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A binuclear aluminium complex as a single competent catalyst for efficient synthesis of urea, biuret, isourea, isothiourea, phosphorylguanidine, and quinazolinones†

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The synthesis and characterisation of two mononuclear aluminium alkyl complexes with the general composition [Al(Me)$_2$\{Ph$_2$P(E)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O\}] (E = Se (**2a**); S (**2b**)), and two binuclear aluminium complexes, [Al(Me)$_2$\{Ph$_2$P-(E)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O\}(AlMe$_3$)\] (E = Se (**3a**) and S (**3b**)), are described. The binuclear aluminium alkyl complex **3a** proved to be a proficient catalyst for the addition of simple nucleophiles to heterocumulenes, leading to the synthesis of a variety of products such as urea, biuret, isourea, isothiourea, phosphorylguanidine, and quinazolinone derivatives, in contrast to its mononuclear analogues. Complex **3a** is the first example of a single competent catalyst, which is also low-cost and eco-friendly and derived from a main-group metal, under solvent-free conditions either at room temperature or mild temperatures. Complex **3a** possessed a wide functional group tolerance including heteroatoms, yielding the corresponding insertion products in good quantities and with high selectivity.

Introduction

There is currently an upsurge of interest in developing efficient hydroelementation reactions to construct C-heteroatom bonds using suitable catalysts. This can be seen as a renaissance in modern organic chemistry because hydroelementation reactions are highly atom-economical; they utilise affordable and easily accessible substrates. Hydroelementation reactions of alkenes and alkynes by a broad range of transition-metal, lanthanide, actinide, and alkali-metal catalysts are well explored to date.[1,2] Hydroelementation of heterocumulenes is now gaining considerable attention, owing to its several advantages such as greater synthetic possibilities such as multiple heterocumulene insertions into one E–H moiety, unsaturated bond selectivity, and double hydroelementations of a single heterocumulene substrate.[3,4] As a result of the insertion of E–H bonds (E = N, P, O, S) into various heterocumulenes (isocyanates, isothiocyanates, and carbodiimides), we can gain access to a variety of products such as heteroatom-rich urea, thiourea, guanidines, and quinazoline/quinazolinone derivatives. The obtained products have been significantly utilized for multidentate ligands in organometallic chemistry, organic synthon, and pharmaceutical analogues.[5–12]

In contrast to the significantly developed catalytic hydroamination of alkynes, alkenes, and carbodiimides to form C–N bonds,[13–15] catalytic hydroamination of isocyanates, leading to urea derivatives, have been explored only by some group 2, titanium, zinc, actinide complexes, *etc.*[16–22] The urea derivatives are useful across a range of biological systems, pharmaceuticals, agrochemicals, synthetic chemistry, supramolecular chemistry, and materials chemistry.[23–31] Moreover, the synthesis of derivatives containing multiple urea moieties within one molecule, such as biuret and triuret derivatives from mono-urea, is quite challenging since the nucleophilic nature of urea compared to secondary amines is considerably less. So far, only a few examples have been reported for the synthesis of such compounds by the catalytic transformation of secondary amines with isocyanates. Recently, Tylor *et al.*[32] reported the use of low-coordinate iron pre-catalyst, (2,6-Mes$_2$C$_6$H$_3$)$_2$Fe (where Mes = 2,4,6-Me$_3$C$_6$H$_2$), in the presence of HNPh$_2$ and Ph-N=

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C=O (1:1 ratio) afforded a mixture of urea and biuret products in a molar ratio of 88:12. Biuret selectivity was increased (to 90–100%) by employing HNPh$_2$ and Ph-N=C=O in a ratio of 1:5; however, it was only successful for aryl isocyanates, as alkyl isocyanates consistently yielded corresponding urea derivatives. Despite the importance of biuret and triuret derivatives in molecular sensors, foldamers, self-assembly, *etc.*, there are hardly any direct catalytic routes. Therefore, the development of efficient, yet simple catalytic systems with good functional group tolerance for the catalytic transformation of the urea moieties is a worthwhile endeavour.

In addition, successive insertion of heterocumulenes into the N–H bonds of amino acid esters followed by cyclisation to form heterocyclic products (quinazolinones) has garnered considerable attention in the area of synthetic organic and pharmaceutical chemistry.[33–35] Fused N-heterocyclic compounds (quinazolinones) have been shown to have wide applications in medicine, particularly in anti-cancer, anti-convulsant, hypotensive, and anti-allergy treatments. They are also good precursors for derivatizing naturally occurring alkaloid derivatives only isolated from natural resources.[36–40] Synthesis of quinazolinones generally needs long and tedious reaction steps with the use of toxic reagents. Therefore, novel and efficient catalytic systems involving earth-abundant, environment-friendly, non-toxic metals and substrates are highly demanded for the construction of N-heterocyclic quinazolinones: to this purpose, zinc,[41] titanium,[42] and rare-earth metal-based complexes[43] were recently developed to catalyse tandem hydroamination of amino acid esters with carbodiimides.

Although tremendous progress has been made over the last decade on these reactions, novel green and sustainable catalytic chemical approaches for achieving the dual goals, environment protection and cost effectiveness, can be further explored.[44] In this context, study on the use of a single catalyst for multielement hydroelementation reactions of heterocumulenes has attracted attention. Recently, Eisen *et al.* illustrated multielement hydroelementation reactions of heterocumulenes using protic E–H bonds containing nucleophiles in the presence of a single actinide pre-catalyst [{(Me$_3$Si)$_2$N}$_2$An{κ^2-(C,N)-CH$_2$-Si(CH$_3$)$_2$N-(SiMe$_3$)$_2$}] (An = Th, U).[20,22,45] However, this reaction needed more time and a relatively high temperature. Our group[18] also demonstrated that a binuclear titanium(IV) complex showed remarkable catalytic activity for the addition of E–H bonds (E = NR$_2$, OR, SR, P(O)R$_2$) towards a wide variety of heterocumulenes under mild conditions. However, till date, there are no known examples of single catalytic systems for hydrolelementation of heterocumulenes with various E–H bonds using main group metals. Herein, we report on a main group metal-based single competent catalytic system that can perform versatile hydroelementation reactions through the addition of E–H (E = N, O, S, P, C) moieties to heterocumulenes, producing highly useful urea and biuret derivatives, isourea derivatives, phosphorylguanidine, and quinazolinone derivatives with high functional group tolerance, in which aluminium complexes are found to be suitable in terms of the high catalytic activity, availability, and low toxicity. Our group has established a series of phosphine amines [Ph$_2$-PNHR] (A; R = 2,6-Me$_2$C$_6$H$_3$, CHPh$_2$, CPh$_3$) and their chalcogen

derivatives [Ph$_2$P(O)NHR] (NPO), [Ph$_2$P(S)NHR] (NPS), and [Ph$_2$P(Se)NHR] (NPSe) containing both hard and soft donor atoms, to understand their coordination behavior with alkali metals, the heavier alkaline-earth metals, and main-group metals.[46–48] Further, we aimed to synthesize the protic amidophosphine chalcogenide ligands, [Ph$_2$P(E)-NH(CH$_2$)$_2$-N(CH$_2$CH$_2$)$_2$O] [E = Se, **1a-H**; S = **1b-H**] containing ethylene-linked morpholine fragment which is more flexible due to the presence of ethylene links. Due to their flexible nature as well as the presence of hard and soft chalcogen donor atoms, these ligands have the potential to exhibit a hemilabile nature. Thus, the study of the coordination behavior of such hemilabile ligands with reactive aluminum metal could be very interesting.

We described the synthesis and structural features of mono- and binuclear aluminium complexes with the molecular formula, [Al(Me)$_2${Ph$_2$P(Se)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O}] (**2a**), [Al(Me)$_2${Ph$_2$P(S)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O}] (**2b**), and [Al(Me)$_2${Ph$_2$P(E)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$-O}(AlMe$_3$)}] (E = Se (**3a**); S (**3b**)) respectively. The catalytic activity of **3a** was shown as the facile synthesis of urea, biuret, isourea, isothiourea, phosphorylguanidine, and quinazolinone derivatives (Fig. 1).

