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Ribose conversion with amino acids into pyrroline platform chemicals – expeditious synthesis of diverse pyrrole-fused alkaloid compounds†

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One-pot conversion of sustainable D-ribose with L-amino acid, methyl esters produced pyrrole-2-carbaldehydes **5** in reasonable yields (32–63%) under pressurized conditions of 2.5 atm at 80 °C. The value-added pyrroline compounds **5** as platform chemicals were utilized for quick installation of poly-heterocyclic cores for the development of pyrrole-motif natural and artificial therapeutic agents. A pyrrole-fused piperazin-2-one scaffold **6** was prepared by reductive amination of pyrrolines **5** with benzylamine. While further cyclization of pyrrolines **5** with ethane-1,2-diamine produced pyrrolo-piperazin-2-ones **7** with an extra imidazolidine ring, the reaction with 2-amino alcohols derived from natural L-amino acids, alanine, valine, and phenylalanine, respectively provided pyrrolo-piperazin-2-ones **8**, **9**, and **10** with oxazolidine as the third structural core. Cell viability and an anti-inflammatory effect of the synthesized compounds were briefly tested by the MTT method and the Griess assay, among which **8h** and **10g** exhibited significant anti-inflammatory effects with negligible cell toxicity.

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Introduction

Pyrrole is an interesting five-membered heterocyclic compound with the nitrogen lone-pair electrons being delocalized within the ring for aromaticity. It is therefore non-basic contrary to the six-membered ring homologue, pyridine. Alkaloid natural products containing pyrrole as a pharmacophore exhibit various biological activities such as sedative, anti-inflammatory, anti-biotic, anti-cancer, anti-hypertensive, anti-convulsant, anti-malarial, and many more.^{1–6} The organic synthesis of pyrrole was reported in the late 19th century,^{7–9} among which the Paal–Knorr method utilizing a 1,4-dicarbonyl compound and primary amine was the first (Fig. 1).^{10–12} The Hantzsch method by the reaction of α -haloketone and β -ketoester with a primary amine is useful for the preparation of 3-carboxylated pyrroles.^{13,14} In

1948, Clauson-Kaas reported furan conversion into 2,5-dimethoxytetrahydrofuran for the efficient preparation of pyrroles.¹⁵ Many others then modified the above original methods for the syntheses of various pyrrole compounds.^{16–33}

Transformation of D-glucose as sustainable biomass into 5-hydroxymethyl-2-furfural (5-HMF) as a value-added platform chemical has been well documented in the literature in recent years.^{34–36} Utilization of reducing sugars for the preparation of pyrroles would also be beneficial and providential. In 1912, Maillard reported the reaction between D-glucose and amino acids at high temperature (>140°) to produce hundreds of small chemicals for flavouring in food chemistry,³⁷ which was later known to include pyrroline **1**, the nitrogen analogue of 5-HMF, in a very small quantity.³⁸ Pyrroline **1** would be a useful platform

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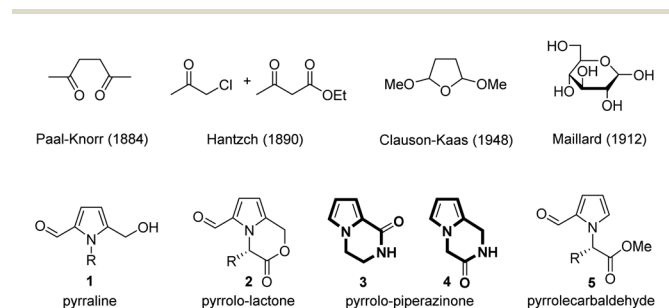


Fig. 1 The original synthetic methods of pyrrole and structures of some pyrrole derivatives.



chemical for the development of pyrrole-motif natural and artificial therapeutic agents by further reactions.^{39–43}

The first chemical synthesis of pyrrolines **1** by Kato from the reaction of D-glucose and primary amines either at 100 °C in H₂O for 1 h or at 70 °C in MeOH for 3 h both with acetic acid just confirmed the formation of pyrrolines **1**.⁴⁴ Monnier reported the synthesis of butyl pyrraline **1** (R = Bu) in only 3.4% yield by the reaction of D-glucose and butylamine in aqueous acetic acid at 100 °C for 2 h.³⁸ We believed that the low yield of pyrraline **1** was ascribed to the unstable imine intermediates under the aqueous acidic condition. We recently studied the reaction conditions of D-glucose and primary amines, and significantly improved the yield of pyrrolines **1** (20–50%) under non-aqueous condition by use of oxalic acid in DMSO at 90 °C for 30 min.⁴⁵ Anti-inflammatory and pain-relieving pyrrolo-lactones **2**, which could be isolated from *Celastrus orbiculatus* (R = Bn) and *Caparis spinosa* (R = Me), were synthesized in 27% and 32% yields, respectively when methyl esters of amino acids, phenylalanine and alanine, were used as primary amines in the above one-pot reaction condition.⁴⁵ Nonetheless, it was still necessary to improve the one-pot reaction conditions of sugars and amino acids for reasonable yields of the pyrrole platform chemicals, which might be realized by reducing the formation of tar by-product under a pressurized reaction condition.

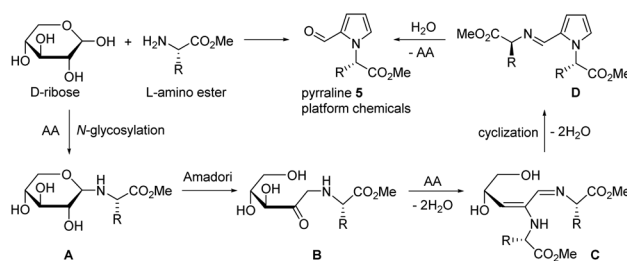
Piperazin-2-one is a privileged structural unit in drug discovery because many of the biologically active natural products and the approved drug molecules contain the above scaffold,^{46–49} which exhibit opiate,⁵⁰ antiviral,⁵¹ anti-cancer,⁵² and anti-diabetes activities⁵³ as well as treatment effects for immunological disorder⁵⁴ and non-Hodgkin's lymphoma.⁵⁵ Pyrrole-fused piperazin-2-ones (**3** and **4** in Fig. 1) would thus be a very promising structural unit for the discovery of new therapeutic agents. In fact, the structure of pyrrolo-piperazinone **3** has been found in numerous antibiotic and cytotoxic alkaloid natural products, such as agelastatins,^{56,57} longamide,⁵⁸ hanishin,⁵⁹ and agesamides.⁶⁰

We envisioned that the structure of pyrrolo-piperazinone **4** would be obtainable from pyrrole-2-carbaldehyde **5**, which might be prepared by the one-pot “Maillard-type” reaction between D-ribose and α-amino acids. Amination of the formyl group and subsequent lactam formation with the carboxylic ester in pyrrole-2-carbaldehyde **5** would form the core structure of pyrrolo-piperazinone **4**. In this paper, we described one-pot conversion of D-ribose with various α-amino acids under a pressurized condition to obtain reasonable yields of pyrrole-2-carbaldehydes **5** as platform chemicals and their further cyclization reactions to pyrrolo-piperazinone derivatives **6–10** as new potential therapeutic agents. Finally, cell viability and anti-inflammatory effect of the synthesized pyrrolo-piperazinones were briefly tested for RAW264.7 cells by the MTT method and the Griess assay.

Results and discussion

One-pot ribose conversion with amino acid

D-Ribose was first reacted with L-valine methyl ester in DMSO with oxalic acid at 90 °C for 30 min to produce pyrraline **5** (R = i-Pr) in 24% yield, which was the previous optimized condition for D-glucose.⁴⁵ Unlike D-glucose case providing pyrrololactones,

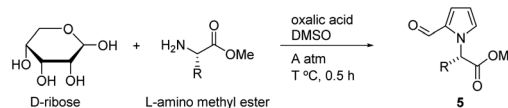


Scheme 1 Ribose conversion with amino ester through *N*-glycosylation, Amadori reaction, and cyclization to produce pyrraline **5** as platform chemicals.

pyrrole-2-carbaldehyde **5** with intact methyl ester was obtained. Pyrroles as the glycosylation end products were believed to be formed through 3-deoxyglucosone intermediate after *N*-glycosylation and Amadori reaction.^{38,61,62} The reaction of D-ribose was thus speculated to follow *N*-glycosylation (A) and Amadori reaction (B) in sequence (Scheme 1). Second amino ester was introduced to give the structure C by imine tautomerization and dehydration, which is the adduct of amino esters to the 3-deoxyglucosone homologue from D-ribose. Cyclization of enamine and dehydration produced pyrrole ring D. Finally, hydrolysis of the imine provided pyrraline **5** and regenerated amino ester. D-Ribose reaction with other amino esters from L-phenylalanine and L-methionine also produced the corresponding pyrrolines **5** in 37% (R = Bn) and 30% (R = CH₂CH₂SMe) yields, respectively, but it was imperative to improve the ribose conversion reaction to utilize pyrrolines **5** as sustainable platform chemicals for the discovery of potent therapeutic agents.

The ribose conversion reaction with α-amino methyl esters under the above condition produced pyrrolines **5** in 24–37% yields as the only isolable product together with dark-brown tarry materials, which suggested that reducing the amount of tar would improve the yield of pyrrolines **5**. The ribose conversion was thus studied for the above three amino esters under pressurized conditions (1–4 atm) at 90 °C to reduce the tar formation (Table 1). We found gradual yield improvements of **5** as pressure was increased with the maximum value at 2.5 atm. The yield of **5** was maintained or slowly fell after 3.0 atm.

Table 1 Optimization of D-ribose conversion (%yield of **5**) with L-amino acid, methyl ester at 90 °C under various pressure conditions



Yield of **5** (%) under each pressure (atm)

AA ^a	1	1.5	2	2.5	3	3.5	4
Val	24	29	30	38	36	36	33
Phe	37	38	39	48	47	46	46
Met	30	35	36	42	37	37	37

^a Amino acid: valine (R = i-Pr), phenylalanine (R = Bn), methionine (R = CH₂CH₂SMe).



Table 2 Optimization of D-ribose conversion (% yield of **5**) with L-amino acid, methyl ester at 2.5 atm under various temperature conditions

AA ^a	Yield of 5 (%) at each temperature (°C)					
	60	70	75	80	85	90
Val	29	31	38	42	39	38
Phe	35	41	45	54	48	48
Met	32	35	37	46	43	42

^a Amino acid: valine (R = *i*-Pr), phenylalanine (R = Bn), methionine (R = CH₂CH₂SMe).

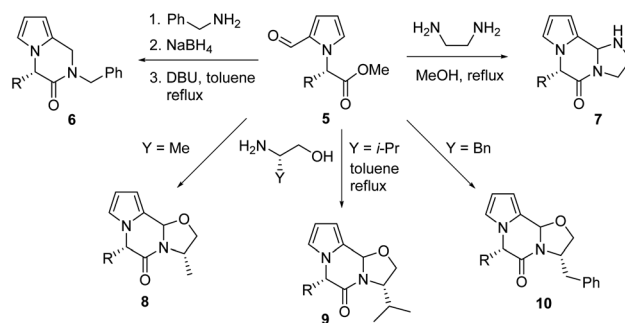
Reaction temperature was then screened from 60 °C to 90 °C at the optimal pressure of 2.5 atm (Table 2). The yield of **5** was progressively improved as temperature was raised up to 80 °C and fell slowly down since then. The best yields of pyrrolines **5** were obtained at 80 °C (2.5 atm) for all three amino esters, which were approximately 150% of those at the previous optimal condition for glucose (90 °C, 1 atm).⁴⁵

Generality of the ribose conversion with α-amino methyl esters and improvement of the yields of pyrrolines **5** under the pressure condition (2.5 atm, 80 °C) compared to the original one (1 atm, 90 °C) were summarized in Table 3, in which 150–300% yield increases for pyrrolines **5** were notified for eleven natural L-α-amino acids. Amino esters reacted with D-ribose as nucleophile and the yields of pyrrolines **1** were reflected by the nucleophilicity of each amino ester, which was differentiated by the α-substituent R in this case. It was initially predicted that R would provide steric hindrance to the amino group, thereby lower yield of **1** could be obtained as the size of R was increased. Surprisingly, it was L-glycine (R = H), however, which gave the lowest yield (32%) of pyrroline **1**, and the highest yield of **1** (63%) was obtained for L-leucine (R = *i*-Bu).

Table 3 Improvement of D-ribose conversion (% yield of **5**) with L-amino acid, methyl ester at 2.5 atm and 80 °C compared at 1.0 atm and 90 °C

Amino Acid ^a	Compound 5	Yield of 5 (%)	
		1.0 atm, 90 °C	2.5 atm, 80 °C
Gly	5a	10	32
Ala	5b	23	38
Val	5c	24	42
Leu	5d	43	63
Ile	5e	20	40
Phe	5f	37	54
Bn	5g	20	53
Asp	5h	18	47
Glu	5i	16	37
Met	5j	30	46
Trp	5k	34	55

^a Amino acid (R): glycine (H), alanine (Me), valine (*i*-Pr), leucine (*i*-Bu), isoleucine (*s*-Bu), phenylalanine (CH₂Ph), benzylalanine (CH₂CH₂Ph), aspartic acid (CH₂CO₂Me), glutamic acid (CH₂CH₂CO₂Me), methionine (CH₂CH₂SMe), tryptophane (3-indole).



Scheme 2 Further cyclization of pyrrolines platform chemicals **5** to pyrrolo-piperazin-2-one derivatives **6–10**.

It seemed that the hydrogen bonding between primary amino and ester groups would reduce the nucleophilicity of amino esters. L-Glycine with no α-substituent may participate in the hydrogen bonding, which reduces the nucleophilicity of the amino group. Primary alkyl or aryl substituents R (*e.g.*, Leu, Phe, Bn) would be good enough to maintain the nucleophilicity of amino group by interrupting the hydrogen bonding without providing steric hindrance to the amino group. Pyrrolines **5** can now be obtained in 32–60% yield by one-pot conversion from D-ribose with L-amino acid methyl esters and certainly be platform chemicals for the syntheses of pyrrole-based poly heterocyclic compounds as potential therapeutic agents.

Cyclization of the platform pyrrolines **5** to pyrrolo-piperazinones **6–10**

We demonstrated three different methods for further cyclization of pyrrolines **5**, derived from eight different L-amino acids – glycine (**a**), alanine (**b**), valine (**c**), isoleucine (**d**), phenylalanine (**e**), benzylalanine (**f**), aspartic acid (**g**), and methionine (**h**) – with five different nitrogen reagents to produce the 2-piperazin-2-one skeleton as the second pharmacophore with the basic pyrrole scaffold (Scheme 2 and Table 4). The 1,5-relationship between the carbonyl carbons of formyl and ester groups in pyrrolines **5** allowed δ-lactam formation with primary amines by reductive amination and cyclization. Benzylamine was utilized for the reductive amination with pyrrolines **5**, which was carefully carried out first by imine formation in MeOH at 25 °C, followed by selective NaBH₄ reduction at 0 °C due to the presence of the sensitive α-amino ester group. The resulting secondary amine underwent lactam formation with the ester group in the presence

Table 4 Yields (%) of the reactions in Scheme 2

Entry	R	6	7	8	9	10
a	H	36	58	12	4	6
b	Me	66	87	41	27	32
c	<i>i</i> -Pr	73	94	73	61	41
d	<i>s</i> -Bu	86	91	77	50	31
e	PhCH ₂	41	86	52	71	62
f	PhCH ₂ CH ₂	64	88	22	51	57
g	MeO ₂ CCH ₂	84	72	27	10	14
h	MeSCH ₂ CH ₂	47	87	24	24	22



of DBU at the reflux temperature of toluene to produce pyrrolo-piperazin-2-ones **6** in 36–84% yields (Table 4).

