $\delta = 6.75$ (AA'XX', 2H), 6.68 (AA'XX', 2H), 6.44 (bs, 1H), 4.29 (d, $J = 2.3$ Hz, 1H), 4.21 (d, $J = 4.2$ Hz, 1H), 4.17 (dd, $J = 4.1, 2.5$ Hz, 1H), 3.73 (s, 3H), 3.51 (s, 3H), 3.50 (s, 3H), 1.29 (s, 9H); ^{13}C NMR (75 MHz, CDCl_3 , 25°C): $\delta = 170.8, 170.2, 153.2, 140.3, 116.3, 114.6, 80.2, 71.1, 59.7, 58.9, 55.6, 51.9, 51.0, 28.5$; IR (CHCl_3): $\nu = 3391, 1746, 1659\text{ cm}^{-1}$; HRMS (ES): calcd (%) for $\text{C}_{18}\text{H}_{29}\text{N}_2\text{O}_6^+$ $[M+H]^+$: 369.2020; found: 369.2012.

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Supporting Information

Representative chemical shifts and vicinal coupling constants of ^1H and ^{13}C NMR of compounds **3** (Table S1), selected vicinal coupling constants for γ -lactams **6** and γ -lactones **7** (Table S2 and S3, respectively), observed NOE for compounds **6** and **7** and copies of NMR spectra (^1H , ^{13}C) for compounds **2**, **3** and **5–8**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Autores: Alcaide, B.; Almendros, P.; Aragoncillo, C.; Callejo, R.; Ruiz, M. P.

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