Results and discussion

Synthesis of mononuclear and binuclear aluminium complexes (2a, 2b, 3a, and 3b)

Protic amidophosphine chalcogenide ligands [Ph$_2$P(E)-NH(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O] [E = Se, **1a-H**; S = **1b-H**] were
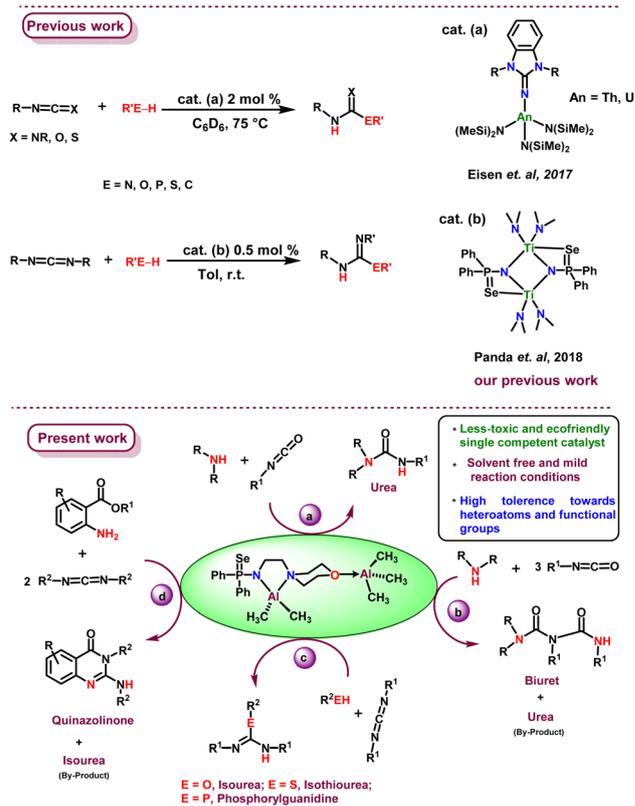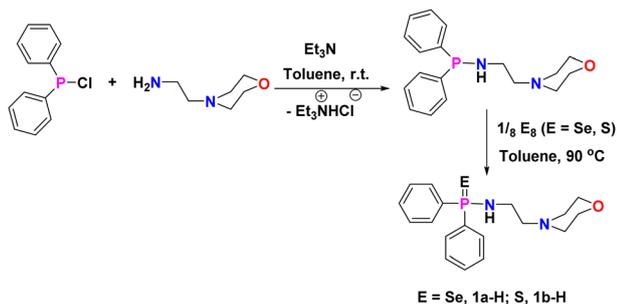

**Fig. 1** Previous reports on hydroelementation and present work.

Scheme 1 Synthesis of flexible aminophosphine chalcogenide ligands **1a-H** and **1b-H**.

synthesised according to published procedure[49] by the reaction between 4-(2-aminoethyl)morpholine and chloro-diphenylphosphine (1 : 1) in the presence of triethylamine in toluene, followed by the addition of elemental sulphur or selenium at 90 °C for 24 hours (Scheme 1). The reaction of ligand **1a-H** or **1b-H** with trimethylaluminium (AlMe$_3$) in a 1 : 1 molar ratio in toluene at 60 °C resulted in the formation of the corresponding mononuclear Al complexes [κ^2-{Ph$_2$P(E)N(CH$_2$)$_2$N-(CH$_2$CH$_2$)$_2$O}Al(Me)$_2$] [E = Se (**2a**), S (**2b**)] as colourless crystalline solids in good yields (Scheme 2). On the other hand, AlMe$_3$ reacted with protic ligand **1a-H/1b-H** in a 2 : 1 molar ratio in toluene at 90 °C for 12 hours, resulting in the formation of a binuclear aluminium complex of molecular formula [Al(Me)$_2${Ph$_2$P(E)N$_2$C$_6$H$_{12}$O}(AlMe$_3$)] (E = Se (**3a**); S (**3b**)) with a good yield (∼91–95%). Each binuclear aluminium complex **3a/3b** was also obtained from the respective mononuclear complex **2a/2b** by its reaction with one equivalent of AlMe$_3$ in toluene at 90 °C (Scheme 2). All the Al-alkyl complexes **2a**, **2b**, **3a**, and **3b** were fully characterised using multinuclear NMR spectroscopy and combustion analysis.

In the ^{1}H NMR spectra of ligands **1a-H** and **1b-H**, the resonance signal for the –NH group is shown as a broad peak at δ_H 3.23 ppm and 3.30 ppm, respectively (Fig. FS1 and FS4 in ESI†). The signals are absent in the ^{1}H NMR spectra of Al complexes **2a** and **2b**, confirming the formation of monoanionic moieties **1a**
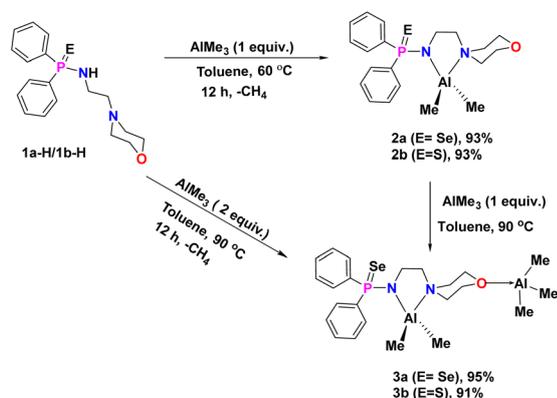
and **1b** respectively. Further, the resonance signal of methyl protons attached to the aluminium metal centre for **2a** and **2b** appeared at δ_H −0.78 and −0.73 ppm, respectively (Fig. FS7 and FS10, in ESI†). In the ^{1}H NMR spectrum of each binuclear complex, two sharp singlets were obtained in 2 : 3 ratios at δ_H −0.89 (for **3a**)/−0.98 (for **3b**) ppm and −0.45 (for **3a**)/−0.35 (for **3b**) ppm for two types of methyl protons attached to the two Al centres, which can be assigned to AlMe$_2$ and AlMe$_3$, respectively. The formation of aluminium complexes is also confirmed by the presence of the complex AA′BB′ multiplet spin system of ethylene protons in the range of δ_H 3.5–1.5 ppm. This occurs due to the restricted rotation of ethylene protons of the anionic ligand upon coordination with aluminium ion. While the –CH$_2$–CH$_2$– unit of the free ligand is expected to rotate freely and hence displayed a simple multiplet signals (A$_2$B$_2$). In the ^{31}P{^{1}H} NMR spectra, the complexes **2a** and **3a** exhibit sharp singlets at δ_P 57.1 ppm and 56.0 ppm, respectively, along with two satellite peaks due to coupling with the adjacent selenium atom, whereas complexes **2b** and **3b** display only a sharp resonance signal at 55.4 and 58.3 ppm, respectively. The molecular structure of ligand **1b-H** is already reported in our previous work.[49] The molecular structures of **1a-H**, **2a**, and **3a** in the solid states were established using single crystal X-ray diffraction analysis and are presented in Fig. 2, 3, and 4, respectively. Pertinent crystallographic and refinement parameters are given in Table TS1 in ESI.† Colourless crystals of complexes **2a** and **3a** were obtained from a saturated solution of toluene at −35 °C after one week. Complex **2a** crystallises in the monoclinic space group P2$_1$/n with four molecules in the unit cell, while complex **3a** crystallises in the monoclinic space group P2$_1$/c with six molecules in the unit cell.

In complex **2a**, ligand **1a** is asymmetrically coordinated to the aluminium ion in κ^2-fashion through anionic amidophosphine nitrogen and the nitrogen atom of the morpholine moiety, as is evident from the presence of two sets of Al–N distances [Al1–N1 is 1.883(2) Å and Al1–N2 is 2.043(2) Å]. Both

Scheme 2 Synthesis of mono- and binuclear aluminium complexes **2a**, **2b**, **3a**, and **3b** supported by flexible aminophosphine chalcogenide.
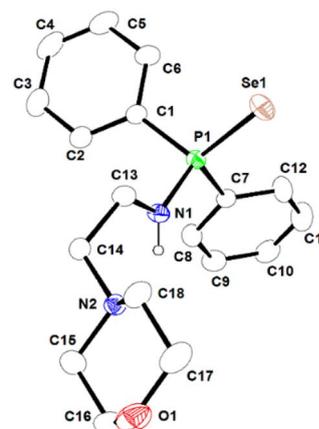

Fig. 2 Molecular structure of ligand **1a-H** in its solid-state. Selected bond lengths (Å) and angles (°) are given. P1–N1 1.661(3), P1–Se1 2.1026(13), P1–C1 1.812(5), P1–C7 1.815(4), N1–C13 1.465(5), N1–P1–Se1 116.75(13), N1–P1–C1 103.2(2), N1–P1–C7 103.53(18), C1–P1–C7 106.47(19). CCDC no. 2151760.
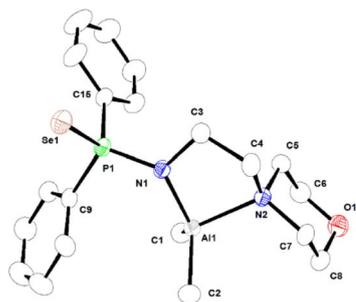
Fig. 3 Molecular structure of complex **2a** in its solid state. Selected bond lengths (Å) and angles (°) are given. Al1–C1 1.964(3), Al1–C2 1.962(4), Al1–N1 1.883(2), Al1–N2 2.043(2), P1–N1 1.636(2), P1–Se1 2.1230(8), N1–C3 1.479(3), C3–C4 1.507(4), N2–C4 1.496(4), P1–C9 1.812(3), P1–C15 1.817(3), N1–Al1–N2 87.23(10), N1–Al1–C1 114.24(13), N1–Al1–C2 117.69(15), N2–Al1–C1 113.08(14), N2–Al1–C2 104.94(14), N1–P1–Se1 116.15(9). CCDC no. 2151762.
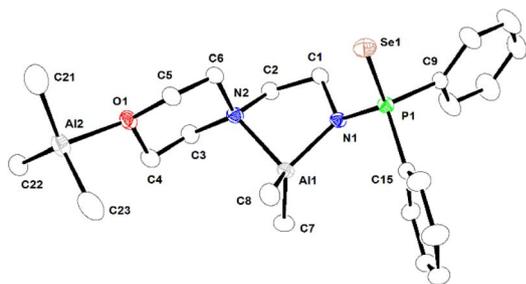