α,ω -Alkanediamine (e.g., 1,2-ethanediamine) can be utilized in lactam formation with pyrrolines **5**, where initially formed imine may react with the second amine by cyclization.^{40,41} One of the resulting two symmetrical secondary amines participated in further cyclization with the ester group to form pyrrolo-piperazinones **7** with an imidazolidine ring as the third core in 58–94% yields (Table 4). The conversion of pyrrolines **5** with norephedrine was reported,⁴² where the initially formed imine was reacted with the alcohol group by cyclization to form an oxazolidine unit, which underwent further cyclization with the ester group to produce pyrrolo-piperazinones with the oxazolidine unit. In a similar manner, 2-amino alcohols derived from natural α -amino acids, alanine (Y = Me), valine (i-Pr), and phenylalanine (Bn), can be utilized for the syntheses of oxazolidine-fused pyrrolo-piperazinones **8**, **9**, and **10**, respectively. Even though somewhat lower yields were notified for the pyrrolines **5** from Gly (**a**, R = H), Asp (**g**, CH₂CO₂CH₃), and Met (**h**, CH₂CH₂SCH₃), fare yields of poly heterocyclic products **8–10** were obtained for the pyrrolines **5** derived from α -amino acids with a simple alkyl substituent (Table 4).

Cell viability (MTT test) and anti-inflammation assays (Griess method)

All the synthesized pyrrolo-piperazinones **6–10** (**a–h**) were briefly screened for cytotoxicity to RAW264.7 cells (Murine macrophages) at a fixed concentration at 20 $\mu\text{g mL}^{-1}$. Four compounds **7a**, **7c**, **8h**, and **10g** showed 80% or higher cell viability by Formazan formation in MTT {3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-thetazolium bromide} assay (see ESI†).⁶³ The other reagents might still be good candidates for antibiotics.

Anti-inflammatory activities to RAW264.7 cells were then tested for the above four samples at five different concentrations (0, 1, 5, 10, 20 $\mu\text{g mL}^{-1}$ each) in 24 h after triggering by 1 $\mu\text{g mL}^{-1}$ of LPS (lipopolysaccharides). Nitric oxide concentration, which is correlated with the inflammation level, was determined by the Griess method.⁶⁴ The measurements were repeated three times. The mean and standard deviation values

of the NO concentration ($\mu\text{g mL}^{-1}$) for the cell treated by each compound at each concentration are listed in Table 5. Pyrrolo-piperazinones **8h** and **10g** containing oxazolidine as the third core exhibited significant anti-inflammation activities, in which IC₅₀ values were estimated to be 20 $\mu\text{g mL}^{-1}$ and 10 $\mu\text{g mL}^{-1}$, respectively. For comparison, IC₅₀ of NIL {L-N⁶-(1-iminoethyl) lysine} as a positive control was measured as 10.17 mM, which is converted as 2.64 $\mu\text{g mL}^{-1}$ (see ESI†).

Experimental

General experimental

Reactions were performed in a well-dried flask under argon atmosphere unless noted otherwise. A mini-clave steel reactor (100 mL, up to 15 bar) made from büchiglasuster (Switzerland) was used for the pressurized reactions. The pressure was controlled by argon gas (see ESI† for picture demonstration). Solvents used as reaction media were dried over pre-dried molecular sieve (4 Å) by microwave oven. Solvents for extraction and chromatography were reagent grade and used as received. The flash column chromatography was performed by the method of Still (*J. Org. Chem.*, 1978, **43**, 2923) with silica gel 60 (70–230 mesh) using a mixture of EtOAc/hexane as gradient eluent. ¹H and ¹³C NMR spectra were respectively recorded on a 400 MHz and 100 MHz NMR spectrometer in deuterated chloroform (CDCl₃) with tetramethylsilane (TMS) as an internal reference unless noted otherwise.

Cell viability assay (MTT method)⁶³

RAW264.7 cells (Murine macrophages) were cultured using Dulbecco's modified Eagle medium (DMEM) (Welgene, Seoul, Korea) containing 10% fetal bovine serum (FBS), 2 mM glutamine, and 100 unit/mL of antibiotics (Gibco BRL, Rockville, MD). Cells were incubated at 37 °C incubators, which maintained a humidified atmosphere of 5% (v/v) air/CO₂. The incubated RAW264.7 cells (5 × 10³/well) were seeded to a 96-cell culture plate to conduct a cell viability assay. The RAW264.7 cells prepared for the viability assay went through 18 h of attachment and stabilization. The growth medium was removed and replaced by a fresh medium without FBS. The synthetic compounds were treated to the cells at a concentration of 20 $\mu\text{g mL}^{-1}$ and the resulting cells were incubated for 24 h. The sample-treated culture medium was removed and 100 $\mu\text{g mL}^{-1}$ of 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-thetazolium bromide (MTT) was added to each well. In 1 h, purple formazan produced by cellular respiration was dissolved in a 200 μL DMSO solution and the absorbance at 560 nm was measured using a multi-plate reader. The analyses were repeated three times. The results were expressed as means of three independent experiments.

Measurement of nitric oxide concentration (Griess assay)⁶⁴

RAW264.7 cells were transferred into 3 × 10⁵ cells per well in a 96-cell culture plate and incubated for 24 h in a 5% CO₂ incubator at 37 °C. Four different concentrations (1, 5, 10, and 20 $\mu\text{g mL}^{-1}$) of synthetic compounds was treated to the incubated RAW264.7 cells. Simultaneously, 1 $\mu\text{g mL}^{-1}$ of

Table 5 Nitric oxide concentration (μM) by Griess assay for RAW264.7 cells after treatment of each reagent ($\mu\text{g mL}^{-1}$) and lipopolysaccharides (LPS, 1 $\mu\text{g mL}^{-1}$)

Conc. ($\mu\text{g mL}^{-1}$)	7a	7c	8h	10g
0 ^a	3.21 ± 0.15	3.21 ± 0.15	3.21 ± 0.15	3.21 ± 0.15
0	25.54 ± 2.60	25.54 ± 2.60	25.54 ± 2.60	25.54 ± 2.60
1	26.23 ± 2.60	25.03 ± 2.13	22.23 ± 2.13	17.31 ± 1.31
5	22.31 ± 1.65	24.32 ± 1.31	21.32 ± 1.31	15.32 ± 2.60
10	20.30 ± 2.65	23.51 ± 1.10	16.31 ± 1.10	14.31 ± 2.11
20	20.02 ± 3.64	21.65 ± 2.51	14.32 ± 2.51	11.10 ± 1.31

^a Without LPS treatment.



lipopolysaccharides (LPS) (Sigma-Aldrich, St. Louis, MO) was added and the resulting cells were incubated for 24 h. The same amount of Griess reagent (Sigma-Aldrich) equal to 100 μL of the culture solution was added according to the manufacturer's recommendations, and the absorbance was measured at 540 nm with a multi-plate reader. The NO concentration in the culture medium was determined using a standard curve for each concentration of sodium nitrite.

General procedure for D-ribose conversion with L-amino acids for the synthesis of pyrrolines 5

Methyl 2-(2-formyl-1H-pyrrol-1-yl)acetate (5a). To a stirred solution of glycine (10.0 g, 0.133 mol, 1 equiv.) in MeOH (7 mL) at 0 °C under argon atmosphere was slowly added thionyl chloride (9.73 mL, 0.133 mol, 1 equiv.) through a syringe. The mixture was then heated at 65 °C for 8 h and cooled to room temperature. The mixture was triturated with Et₂O to give glycine methyl ester, ammonium chloride salt as white crystalline salt (16.57 g, 0.133 mol).

Under ambient pressure. To a stirred solution of the above glycine methyl ester, ammonium chloride salt (8.35 g, 66.5 mmol, 1 equiv.) in DMSO (20 mL) were added Et₃N (18.4 mL, 0.133 mol, 2 equiv.) and D-ribose (10.0 g, 66.6 mmol, 1 equiv.). After complete dissolution, oxalic acid (12.0 g, 0.133 mol, 2 equiv.) was added and the resulting mixture was heated at 90 °C for 30 min. Upon cooling to room temperature, the mixture was filtered through a short pad of SiO₂ with EtOAc rinsing. The filtrate was concentrated and purified by SiO₂ flash column chromatography to give **5a** (1.08 g, 6.45 mmol) in 10% yield as light-yellow liquid.

Under pressure bottle at 2.5 bar. A mixture of glycine methyl ester, ammonium chloride salt (2.00 g, 15.9 mmol) and Et₃N (2.18 mL, 15.9 mmol) in dry DMSO (10 mL) was stirred in a mini-clave steel reactor and then D-ribose (4.73 g, 31.8 mmol) and oxalic acid (1.41 g, 15.9 mmol) were added. The mixture was pressurized to 2.5 bar with argon and heated at 80 °C for 0.5 h. The mixture was then cooled to room temperature and depressurized. The resulting viscous mixture was filtered through a short pad of SiO₂ rinsing with EtOAc. The filtrate was concentrated and purified by SiO₂ flash column chromatography (eluent 7 : 1 EtOAc/hexane) to give **5a** (0.85 g, 5.09 mmol) in 32% yield as light-yellow liquid.

Data for 5a. $R_f = 0.50$ (4 : 6 EtOAc/hexane); ¹H NMR $\delta = 3.77$ (s, 3H), 5.08 (s, 2H), 6.31 (dd, $J = 2.4, 1.6$ Hz, 1H), 6.92 (dd, $J = 4.0, 2.4$ Hz, 1H), 7.00 (dd, $J = 4.0, 1.6$ Hz, 1H), 9.54 (s, 1H) ppm; ¹³C NMR $\delta = 50.0, 52.5, 110.2, 124.6, 124.6, 132.0, 168.7, 179.8$ ppm; IR $\nu = 3111, 2941, 2904, 2840, 1740, 1650, 1528, 1480, 1403, 1359, 1321, 1216, 1081, 1031, 999, 761$ cm⁻¹; HRMS (EI) calcd for C₈H₉NO₃, 167.0582, found 167.0582.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)propanoate (5b). The mixture of L-alanine methyl ester, ammonium chloride salt (2.00 g, 14.3 mmol), Et₃N (2.0 mL, 14.3 mmol), D-ribose (4.35 g, 28.6 mmol), and oxalic acid (1.27 g, 14.3 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5b** (985 mg, 5.4 mmol) in 38% yield as light-

brown liquid after purification by SiO₂ column chromatography.

Data for 5b. $R_f = 0.53$ (4 : 6 EtOAc/hexane); ¹H NMR $\delta = 1.73$ (d, $J = 7.6$ Hz, 3H), 3.71 (s, 3H), 5.86 (q, $J = 7.6$ Hz, 1H), 6.30 (dd, $J = 4.0, 2.0$ Hz, 1H), 6.98 (dd, $J = 4.0, 1.6$ Hz, 1H), 7.18 (ddd, $J = 2.0, 1.6, 1.2$ Hz, 1H), 9.50 (d, $J = 1.2$ Hz, 1H) ppm; ¹³C NMR $\delta = 17.6, 52.2, 55.1, 110.0, 125.1, 128.7, 131.3, 171.2, 179.3$ ppm; IR $\nu = 3116, 2999, 2954, 2851, 2809, 1729, 1608, 1517, 1470, 1406, 1364, 1339, 1313, 1211, 1090, 1066, 1033, 983, 743$ cm⁻¹; HRMS (ESI) calcd for C₉H₁₁NO₃ + Na 204.0631, found 204.0636.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-3-methylbutanoate (5c). The mixture of L-valine methyl ester, ammonium chloride salt (2.00 g, 11.9 mmol), Et₃N (1.7 mL, 11.9 mmol), D-ribose (3.59 g, 23.8 mmol), and oxalic acid (1.07 g, 11.9 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5c** (1.05 g, 5.0 mmol) in 42% yield as light-brown liquid after purification by SiO₂ column chromatography.

Data for 5c. $R_f = 0.76$ (4 : 6 EtOAc/hexane); ¹H NMR $\delta = 0.78$ (d, $J = 6.4$ Hz, 3H), 1.01 (d, $J = 6.4$ Hz, 3H), 2.40 (m, 1H), 3.75 (s, 3H), 5.99 (d, $J = 10.4$ Hz, 1H), 6.31 (ddd, $J = 4.0, 2.8, 1.2$ Hz, 1H), 6.93 (ddd, $J = 4.0, 1.6, 1.6$ Hz, 1H), 7.39 (ddd, $J = 2.8, 1.6, 1.2$ Hz, 1H), 9.54 (dd, $J = 1.6, 1.2$ Hz, 1H) ppm; ¹³C NMR $\delta = 18.5, 19.2, 33.0, 52.2, 63.8, 110.7, 125.3, 129.9, 131.9, 171.2, 179.9$ ppm; IR $\nu = 3126, 2952, 2874, 2846, 2813, 1729, 1655, 1523, 1460, 1408, 1373, 1338, 1258, 1201, 1147, 1062, 1033, 1000, 877, 825, 743$ cm⁻¹; HRMS (ESI) calcd for C₁₁H₁₅NO₃ + Na 232.0944, found 232.0942.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-methylpentanoate (5d). The mixture of L-leucine methyl ester, ammonium chloride salt (2.00 g, 11.0 mmol), Et₃N (1.6 mL, 11.0 mmol), D-ribose (3.32 g, 22.0 mmol), and oxalic acid (0.99 g, 11.0 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5d** (1.55 g, 6.93 mmol) in 63% yield as light-brown liquid after purification by SiO₂ column chromatography.

Data for 5d. $R_f = 0.76$ (4 : 6 EtOAc/hexane); ¹H NMR $\delta = 0.90$ (d, $J = 6.8$ Hz, 3H), 0.93 (d, $J = 6.8$ Hz, 3H), 1.40 (m, 1H), 1.99 (dd, $J = 8.0, 6.8$ Hz, 2H), 3.72 (s, 3H), 6.10 (t, $J = 8.0$ Hz, 1H), 6.32 (dd, $J = 4.0, 2.8$ Hz, 1H), 6.96 (dd, $J = 4.0, 1.6$ Hz, 1H), 7.21 (ddd, $J = 2.8, 1.6, 1.2$ Hz, 1H), 9.52 (d, $J = 1.2$ Hz, 1H) ppm; ¹³C NMR $\delta = 21.3, 22.8, 24.6, 41.3, 52.4, 57.4, 110.4, 125.5, 129.5, 131.6, 171.5, 179.6$ ppm; IR $\nu = 3119, 2963, 2873, 2810, 2773, 2729, 1750, 1657, 1534, 1473, 1411, 1373, 1348, 1273, 1203, 1164, 1132, 1080, 1029, 1001, 911, 878, 832, 778, 753$ cm⁻¹; HRMS (EI) calcd for C₁₂H₁₇NO₃, 223.1208, found 223.1207.

Methyl (2S,3S)-2-(2-formyl-1H-pyrrol-1-yl)-3-methylpentanoate (5e). The mixture of L-isoleucine methyl ester, ammonium chloride salt (2.00 g, 11.0 mmol), Et₃N (1.5 mL, 11.0 mmol), D-ribose (3.31 g, 22.0 mmol), and oxalic acid (0.88 g, 11.0 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5e** (982 mg, 4.4 mmol) in 40% yield as light-brown liquid after purification by SiO₂ column chromatography.

Data for 5e. $R_f = 0.80$ (4 : 6 EtOAc/hexane); ¹H NMR $\delta = 0.83$ (t, $J = 7.2$ Hz, 3H), 0.98 (d, $J = 6.8$ Hz, 3H), 1.00–1.24 (m, 2H), 2.18 (m, 1H), 3.74 (s, 3H), 6.06 (d, $J = 9.6$ Hz, 1H), 6.31 (dd, $J =$



3.2, 2.4 Hz, 1H), 6.93 (dd, $J = 3.2, 1.6$ Hz, 1H), 7.41 (ddd, $J = 2.4, 1.6, 1.2$ Hz, 1H), 9.53 (s, 1H) ppm; ^{13}C NMR $\delta = 10.5, 15.3, 24.7, 38.8, 52.0, 62.6, 110.5, 125.2, 129.7, 131.8, 171.0, 179.6$ ppm; IR $\nu = 3116, 2961, 2862, 2703, 1735, 1655, 1530, 1468, 1410, 1375, 1343, 1250, 1202, 1151, 1070, 1026, 991, 750$ cm^{-1} ; HRMS (EI) calcd for $\text{C}_{12}\text{H}_{17}\text{NO}_3$ 223.1208, found 223.1207; HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{NO}_3 + \text{Na}$ 246.1101, found 246.1105.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-3-phenylpropanoate (5f). The mixture of L-phenylalanine methyl ester, ammonium chloride salt (2.00 g, 9.3 mmol), Et_3N (1.3 mL, 9.3 mmol), D-ribose (2.80 g, 18.6 mmol), and oxalic acid (0.84 g, 9.3 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5f** (1.29 g, 5.02 mmol) in 54% yield as light-brown liquid after purification by SiO_2 column chromatography.

Data for 5f. $R_f = 0.88$ (4 : 6 EtOAc/hexane); ^1H NMR $\delta = 3.27$ (dd, $J = 14.0, 10.0$ Hz, 1H), 3.54 (dd, $J = 14.0, 5.6$ Hz, 1H), 3.74 (s, 3H), 6.06 (br s or dd, $J = 10.0, 5.6$ Hz, calcd. 1H), 6.21 (dd, $J = 4.0, 2.8$ Hz, 1H), 6.91 (dd, $J = 4.0, 1.6$ Hz, 1H), 6.98–7.03 (m, 3H), 7.15–7.23 (m, 3H), 9.43 (d, $J = 0.8$ Hz, 1H) ppm; ^{13}C NMR $\delta = 39.0, 52.6, 61.1, 110.2, 125.6, 126.9, 128.4, 128.9, 130.6, 131.2, 136.0, 170.3, 179.5$ ppm; IR $\nu = 3114, 3067, 3029, 2955, 2845, 2812, 1740, 1654, 1530, 1500, 1472, 1409, 1373, 1343, 1277, 1215, 1079, 1032, 1002, 744, 698$ cm^{-1} ; HRMS (EI) calcd for $\text{C}_{15}\text{H}_{15}\text{NO}_3 + \text{Na}$ 280.0944, found 280.0948.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-phenylbutanoate (5g). The mixture of L-homophenylalanine methyl ester, ammonium chloride salt (2.00 g, 8.7 mmol), Et_3N (1.2 mL, 8.7 mmol), D-ribose (2.62 g, 17.4 mmol), and oxalic acid (0.79 g, 8.7 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5g** (1.25 g, 4.6 mmol) in 53% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 5g. $R_f = 0.71$ (4 : 6 EtOAc/hexane); ^1H NMR $\delta = 2.26$ –2.36 (m, 1H), 2.45–2.60 (m, 3H), 3.70 (s, 3H), 5.89 (br d, $J = 8.0$ Hz, 1H), 6.34 (dd, $J = 4.0, 2.8$ Hz, 1H), 6.98 (dd, $J = 4.0, 1.6$ Hz, 1H), 7.07–7.12 (m, 2H), 7.15–7.20 (m, 2H), 7.22–7.28 (m, 2H), 9.51 (d, $J = 1, 2$ Hz, 1H) ppm; ^{13}C NMR $\delta = 31.8, 34.0, 52.5, 58.9, 110.5, 125.5, 126.2, 128.2, 128.4, 129.7, 131.6, 140.0, 170.8, 179.6$ ppm; IR $\nu = 3114, 3067, 3027, 2955, 2847, 2810, 1735, 1644, 1532, 1502, 1472, 1413, 1375, 1340, 1254, 1209, 1179, 1087, 1031, 1008, 734, 686$ cm^{-1} ; HRMS (FAB) calcd for $\text{C}_{16}\text{H}_{18}\text{NO}_3$ 272.1287, found 272.1284.

Dimethyl (S)-2-(2-formyl-1H-pyrrol-1-yl)succinate (5h). The mixture of L-aspartic acid dimethyl ester, ammonium chloride salt (2.00 g, 10.1 mmol), Et_3N (1.4 mL, 10.1 mmol), D-ribose (3.04 g, 20.2 mmol), and oxalic acid (0.92 g, 10.1 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5h** (1.14 g, 4.76 mmol) in 47% yield as light-brown liquid after purification by SiO_2 column chromatography.

Data for 5h. $R_f = 0.45$ (4 : 6 EtOAc/hexane); ^1H NMR $\delta = 3.06$ (dd, $J = 17.2, 8.4$ Hz, 1H), 3.39 (dd, $J = 17.2, 4.8$ Hz, 1H), 3.66 (s, 3H), 3.74 (s, 3H), 5.42 (d, $J = 14.8$ Hz, 1H), 5.87 (br s, 1H), 6.29 (dd, $J = 4.0, 2.8$ Hz, 1H), 7.01 (dd, $J = 4.0, 1.6$ Hz, 1H), 7.13 (ddd, $J = 2.8, 1.6, 1.2$ Hz, 1H), 9.48 (d, $J = 1.2$ Hz, 1H) ppm; ^{13}C NMR $\delta = 37.1, 52.1, 52.9, 57.5, 110.2, 125.9, 131.0, 131.9, 169.2, 170.7,$

179.3 ppm; IR $\nu = 3116, 3002, 2952, 2848, 2817, 1737, 1652, 1533, 1474, 1433, 1413, 1370, 1339, 1276, 1221, 1166, 1084, 1039, 1008, 755$ cm^{-1} ; HRMS (EI) calcd for $\text{C}_{11}\text{H}_{13}\text{NO}_5$ 239.0794, found 239.0797.

Dimethyl (S)-2-(2-formyl-1H-pyrrol-1-yl)pentanedioate (5i). The mixture of L-glutamic acid dimethyl ester, ammonium chloride salt (2.00 g, 9.45 mmol), Et_3N (1.3 mL, 9.45 mmol), D-ribose (2.84 g, 18.9 mmol), and oxalic acid (0.86 g, 9.45 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5i** (885 mg, 3.50 mmol) in 37% yield as light-brown liquid after purification by SiO_2 column chromatography.

Data for 5i. $R_f = 0.46$ (4 : 6 EtOAc/hexane); ^1H NMR $\delta = 2.19$ –2.37 (m, 3H), 2.55–2.65 (m, 1H), 3.65 (s, 3H), 3.74 (s, 3H), 5.95 (br s, 1H), 6.33 (dd, $J = 4.0, 2.8$ Hz, 1H), 6.99 (dd, $J = 4.0, 1.6$ Hz, 1H), 7.15 (ddd, $J = 2.8, 1.6, 1.2$ Hz, 1H), 9.51 (d, $J = 1.2$ Hz, 1H) ppm; ^{13}C NMR $\delta = 27.8, 30.0, 51.8, 52.7, 58.6, 110.7, 125.6, 130.1, 131.6, 170.4, 172.6, 179.7$ ppm; IR $\nu = 3120, 2996, 2960, 2927, 2857, 2811, 2727, 1744, 1664, 1535, 1478, 1443, 1417, 1368, 1337, 1268, 1211, 1181, 1097, 1036, 1017, 887, 849, 834, 765$ cm^{-1} ; HRMS (EI) calcd for $\text{C}_{12}\text{H}_{15}\text{NO}_5$ 253.0950, found 253.0948.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-(methylthio)butanoate (5j). The mixture of L-methionine methyl ester, ammonium chloride salt (2.00 g, 10.0 mmol), Et_3N (1.4 mL, 10.1 mmol), D-ribose (3.01 g, 20.0 mmol), and oxalic acid (0.90 g, 10.0 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5j** (1.11 g, 4.60 mmol) in 46% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 5j. $R_f = 0.59$ (4 : 6 EtOAc/hexane); ^1H NMR $\delta = 2.07$ (s, 3H), 2.21–2.36 (m, 2H), 2.36–2.44 (m, 1H), 2.48–2.58 (m, 1H), 3.74 (s, 3H), 5.91 (br s, 1H), 6.33 (dd, $J = 4.0, 2.8$ Hz, 1H), 7.00 (dd, $J = 4.0, 1.6$ Hz, 1H), 7.16 (dd, $J = 2.8, 1.6$ Hz, 1H) ppm; ^{13}C NMR $\delta = 16.2, 30.1, 31.4, 52.7, 58.7, 110.5, 110.0, 125.7, 130.5, 131.5, 170.5, 179.5$ ppm; IR $\nu = 3112, 2946, 2918, 2843, 2817, 1741, 1650, 1532, 1472, 1407, 1373, 1342, 1272, 1226, 1208, 1085, 1031, 1003, 750$ cm^{-1} ; HRMS (EI) calcd for $\text{C}_{11}\text{H}_{15}\text{NO}_3\text{S}$ 241.0773, found 241.0771.

Methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-3-(1H-indol-3-yl)propanoate (5k). The mixture of L-tryptophan methyl ester, ammonium chloride salt (2.00 g, 7.85 mmol), Et_3N (1.1 mL, 7.85 mmol), D-ribose (2.36 g, 15.7 mmol), and oxalic acid (0.71 g, 7.85 mmol) in dry DMSO (10 mL) was pressurized to 2.5 bar by argon and reacted at 80 °C for 30 min to give **5k** (1.28 g, 4.32 mmol) in 55% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 5k. $R_f = 0.40$ (4 : 6 EtOAc/hexane); ^1H NMR $\delta = 3.47$ (dd, $J = 14.4, 9.2$ Hz, 1H), 3.71 (dd, $J = 14.4, 5.6$ Hz, 1H), 3.73 (s, 3H), 6.09 (br s, 1H), 6.17 (dd, $J = 3.6, 2.4$ Hz, 1H), 6.71 (d, $J = 2.4$ Hz, 1H), 6.93 (dd, $J = 3.6, 1.6$ Hz, 1H), 7.01 (br s, 1H), 7.11 (ddd, $J = 8.4, 6.8, 0.8$ Hz, 1H), 7.18 (ddd, $J = 8.4, 6.8, 1.2$ Hz, 1H), 7.31 (d, $J = 8.4$ Hz, 1H), 7.54 (d, $J = 8.4$ Hz, 1H), 7.99 (br s, 1H), 9.48 (d, $J = 1, 2$ Hz, 1H) ppm; ^{13}C NMR $\delta = 28.6, 52.6, 60.5, 110.0, 110.3, 111.1, 118.3, 119.6, 122.1, 122.7, 125.7, 127.0, 130.8, 131.2, 135.9, 170.6, 179.5$ ppm; IR $\nu = 3017, 2872, 1743, 1658, 1457, 1402, 1372, 1345, 1223, 1151, 1092, 1079, 1034, 997,$



977, 912, 758, 733 703, 666, 651 cm^{-1} ; HRMS (FAB) calcd for $\text{C}_{17}\text{H}_{17}\text{N}_2\text{O}_3$ 297.1239, found 297.1237.

General procedure for reductive amination of pyrrolines 5 with benzylamine

2-Benzyl-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6a). The mixture of methyl 2-(2-formyl-1*H*-pyrrol-1-yl)acetate (**5a**) (120 mg, 0.72 mmol) and benzylamine (116 mg, 1.08 mmol) in MeOH (5 mL) was stirred at room temperature for 12 h, and then NaBH_4 (20 mg, 0.53 mmol) was added at 0 °C. The mixture was stirred at 0 °C for 9 h, quenched with 10% NaHCO_3 solution, and extracted with EtOAc. The organic layer was washed with brine and H_2O , dried over anhydrous Na_2SO_4 , filtered, and concentrated under reduced pressure to give the crude product, which was treated with DBU (0.53 g, 3.48 mmol) in toluene (10 mL). The mixture was heated at 120 °C for 12 h and cooled to room temperature. The reaction mixture was concentrated under reduced pressure and purified by SiO_2 flash column chromatography to give **6a** (59 mg, 0.26 mmol) in 36% yield as light-yellow liquid.

Data for 6a. $^1\text{H-NMR}$ δ = 4.43 (s, 2H), 4.70 (s, 2H), 4.75 (s, 2H), 5.91 (dd, J = 2.4, 1.6 Hz, 1H), 6.21 (dd, J = 3.6, 2.4 Hz, 1H), 6.61 (dd, J = 2.4, 1.6 Hz, 1H), 7.26–7.37 (m, 5H) ppm; $^{13}\text{C-NMR}$ δ = 44.2, 48.4, 50.0, 103.2, 109.6, 118.0, 121.9, 127.9, 128.2, 128.8, 135.8, 164.6 ppm; IR (neat) ν = 3034, 2926, 2848, 1715, 1651, 1543, 1491, 1450, 1424, 1323, 1256, 1204, 1182, 1073, 1025, 950, 902, 816, 742, 697, 608 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{14}\text{H}_{14}\text{N}_2\text{O}$ + Na 249.0998, found 249.1001.

(*S*)-2-Benzyl-4-methyl-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6b). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)propanoate (**5b**) (120 mg, 0.66 mmol) and benzylamine (106 mg, 0.99 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH_4 (20 mg, 0.53 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.50 g, 3.28 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6b** (105 mg, 0.44 mmol) in 66% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 6b. $^1\text{H-NMR}$ δ = 1.68 (d, J = 7.2 Hz, 3H), 4.36 (A of ABq, J = 15.2 Hz, 1H), 4.42 (B of ABq, J = 15.2 Hz, 1H), 4.72 (s, 2H), 4.74 (q, J = 7.2 Hz, 1H), 5.89 (m, 1H), 6.20 (dd, J = 3.6, 2.8 Hz, 1H), 6.64 (dd, J = 2.8, 2.0 Hz, 1H), 7.24–7.36 (m, 5H) ppm; $^{13}\text{C-NMR}$ δ = 20.2, 43.8, 50.2, 54.7, 103.1, 109.4, 117.0, 121.6, 127.7, 128.0, 128.7, 135.9, 168.1 ppm; IR (neat) ν = 3068, 3030, 2974, 2926, 2848, 1711, 1651, 1543, 1483, 1450, 1319, 1256, 1204, 1144, 1073, 1029, 965, 932, 896, 738, 697, 611 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{15}\text{H}_{16}\text{N}_2\text{O}$ + Na 263.1155, found 263.1158.

(*S*)-2-Benzyl-4-isopropyl-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6c). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylbutanoate (**5c**) (120 mg, 0.57 mmol) and benzylamine (87 mg, 0.81 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH_4 (16 mg, 0.43 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.41 g, 2.69 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6c** (112 mg, 0.42 mmol) in 73% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 6c. $^1\text{H-NMR}$ δ = 0.84 (d, J = 7.2 Hz, 3H), 1.06 (d, J = 7.2 Hz, 3H), 2.39 (m, 1H), 4.27 (A of ABq, J = 15.6 Hz, 1H), 4.39 (B of ABq, J = 15.6 Hz, 1H), 4.52 (d, J = 4.4 Hz, 1H), 4.59 (A of ABq, J = 14.8 Hz, 1H), 4.82 (B of ABq, J = 14.8 Hz, 1H), 5.89 (dd, J = 3.6, 1.6 Hz, 1H), 6.16 (dd, J = 3.6, 2.8 Hz, 1H), 6.57 (dd, J = 2.8, 1.6 Hz, 1H), 7.22–7.34 (m, 5H) ppm; $^{13}\text{C-NMR}$ δ = 17.6, 19.9, 34.7, 44.2, 50.2, 65.2, 103.0, 108.6, 119.1, 122.5, 127.7, 128.2, 128.7, 136.0, 167.4 ppm; IR (neat) ν = 3094, 3027, 2967, 2933, 2870, 1655, 1543, 1495, 1469, 1454, 1387, 1353, 1290, 1275, 1216, 1152, 1070, 991, 957, 891, 861, 790, 749, 716, 696, 662, 615 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{17}\text{H}_{20}\text{N}_2\text{O}$ + Na 291.1468, found 291.1470.