Fig. 4 Molecular structure of binuclear complex **3a** in the solid state. Selected bond lengths (Å) and angles (°) are given. Al1–N1 1.878(2), Al1–C8 1.949(3), Al1–C7 1.956(3), Al1–N2 2.063(3), Al2–C22 1.956(4), Al2–C21 1.959(5), Al2–C23 1.969(4), Al2–O1 2.001(2), Se1–P1 2.1195 (8), P1–N1 1.644(2), P1–C15 1.807(3), P1–C9 1.818(3); N1–Al1–C8 116.72(14), N1–Al1–C7 116.17(14), C8–Al1–C7 114.86(17), N1–Al1–N2 86.68(10), C8–Al1–N2 113.40(14), C7–Al1–N2 104.80(14), C22–Al2–C21 117.78(19), C22–Al2–C23 117.38(18), C21–Al2–C23 113.4 (2), C22–Al2–O1 100.30(14), C21–Al2–O1 103.06(15), C23–Al2–O1 100.89(16). CCDC no. 2209321.

Al–N bond distances correspond to the anionic and neutral coordination of the nitrogen atoms to the aluminium metal centre. The selenium atom remains uncoordinated. The Al–C and Al–N bond distances are within the range that we previously reported for the aluminium metal complex [κ²-{2-F-C₆H₄NP(Se)Ph₂}₂Al(Me)] and other reported Al complexes.[50] The central Al ion is coordinated four-fold *via* the chelation of one amido nitrogen, one morpholine ring nitrogen from ligand **1a**, and two methyl groups, and adopts a distorted tetrahedral geometry around it with the formation of a five-membered metallacycle, Al1–N1–C3–C4–N2. The metallacycle is not coplanar due to the presence of two sp³ carbon atoms C3 and C4 in the ring.[51,52]

In complex **3a**, the ligation of **1a** (aminophosphine selenide) is similar to that of complex **2a**. Additionally, there is a bond between the oxygen atom of the morpholine moiety of ligand **1a-H** and another AlMe₃ group, making complex **3a** binuclear. The coordination of the oxygen atom present in a multidentate ligand to the AlMe₃ group is known in the literature.[51,53,54] The Al–N bond distances [Al1–N1 being 1.878(2) Å and Al1–N2

2.063(3) Å] are similar to those in complex **2a**. Al–C bond distances [1.946(3)–1.969(4) Å] are also within the ranges previously reported.[55] The second Al ion is bonded with the oxygen atom of the morpholine moiety and three methyl groups, adopting a distorted tetrahedral geometry around the metal ion.

Catalytic study

Formation of urea derivatives

Given the importance of urea derivatives, we wanted to examine the catalytic activity of all the mononuclear and binuclear aluminium metal complexes (**2a**, **2b**, **3a**, and **3b**) in the hydroamination of isocyanates with secondary amines.

Initially, all Al-metal complexes were screened as catalysts to mediate the hydroamination reaction of *p*-tolylisocyanate with diisopropylamine. Catalytic experiments were performed using 5 mol% of the metal complex along with an equimolar amount of *p*-tolylisocyanate and diisopropylamine under neat conditions at room temperature for one hour (Table 1, entries **1–3**). To our delight, all complexes **2a**, **2b**, **3a**, and **3b** proved to be active catalysts in this addition reaction, affording the corresponding urea products in excellent yields of up to 99% (Table 1, entries **1–4**). We also performed control reactions between *p*-tolylisocyanate and diisopropylamine at ambient temperature, and when heated to 60 °C without using any catalyst, no detectable product was obtained (Table 1, entries **11** and **12**). Among all the catalysts, the binuclear aluminium complexes demonstrated the better reactivity compared to mononuclear complexes in forming the desired urea product. We selected **3a** for optimisation of catalytic reaction conditions.

At first, we examined the influence of catalyst loading on the yield of urea. The yield of urea obtained from the hydroamination of *p*-tolylisocyanate and diisopropylamine using

Table 1 Screening and optimisation results for hydroamination of *p*-tolylisocyanate with diisopropylamine[a,b]

Entry	Catalyst	Solvent	Cat. (mol%)	Time (h)	T (°)	Yield[b] (%)
1	**2a**	Neat	5	1	r.t.	92
2	**2b**	Neat	5	1	r.t.	90
3	**3a**	Neat	5	1	r.t.	99
4	**3b**	Neat	5	1	r.t.	96
5	**3a**	Neat	2.5	1	r.t.	99
6	**3a**	Neat	1	1	r.t.	99
7	**3a**	Neat	0.5	1	r.t.	89
8	**3a**	Toluene	1	1	r.t.	99
9	**3a**	Hexane	1	1	r.t.	75
10	**3a**	THF	1	1	r.t.	40
11	—	Neat	—	12	r.t.	—
12	—	Neat	—	12	60	—

[a] Molar ratio of *p*-methyl-phenylisocyanate : diisopropylamine = 1 : 1. [b] Isolated yield.

1 mol% of complex **3a** was almost as much as that obtained from using 5 mol% of catalyst (Table 1, entry **6**). When the catalyst loading was decreased to 0.5 mol%, the yield of urea reduced (Table 1, entry **6**). Thus, 1 mol% of catalyst was selected as the optimised condition. We also studied the impact on product yields when various solvents, such as toluene, hexane, and THF were used in the hydroamination reaction between *p*-tolylisocyanate and diisopropylamine using 1 mol% of complex **3a** at room temperature for one hour (Table 1, entries **8–10**). The lowest yield (40%) of urea obtained was when THF was used as the solvent. This can be attributed to the coordinating nature of this ethereal solvent during the reaction conversion (Table 1, entry **10**).

After successful optimisation, we extended our study of complex **3a** as a competent catalyst in the addition of N–H bonds of a number of nucleophilic secondary amines to the *p*-tolylisocyanate/*p*-chlorophenyl-isocyanate. Catalytic experiments were conducted using 1 mol% of the binuclear aluminium complex (**3a**) and equimolar amounts of either *p*-tolylisocyanate or *p*-chlorophenyl-isocyanate and secondary amines at room temperature for one hour under neat conditions. The reactions displayed a broad substrate scope. In each case, the urea derivatives (**4a–p**) were isolated and analysed through ^{1}H and ^{13}C NMR spectroscopy (FS19–FS50, see the ESI†). The yields were calculated after isolating pure products. The results of the catalytic hydroamination to *p*-tolylisocyanate or *p*-chlorophenyl-isocyanate are presented in Table 2. We observed that the reaction of either *p*-tolylisocyanate or *p*-chlorophenyl-isocyanate with dialkyl amines, diallyl amines, dibenzyl amines, and arylalkyl amines was smooth at room temperature and selectively produced the corresponding urea products (with up to 99% yield) (Table 2, entries **4a–f** and **4m–**
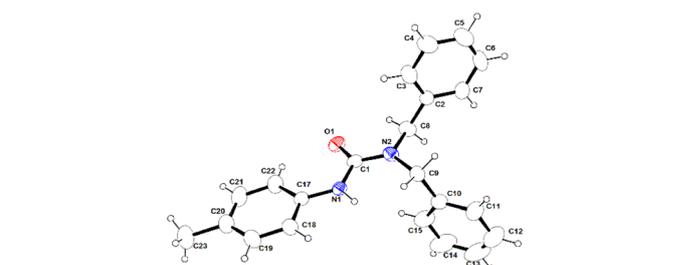
Table 2 Catalytic hydroamination of isocyanates with secondary amines using catalyst **3a**[a,b]

^{a} Reaction conditions: catalyst **3a** (0.00384 mmol), secondary amine (0.384 mmol), and respective isocyanate (0.384 mmol) under neat conditions at room temperature for 1 h. ^{b} Yields were determined by isolation of the products.