(*S*)-2-Benzyl-4-((*S*)-*sec*-butyl)-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6d). The reaction of methyl (2*S*,3*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylpentanoate (**5e**) (0.12 g, 0.54 mmol) and benzylamine (87 mg, 0.81 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH_4 (16 mg, 0.43 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.41 g, 2.69 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6d** (131 mg, 0.46 mmol) in 86% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 6d. $^1\text{H-NMR}$ δ = 0.90 (t, J = 7.2 Hz, 3H), 1.00 (d, J = 6.8 Hz, 3H), 1.05–1.17 (m, 1H), 1.49–1.60 (m, 1H), 2.05–2.16 (m, 1H), 4.30 (A of ABq, J = 15.2 Hz, 1H), 4.43 (B of ABq, J = 15.2 Hz, 1H), 4.62 (d, J = 4.4 Hz, 1H), 4.67 (A of ABq, J = 14.8 Hz, 1H), 4.78 (B of ABq, J = 14.8 Hz, 1H), 5.89 (dd, J = 3.2, 2.0 Hz, 1H), 6.18 (dd, J = 3.2, 2.8 Hz, 1H), 6.59 (dd, J = 2.8, 2.0 Hz, 1H), 7.26–7.36 (m, 5H) ppm; $^{13}\text{C-NMR}$ δ = 11.5, 15.9, 24.9, 41.7, 44.3, 50.3, 64.3, 103.0, 108.9, 118.8, 122.6, 127.8, 128.3, 128.7, 136.1, 167.2 ppm; IR (neat) ν = 3019, 2963, 2926, 2874, 1707, 1651, 1543, 1487, 1454, 1323, 1215, 1141, 1073, 1029, 950, 928, 898, 742, 697, 667, 634, 611 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{18}\text{H}_{22}\text{N}_2\text{O}$ + Na 305.1624, found 305.1628.

(*S*)-2,4-Dibenzyl-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6e). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-phenylpropanoate (**5f**) (120 mg, 0.47 mmol) and benzylamine (76 mg, 0.71 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH_4 (17 mg, 0.45 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.43 g, 2.82 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6e** (61 mg, 0.19 mmol) in 41% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 6e. $^1\text{H-NMR}$ δ = 3.09 (d, J = 15.2 Hz, 3H), 3.26 (d of A of ABq, J_{AB} = 13.6, J_{d} = 4.4 Hz, 1H), 3.41 (d of B of ABq, J_{AB} = 13.6, J_{d} = 4.4 Hz, 1H), 3.93 (d, J = 15.2 Hz, 1H), 4.39 (A of ABq, J_{AB} = 14.8 Hz, 1H), 4.65 (B of ABq, J_{AB} = 14.8 Hz, 1H), 5.03 (t, J = 4.4 Hz, 1H), 5.71 (dd, J = 3.6, 1.6 Hz, 1H), 6.22 (dd, J = 3.6, 2.8 Hz, 1H), 6.62 (dd, J = 2.8, 1.6 Hz, 1H), 6.66–6.70 (m, 2H), 7.00–7.06 (m, 2H), 7.13–7.17 (m, 3H), 7.24–7.32 (m, 3H) ppm; $^{13}\text{C-NMR}$ δ = 41.5, 43.6, 50.1, 60.0, 102.4, 109.8, 116.9, 122.8, 127.2, 127.7, 128.1, 128.5, 128.6, 129.6, 134.9, 135.6, 166.6 ppm; IR (neat) ν = 3068, 3027, 2933, 2844, 1647, 1483, 1439, 1394, 1327, 1252, 1204, 1170, 1077, 1029, 965, 898, 861, 742, 693, 663, 630, 611 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{21}\text{H}_{20}\text{N}_2\text{O}$ + Na 339.1468, found 339.1470.



(S)-2-Benzyl-4-phenethyl-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6f). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-4-phenylbutanoate (**5g**) (120 mg, 0.44 mmol) and benzylamine (71 mg, 0.66 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH₄ (13 mg, 0.34 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.34 g, 2.23 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6f** in 64% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 6f. ¹H-NMR δ = 2.25–2.40 (m, 2H), 2.44–2.53 (m, 1H), 2.56–2.65 (m, 1H), 4.31 (A of ABq, *J*_{AB} = 15.6 Hz, 1H), 4.39 (B of ABq, *J*_{AB} = 15.6 Hz, 1H), 4.61 (A of ABq, *J*_{AB} = 14.4 Hz, 1H), 4.74 (B of ABq, *J*_{AB} = 14.4 Hz, 1H), 4.75 (dd, *J* = 5.6, 5.2 Hz, 1H), 5.89 (dd, *J* = 3.6, 1.6 Hz, 1H), 6.21 (dd, *J* = 3.6, 2.8 Hz, 1H), 6.60 (dd, *J* = 2.8, 1.6 Hz, 1H), 7.09–7.18 (m, 3H), 7.21–7.33 (m, 7H) ppm; ¹³C-NMR δ = 30.6, 36.2, 43.9, 50.1, 58.7, 103.1, 109.4, 117.6, 121.9, 126.0, 127.7, 128.0, 128.2, 128.3, 128.6, 135.9, 140.2, 167.2 ppm; IR (neat) ν = 3067, 3027, 2922, 2856, 1652, 1485, 1452, 1328, 1256, 1078, 1026, 746, 698 cm⁻¹; HRMS (ESI) calcd for C₂₂H₂₂N₂O + Na 353.1624, found 353.1626.

Methyl (*S*)-2-(2-benzyl-3-oxo-1,2,3,4-tetrahydropyrrolo[1,2-*a*]pyrazin-4-yl)acetate (6g). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)succinate (**5h**) (120 mg, 0.50 mmol) and benzylamine (80 mg, 0.75 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH₄ (15 mg, 0.40 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.38 g, 2.50 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6g** (125 mg, 0.42 mmol) in 84% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 6g. ¹H-NMR δ = 3.14 (d of A of ABq, *J*_{AB} = 16.8, *J*_d = 4.8 Hz, 1H), 3.18 (d of B of ABq, *J*_{AB} = 16.8, *J*_d = 5.2 Hz, 1H), 3.62 (s, 3H), 4.37 (d of A of ABq, *J*_{AB} = 15.2, *J*_d = 0.8 Hz, 1H), 4.68 (B of ABq, *J*_{AB} = 15.2 Hz, 1H), 4.70 (A of ABq, *J*_{AB} = 14.8 Hz, 1H), 4.79 (B of ABq, *J*_{AB} = 14.8 Hz, 1H), 5.05 (dd, *J* = 5.2, 4.8 Hz, 1H), 5.88 (dd, *J* = 3.6, 1.6 Hz, 1H), 6.19 (dd, *J* = 3.6, 2.8 Hz, 1H), 6.63 (dd, *J* = 2.8, 1.6 Hz, 1H), 7.26–7.37 (m, 5H) ppm; ¹³C-NMR δ = 38.3, 44.0, 50.4, 52.0, 55.0, 103.3, 109.7, 117.3, 122.2, 127.7, 128.1, 128.7, 135.7, 166.4, 170.2 ppm; IR (neat) ν = 3031, 2923, 2854, 1735, 1654, 1487, 1437, 1370, 1330, 1249, 1201, 1168, 1077, 1018, 987, 896, 744, 699 cm⁻¹; HRMS (ESI) calcd for C₁₇H₁₈N₂O₃ + Na 321.1210, found 321.1214.

(S)-2-Benzyl-4-(2-(methylthio)ethyl)-1,2-dihydropyrrolo[1,2-*a*]pyrazin-3(4*H*)-one (6h). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-4-(methylthio)butanoate (**5j**) (120 mg, 0.50 mmol) and benzylamine (80 mg, 0.75 mmol) in MeOH (5 mL) at room temperature for 12 h, followed by NaBH₄ (15 mg, 0.40 mmol) reduction at 0 °C for 9 h, and then cyclization by DBU (0.38 g, 2.50 mmol) in toluene (10 mL) at 120 °C for 12 h produced **6h** (71 mg, 0.24 mmol) in 47% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 6h. ¹H-NMR δ = 2.06 (s, 3H), 2.23–2.33 (m, 2H), 2.34–2.49 (m, 2H), 4.33 (A of ABq, *J* = 15.6 Hz, 1H), 4.41 (B of ABq, *J* = 15.6 Hz, 1H), 4.67 (A of ABq, *J* = 14.8 Hz, 1H), 4.73 (B of ABq, *J* = 14.8 Hz, 1H), 4.87 (t, *J* = 5.6 Hz, 1H), 5.89 (dd, *J* = 2.8, 1.6 Hz, 1H), 6.19 (dd, *J* = 3.6, 2.8 Hz, 1H), 6.63 (dd, *J* = 2.8, 1.6 Hz, 1H), 7.24–7.36 (m, 5H) ppm; ¹³C-NMR δ = 15.2, 29.2, 33.6, 44.0, 50.4,

58.0, 103.4, 109.6, 117.9, 122.1, 127.9, 128.2, 128.8, 136.0, 167.3 ppm; IR (neat) ν = 3008, 2915, 2837, 1647, 1483, 1431, 1331, 1286, 1252, 1159, 1073, 1025, 950, 898, 820, 742, 697, 626, 611 cm⁻¹; HRMS (ESI) calcd for C₁₇H₂₀N₂OS + Na 323.1189, found 323.1192.

General procedure for cyclization of pyrrolines **5** with ethane-1,2-diamine

1,2,3,10*b*-Tetrahydroimidazo[1,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (7a). The mixture of methyl 2-(2-formyl-1*H*-pyrrol-1-yl)acetate (**5a**) (1.00 g, 5.98 mmol) and ethane-1,2-diamine (360 mg, 5.99 mmol) in MeOH (10 mL) was heated at 70 °C for 1 h and cooled to room temperature. The reaction mixture was concentrated under reduced pressure and purified by SiO₂ flash column chromatography to give **7a** (615 mg, 3.47 mmol) in 58% yield as white solid.

Data for 7a. ¹H-NMR δ = 2.14 (br s, 1H), 3.18–3.30 (m, 1H), 3.48–3.62 (m, 3H), 4.55 (A of ABq, *J* = 16.8 Hz, 1H), 4.60 (B of ABq, *J* = 16.8 Hz, 1H), 5.25 (br s, 1H), 6.22–6.26 (m, 2H), 6.66 (dd, *J* = 2.0, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 43.9, 45.0, 49.0, 70.4, 104.2, 109.5, 119.1, 124.8, 162.1 ppm; IR (KBr) ν = 3226, 3115, 3098, 2976, 2960, 2885, 2857, 1636, 1470, 1441, 1305, 1216, 1173, 1159, 1126, 1070, 1004, 968, 951, 932, 906, 856, 770, 756, 729, 681 cm⁻¹; HRMS (ESI) calcd for C₉H₁₁N₃O + Na 200.0794, found 200.0797.

(6*S*)-6-Methyl-1,2,3,10*b*-tetrahydroimidazo[1,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (7b). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)propanoate (**5b**) (1.00 g, 5.52 mmol) and ethane-1,2-diamine (332 mg, 5.52 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7b** (918 mg, 4.80 mmol) in 87% yield (a 3 : 1 mixture of stereoisomers) as white solid after purification by SiO₂ column chromatography.

Data for 7b. ¹H-NMR (major) δ = 1.61 (d, *J* = 7.2 Hz, 3H), 2.14 (br s, 1H), 3.20–3.31 (m, 1H), 3.47–3.61 (m, 3H), 4.68 (q, *J* = 7.2 Hz, 1H), 5.26 (br s, 1H), 6.22–6.28 (m, 2H), 6.68 (dd, *J* = 2.4, 2.0 Hz, 1H) ppm; ¹³C-NMR (major) δ = 21.2, 43.8, 44.8, 55.8, 69.7, 103.8, 109.3, 117.9, 124.2, 165.7 ppm; (minor) δ = 14.6, 44.2, 44.8, 53.4, 69.7, 103.9, 108.7, 116.9, 125.9, 164.6 ppm; IR (KBr) ν = 3065, 3030, 2946, 2920, 2872, 2844, 1648, 1543, 1486, 1460, 1431, 1357, 1329, 1252, 1221, 1140, 1073, 1025, 962, 766, 739, 700 cm⁻¹; HRMS (ESI) calcd for C₁₀H₁₃N₃O + Na 214.0951, found 214.0954.

(6*S*)-6-Isopropyl-1,2,3,10*b*-tetrahydroimidazo[1,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (7c). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylbutanoate (**5c**) (1.00 g, 4.78 mmol) and ethane-1,2-diamine (287 mg, 4.78 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7c** (985 mg, 4.49 mmol) in 94% yield as white solid after purification by SiO₂ column chromatography.

Data for 7c. ¹H-NMR δ = 0.93 (d, *J* = 6.4 Hz, 3H), 1.08 (d, *J* = 6.8 Hz, 3H), 2.10 (br s, 1H), 2.22–2.34 (m, 1H), 3.17–3.28 (m, 1H), 3.47–3.60 (m, 3H), 4.39 (d, *J* = 5.2 Hz, 1H), 5.25 (s, 1H), 6.22 (dd, *J* = 3.6, 2.0 Hz, 1H), 6.24 (dd, *J* = 3.6, 1.2 Hz, 1H), 6.64 (dd, *J* = 2.0, 1.2 Hz, 1H) ppm; ¹³C-NMR δ = 18.1, 19.6, 34.3, 44.2, 45.0, 66.3, 70.4, 103.8, 108.7, 120.0, 125.6, 165.1 ppm; IR (KBr) ν = 3278, 2971, 2891, 1654, 1567, 1463, 1430, 1395, 1372, 1325,



1303, 1251, 1221, 1178, 1153, 1112, 1075, 950, 922, 903, 855, 750, 717, 667 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{N}_3\text{O} + \text{Na}$ 242.1264, found 242.1265.

(6S)-6-((S)-sec-Butyl)-1,2,3,10b-tetrahydroimidazo[1,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (7d). The reaction of methyl (2S,3S)-2-(2-formyl-1H-pyrrol-1-yl)-3-methylpentanoate (**5e**) (1.00 g, 4.48 mmol) and ethane-1,2-diamine (270 mg, 4.48 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7d** (951 mg, 4.08 mmol) in 91% yield as white solid after purification by SiO_2 column chromatography.

Data for 7d. $^1\text{H-NMR}$ δ = 0.90 (t, J = 7.2 Hz, 3H), 0.98 (d, J = 7.2 Hz, 3H), 1.05–1.17 (m, 1H), 1.49–1.61 (m, 1H), 1.92–2.04 (m, 1H), 2.25 (br s, 1H), 3.13–3.24 (m, 1H), 3.42–3.56 (m, 3H), 4.42 (d, J = 5.6 Hz, 1H), 5.21 (br s, 1H), 6.17–6.21 (m, 2H), 6.62 (dd, J = 2.0, 2.0 Hz, 1H) ppm; $^{13}\text{C-NMR}$ δ = 11.1, 15.3, 24.7, 40.8, 44.0, 44.7, 65.0, 70.2, 103.5, 108.6, 119.3, 125.4, 164.6 ppm; IR (KBr) ν = 3292, 3103, 2962, 2931, 2880, 2860, 1638, 1464, 1430, 1349, 1323, 1277, 1247, 1221, 1189, 1108, 1078, 1025, 958, 902, 877, 772, 710 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{13}\text{H}_{19}\text{N}_3\text{O} + \text{Na}$ 256.1420, found 256.1421.