Fig. 5 Molecular structure of urea product **4o** compound in the solid state. Selected bond lengths (Å) and angles (°) are given. N1–C1 1.368(3), N1–C17 1.418(4), N1–H1 0.8600, O1–C1 1.228(3), C2–C7 1.363(5), C2–C3 1.379(5), C1–N1-C17 127.1(2), C1–N1–H1 116.5, C17–N1–H1 116.5, C7–C2–C3 117.2(3), C7–C2–C8 121.3(3), C3–C2–C8 121.5(3). CCDC No. 2209322.†

p). Even heterocyclic amines such as pyrrolidine, piperidine, and morpholine afforded excellent yields of the corresponding urea derivatives under similar reaction conditions (Table 2, entries **4g–l**). The molecular structure of the urea product **4o** in the solid state is shown in Fig. 5.

Formation of biuret derivatives

The synthesis of biuret and triuret derivatives from mono-urea derivatives is more challenging as it typically requires elevated temperatures due to its reduced reactivity compared to secondary amines,[56] owing to the electron-withdrawing effect of the carbonyl group. Reports in literature on the catalytic synthesis of biuret and triuret derivatives are limited to the use of catalysts such as organotin, $SOCl_2$, and $ClSO_2OH$ at high temperatures.[57,58] After the successful synthesis of urea derivatives, we applied the binuclear aluminium catalyst **3a** to the process of directly transforming secondary amines to biuret derivatives under neat reaction conditions. Results of the catalytic transformation of secondary amines to biuret derivatives are set out in Table 3.

The initial reaction between diisopropylamine and *p*-tolylisocyanate in a 1 : 2 molar ratio in the presence of 1 mol% of complex **3a** at room temperature after six hours resulted in the formation of the biuret compound (53% yield) along with the corresponding urea derivative as a co-product. However, an increased amount of *p*-tolylisocyanate, 3 equivalents with respect to the diisopropylamine, afforded 80% of the biuret compound after six hours at room temperature (Table 3, entry **5a**). A further increase of isocyanate yielded a mixture of urea, biuret, and triuret derivatives. Thus, we selected the isocyanate and the respective secondary amine in a 3 : 1 molar ratio to explore the efficiency of catalyst **3a** under solvent-free conditions at room temperature. Al catalyst **3a** is compatible with both electron-releasing and electron-withdrawing functional groups, as exemplified by methyl and chloro moieties (Table 3, entries **5a–n**). In each case, the biuret derivatives were isolated and analysed through ^{1}H and ^{13}C NMR spectroscopy (Fig. FS51–FS77†). Yields were calculated after isolating the pure products.
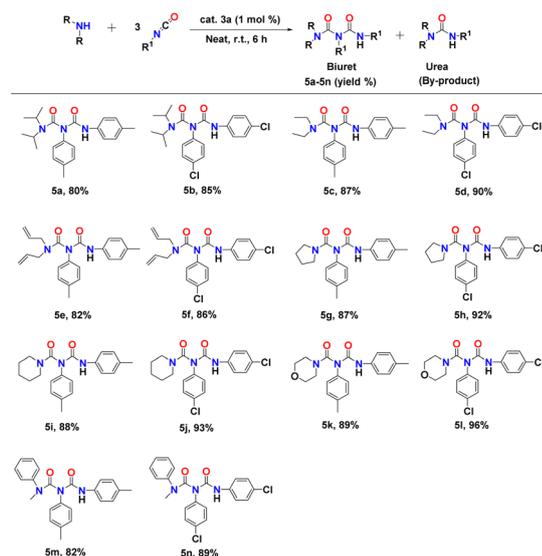
The reaction between diisopropylamine and *p*-chloro-phenylisocyanate in a 1 : 3 molar ratio resulted in good
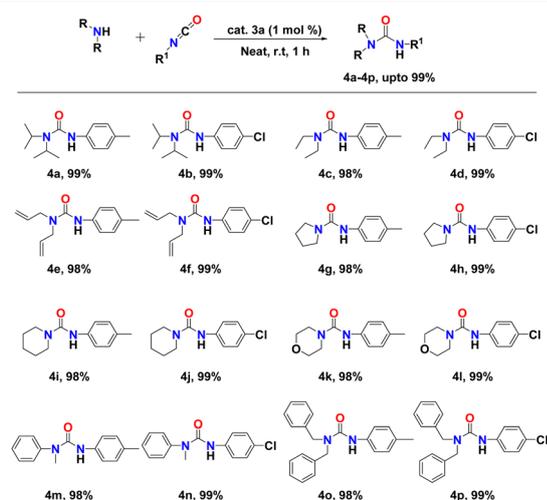
Table 3 Catalytic synthesis of biuret derivatives from secondary amines and isocyanates using Al catalyst **3a**[a,b]

[a] Reaction conditions: catalyst **3a** (0.00384 mmol), secondary amine (0.384 mmol, 1 equiv.), and respective isocyanate (1.15 mmol, 3 equiv.) under neat conditions at room temperature for 1 h. [b] Yields were determined by isolation of the products.

conversion, yielding 85% of biuret under optimum conditions (Table 3, entry **5b**). Use of diethylamine, diallylamine, and N-methylaniline with either p-tolylisocyanate or p-chlorophenyl-isocyanate also resulted in smooth conversions. The reactions (conducted at room temperature under neat conditions for six hours) yielded the desired biuret compounds as major products (82–90%) along with corresponding urea derivatives as minor products (Table 3, entries **5c–f**). This protocol was also used for heterocyclic secondary amines such as pyrrolidine, piperidine, and morpholine, which showed excellent conversion to the corresponding biuret derivatives under neat reaction conditions (Table 3, entries **5g–l**). These results indicate the high proficiency and excellent functional group tolerance of catalyst **3a**.

A most plausible mechanism of biurets formation from the secondary amines and isocyanates using Al catalyst **3a** is proposed based on previous studies.[16,59] It was proposed that in the initial step, more nucleophilic secondary amine reacts on both the Al-centers of electrophilic pre-catalyst to form active catalytic species aluminum amine which further participates in several catalytic steps to give the desired product. The detailed mechanism and scheme are provided in the ESI (Scheme S1†).

Formation of isourea, isothiourea, and phosphorylguanidine

Catalytic intermolecular addition of alcohols to carbodiimides has been developed as an efficient atom-economic tool to construct isourea derivatives, which were found to have many interesting applications, such as being alkylating agents and intermediates.[60] Recently, actinide catalysts {(BimR[1]/R[2]N)An [N(SiMe_3)_2]} (An = Th, U)[61] and hafnium metal complexes[62] were employed to afford higher yields of isourea derivatives from the

reaction of alcohols with various carbodiimides in relatively short reaction times. However, preparing the actinide-amide catalysts was rather complicated. Therefore, developing simple and efficient catalysts which demonstrate high tolerance towards diversified carbodiimides and alcohols is highly desirable. Moreover, there are only a few reports in literature of catalysed hydrothiolation (i.e., addition of S–H bond) to carbodiimides at high temperatures which afford products in moderate-to-high yields. Recently, Yao et al.[63] reported the addition of alcohol to carbodiimides to obtain isourea derivatives in the presence of commercially available rare-earth metal amide La[N(SiMe_3)_2]_3. The same catalyst system also demonstrated good catalytic activity in the hydrothiolation reaction between phenyl isocyanate and thiols to yield thiocarbamates showing good functional group tolerance.[64]

Encouraged by high activity and chemoselectivity of binuclear aluminium complex $[Al(Me)_2\{Ph_2P(Se)N(CH_2)_2$-$N(CH_2CH_2)_2O\}$-$(AlMe_3)]$ (**3a**) as a pre-catalyst for the production of urea and biuret derivatives via hydroamination of secondary amines, we explored the activity of aluminium pre-catalysts **2a**, **2b**, **3a**, and **3b** in hydroalkoxylation, hydrothiolation, and hydrophosphorylation with carbodiimides too. The intermolecular addition of alcohols, thiols, and diphenylphosphine oxide to carbodiimides results in the formation of isourea, isothiourea, and phosphorylguanidine, respectively. The results of the catalytic addition reactions of a series of REH (E = O, S, P) moieties to N,N′-diisopropylcarbodiimide (DIC) and N,N′-dicyclohexyl-carbodiimide (DCC) are depicted below.

In this context, the reaction of 2-methylphenol with DIC was first investigated using different aluminium pre-catalysts (**2a**, **2b**, **3a**, and **3b**). As a control experiment, a blank reaction, i.e., a reaction between 2-methylphenol and DIC with no catalyst, was carried out at room temperature for one hour under

Table 4 Screening and optimization results of addition of 2-methyl-phenol to diisopropylcarbodiimide[a,b]

Entry	Catalyst	Solvent	Cat. (mol%)	Time (h)	Temp. (°)	Yield[b] (%)
1	None	Neat	—	12	r.t.	0
2	None	Neat	—	12	60	0
3	**2a**	Neat	5	1	r.t.	80
4	**2b**	Neat	5	1	r.t.	78
5	**3a**	Neat	5	1	r.t.	92
6	**3b**	Neat	5	1	r.t.	90
7	**3a**	Neat	2.5	1	r.t.	92
8	**3a**	Neat	1	1	r.t.	92
9	**3a**	Neat	0.5	1	r.t.	88
10	**3a**	Toluene	1	1	r.t.	92
11	**3a**	Hexane	1	1	r.t.	75
12	**3a**	THF	1	1	r.t.	40

[a] Reactions were performed using a molar ratio of diisopropylcarbodiimides : 2-methylphenol = 1 : 1. [b] Isolated yield.

solvent-free conditions, and no product was seen to be formed (Table 4, entries **1** and **2**). In contrast, with the addition of a catalytic amount (5 mol%) of the aluminium complexes **2a**, **2b**, **3a**, and **3b**, intermolecular insertion of O–H bond to carbodiimides took place smoothly, affording the corresponding isourea derivatives in high yields (Table 4, entries **3–6**). In this case also, the binuclear aluminium(III) catalysts were found to be more efficient. The catalyst **3a** was selected for the optimization of reaction conditions.