(6S)-6-Benzyl-1,2,3,10b-tetrahydroimidazo[1,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (7e). The reaction of methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-3-phenylpropanoate (**5f**) (1.00 g, 3.89 mmol) and ethane-1,2-diamine (234 mg, 3.89 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7e** (894 mg, 3.34 mmol) in 86% yield as white solid after purification by SiO_2 column chromatography.

Data for 7e. $^1\text{H-NMR}$ δ = 1.94 (br s, 1H), 2.90–2.99 (m, 1H), 3.24 (d of A of ABq, $J_{\text{AB}} = 13.6$, $J_{\text{d}} = 4.4$ Hz, 1H), 3.30 (d of B of ABq, $J_{\text{AB}} = 13.6$, $J_{\text{d}} = 4.8$ Hz, 1H), 3.25–3.39 (m, 2H), 3.43–3.52 (m, 1H), 3.79 (s, 1H), 4.90 (dd, $J = 4.8$, 4.4 Hz, 1H), 6.07 (dd, $J = 3.6$, 1.2 Hz, 1H), 6.23 (dd, $J = 3.6$, 2.8 Hz, 1H), 6.59 (dd, $J = 2.8$, 1.2 Hz, 1H), 6.74–6.79 (m, 2H), 7.12–7.18 (m, 2H), 7.19–7.24 (m, 1H) ppm; $^{13}\text{C-NMR}$ δ = 41.4, 43.6, 44.7, 61.3, 69.6, 103.5, 109.7, 118.2, 125.6, 127.5, 128.2, 129.5, 134.8, 164.0 ppm; IR (KBr) ν = 3276, 3064, 3031, 2951, 2885, 2857, 1644, 1469, 1459, 1436, 1328, 1306, 1217, 1173, 1119, 1076, 942, 914, 773, 728, 696 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{16}\text{H}_{18}\text{N}_3\text{O} [\text{M} + 1]^+$ 268.1444, found 268.1448.

(6S)-6-Phenethyl-1,2,3,10b-tetrahydroimidazo[1,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (7f). The reaction of methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-phenylbutanoate (**5g**) (1.00 g, 3.69 mmol) and ethane-1,2-diamine (222 mg, 3.69 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7f** (914 mg, 3.25 mmol) in 88% yield as white solid after purification by SiO_2 column chromatography.

Data for 7f. $^1\text{H-NMR}$ δ = 2.08 (br s, 1H), 2.14–2.24 (m, 1H), 2.25–2.35 (m, 1H), 2.58–2.67 (m, 1H), 2.68–2.77 (m, 1H), 3.17–3.28 (m, 1H), 3.47–3.60 (m, 3H), 4.63 (dd, $J = 6.8$, 6.4 Hz, 1H), 5.24 (s, 1H), 6.23–6.27 (m, 2H), 6.66 (dd, $J = 2.4$, 1.6 Hz, 1H), 7.13–7.21 (m, 3H), 7.24–7.30 (m, 2H) ppm; $^{13}\text{C-NMR}$ δ = 31.3, 36.7, 44.2, 45.0, 60.1, 70.2, 104.2, 109.4, 119.1, 125.1, 126.2, 128.3, 128.5, 140.0, 165.3 ppm; IR (KBr) ν = 3276, 3028, 2950, 2885, 2859, 1652, 1458, 1429, 1334, 1305, 1221, 1158, 1118, 1073, 912, 771, 752, 698 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{17}\text{H}_{20}\text{N}_3\text{O} [\text{M} + 1]^+$ 282.1601, found 282.1604.

Methyl 2-((6S)-5-oxo-1,2,3,5,6,10b-hexahydroimidazo[1,2-a]pyrrolo[2,1-c]pyrazin-6-yl)acetate (7g). The reaction of dimethyl

(S)-2-(2-formyl-1H-pyrrol-1-yl)succinate (**5h**) (1.00 g, 4.18 mmol) and ethane-1,2-diamine (251 mg, 4.18 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7g** (750 mg, 3.01 mmol) in 72% yield (a 3 : 1 mixture of stereoisomers) as white solid after purification by SiO_2 column chromatography.

Data for 7g. $^1\text{H-NMR}$ (major) δ = 2.31 (br s, 1H), 2.91 (d of A of ABq, $J_{\text{AB}} = 16.8$, $J_{\text{d}} = 8.0$ Hz, 1H), 3.02 (d of B of ABq, $J_{\text{AB}} = 16.8$, $J_{\text{d}} = 4.4$ Hz, 1H), 3.17–3.48 (m, 1H), 3.45–3.59 (m, 3H), 3.66 (s, 3H), 4.99 (dd, $J = 8.0$, 4.4 Hz, 1H), 5.26 (s, 1H), 6.18–6.23 (m, 2H), 6.72 (br s, 1H) ppm; (minor) δ = 2.31 (br s, 1H), 3.17–3.38 (m, 3H), 3.45–3.58 (m, 3H), 3.67 (s, 3H), 4.91 (dd, $J = 5.2$, 4.8 Hz, 1H), 5.23 (s, 1H), 6.22–6.27 (m, 2H), 6.62 (br s, 1H) ppm; $^{13}\text{C-NMR}$ (major) δ = 38.9, 44.0, 44.8, 52.0, 56.1, 70.0, 104.1, 109.5, 119.1, 124.7, 163.7, 169.9 ppm; (minor) δ = 35.1, 44.3, 44.8, 51.9, 54.5, 70.0, 104.7, 109.3, 116.8, 125.1, 163.7, 170.5 ppm; IR (KBr) ν = 3287, 2999, 2941, 2878, 1734, 1653, 1461, 1438, 1376, 1330, 1307, 1214, 1173, 1118, 1072, 909, 750, 725 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{16}\text{N}_3\text{O}_3 [\text{M} + 1]^+$ 250.1186, found 250.1188.

(6S)-6-(2-(Methylthio)ethyl)-1,2,3,10b-tetrahydroimidazo[1,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (7h). The reaction of methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-(methylthio)butanoate (**5j**) (1.00 g, 4.18 mmol) and ethane-1,2-diamine (251 mg, 4.18 mmol) in MeOH (10 mL) at 70 °C for 1 h produced **7h** (914 mg, 3.64 mmol) in 87% yield as white solid after purification by SiO_2 column chromatography.

Data for 7h. $^1\text{H-NMR}$ δ = 2.00–2.11 (m, 1H), 2.07 (s, 3H), 2.15–2.25 (m, 1H), 2.38–2.46 (m, 1H), 2.50–2.58 (m, 1H), 3.14–3.24 (m, 1H), 3.42–3.52 (m, 3H), 4.71 (dd, $J = 8.0$, 5.2 Hz, 1H), 5.20 (s, 1H), 6.17–6.21 (m, 2H), 6.67 (dd, $J = 2.8$, 1.6 Hz, 1H) ppm; $^{13}\text{C-NMR}$ δ = 14.7, 29.1, 33.6, 43.7, 44.6, 58.5, 69.7, 103.7, 108.9, 118.7, 124.6, 164.6 ppm; IR (KBr) ν = 3272, 3108, 2959, 2922, 2885, 2851, 1643, 1454, 1412, 1335, 1298, 1220, 1159, 1156, 1073, 948, 923, 897, 761, 708 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{18}\text{N}_3\text{OS} [\text{M} + 1]^+$ 252.1165, found 252.1168.

General procedure for cyclization of pyrrolines 5 with (S)-2-aminopropan-1-ol

(3S)-3-Methyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8a). The mixture of methyl 2-(2-formyl-1H-pyrrol-1-yl)acetate (**5a**) (1.12 g, 6.70 mmol) and (S)-2-aminopropan-1-ol (0.52 mL, 6.70 mmol) in toluene (5 mL) was stirred at room temperature for 2.5 h and then heated at 110 °C for 6 h. The reaction mixture was cooled to room temperature, concentrated under reduced pressure, and purified by SiO_2 flash column chromatography to give **8a** (154 mg, 0.80 mmol) in 12% yield as light-yellow liquid.

Data for 8a. $^1\text{H-NMR}$ δ = 1.41 (d, $J = 6.0$ Hz, 3H), 3.63 (ddd, $J = 6.8$, 6.4, 1.2 Hz, 1H), 4.40 (dd, $J = 7.2$, 6.8 Hz, 1H), 4.44 (ddq, $J_{\text{d}} = 7.2$, 6.4, $J_{\text{q}} = 6.0$ Hz, 1H), 4.60 (A of ABq, $J_{\text{AB}} = 16.8$ Hz, 1H), 4.65 (d of B of ABq, $J_{\text{AB}} = 16.8$, $J_{\text{d}} = 0.8$ Hz, 1H), 5.88 (br s, 1H), 6.29 (dd, $J = 4.0$, 2.4 Hz, 1H), 6.33 (ddd, $J = 4.0$, 1.6, 0.8 Hz, 1H), 6.64 (dd, $J = 2.4$, 1.6 Hz, 1H) ppm; $^{13}\text{C-NMR}$ δ = 18.0, 48.5, 51.0, 72.2, 81.7, 106.2, 110.3, 119.1, 122.2, 162.7 ppm; IR (neat) ν = 2928, 2870, 1712, 1660, 1542, 1463, 1428, 1345, 1310, 1229,



1168, 1075, 1046, 976, 747, 720 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{10}\text{H}_{12}\text{N}_2\text{O}_2 + \text{Na}$, 215.0791, found 215.0791.

(3S,6S)-3,6-Dimethyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8b). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)propanoate (**5b**) (1.12 g, 6.19 mmol) and (*S*)-2-aminopropan-1-ol (0.49 mL, 6.19 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **8b** (523 mg, 2.53 mmol) in 41% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 8b. $^1\text{H-NMR}$ $\delta = 1.39$ (d, $J = 6.8$ Hz, 3H), 1.63 (d, $J = 6.8$ Hz, 3H), 3.59–3.67 (m, 1H), 4.34–4.44 (m, 2H), 4.67 (q, $J = 6.8$ Hz, 1H), 5.79 (br s, 1H), 6.26–6.31 (m, 2H), 6.60 (dd, $J = 2.4$, 2.0 Hz, 1H) ppm; $^{13}\text{C-NMR}$ $\delta = 16.3$, 17.9, 51.4, 53.5, 72.1, 81.5, 106.3, 110.0, 117.7, 122.9, 165.7 ppm; IR (neat) $\nu = 3129$, 2989, 2931, 2872, 1714, 1655, 1539, 1460, 1422, 1367, 1302, 1206, 1176, 1142, 1018, 978, 920, 820, 746, 719 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{11}\text{H}_{14}\text{N}_2\text{O}_2 + \text{Na}$, 229.0947, found 229.0952.

(3S,6S)-6-Isopropyl-3-methyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8c). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylbutanoate (**5c**) (1.12 g, 5.36 mmol) and (*S*)-2-aminopropan-1-ol (0.42 mL, 5.36 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **8c** (917 mg, 3.91 mmol) in 73% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 8c. $^1\text{H-NMR}$ $\delta = 0.92$ (d, $J = 6.8$ Hz, 3H), 1.10 (d, $J = 6.8$ Hz, 3H), 1.40 (d, $J = 6.0$ Hz, 3H), 2.27 (m, 1H), 3.60–3.68 (m, 1H), 4.33–4.43 (m, 3H), 5.80 (s, 1H), 6.26 (dd, $J = 4.0$, 2.8 Hz, 1H), 6.30 (ddd, $J = 4.0$, 1.6, 0.8 Hz, 1H), 6.62 (dd, $J = 2.8$, 1.6 Hz, 1H) ppm; $^{13}\text{C-NMR}$ $\delta = 17.8$, 18.0, 19.3, 34.9, 51.1, 65.8, 72.3, 82.1, 105.2, 109.4, 119.7, 123.8, 165.0 ppm; IR (neat) $\nu = 3116$, 2963, 2920, 2857, 1714, 1666, 1564, 1449, 1417, 1381, 1370, 1301, 1229, 1197, 1100, 1057, 973, 867, 814, 766, 703 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{13}\text{H}_{18}\text{N}_2\text{O}_2 + \text{Na}$ 257.1260, found 257.1262.

(3S,6S)-6-((*S*)-*sec*-Butyl)-3-methyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8d). The reaction of methyl (2*S*,3*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylpentanoate (**5e**) (1.12 g, 5.02 mmol) and (*S*)-2-aminopropan-1-ol (0.39 mL, 5.02 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **8d** (959 mg, 3.86 mmol) in 77% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 8d. $^1\text{H-NMR}$ $\delta = 0.90$ (d, $J = 6.8$ Hz, 3H), 0.93 (t, $J = 7.6$ Hz, 3H), 1.08–1.20 (m, 1H), 1.38 (d, $J = 6.8$ Hz, 3H), 1.54–1.65 (m, 1H), 1.91–2.02 (m, 1H), 3.57–3.65 (m, 1H), 4.31–4.40 (m, 2H), 4.51 (d, $J = 4.8$ Hz, 1H), 5.79 (br s, 1H), 6.24 (dd, $J = 3.6$, 2.8 Hz, 1H), 6.27 (ddd, $J = 3.6$, 1.6, 0.8 Hz, 1H), 6.61 (dd, $J = 2.8$, 1.6 Hz, 1H) ppm; $^{13}\text{C-NMR}$ $\delta = 11.4$, 15.0, 17.6, 25.0, 41.7, 50.9, 64.3, 72.0, 81.9, 104.9, 109.4, 119.0, 123.6, 164.5 ppm; IR (neat) $\nu = 3099$, 2958, 2925, 2867, 1709, 1666, 1563, 1539, 1460, 1430, 1386, 1295, 1216, 1195, 1068, 1055, 978, 871, 817, 766, 708 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{14}\text{H}_{20}\text{N}_2\text{O}_2 + \text{Na}$ 271.1417, found 271.1419.

(3S,6S)-6-Benzyl-3-methyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8e). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-phenylpropanoate (**5f**) (1.12 g, 4.36 mmol) and (*S*)-2-aminopropan-1-ol (0.34 mL, 4.36 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C

for 6 h produced **8e** (639 mg, 2.26 mmol) in 52% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 8e. $^1\text{H-NMR}$ $\delta = 1.21$ (d, $J = 6.0$ Hz, 3H), 3.23 (dd, $J = 13.6$, 4.4 Hz, 1H), 3.30–3.37 (m, 2H), 4.18–4.30 (m, 2H), 4.35 (s, 1H), 4.93 (t, $J = 4.4$ Hz, 1H), 6.10 (ddd, $J = 3.6$, 1.6, 0.8 Hz, 1H), 6.31 (dd, $J = 3.6$, 2.8 Hz, 1H), 6.66–6.72 (m, 3H), 7.11–7.16 (m, 2H), 7.20–7.25 (m, 1H) ppm; $^{13}\text{C-NMR}$ $\delta = 17.2$, 41.8, 50.6, 60.4, 72.1, 80.8, 104.7, 110.5, 117.6, 124.0, 127.5, 128.0, 129.8, 134.3, 163.8 ppm; IR (neat) $\nu = 3027$, 2962, 2923, 2861, 1704, 1659, 1561, 1456, 1437, 1404, 1361, 1311, 1234, 1165, 1077, 1041, 972, 822, 744, 695 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{17}\text{H}_{18}\text{N}_2\text{O}_2 + \text{Na}$ 305.1260, found 305.1264.