Thereafter, we set out to conduct a routine optimisation of factors that could influence isourea/isothiourea conversion, including catalyst loading and polar/non-polar solvent effect. At first, we investigated the effect of catalyst loading on the product yield. We observed no discernible change in the yield of the isourea product upon reducing the catalyst loading from 5 mol% to 1 mol% (of **3a**) at room temperature within one hour (Table 4, entries **5**, **7** and **8**). When the catalyst loading was reduced further to 0.5 mol%, the conversion decelerated by up to 88% (Table 4, entry **9**). Thus, 1 mol% of the catalyst loading was taken as an ideal condition for the model reaction during the optimisation. Further, we screened the effect of the various solvents such as toluene, hexane, and THF (Table 4, entries **10–12**). However, the addition of polar and non-polar solvents appeared to be disadvantageous to isourea product formation. Conversion in the THF solvent was sluggish due to the coordinating nature of this solvent during the reaction conversion (Table 4, entry **12**).

The scope of the intermolecular addition reaction of various aryl alcohol substrate to dicyclohexylcarbodiimide (DCC) and diisopropylcarbodiimide (DIC) was studied by varying the steric bulkiness and nucleophilicity of the alcohols. All the catalytic experiments were performed using 1 mol% of catalyst **3a** at room temperature under neat conditions for one hour. The respective isourea derivatives (Table 5, entries **6a–s**) were isolated in each case and characterized by ^{1}H and ^{13}C NMR spectroscopy (FS78-FS111, see the ESI†). The yields were calculated after isolating pure products. The results of the intermolecular coupling reactions are shown in Table 5.

It was observed that aryl alcohols with electron-donating groups, such as simple phenol, 2-methylphenol, 2-methoxyphenol, and 4-methoxyphenol afforded excellent conversion, with yields of 88–94% (Table 5, entries **6a–f**). Aryl alcohols containing electron-withdrawing groups such as chloro, bromo, iodo, nitro, and trifluoromethyl, also converted to corresponding isourea derivatives in good yields of 85–90% (Table 5, entries **6g–m**) within one hour at room temperature. Even the addition of α-naphthol to DIC resulted in the formation of the respective isourea product with a yield of 83% (Table 5, entry **6n**). Reduced reactivity of α-naphthol was observed in case of DCC (Table 5, entry **6o**) due to the steric hindrance of both moieties. In the case of α-naphthol, our research group had observed no reactivity when the binuclear Ti-catalyst[18] was used, clearly indicating the high reactivity of binuclear aluminium complex **3a**. Benzyl alcohol also reacted smoothly with both carbodiimides and yielded the corresponding isourea at 86% (Table 5, entries **6p** and **q**). Aliphatic alcohols such as butanol significantly increased the rate of hydroalkoxylation reaction

Table 5 Addition of various alcohols to diisopropylcarbodiimide and dicyclohexylcarbodiimide using pre-catalysts **3a**[a,b]
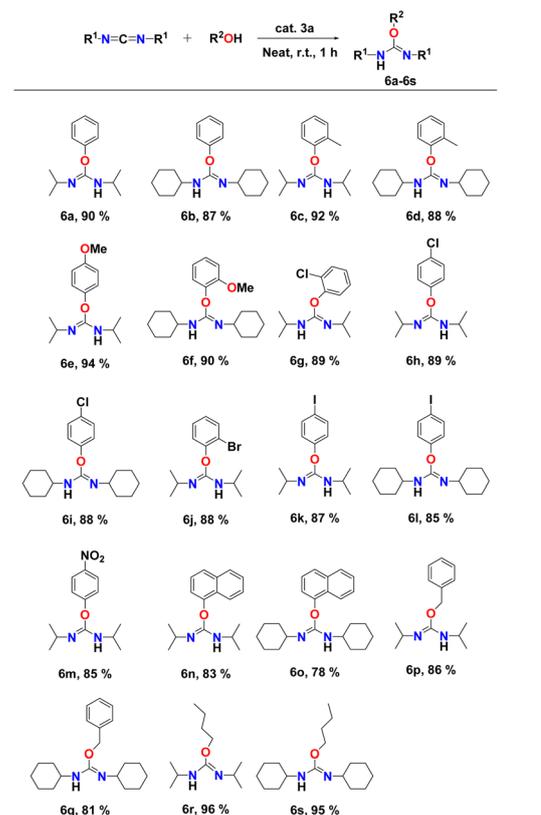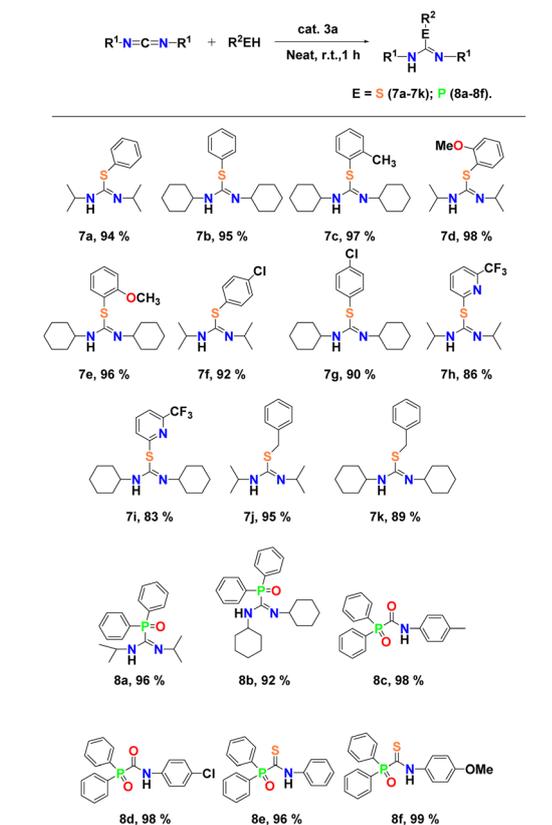

[a] Reaction conditions: catalyst **3a** (0.00384 mmol), alcohol (0.384 mmol), and carbodiimide (0.384 mmol) under neat condition at room temperature for 1 h. [b] Yields were determined by isolation of the products.

compared to aryl alcohols (Table 5, entries **6r** and **s**). Dicyclohexylcarbodiimide (DCC) exhibited better reactivity than diisopropylcarbodiimide (DIC) due to the presence of the bulky cyclohexyl group which shows greater electron donation than the isopropyl moieties. Compared to previous hydroalkoxylation reactions,[61,63] higher conversions, even at room temperature and in a short amount of time, were observed, suggesting a higher reactivity of aluminium complex **3a**.

Encouraged by the high reactivity of complex **3a** as a competent catalyst in the case of hydroalkoxylation, we proceeded with its utilisation in the addition reaction of aromatic thiols to carbodiimides. The results of the intermolecular addition reactions of thiophenols to carbodiimides are shown in Table 6. At first, the simple thiophenols were treated with either diisopropylcarbodiimide or dicyclohexylcarbodiimide moieties in the presence of binuclear aluminium pre-catalyst **3a** at room temperature under neat conditions and the corresponding isothiourea derivatives were obtained in good yield (~95%) in each case (Table 6, entries **7a** and **b**). Later, we studied the scope of the reaction with regard to thiol substrates under the same reaction conditions. Aromatic thiols bearing electron-donating groups such as methyl and methoxy groups

Table 6 Catalytic hydrothiolation and hydrophosphorylation of carbodiimides using binuclear aluminium catalyst **3a**[a,b]

^{a} Reaction conditions: catalyst **3a** (0.00384 mmol), thiol/diphenylphosphine oxide (0.384 mmol), and carbodiimide (0.384 mmol) under neat condition at room temperature for 1 h. ^{b} Yields were determined by isolation of the products.

converted efficiently into the respective isothiourea derivatives in excellent yields of 98% (Table 6, entries **7c** and **d**). Even aromatic thiols bearing electron-withdrawing groups (chloro and trifluoromethyl) reacted smoothly to give respective isothiourea products in yields of up to 92% (Table 6, entries **7f–i**). Benzylthiophenol also reacted moderately to yield the corresponding isothiourea product (95%) (Table 6, entries **7j** and **k**). The respective isothiourea derivatives **7a–k** were isolated in each case and characterised by ^{1}H and ^{13}C NMR spectroscopy (Fig. FS112–FS132, see the ESI†). Yields were calculated after the pure products were isolated.