(3S,6S)-3-Methyl-6-phenethyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8f). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-4-phenylbutanoate (**5g**) (1.12 g, 4.13 mmol) and (*S*)-2-aminopropan-1-ol (0.32 mL, 4.13 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **8f** (269 mg, 0.91 mmol) in 22% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 8f. $^1\text{H-NMR}$ $\delta = 1.37$ (d, $J = 6.4$ Hz, 3H), 2.24–2.33 (m, 2H), 2.47–2.55 (m, 1H), 2.60–2.68 (m, 1H), 3.59–3.66 (m, 1H), 4.35–4.44 (m, 2H), 4.68 (t, $J = 6.0$ Hz, 1H), 5.78 (s, 1H), 6.30 (dd, $J = 3.6$, 2.8 Hz, 1H), 6.32 (ddd, $J = 3.6$, 1.6, 0.8 Hz, 1H), 6.66 (dd, $J = 2.8$, 1.6 Hz, 1H), 7.12–7.16 (m, 2H), 7.16–7.22 (m, 1H), 7.24–7.30 (m, 2H) ppm; $^{13}\text{C-NMR}$ $\delta = 17.8$, 30.9, 37.4, 51.1, 59.5, 72.3, 81.7, 105.7, 110.2, 118.7, 122.9, 126.3, 128.3, 128.5, 140.0, 165.6 ppm; IR (neat) $\nu = 3016$, 2966, 2930, 2857, 1714, 1666, 1561, 1449, 1434, 1406, 1359, 1302, 1227, 1168, 1076, 1058, 977, 826, 766, 725, 693 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{18}\text{H}_{20}\text{N}_2\text{O}_2 + \text{Na}$, 319.1417, found 319.1419.

Methyl 2-((3S,6S)-3-methyl-5-oxo-2,3,5,6-tetrahydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-6-yl)acetate (8g). The reaction of dimethyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)succinate (**5h**) (1.12 g, 4.68 mmol) and (*S*)-2-aminopropan-1-ol (0.36 mL, 4.68 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **8g** (334 mg, 1.26 mmol) in 27% yield (a 1.05 : 1 mixture of stereoisomers) as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 8g. $^1\text{H-NMR}$ (major) $\delta = 1.42$ (d, $J = 6.4$ Hz, 3H), 2.97 (dd, $J = 16.4$, 6.8 Hz, 1H), 3.06 (dd, $J = 16.4$, 4.4 Hz, 1H), 3.60–3.70 (m, 1H), 3.65 (s, 3H), 4.35–4.46 (m, 2H), 4.99 (dd, $J = 6.7$, 4.4 Hz, 1H), 5.82 (br s, 1H), 6.26 (dd, $J = 3.6$, 1.6 Hz, 1H), 6.30 (dd, $J = 3.6$, 2.4 Hz, 1H), 6.70 (dd, $J = 2.4$, 1.6 Hz, 1H) ppm; (minor) $\delta = 1.40$ (d, $J = 6.4$ Hz, 3H), 3.21 (dd, $J = 17.2$, 5.6 Hz, 1H), 3.36 (dd, $J = 17.2$, 5.6 Hz, 1H), 3.60–3.70 (m, 1H), 3.71 (s, 3H), 4.35–4.48 (m, 2H), 5.00 (t, $J = 5.6$ Hz, 1H), 5.79 (br s, 1H), 6.27–6.36 (m, 2H), 6.64 (m, 1H) ppm; $^{13}\text{C-NMR}$ (major) $\delta = 17.9$, 39.5, 51.2, 52.2, 54.5, 72.4, 81.5, 106.8, 110.4, 118.8, 122.9, 164.1, 169.9 ppm; (minor) $\delta = 17.6$, 36.2, 51.7, 52.1, 55.8, 72.0, 81.3, 105.8, 110.5, 117.5, 122.7, 164.7, 170.6 ppm; IR (neat) $\nu = 2957$, 2926, 2856, 1737, 1671, 1563, 1461, 1442, 1379, 1336, 1310, 1272, 1220, 1203, 1172, 1077, 1055, 976, 914, 776, 733, 673 cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{13}\text{H}_{16}\text{N}_2\text{O}_4 + \text{Na}$ 287.1002, found 287.1002.

(3S,6S)-3-Methyl-6-(2-(methylthio)ethyl)-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (8h). The reaction



of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-4-(methylthio)butanoate (**5j**) (1.12 g, 4.68 mmol) and (*S*)-2-aminopropan-1-ol (0.36 mL, 4.68 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **8h** (299 mg, 1.12 mmol) in 24% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 8h. ¹H-NMR δ = 1.40 (d, *J* = 6.0 Hz, 3H), 2.09 (s, 3H), 2.12–2.22 (m, 1H), 2.22–2.31 (m, 1H), 2.33–2.41 (m, 1H), 2.47–2.55 (m, 1H), 3.61–3.69 (m, 1H), 4.34–4.44 (m, 2H), 4.78 (dd, *J* = 6.8, 5.6 Hz, 1H), 5.80 (s, 1H), 6.28 (dd, *J* = 4.0, 2.8 Hz, 1H), 6.31 (ddd, *J* = 4.0, 1.6, 0.8 Hz, 1H), 6.68 (dd, *J* = 2.8, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 15.2, 17.7, 29.2, 34.9, 51.1, 58.6, 72.3, 81.7, 105.8, 110.2, 118.8, 122.9, 165.4 ppm; IR (neat) ν = 2967, 2910, 2862, 1645, 1556, 1465, 1412, 1398, 1354, 1307, 1228, 1168, 1041, 975, 830, 766, 719 cm⁻¹; HRMS (ESI) calcd for C₁₃H₁₈N₂O₂S + Na, 289.0981, found 289.0985.

General procedure for cyclization of pyrrolines **5** with (*S*)-2-amino-3-methylbutan-1-ol (*L*-valinol)

(3*S*,6*S*)-3-Isopropyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9a). The mixture of methyl 2-(2-formyl-1*H*-pyrrol-1-yl)acetate (**5a**) (1.12 g, 6.70 mmol) and *L*-valinol (0.69 g, 6.70 mmol) in toluene (5 mL) was stirred at room temperature for 2.5 h and then heated at 110 °C for 6 h. The reaction mixture was cooled to room temperature, concentrated under reduced pressure, and purified by SiO₂ flash column chromatography to give **9a** (59 mg, 0.27 mmol) in 4% yield as light-yellow liquid.

Data for 9a. ¹H-NMR δ = 0.98 (d, *J* = 6.8 Hz, 3H), 1.01 (d, *J* = 6.4 Hz, 3H), 2.14 (m, 1H), 3.83 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.21 (dd, *J* = 8.8, 8.0 Hz, 1H), 4.29 (ddd, *J* = 8.0, 7.2, 6.8 Hz, 1H), 4.63 (A of ABq, *J*_{AB} = 17.2 Hz, 1H), 4.72 (B of ABq, *J*_{AB} = 17.2 Hz, 1H), 5.74 (s, 1H), 6.30 (dd, *J* = 3.6, 2.4 Hz, 1H), 6.33 (ddd, *J* = 3.6, 1.6, 0.8 Hz, 1H), 6.65 (dd, *J* = 2.4, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 17.5, 19.2, 30.8, 48.4, 60.2, 67.7, 82.5, 106.5, 110.4, 119.1, 121.9, 163.9 ppm; IR (neat) ν = 2952, 2929, 2872, 1666, 1561, 1460, 1429, 1367, 1322, 1268, 1227, 1189, 1081, 1048, 973, 870, 825, 761, 713 cm⁻¹; HRMS (ESI) calcd for C₁₂H₁₆N₂O₂ + Na, 243.1104, found 243.1107.

(3*S*,6*S*)-3-Isopropyl-6-methyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9b). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)propanoate (**5b**) (1.12 g, 6.19 mmol) and *L*-valinol (0.64 g, 6.19 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9b** (392 mg, 1.67 mmol) in 27% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9b. ¹H-NMR δ = 0.97 (d, *J* = 7.2 Hz, 3H), 1.01 (d, *J* = 6.8 Hz, 3H), 1.79 (d, *J* = 7.2 Hz, 3H), 2.11 (m, 1H), 3.83 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.17 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.26 (ddd, *J* = 8.0, 7.6, 6.8 Hz, 1H), 4.68 (q, *J* = 7.2 Hz, 1H), 5.74 (s, 1H), 6.30 (dd, *J* = 3.6, 2.8 Hz, 1H), 6.33 (ddd, *J* = 3.6, 1.6, 0.8 Hz, 1H), 6.76 (dd, *J* = 2.8, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 17.2, 17.7, 19.3, 30.8, 53.4, 60.7, 67.6, 82.2, 106.6, 110.1, 117.9, 122.4, 167.1 ppm; IR (neat) ν = 2958, 2942, 2872, 1703, 1661, 1562, 1544, 1460, 1422, 1365, 1301, 1216, 1111, 1085, 1058, 984, 950, 857, 825, 751, 708 cm⁻¹; HRMS (ESI) calcd for C₁₃H₁₈N₂O₂ + Na, 257.1260, found 257.1263.

(3*S*,6*S*)-3,6-Diisopropyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9c). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylbutanoate (**5c**) (1.12 g, 5.36 mmol) and *L*-valinol (0.55 g, 5.36 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9c** (858 mg, 3.27 mmol) in 61% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9c. ¹H-NMR δ = 0.95 (d, *J* = 6.8 Hz, 3H), 0.99 (d, *J* = 7.2 Hz, 3H), 1.02 (d, *J* = 6.8 Hz, 3H), 1.03 (d, *J* = 6.8 Hz, 3H), 2.17–2.33 (m, 2H), 3.86 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.17 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.28 (ddd, *J* = 7.6, 7.2, 6.8 Hz, 1H), 4.46 (d, *J* = 5.2 Hz, 1H), 5.77 (s, 1H), 6.26 (dd, *J* = 3.6, 2.8 Hz, 1H), 6.28 (ddd, *J* = 3.6, 1.6, 0.8 Hz, 1H), 6.63 (dd, *J* = 2.8, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 17.5, 18.2, 19.2, 19.2, 30.3, 35.0, 60.1, 65.9, 67.2, 83.0, 105.2, 109.5, 119.4, 123.8, 165.9 ppm; IR (neat) ν = 3100, 2958, 2857, 1702, 1661, 1561, 1455, 1429, 1396, 1375, 1306, 1227, 1189, 1105, 1058, 967, 867, 825, 765, 708 cm⁻¹; HRMS (ESI) calcd for C₁₅H₂₂N₂O₂ + Na, 285.1573, found 285.1575.

(3*S*,6*S*)-6-((*S*)-*sec*-Butyl)-3-isopropyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9d). The reaction of methyl (2*S*,3*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylpentanoate (**5e**) (1.12 g, 5.02 mmol) and *L*-valinol (0.52 g, 5.02 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9d** (694 mg, 2.51 mmol) in 50% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9d. ¹H-NMR δ = 0.90 (d, *J* = 7.2 Hz, 3H), 0.95 (t, *J* = 7.6 Hz, 3H), 0.98 (d, *J* = 6.0 Hz, 3H), 1.00 (d, *J* = 6.8 Hz, 3H), 1.08–2.22 (m, 1H), 1.57–1.68 (m, 1H), 1.93–2.03 (m, 1H), 2.14–2.26 (m, 1H), 3.85 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.17 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.28 (ddd, *J* = 7.6, 7.2, 6.8 Hz, 1H), 4.56 (d, *J* = 5.2 Hz, 1H), 5.77 (s, 1H), 6.26–6.28 (m, 2H), 6.63 (dd, *J* = 2.8, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 11.6, 15.2, 17.6, 19.2, 25.4, 30.4, 42.0, 60.2, 64.6, 67.3, 83.0, 105.2, 109.7, 119.0, 123.8, 165.6 ppm; IR (neat) ν = 2958, 2939, 2878, 1709, 1655, 1568, 1544, 1460, 1431, 1381, 1295, 1232, 1200, 1077, 1058, 967, 879, 833, 766, 713 cm⁻¹; HRMS (ESI) calcd for C₁₆H₂₄N₂O₂ + Na, 299.1730, found 299.1734.

(3*S*,6*S*)-6-Benzyl-3-isopropyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9e). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-phenylpropanoate (**5f**) (1.12 g, 4.36 mmol) and *L*-valinol (0.45 g, 4.36 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9e** (961 mg, 3.10 mmol) in 71% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9e. ¹H-NMR δ = 0.76 (d, *J* = 7.2 Hz, 3H), 0.88 (d, *J* = 6.8 Hz, 3H), 2.09 (m, 1H), 3.29 (d of A of ABq, *J*_{AB} = 13.6, *J*_d = 4.8 Hz, 1H), 3.34 (d of B of ABq, *J*_{AB} = 13.6, *J*_d = 4.4 Hz, 1H), 3.68 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.04 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.17 (ddd, *J* = 7.6, 7.2, 6.8 Hz, 1H), 4.86 (s, 1H), 4.96 (t, *J* = 4.8 Hz, 1H), 6.16 (ddd, *J* = 3.6, 1.6, 0.8 Hz, 1H), 6.31 (dd, *J* = 3.6, 2.8 Hz, 1H), 6.64 (dd, *J* = 2.8, 1.6 Hz, 1H), 6.66–6.70 (m, 2H), 7.12–7.23 (m, 3H) ppm; ¹³C-NMR δ = 17.1, 19.0, 30.0, 41.6, 60.2, 60.6, 66.6, 82.2, 105.1, 110.4, 117.7, 123.6, 127.2, 128.2, 129.4, 134.5, 165.3 ppm; IR (neat) ν = 3032, 2962, 2926, 2872, 1708, 1661, 1556, 1455, 1430, 1403, 1350, 1306, 1297, 1237, 1175, 1113, 1079, 1041, 967, 853, 816, 729, 693 cm⁻¹; HRMS (ESI) calcd for C₁₉H₂₂N₂O₂ + Na, 333.1573, found 333.1575.



(3*S*,6*S*)-3-Isopropyl-6-phenethyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9f). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-4-phenylbutanoate (**5g**) (1.12 g, 4.13 mmol) and *L*-valinol (0.43 g, 4.13 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9f** (683 mg, 2.11 mmol) in 51% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9f. ¹H-NMR δ = 0.99 (d, *J* = 7.2 Hz, 3H), 1.02 (d, *J* = 7.2 Hz, 3H), 2.19 (m, 1H), 2.25–2.32 (m, 2H), 2.41–2.50 (m, 1H), 2.63–2.72 (m, 1H), 3.86 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.20 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.30 (ddd, *J* = 7.6, 7.2, 6.8 Hz, 1H), 4.71 (t, *J* = 5.6 Hz, 1H), 5.79 (s, 1H), 6.29–6.33 (m, 2H), 6.63 (dd, *J* = 2.4, 1.6 Hz, 1H), 7.11–7.15 (m, 2H), 7.16–7.22 (m, 1H), 7.24–7.30 (m, 2H) ppm; ¹³C-NMR δ = 17.5, 19.2, 30.6, 31.0, 38.0, 59.6, 60.1, 67.6, 82.6, 105.9, 110.3, 118.6, 122.8, 126.3, 128.3, 128.5, 140.1, 166.6 ppm; IR (neat) ν = 3015, 2963, 2925, 2878, 1709, 1666, 1549, 1455, 1422, 1403, 1343, 1302, 1232, 1158, 1058, 983, 876, 828, 713, 698 cm⁻¹; HRMS (ESI) calcd for C₂₀H₂₄N₂O₂ + Na, 347.1730, found 347.1732.

Methyl 2-((3*S*,6*S*)-3-isopropyl-5-oxo-2,3,5,6-tetrahydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-6-yl)acetate (9g). The reaction of dimethyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)succinate (**5h**) (1.12 g, 4.68 mmol) and *L*-valinol (0.48 g, 4.69 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9g** (137 mg, 0.47 mmol) in 10% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9g. ¹H-NMR δ = 0.99 (d, *J* = 6.8 Hz, 3H), 0.99 (d, *J* = 7.2 Hz, 3H), 2.26 (m, 1H), 3.00 (d of A of ABq, *J*_{AB} = 16.4, *J*_d = 6.8 Hz, 1H), 3.08 (d of B of ABq, *J*_{AB} = 16.4, *J*_d = 4.4 Hz, 1H), 3.65 (s, 3H), 3.89 (dd, *J* = 8.0, 6.0 Hz, 1H), 4.21 (dd, *J* = 8.0, 7.6 Hz, 1H), 4.26 (ddd, *J* = 7.6, 6.8, 6.0 Hz, 1H), 5.01 (dd, *J* = 6.4, 4.4 Hz, 1H), 5.79 (s, 1H), 6.27 (dd, *J* = 4.0, 2.8 Hz, 1H), 6.29 (ddd, *J* = 4.0, 1.6, 0.8 Hz, 1H), 6.70 (dd, *J* = 2.8, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 17.2, 19.0, 30.4, 39.7, 52.1, 55.9, 60.3, 67.5, 82.5, 106.0, 110.5, 118.6, 122.8, 165.0, 169.8 ppm; IR (neat) ν = 2958, 2931, 2862, 1740, 1655, 1570, 1449, 1439, 1399, 1371, 1317, 1237, 1191, 1168, 1063, 978, 862, 822, 772, 713 cm⁻¹; HRMS (ESI) calcd for C₁₅H₂₀N₂O₄ + Na, 315.1315, found 315.1316.

(3*S*,6*S*)-3-isopropyl-6-(2-(methylthio)ethyl)-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (9h). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-4-(methylthio)butanoate (**5j**) (1.12 g, 4.68 mmol) and *L*-valinol (0.48 g, 4.65 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **9h** (331 mg, 1.12 mmol) in 24% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 9h. ¹H-NMR δ = 0.96 (d, *J* = 6.8 Hz, 3H), 0.97 (d, *J* = 6.8 Hz, 3H), 2.06 (s, 3H), 2.13–2.36 (m, 4H), 2.46–2.55 (m, 1H), 3.84 (dd, *J* = 8.8, 6.8 Hz, 1H), 4.17 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.25 (ddd, *J* = 7.6, 7.2, 6.8 Hz, 1H), 4.78 (dd, *J* = 6.4, 5.6 Hz, 1H), 5.74 (s, 1H), 6.26 (dd, *J* = 4.0, 2.8 Hz, 1H), 6.28 (ddd, *J* = 4.0, 1.6, 0.8 Hz, 1H), 6.67 (dd, *J* = 2.8, 1.6 Hz, 1H) ppm; ¹³C-NMR δ = 15.3, 17.5, 19.2, 29.2, 30.5, 35.3, 58.7, 60.1, 67.5, 82.6, 106.0, 110.3, 118.7, 122.8, 166.4 ppm; IR (neat) ν = 2958, 2910, 2872, 1703, 1661, 1550, 1544, 1449, 1422, 1406, 1345, 1307, 1237,

1163, 1114, 1053, 978, 870, 831, 777, 715 cm⁻¹; HRMS (ESI) calcd for C₁₅H₂₂N₂O₂S + Na, 317.1294, found 317.1296.

General procedure for cyclization of pyrrolines **5** with (*S*)-2-amino-2-phenylethan-1-ol (*L*-phenylalaninol)

(3*S*)-3-Benzyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (10a). The mixture of methyl 2-(2-formyl-1*H*-pyrrol-1-yl)acetate (**5a**) (1.12 g, 6.70 mmol) and *L*-phenylalaninol (1.01 g, 6.70 mmol) in toluene (5 mL) was stirred at room temperature for 2.5 h and then heated at 110 °C for 6 h. The reaction mixture was cooled to room temperature, concentrated under reduced pressure, and purified by SiO₂ flash column chromatography to give **10a** (108 mg, 0.40 mmol) in 6% yield as light-yellow liquid.

Data for 10a. ¹H-NMR δ = 2.98 (dd, *J* = 13.6, 8.8 Hz, 3H), 3.29 (dd, *J* = 13.6, 4.0 Hz, 1H), 3.85 (dd, *J* = 9.2, 8.0 Hz, 1H), 4.21 (dd, *J* = 9.2, 7.6 Hz, 1H), 4.60–4.68 (m, 1H), 4.64 (A of ABq, *J*_{AB} = 17.2 Hz, 1H), 4.69 (B of ABq, *J*_{AB} = 17.2 Hz, 1H), 5.54 (s, 1H), 6.26–6.30 (m, 2H), 6.65 (dd, *J* = 2.4, 1.6 Hz, 1H), 7.22–7.28 (m, 3H), 7.29–7.36 (m, 2H) ppm; ¹³C-NMR δ = 37.7, 48.6, 55.7, 69.6, 82.5, 106.1, 110.3, 119.1, 122.3, 126.9, 128.7, 129.5, 136.2, 163.0 ppm; IR (neat) ν = 3026, 2925, 2877, 1719, 1666, 1547, 1498, 1465, 1429, 1347, 1317, 1269, 1216, 1079, 1047, 973, 750, 693 cm⁻¹; HRMS (ESI) calcd for C₁₆H₁₆N₂O₂ + Na, 291.1104, found 291.1107.

(3*S*,6*S*)-3-Benzyl-6-methyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (10b). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)propanoate (**5b**) (1.12 g, 6.19 mmol) and *L*-phenylalaninol (0.94 g, 6.19 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10b** (559 mg, 1.98 mmol) in 32% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 10b. ¹H-NMR δ = 1.65 (d, *J* = 7.2 Hz, 3H), 3.08 (dd, *J* = 13.6, 8.0 Hz, 3H), 3.18 (dd, *J* = 13.6, 4.0 Hz, 1H), 3.88 (dd, *J* = 8.8, 8.0 Hz, 1H), 4.24 (dd, *J* = 8.8, 8.0 Hz, 1H), 4.62 (dddd, *J* = 8.0, 8.0, 8.0, 4.0 Hz, 1H), 4.71 (q, *J* = 7.2 Hz, 1H), 5.41 (s, 1H), 6.22 (ddd, *J* = 4.0, 1.6, 0.8 Hz, 1H), 6.26 (dd, *J* = 4.0, 2.8 Hz, 1H), 6.65 (dd, *J* = 2.8, 1.6 Hz, 1H), 7.20–7.28 (m, 3H), 7.29–7.34 (m, 2H) ppm; ¹³C-NMR δ = 22.4, 37.2, 55.3, 55.7, 69.4, 82.3, 105.6, 110.3, 118.1, 122.1, 127.0, 128.6, 129.8, 136.1, 166.7 ppm; IR (neat) ν = 3027, 2973, 2920, 2857, 1714, 1655, 1566, 1449, 1422, 1402, 1370, 1307, 1221, 1153, 1114, 1074, 1031, 973, 819, 751, 698 cm⁻¹; HRMS (ESI) calcd for C₁₇H₁₈N₂O₂ + Na, 305.1260, found 305.1264.

(3*S*,6*S*)-3-Benzyl-6-isopropyl-2,3-dihydro-10*bH*-oxazolo[3,2-*a*]pyrrolo[2,1-*c*]pyrazin-5(6*H*)-one (10c). The reaction of methyl (*S*)-2-(2-formyl-1*H*-pyrrol-1-yl)-3-methylbutanoate (**5c**) (1.12 g, 5.36 mmol) and *L*-phenylalaninol (0.81 g, 5.36 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10c** (682 mg, 2.20 mmol) in 41% yield as light-yellow liquid after purification by SiO₂ column chromatography.

Data for 10c. ¹H-NMR δ = 0.89 (d, *J* = 6.8 Hz, 3H), 1.00 (d, *J* = 6.4 Hz, 3H), 2.25 (m, 1H), 2.92 (dd, *J* = 13.2, 9.2 Hz, 1H), 3.34 (dd, *J* = 13.2, 4.0 Hz, 1H), 3.85 (dd, *J* = 8.8, 7.2 Hz, 1H), 4.17 (dd, *J* = 8.8, 7.6 Hz, 1H), 4.44 (d, *J* = 4.8 Hz, 1H), 4.60 (dddd, *J* = 9.2, 7.6, 7.2, 4.0 Hz, 1H), 5.64 (s, 1H), 6.24 (dd, *J* = 3.6, 2.4 Hz, 1H),



6.26 (ddd, $J = 3.6, 1.6, 0.8$ Hz, 1H), 6.62 (dd, $J = 2.4, 1.6$ Hz, 1H), 7.22–7.28 (m, 3H), 7.29–7.34 (m, 2H) ppm; $^{13}\text{C-NMR}$ $\delta = 18.1, 19.3, 34.8, 37.7, 56.0, 65.9, 69.8, 82.7, 105.2, 109.4, 119.6, 123.8, 126.9, 128.6, 129.5, 136.4, 165.4$ ppm; IR (neat) $\nu = 3032, 2958, 2925, 2878, 1666, 1560, 1465, 1425, 1399, 1361, 1302, 1227, 1194, 1158, 1063, 1058, 1030, 967, 861, 756, 703$ cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{19}\text{H}_{22}\text{N}_2\text{O}_2 + \text{Na}$, 333.1573, found 333.1576.

(3S,6S)-3-Benzyl-6-((S)-sec-butyl)-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (10d). The reaction of methyl (2S,3S)-2-(2-formyl-1H-pyrrol-1-yl)-3-methylpentanoate (**5e**) (1.12 g, 5.02 mmol) and L-phenylalaninol (0.76 g, 5.02 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10d** (505 mg, 1.56 mmol) in 31% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 10d. $^1\text{H-NMR}$ $\delta = 0.91$ (d, $J = 6.8$ Hz, 3H), 0.95 (t, $J = 7.2$ Hz, 3H), 1.00–1.14 (m, 1H), 1.50–1.62 (m, 1H), 1.92–2.04 (m, 1H), 2.93 (dd, $J = 13.2, 8.8$ Hz, 1H), 3.33 (dd, $J = 13.2, 4.4$ Hz, 1H), 3.85 (dd, $J = 8.8, 7.6$ Hz, 1H), 4.17 (dd, $J = 8.8, 7.6$ Hz, 1H), 4.55 (d, $J = 5.2$ Hz, 1H), 4.60 (dddd, $J = 8.8, 7.6, 7.6, 4.4$ Hz, 1H), 5.64 (s, 1H), 6.23–6.26 (m, 2H), 6.62 (dd, $J = 2.8, 1.6$ Hz, 1H), 7.22–7.28 (m, 3H), 7.29–7.35 (m, 2H) ppm; $^{13}\text{C-NMR}$ $\delta = 11.6, 15.4, 25.1, 37.8, 41.8, 56.1, 64.7, 69.8, 82.7, 105.1, 109.6, 119.2, 123.8, 126.9, 128.6, 129.5, 136.4, 165.2$ ppm; IR (neat) $\nu = 3020, 2958, 2920, 2872, 1705, 1655, 1561, 1455, 1431, 1398, 1366, 1290, 1227, 1189, 1151, 1068, 1052, 1026, 978, 862, 735, 703$ cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{20}\text{H}_{24}\text{N}_2\text{O}_2 + \text{Na}$, 347.1730, found 347.1732.

(3S,6S)-3,6-Dibenzyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (10e). The reaction of methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-3-phenylpropanoate (**5f**) (1.12 g, 4.36 mmol) and L-phenylalaninol (0.66 g, 4.36 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10e** (969 mg, 2.70 mmol) in 62% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 10e. $^1\text{H-NMR}$ $\delta = 2.41$ (dd, $J = 13.2, 10.4$ Hz, 1H), 3.28 (d of A of ABq, $J_{\text{AB}} = 13.6, J_{\text{d}} = 4.8$ Hz, 1H), 3.32 (d of B of ABq, $J_{\text{AB}} = 13.6, J_{\text{d}} = 4.8$ Hz, 1H), 3.44 (dd, $J = 13.2, 4.4$ Hz, 1H), 3.56 (dd, $J = 9.2, 7.6$ Hz, 1H), 3.99 (dd, $J = 9.2, 7.6$ Hz, 1H), 4.45 (dddd, $J = 10.4, 7.6, 7.6, 4.4$ Hz, 1H), 4.52 (s, 1H), 4.95 (t, $J = 4.8$ Hz, 1H), 6.12 (ddd, $J = 4.0, 1.6, 0.8$ Hz, 1H), 6.28 (dd, $J = 4.0, 2.8$ Hz, 1H), 6.63 (dd, $J = 2.8, 1.6$ Hz, 1H), 6.71–6.76 (m, 2H), 7.15–7.32 (m, 8H) ppm; $^{13}\text{C-NMR}$ $\delta = 37.6, 41.8, 55.7, 60.6, 70.1, 81.4, 104.9, 110.4, 117.9, 123.7, 126.8, 127.5, 128.2, 128.7, 129.1, 129.7, 134.5, 136.5, 164.2$ ppm; IR (neat) $\nu = 3016, 2915, 2862, 1655, 1544, 1460, 1438, 1405, 1361, 1316, 1206, 1158, 1079, 1049, 1029, 975, 851, 740, 698$ cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{23}\text{H}_{22}\text{N}_2\text{O}_2 + \text{Na}$, 381.1573, found 381.1577.

(3S,6S)-3-Benzyl-6-phenethyl-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (10f). The reaction of methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-phenylbutanoate (**5g**) (1.12 g, 4.13 mmol) and L-phenylalaninol (0.63 g, 4.13 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10f** (877 mg, 2.35 mmol) in 57% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 10f. $^1\text{H-NMR}$ $\delta = 2.19$ –2.36 (m, 2H), 2.47–2.58 (m, 1H), 2.63–2.73 (m, 1H), 2.99 (dd, $J = 13.6, 8.4$ Hz, 1H), 3.21 (dd, $J = 13.6, 4.0$ Hz, 1H), 3.86 (dd, $J = 8.8, 7.6$ Hz, 1H), 4.21 (dd, $J =$

8.8, 7.6 Hz, 1H), 4.62 (dddd, $J = 8.4, 7.6, 7.6, 4.0$ Hz, 1H), 4.69 (t, $J = 6.0$ Hz, 1H), 5.51 (s, 1H), 6.26 (ddd, $J = 3.6, 1.6, 0.8$ Hz, 1H), 6.28 (dd, $J = 3.6, 2.8$ Hz, 1H), 6.65 (dd, $J = 2.8, 1.6$ Hz, 1H), 7.14–7.19 (m, 2H), 7.19–7.33 (m, 8H) ppm; $^{13}\text{C-NMR}$ $\delta = 31.0, 37.5, 37.5, 55.6, 59.5, 69.6, 82.4, 105.7, 110.2, 118.7, 122.9, 126.3, 127.0, 128.3, 128.6, 128.6, 129.6, 136.2, 140.0, 165.9$ ppm; IR (neat) $\nu = 3025, 2964, 2920, 2862, 1709, 1666, 1544, 1443, 1431, 1338, 1325, 1211, 1074, 1026, 973, 772, 687$ cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{24}\text{H}_{24}\text{N}_2\text{O}_2 + \text{Na}$, 395.1730, found 395.1733.