Complex **3a** is also found to be a potent catalyst in the hydrophosphorylation of heterocumulenes with diphenylphosphine oxide [Ph$_2$P(O)H] under conditions similar to hydroalkoxylation discussed above. The reaction of DIC and DCC with diphenylphosphine oxide smoothly afforded the corresponding phosphorylguanidine in each case (Table 6, entries **8a** and **b**). In addition, the presence of two resonance peaks in the ^{31}P NMR spectra in the case of DIC indicated the formation of E and Z-isomers of the respective phosphorylguanidine products (Fig. FS134†). Substituting DIC with a bulkier carbodiimide (such as DCC) allowed us to successfully obtain only one isomer

of phosphorylguanidine (Fig. FS137†). These results are consistent with those previously reported by our group[18] and Westerhausen et al.[65] for hydrophosphorylation reaction of carbodiimides catalysed by alkali metals. Analogous reactions of diphenylphosphine oxide with isocyanates and isothiocyanates resulted the facile formation of corresponding 1-(diphenylphosphoryl)-N-(p-tolyl)formamide, N-(4-chlorophenyl)-1-(diphenylphosphoryl)-formamide (Table 6, entries **8c** and **d**) and 1-(diphenyl phosphoryl)-N-(p-tolyl)-methanethioamide, N-(4-chloro-phenyl)-1-(diphenylphosphoryl)methanethioamide (Table 6, entries **8e** and **f**), indicating the versatility of the catalyst. We were able to crystallise **8f**. The molecular structure of **8f** in the solid state is already known[66] and has been provided in the ESI (see Fig. FS182†).

Formation of quinazolinones

Insertion of heterocumulenes into N–H bonds of amino acid esters, followed by cyclisation, results in the formation of six-membered nitrogen-containing heterocyclic compound quinazolinones. These have been widely used in anti-cancer, anti-malaria, anti-inflammatory, and anti-tuberculosis medication due to their diverse biological properties.[67] This class of compounds and their derivatives also have significant uses in the synthesis of natural products.[37]
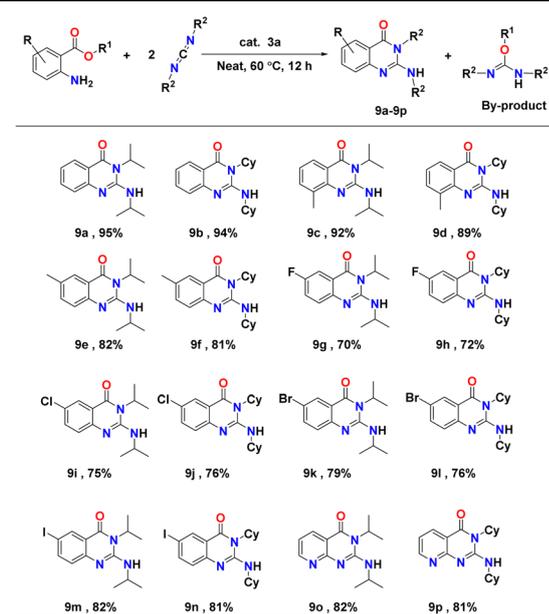
In continuation of our research, we extended the applicability of aluminium complex **3a** as a catalyst in the hydroamination/cyclisation of amino acid esters with carbodiimides to afford corresponding quinazolinones under mild conditions with a broad substrate scope. Initially, the catalytic activity of complex **3a** was tested with a catalyst loading of 5 mol% starting with ethyl 2-amino-benzoate and N,N′ diisopropylcarbodiimide (DIC) in a 1 : 2 molar ratio at 60 °C under solvent-free conditions. To our delight, 95% of the corresponding cyclic aminoquinazolinone product was isolated after 12 hours (Table 7, entry **9a**). The use of 2 equivalents of carbodiimides is required for complete conversion of ethyl 2-aminobenzoate, as alcohol is discharged as a side product during this reaction; this reacts further with the second molecule of carbodiimides to form isourea as by-product. This phenomenon was also observed in earlier reports.[43]

In order to analyse the substrate scope further, the hydroamination/cyclisation reactions of a series of substituted amino acid esters with carbodiimides catalysed by complex **3a** were investigated under optimum conditions (i.e., substituted amino acid ester and carbodiimide in a 1 : 2 molar ratio with 5 mol% of the complex **3a** under solvent-free conditions at 60 °C). In each case, the corresponding quinazolinone derivatives (**9a–p**) were isolated and analysed through ^{1}H and ^{13}C NMR spectroscopy (see Fig. FS150–FS181 in the ESI†). Yields were calculated after isolating the pure products. The reactions evidenced a broad substrate scope. Results of the catalytic hydroamination/cyclisation reactions of aminoesters with carbodiimides are presented in Table 7.

In most cases, very good substrate conversion, producing the corresponding quinazolinone derivatives with excellent chemoselectivity, was achieved. It was observed that the reaction of

Table 7 Substrate scope for the guanylation/cyclisation of amino acid esters with carbodiimides catalysed by complex 3a[a,b,c]

9a, 95%   9b, 94%   9c, 92%   9d, 89%

9e, 82%   9f, 81%   9g, 70%   9h, 72%

9i, 75%   9j, 76%   9k, 79%   9l, 76%

9m, 82%   9n, 81%   9o, 82%   9p, 81%

[a] Reaction conditions: catalyst **3a** (0.0095 mmol, 5 mol%), amino acid ester (0.192 mmol, 1 equiv.), and carbodiimide (0.384 mmol, 2 equiv.) under neat conditions at 60 °C for 12 h. [b] Yields were determined by isolation of the products.

either diisopropylcarbodiimide (DIC) or *N,N'*-dicyclohexylcarbodiimide (DCC) with substituted amino acid esters, bearing electron-donating groups (methyl and methoxy) on the aryl ring proceeded smoothly at 60 °C under neat conditions and afforded the respective aminoquinazolinones derivatives in good yields of ~80–92% (Table 7, entries **9c** and **f**). In contrast, amino acid esters with electron-withdrawing groups (such as fluoro, chloro, bromo, and iodo), showed slightly lower reactivity and conversion (~70–80%) under similar conditions, due to the deactivation of the aryl moiety (Table 7, entries **9g–n**). The heterocyclic amino acid esters also showed excellent conversion to the corresponding aminoquinazolinones derivatives under mild reaction conditions (Table 7, entries **9o** and **p**).

Based on the previous reports,[41–43] a most plausible mechanism for the catalytic guanylation/cyclization of amino acid esters using Al catalyst **3a** has been proposed. In the first step, aminolysis of the Al-alkyl complex with aminobenzoate takes place to generate active catalytic species (I) with the elimination of two volatile methane molecules, which further participates in several catalytic steps to give the desired product. The detailed mechanism and scheme are provided in the ESI (Scheme S2†).

Experimental section

General

All manipulations of air-sensitive materials were performed with the rigorous exclusion of oxygen and moisture in flame-dried Schlenk-type glassware either on a dual manifold Schlenk line, interfaced to a high vacuum (10⁻⁴ torr) line or in an argon-filled M.

Braun glove box. Hydrocarbon solvents (toluene and *n*-pentane) were distilled under nitrogen from LiAlH₄ and stored in the glove box. ¹H NMR (400 MHz), ¹³C{¹H} (100 MHz) NMR ³¹P{¹H} (161.9 MHz) spectra were recorded on a BRUKER AVANCE III-400 spectrometer. BRUKER ALPHA FT-IR was used for FT-IR measurement. Elemental analyses were performed on a BRUKER EURO EA at the Indian Institute of Technology Hyderabad. The NMR solvent CDCl₃, C₆D₆ and DMSO-*d₆* were purchased from Sigma Aldrich and used without further purification.

Preparation of [Ph₂P(E)NH(CH₂)₂N(CH₂CH₂)₂O] [E = Se (1a-H), S (1b-H)]

In a degassed 25 ml Schlenk tube, triethylamine (0.932 g, 9.2 mmol, 1.2 equiv.) was slowly added to the solution of toluene (10 ml) and 4-(2-aminoethyl)morpholine (1.0 g, 7.68 mmol, 1 equiv.) kept at ice-cold temperature. After stirring for 30 min., chloro-diphenylphosphine (2.03 g, 9.2 mmol, 1.2 equiv.) was added dropwise for 15 minutes to the above solution while it was being vigorously stirred. The resulting reaction mixture was stirred for another 12 hours at room temperature and the formation of a white precipitate of triethylammonium chloride was observed during the reaction. The solution was filtered to remove the triethylammonium chloride salt. The elemental Se (0.73 g, 9.2 mmol, 1.2 equiv.) or S (0.3 g, 9.2 mmol, 1.2 equiv.) was then added to the filtrate under an inert atmosphere. The resulting solution was stirred for another 12 hours at 90 °C. Finally, the reaction mixture was filtered to remove the excess S/Se and the filtrate was evaporated under reduced pressure to give a pale-yellow sticky compound, which resulted in a white powder after being washed with hexane in each case. Colourless crystals of **1a-H** were obtained in diethyl ether at room temperature.