Methyl 2-((3S,6S)-3-benzyl-5-oxo-2,3,5,6-tetrahydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-6-yl)acetate (10g). The reaction of dimethyl (S)-2-(2-formyl-1H-pyrrol-1-yl)succinate (**5h**) (1.12 g, 4.68 mmol) and L-phenylalaninol (0.71 g, 4.69 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10g** (223 mg, 0.66 mmol) in 14% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 10g. $^1\text{H-NMR}$ $\delta = 2.91$ (dd, $J = 16.4, 7.6$ Hz, 1H), 3.02 (dd, $J = 13.6, 8.8$ Hz, 1H), 3.07 (dd, $J = 16.4, 4.0$ Hz, 1H), 3.29 (dd, $J = 13.6, 4.0$ Hz, 1H), 3.69 (s, 3H), 3.89 (dd, $J = 9.2, 7.6$ Hz, 1H), 4.22 (dd, $J = 9.2, 7.6$ Hz, 1H), 4.59 (dddd, $J = 8.8, 7.6, 7.6, 4.0$ Hz, 1H), 5.05 (dd, $J = 7.6, 4.0$ Hz, 1H), 5.54 (s, 1H), 6.22–6.27 (m, 2H), 6.70 (dd, $J = 2.4, 1.6$ Hz, 1H), 7.22–7.36 (m, 5H) ppm; $^{13}\text{C-NMR}$ $\delta = 37.2, 39.7, 52.2, 55.8, 55.9, 69.7, 82.3, 105.8, 110.4, 118.9, 122.8, 127.0, 128.7, 129.6, 136.2, 164.4, 169.9$ ppm; IR (neat) $\nu = 3032, 2947, 2927, 2867, 1735, 1666, 1555, 1455, 1438, 1442, 1400, 1365, 1317, 1221, 1168, 1084, 1026, 1029, 973, 898, 858, 830, 766, 703$ cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{19}\text{H}_{20}\text{N}_2\text{O}_4 + \text{Na}$, 363.1315, found 363.1319.

(3S,6S)-3-Benzyl-6-(2-(methylthio)ethyl)-2,3-dihydro-10bH-oxazolo[3,2-a]pyrrolo[2,1-c]pyrazin-5(6H)-one (10h). The reaction of methyl (S)-2-(2-formyl-1H-pyrrol-1-yl)-4-(methylthio)butanoate (**5j**) (1.12 g, 4.68 mmol) and L-phenylalaninol (0.70 g, 4.65 mmol) in toluene (5 mL) at room temperature for 2.5 h and then at 110 °C for 6 h produced **10h** (353 mg, 1.03 mmol) in 22% yield as light-yellow liquid after purification by SiO_2 column chromatography.

Data for 10h. $^1\text{H-NMR}$ $\delta = 2.07$ –2.17 (m, 1H), 2.11 (s, 3H), 2.20–2.31 (m, 1H), 2.32–2.40 (m, 1H), 2.48–2.57 (m, 1H), 3.04 (dd, $J = 13.6, 8.4$ Hz, 1H), 3.22 (dd, $J = 13.6, 4.0$ Hz, 1H), 3.88 (dd, $J = 9.2, 7.6$ Hz, 1H), 4.21 (dd, $J = 9.2, 7.6$ Hz, 1H), 4.61 (dddd, $J = 8.4, 7.6, 7.6, 4.0$ Hz, 1H), 4.79 (dd, $J = 7.2, 5.6$ Hz, 1H), 5.49 (s, 1H), 6.23–6.27 (m, 2H), 6.67 (dd, $J = 2.4, 2.0$ Hz, 1H), 7.20–7.35 (m, 5H) ppm; $^{13}\text{C-NMR}$ $\delta = 15.2, 29.3, 35.0, 37.3, 55.6, 58.6, 69.5, 82.4, 105.7, 110.1, 118.9, 122.9, 127.0, 128.6, 129.6, 136.2, 165.7$ ppm; IR (neat) $\nu = 3015, 2915, 2846, 1709, 1655, 1570, 1539, 1478, 1455, 1426, 1347, 1323, 1302, 1211, 1200, 1147, 1075, 1032, 977, 854, 818, 739, 701$ cm^{-1} ; HRMS (ESI) calcd for $\text{C}_{19}\text{H}_{22}\text{N}_2\text{O}_2\text{S} + \text{Na}$, 365.1294, found 365.1296.

Conclusions

We demonstrated a practically efficient transformation method of D-ribose as sustainable reducing sugar with various α -amino acids into pyrralines **5** as platform chemicals. Up to 300% yield increment of pyrralines **5** (32–63% yield) were realized by one-pot pressurized conversion of D-ribose with various α -



amino esters at 2.5 atm and 80 °C. The pyrrole-based platform chemicals **5** containing formyl and ester groups as linchpin units were further cyclized to form the piperazin-2-one scaffold as the second pharmacophore. Reductive amination of the formyl group with benzylamine, followed by intramolecular amination with the ester group provided pyrrolo-piperazinones **6** in reasonable yields. 1,2-Ethanediamine reacted with the formyl group of pyrralines **5** by double amination, and the resulting secondary amine underwent subsequent amination with the ester group to produce pyrrolo-piperazinones **7** with an imidazolidine ring as the third structural unit in high yields. Likewise, 2-amino alcohols derived from natural α -amino acids, alanine, valine, and phenylalanine, respectively reacted with the formyl group of pyrralines **5** to give intermediate oxazolidines, which underwent further cyclization with the ester group to produce triply fused heterocycles **8–10** of pyrrole, piperazin-2-one, and oxazolidine in acceptable yields. Pyrrolo-piperazinones **8h** and **10g** with an oxazolidine motif exhibited significant anti-inflammation activities with high cell viability. The practical synthetic method of platform chemicals **5** from sustainable biomass would open a paved road to the discovery of new therapeutic agents and value-added functional materials.

Author contributions

S. Cho: synthesis (lead); L. Gu: synthesis (equal); I. J. In: synthesis (supporting); B. Wu: investigation (equal), synthesis (supporting); T. Lee: bioassays (lead); H. Kim: bioassay (equal), funding acquisition (equal); S. Koo: project administration (lead), funding acquisition (lead), investigation (lead), formal analysis (lead), data curation (lead), writing manuscript (lead).

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- V. Bhardwaj, D. Gumber, V. Abbot, S. Dhiman and P. Sharma, *RSC Adv.*, 2015, **5**, 15233–15266.
- A. Domagala, T. Jarosz and M. Lapkowski, *Eur. J. Med. Chem.*, 2015, **100**, 176–187.
- D. O'Hagan, *Nat. Prod. Rep.*, 2000, **17**, 435–446.
- S. Thirumalairajan, B. M. Pearce and A. Thompson, *Chem. Commun.*, 2010, **46**, 1797–1812.
- H. Fan, J. Peng, M. T. Hamann and J.-F. Hu, *Chem. Rev.*, 2008, **108**, 264–287.
- S. S. Gholap, *Eur. J. Med. Chem.*, 2016, **110**, 13–31.
- H. Li, H. Guo, Z. Fang, T. M. Aida and R. L. Smith Jr, *Green Chem.*, 2020, **22**, 582–611.
- H. Hoffmann and T. Lindel, *Synthesis*, 2003, 1753–1783.
- R. Khajuria, S. Dhamb and K. K. Kapoor, *RSC Adv.*, 2016, **6**, 37039–37066.
- C. Paal, *Ber. Dtsch. Chem. Ges.*, 1884, **17**, 2756–2767.
- L. Knorr, *Ber. Dtsch. Chem. Ges.*, 1884, **17**, 2863–2870.
- C. Paal, *Ber. Dtsch. Chem. Ges.*, 1885, **18**, 367–371.
- A. Hantzsch, *Ber. Dtsch. Chem. Ges.*, 1890, **23**, 1474–1476.
- F. Feist, *Ber. Dtsch. Chem. Ges.*, 1902, **35**, 1537–1544.
- N. Clauson-Kaas, F. Limborg and J. Fakstorp, *Acta Chem. Scand.*, 1948, **2**, 109–115.
- A. Kornienko and J. J. La Clair, *Nat. Prod. Rep.*, 2017, **34**, 1051–1060.
- Y. Ju, D. Miao, R. Yu and S. Koo, *Org. Biomol. Chem.*, 2015, **13**, 2588–2599.
- X. Jiang, H. Jin, T. Wang, H. Yoo and S. Koo, *Synthesis*, 2019, **51**, 3259–3268.
- H. Jin, X. Jiang, H. Yoo, T. Wang, C. G. Sung, U. Choi, C.-R. Lee, H. Yu and S. Koo, *ChemistrySelect*, 2020, **5**, 12421–12424.
- R. U. Braun, K. Zeitler and T. J. J. Müller, *Org. Lett.*, 2001, **3**, 3297–3300.
- G. Minetto, L. F. Raveglia and M. Taddei, *Org. Lett.*, 2004, **6**, 389–392.
- B. Wang, Y. Gu, C. Luo, T. Yang, L. Yang and J. Suo, *Tetrahedron Lett.*, 2004, **45**, 3417–3419.
- M. Leonardi, V. Estévez, M. Villacampa and J. C. Menéndez, *Synthesis*, 2018, **50**, 816–828.
- M. W. Roomi and S. F. MacDonald, *Can. J. Chem.*, 1970, **48**, 1689–1697.
- V. Estévez, M. Villacampa and J. C. Menéndez, *Chem. Soc. Rev.*, 2010, **39**, 4402–4421.
- V. Estévez, M. Villacampa and J. C. Menéndez, *Chem. Soc. Rev.*, 2014, **43**, 4633–4657.
- Y. Fang, D. Leysen and H. C. J. Ottenheijm, *Synth. Commun.*, 1995, **25**, 1857–1861.
- B. S. Gourlay, P. P. Molesworth, J. H. Ryan and J. A. Smith, *Tetrahedron Lett.*, 2006, **47**, 799–801.
- B. Zuo, J. Chen, M. Liua, J. Ding, H. Wu and W. Su, *J. Chem. Res.*, 2009, 14–16.
- D. Bandyopadhyay, S. Mukherjee and B. K. Banik, *Molecules*, 2010, **15**, 2520–2525.
- G. Balme, *Angew. Chem., Int. Ed.*, 2004, **43**, 6238–6241.
- S. Michlik and R. Kempe, *Nat. Chem.*, 2013, **5**, 140–144.
- Y. Yamamoto, H. Hayashi, T. Saigoku and H. Nishiyama, *J. Am. Chem. Soc.*, 2005, **127**, 10804–10805.
- A. A. Rosatella, S. P. Simeonov, R. F. M. Frade and C. A. M. Afonso, *Green Chem.*, 2011, **13**, 754–793.
- J. B. Binder and R. T. Raines, *J. Am. Chem. Soc.*, 2009, **131**, 1979–1985.
- X. Tong, Y. Ma and Y. Li, *Appl. Catal., A*, 2010, **385**, 1–13.
- S. I. F. S. Martins, W. M. F. Jongen and M. A. J. S. von Boekel, *Trends Food Sci. Technol.*, 2001, **11**, 364–373.



- 38 F. Hayase, R. H. Nagaraj, S. Miyata, F. G. Njoroge and V. M. Monnier, *J. Biol. Chem.*, 1989, **263**, 3758–3764.
- 39 G. V. Mokrov, A. M. Likhosherstov, V. S. Troitskaya and T. A. Gudasheva, *Russ. J. Org. Chem.*, 2009, **45**, 1829–1833.
- 40 G. V. Mokrov, A. M. Likhosherstov, V. P. Lezina, T. A. Gudasheva, I. S. Bushmarinov and M. Yu. Antipin, *Russ. Chem. Bull.*, 2010, **59**, 1254–1266.
- 41 G. V. Mokrov, A. M. Likhosherstov, V. P. Lezina, T. A. Gudasheva, I. S. Bushmarinov and M. Yu. Antipin, *Russ. Chem. Bull.*, 2011, **60**, 1694–1702.
- 42 A. S. Demir, N. T. Subasia and E. Sahin, *Tetrahedron: Asymmetry*, 2006, **17**, 2625–2631.
- 43 J. M. Wood, D. P. Fukert and M. A. Bimble, *Nat. Prod. Rep.*, 2019, **36**, 289–306.
- 44 H. Kato and M. Fujimaki, *Agric. Biol. Chem.*, 1970, **34**, 1071–1077.
- 45 N. D. Adhikary, S. Kwon, W.-J. Chung and S. Koo, *J. Org. Chem.*, 2015, **80**, 7693–7701.
- 46 A. M. Valdivielso, P. Ventosa-Andrés, M. T. García-López, R. Herranz and M. Gutiérrez-Rodríguez, *Eur. J. Org. Chem.*, 2013, 155–161.
- 47 C. De Risi, M. Pelà, G. P. Pollini, C. Trapella and V. Zanirato, *Tetrahedron: Asymmetry*, 2010, **21**, 255–274.
- 48 H. Zhang, T. Cravillion, N.-K. Lim, Q. Tian, D. Beaudry, J. L. Defreese, A. Fettes, P. James, D. Linder and S. Malhotra, *et. al.*, *Org. Process Res. Dev.*, 2018, **22**, 978–990.
- 49 C. Sandoval, N.-K. Lim and H. Zhang, *Org. Lett.*, 2018, **20**, 1252–1255.
- 50 T. Yamashita, E. Tsuru, E. Banjo, M. Doe, K. Shibata, M. Yasuda and M. Gemba, *Chem. Pharm. Bull.*, 1997, **45**, 1940–1944.
- 51 J. Sanchez-Cespedes, C. L. Moyer, L. R. Whitby, D. L. Boger and G. R. Nemerow, *Antiviral Res.*, 2014, **108**, 65–73.
- 52 P. Z. Aviv, M. Shubely, Y. Moskovits, O. Viskind, A. Albeck, D. Vertommen, S. Ruthstein, M. Shokhen and A. Gruzman, *ChemistrySelect*, 2016, **1**, 4658–4667.
- 53 H. J. Kim, W. Y. Kwak, J. P. Min, J. Y. Lee, T. H. Yoon, H. D. Kim, C. Y. Shin, M. K. Kim, S. H. Choi, H. S. Kim, *et al.*, *Bioorg. Med. Chem. Lett.*, 2011, **21**, 3809–3812.
- 54 Q. Liu, Q. Shi, D. Marcoux, D. G. Batt, L. Cornelius, L.-Y. Qin, Z. Ruan, J. Neels, M. Beaudoin-Bertrand, A. S. Srivastava, *et al.*, *J. Med. Chem.*, 2017, **60**, 5193–5208.
- 55 W.-Q. Zuo, R. Hu, W.-L. Wang, Y.-X. Zhu, Y. Xu, L.-T. Yu, Z.-H. Liu and N.-Y. Wang, *Bioorg. Chem.*, 2020, **105**, 104344.
- 56 M. D'Ambrosio, A. Guerriero, C. Debitus, O. Ribes, J. Pusset, S. Leroy and F. Pietra, *J. Chem. Soc., Chem. Commun.*, 1993, 1305–1306.
- 57 T. W. Hong, D. R. Jiménez and T. F. Molinski, *J. Nat. Prod.*, 1998, **61**, 158–161.
- 58 F. Caferi, E. Fattorusso, A. Mangoni and O. Tagliatela-Scafati, *Tetrahedron Lett.*, 1995, **36**, 7893–7896.
- 59 I. Mancini, G. Guella, P. Amade, C. Roussakis and F. Pietra, *Tetrahedron Lett.*, 1997, **38**, 6271–6274.
- 60 M. Tsuda, T. Yasuda, E. Fukushi, J. Kawabata, M. Sekiguchi, J. Fromont and J. Kobayashi, *Org. Lett.*, 2006, **8**, 4235–4238.
- 61 T. Henle and A. Bachmann, *Z. Lebensm.-Unters. Forsch.*, 1996, **202**, 72–74.
- 62 T. Niwa, *J. Chromatogr. B: Biomed. Sci. Appl.*, 1999, **731**, 23–36.
- 63 T. Mosmann, *J. Immunol. Methods*, 1983, **65**, 55–63.
- 64 M. J. Moorcroft, J. Davis and R. G. Compton, *Talanta*, 2001, **54**, 785–803.