1a-H. Yield 2.8 g, 93%. ¹H NMR (400 MHz, CDCl₃, 25 °C): δ_H 7.89–8.15 (m, 4H, Ar), 7.35–7.56 (m, 6H, Ar), 3.60–3.74 (m, 4H, OC*H*₂ morph), 3.15–3.31 (br, 1H, N*H*), 2.99 (dq, 2H, NHC*H*₂, *J* = 10.45, 5.48 Hz), 2.51–2.64 (m, 2H, NC*H*₂), 2.33–2.51 (m, 4H, NC*H*₂) ppm. ¹³C{¹H} NMR (100 MHz, CDCl₃, 25 °C): δ_C 134.0 (Ar), 133.0 (Ar), 131.7(Ar), 128.35 (Ar), 67.0 (OC*H*₂ morph), 57.70 (NC*H*₂), 53.0 (NC*H*₂ morph), 34.0 (NHC*H*₂) ppm. ³¹P{¹H} NMR (161.9 MHz, CDCl₃, 25 °C): δ_P 57.5 ppm. Elemental analysis. C₁₈H₂₃N₂OPSe (393.3). Calcd C 54.97, H 5.89, N 7.12; found C 54.75, H 5.64, N 6.96.

1b-H. Yield 2.57 g, 97%. ¹H NMR (400 MHz, CDCl₃, 25 °C): δ_H 7.91–8.10 (m, 4H, Ar), 7.40–7.55 (m, 6H, Ar), 3.67 (t, 4H, OC*H*₂ morph, *J* = 4.65 Hz), 3.20–3.41 (br, 1H, N*H*), 2.96–3.10 (m, 2H, NC*H*₂), 2.58 (t, 2H, NC*H*₂, *J* = 5.87 Hz), 2.47 (t, 4H, NC*H*₂ morph, *J* = 4.89 Hz) ppm. ¹³C{¹H} NMR (100 MHz, CDCl₃, 25 °C): δ_C 134.6 (Ar), 133.6 (Ar), 131.4 (Ar), 128.37 (Ar), 66.7 (OC*H*₂ morph), 58.0 (NC*H*₂), 53.0 (NC*H*₂ morph), 37.0 (NHC*H*₂) ppm. ³¹P{¹H} NMR (161.9 MHz, CDCl₃, 25 °C): δ_P 59.6 ppm. Elemental analysis. C₁₈H₂₃N₂OPS (346.4). Calcd C 62.41, H 6.69, N 8.09; Found C 62.23, H 6.57, N 7.88.

Preparation of [Al(Me)₂{Ph₂P(E)N(CH₂)₂N(CH₂CH₂)₂O}] [E = Se (2a), S (2b)]

Inside the glove box in a degassed 25 ml Schlenk flask, ligand **1a** (150 mg, 0.381 mmol) or **1b** (150 mg, 0.432 mmol) and 5 ml of

toluene were added. Thereafter, the reaction solution was taken out from the glovebox. To this solution, trimethylaluminum solution (2.0 M in toluene) (0.19 ml, 0.381 mmol for **1a** or 0.22 ml, 0.432 mmol for **1b**) was added, and the resulting reaction mixture was stirred continuously for 12 hours at 60 °C. Then the solvent was evaporated under a high vacuum to produce a colourless residue, which resulted in a white solid after being washed with hexane in each case. The white solid was dissolved in 3 ml of toluene and kept aside for re-crystallization at −35 °C. Colourless crystals of **2a** were obtained after seven days.

2a. Yield 159 mg, 93%. ^{1}H NMR (400 MHz, C$_6$D$_6$, 25 °C): δ_H 8.25–8.40 (m, 4H, Ar), 7.09–7.18 (m, 4H, Ar), 7.01–7.09 (m, 2H, Ar), 3.27 (ddd, 2H, $J = 12.72, 10.03, 2.69$ Hz), 3.11 (dt, 2H, $J = 12.72, 3.67$ Hz), 3.01 (dt, 2H, $J = 8.07, 5.99$ Hz), 2.58 (dt, 2H, $J = 12.72, 3.42$ Hz), 2.08 (t, 2H, $J = 6.11$ Hz), 1.66 (ddd, 2H, $J = 13.20, 9.78, 3.42$ Hz), −0.77 (s, 6H, Al(CH$_3$)$_2$) ppm. ^{13}C{^{1}H} NMR (100 MHz, C$_6$D$_6$, 25 °C): δ_C 137.0 (Ar), 136.0 (Ar), 133.0 (Ar), 132.0 (Ar), 64.0 (OCH$_2$ morph), 58.5 (NCH$_2$), 52.6 (NCH$_2$ morph), 41.0 (NCH$_2$ anionic), −7.0 (AlMe$_3$) ppm. ^{31}P{^{1}H} NMR (161.9 MHz, C$_6$D$_6$, 25 °C): δ_p 56.9 ppm. Elemental analysis. C$_{20}$H$_{28}$AlN$_2$OPSe (449.35). Calcd C 53.46, H 6.28, N 6.23; found C 53.29, H 6.21, N 6.13.

2b. Yield 162 mg, 93%. ^{1}H NMR (400 MHz, C$_6$D$_6$, 25 °C): δ_H 8.21–8.37 (m, 4H, Ar), 7.12–7.20 (m, 4H, Ar), 7.04–7.11 (m, 2H, Ar), 3.24–3.35 (m, 2H), 3.12 (dt, 2H, $J = 12.84, 3.61$ Hz), 2.97 (dt, 2H, $J = 7.34, 6.11$ Hz), 2.55 (dt, 2H, $J = 12.72, 3.18$ Hz), 2.05 (t, 2H, $J = 6.11$ Hz), 1.64 (ddd, 2H, $J = 12.96, 9.78, 3.67$ Hz), - 0.73 (s, 6H, Al(CH$_3$)$_2$) ppm. ^{13}C{^{1}H} NMR (100 MHz, C$_6$D$_6$, 25 °C): δ_C 137.5 (Ar), 136.5 (Ar), 132.3 (Ar), 132.2 (Ar), 63.0 (OCH$_2$ morph), 58.6 (NCH$_2$), 52.0 (NCH$_2$ morph), 39.7 (NCH$_2$ anionic), −7.30 (AlMe$_3$) ppm. ^{31}P{^{1}H} NMR (161.9 MHz, C$_6$D$_6$, 25 °C): δ_P 55.4 ppm. Elemental analysis. C$_{20}$H$_{28}$AlN$_2$OPS (402.47). Calcd C 59.69, H 7.01, N 6.96; found C 59.53, H 6.82, N 6.68.

Preparation of [Al(Me)$_2${Ph$_2$P(E)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O}(AlMe$_3$)] (E = Se (3a) and S (3b))

Route 1. Inside the glovebox, in a degassed 25 ml Schlenk flask, ligand **1a-H** (200 mg, 0.508 mmol)/**1b-H** (176 mg, 0.508 mmol) and 5 ml of toluene were added. Thereafter, the reaction solution was taken out from the glovebox. To this solution, trimethylaluminium solution-2.0 M in toluene (0.51 ml, 1.02 mmol) was added, and the resulting reaction mixture was stirred continuously for 12 hours at 90 °C temperature. Then the solvent was evaporated under high vacuum to produce a solid residue which resulted in a white solid in each case after being washed with hexane inside the glovebox. The white solid was dissolved in 3 ml of toluene and kept aside for re-crystallisation at −35 °C. Colourless crystals of **3a** were obtained within one week.

Route 2. Inside the glovebox, in a degassed 25 ml Schlenk flask, complex **2a** (200 mg, 0.445 mmol)/**2b** (179 mg, 0.445 mmol) and 5 ml of toluene were added. Thereafter, the reaction solution was taken out from the glovebox. To this solution, trimethylaluminium solution-2.0 M in toluene (0.22 ml, 0.445 mmol) was added, and the resulting reaction mixture was stirred continuously for 12 hours at 90 °C. Then the solvent was

evaporated under high vacuum to produce a solid residue which resulted in a white solid in each case after being washed with hexane inside the glovebox. The white solid was then dissolved in 3 ml of toluene and keep aside for re-crystallisation at −35 °C.

3a. Yield 252 mg, 95%. ^{1}H NMR (400 MHz, 25 °C, C$_6$D$_6$): δ_H 8.21–8.16 (m, 4H, ArH), 7.15–7.11 (m, 4H, ArH), 7.08–7.03 (m, 2H, ArH), 3.34 (d, $J = 12.8$ Hz, 2H, OCH$_2$), 3.31–3.24 (m, 2H, OCH$_2$), 2.89 (dd, $J = 13.6, 6.2$ Hz, 2H, CH$_{2(methylene)}$), 2.36 (d, $J = 13.4$ Hz, 2H, CH$_{2(methylene)}$), 1.92 (t, $J = 6.0$ Hz, 2H), 1.60–1.54 (m, 2H, CH$_{2(morpholine)}$), −0.46 (s, 9H, AlMe$_3$), −0.88 (s, 6H, AlMe$_2$) ppm. ^{13}C{^{1}H} NMR (100 MHz, 25 °C, C$_6$D$_6$): δ_C 136.8 (C_{Ar}), 135.9 (C_{Ar}), 132.8 (C_{Ar}), 132.7 (C_{Ar}), 131.7 (C_{Ar}), 128.9 (C_{Ar}), 128.8 (C_{Ar}), 65.9 (C_{Ar}), 51.2 (C_{Ar}), 41.1 (C_{Ar}), −6.85 (AlMe$_2$), −7.73 (AlMe$_2$) ppm. ^{31}P{^{1}H} NMR (243 MHz, 25 °C, C$_6$D$_6$): δ_P 56.0 ppm. Elemental analysis. C$_{23}$H$_{37}$Al$_2$N$_2$OPSe (521.4). Calcd C 52.98, H 7.15, N 5.37; found C 52.62, H 7.03, N 5.19.

3b. Yield 250 mg, 91%. ^{1}H NMR (600 MHz, 25 °C, C$_6$D$_6$): δ_H 8.01–7.93 (m, 4H, ArH), 7.12 (ddd, $J = 9.3$ Hz, 5.4 Hz, 2.7 Hz, 4H, ArH), 7.06 (t, $J = 7.3$ Hz, 2H, ArH), 3.34 (d, $J = 10.1$ Hz, 2H, OCH$_2$), 3.21 (t, $J = 11.3$ Hz, 2H, OCH$_2$), 2.91 (d, $J = 7.0$ Hz, 2H, CH$_{2(methylene)}$), 2.25 (d, $J = 13.3$ Hz, 2H, NCH$_{2(methylene)}$), 1.87 (t, $J = 4.4$ Hz, 2H, NCH$_{2(morpholine)}$), 1.55 (t, $J = 9.9$ Hz, 2H, CH$_{2(morpholine)}$), −0.35 (s, 9H, AlMe$_3$), −0.98 (s, 6H, AlMe$_2$). ^{13}C{^{1}H} NMR (100 MHz, 25 °C, C$_6$D$_6$): δ_C 132.4 (C_{Ar}), 133.3 (C_{Ar}), 132.2 (C_{Ar}), 128.91 (C_{Ar}), 128.8 (C_{Ar}) 128.2 (C_{Ar}), 128.0 (C_{Ar}), 127.9 (C_{Ar}), 65.7 (OCH$_2$), 58.47 (CCN$_{(morpholine)}$), 50.91 (C_{Ar}), 40.15 (NCH$_2$C), −6.66 (AlMe$_2$), −7.73 (AlMe$_3$) ppm. ^{31}P{^{1}H} NMR (243 MHz, 25 °C, C$_6$D$_6$): δ_P 58.31ppm. Elemental analysis. C$_{23}$H$_{37}$Al$_2$N$_2$OPS (474.56). Calcd C 58.21, H 7.86, N 5.90; found C 52.16, H 7.77, N 5.82.

Catalytic experiments

Procedure for synthesis of urea derivatives

Inside the glovebox, in a degassed 25 ml Schlenk tube, a solution of secondary amine (0.384 mmol, 1 equiv.) was added into the mixture of the chosen isocyanate (0.384 mmol, 1 equiv.) and aluminium metal complex (**3a**) (0.00384 mmol, 1 mol%). A white solid started to form during the reaction at room temperature, and an additional hour was allowed for the reaction to be completed. A white solid compound was obtained in each case which was characterized directly by ^{1}H and ^{13}C{^{1}H} NMR spectroscopy without any further purification. The yields of amines were calculated from isolated pure products.

Procedure for synthesis of biuret compounds

Inside the glovebox in a degassed 25 ml Schlenk tube, secondary amine (0.384 mmol, 1 equiv.) was added to the mixture of the chosen isocyanate (1.15 mmol, 3 equiv.) and aluminium complex (**3a**) (0.00384 mmol, 1 mol%). A white solid started to form during the reaction when it was stirred at room temperature for six hours. A white solid compound was obtained in each case, which was purified by washing with n-hexane several times and the desired product was further purified by the column technique (EtOAc : pet ether : 1 : 10). The yield of biuret

was calculated from isolated pure products. The products were characterised using ^{1}H and ^{13}C{^{1}H} NMR spectroscopy.

Procedure for synthesis of isourea and isothiourea derivatives

Inside the glovebox, in a degassed 25 ml Schlenk tube, the chosen aryl alcohol/thiol (0.384 mmol, 1 equiv.) was added into the mixture of carbodiimide (0.384 mmol, 1 equiv.) and aluminium complex (**3a**) (0.00384 mmol, 1 mol%). A white solid started to form during the reaction, as it was stirred at room temperature for one hour. The corresponding isourea and iso-thiourea derivatives obtained were characterised directly by ^{1}H and ^{13}C{^{1}H} NMR spectroscopy without any further purification. The yields of isourea and thiourea were calculated from the pure products isolated.

Procedure for the synthesis of phosphorylguanidine

Inside the glovebox, in a degassed 25 ml Schlenk tube, diphenylphosphine oxide (0.384 mmol, 1 equiv.) was added to the mixture of carbodiimide (0.384 mmol, 1 equiv.) and aluminium complex (**3a**) (0.00384 mmol, 1 mol%). A white solid started to form during the reaction, as it was stirred at room temperature for one hour. The reaction mixture was quenched with ethanol and then washed with dichloromethane, followed by Celite filtration to obtain a pure white or yellow solid of phosphoguanidine. The yield of phosphoguanidine was calculated from the isolated product. The isolated products were identified by ^{1}H, ^{13}C{^{1}H}, and ^{31}P{^{1}H} NMR spectroscopy.

Procedure for the synthesis of quinazolinones

Inside the glovebox in a degassed 25 ml Schlenk tube, a solution of amino acid ester (0.192 mmol, 1 equiv.) was added dropwise to the mixture of carbodiimide (0.384 mmol, 2 equiv.) and aluminium complex (**3a**) (0.0095 mmol, 5 mol%). The yellow-coloured reaction mixture was heated at 60 °C for 12 hours to complete the reaction. The progress of reactions was monitored by TLC. Subsequently, the reaction mixture was quenched by adding 20 ml of ethyl acetate solvent. The basic workup was done by adding 5 ml of a saturated sodium bicarbonate solution to the reaction mixture. The organic layer was separated from the product and purified by column chromatography using 5% ethyl acetate as an eluent solvent. The yields of quinazolinones were calculated from pure isolated products. The isolated products were characterised using ^{1}H and ^{13}C{^{1}H} NMR spectroscopy.

Conclusion

To summarise, we synthesised and characterised a series of mononuclear and binuclear aluminium complexes with the general composition [Al(Me)$_2$\{Ph$_2$P(E)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O\}] E = Se (**2a**); S (**2b**) and [Al(Me)$_2$\{Ph$_2$P(E)N(CH$_2$)$_2$N(CH$_2$CH$_2$)$_2$O\}-(AlMe$_3$)\] (E = Se (**3a**) and S (**3b**)). We demonstrated the superior catalytic efficiency of the binuclear aluminium metal complex **3a** in the facile synthesis of a variety of products such as urea, biuret, isourea, isothiourea, phosphorylguanidine, and quinazolinone derivatives. We also demonstrated that the efficiency

of the binuclear complex **3a** exceeds that of its mononuclear analogues and previously reported catalysts. We noted that the reaction of isocyanates with a variety of secondary amines in a 1 : 1 molar ratio, catalysed by complex **3a** at room temperature, proceeded smoothly and resulted in the selective production of the corresponding urea in up to 99% yield. Biuret derivatives were synthesised in very good yields (of up to 80%) *via* the direct transformation of secondary amines with isocyanates (1 : 3 molar ratio) using the same catalyst **3a** under solvent-free and mild conditions. This catalyst also exhibited excellent reactivity and selectivity in the addition of E–H bonds (E = OR, SR, P(O)R$_2$) to a wide variety of heterocumulenes under mild conditions. The application of complex **3a** as a catalyst was successfully extended to the hydroamination/cyclisation of amino acid esters with carbodiimides to afford the corresponding quinazolinones in yields of up to 95%. In each case, complex **3a** displayed a high tolerance toward heteroatoms and functional groups under mild conditions with a broad substrate scope.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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