Anion receptors have attracted growing interest because of their role in chemistry, the environment, biology and medicine. The mis-regulation of anion flux causes a variety of lethal human diseases. Recently, triazole has been found to be an excellent motif for molecular recognition. This review depicts an overall picture of developments in the design and synthesis of anion receptors along with an up-to-date emphasis on the triazole unit as a motif for anion recognition. The acidic CH of triazole is involved in binding with the anions, which makes these receptors different from other classes of receptors. The chemoselectivity and regioselectivity of the click reaction provides further impetus for future developments in this area.

Introduction

Molecular recognition has attracted considerable interest in recent years because it is integral in many scientific areas, such as biology, chemistry, and pharmacology. Molecular recognition of cations, anions, and neutral molecules are important in biology and chemistry. Although rigorous attention has been paid to the recognition of cations, recognition of anions has received less attention. Anions are everywhere in living systems and are vital in carrying out many biochemical operations for sustaining life. Anions such as chloride, phosphate, and sulfate regulate the flux of key metabolites into and out of cells while maintaining osmotic balance. Among all anions, anion receptors specific to chloride and fluoride have attracted growing interest because of their role in chemistry, biology, and medicine. The mis-regulation of chloride ion flux causes severe human diseases, such as cystic fibrosis, myotonia, and epilepsy. Accumulation of excess fluoride ions in living organisms causes collagen breakdown, bone disorder, impact on the immune system and thyroid activity. Oxalate, arsenate, and nitrite can produce chronic diseases. Naturally occurring phosphatase and sulfate can cause renal failure for patients, due to poor catabolic activity.

In recent years, increasing attention has been devoted to the synthesis of receptors for recognition of anions. Serious efforts have been paid since the beginning of anion coordination chemistry in the late 1960s for the development of synthetic...
receptors for recognition of anions. However, the major binding motifs that have been utilized until now are as follows: cationic polyammonium, quaternary ammonium, amide, urea, thiourea, guanidinium, pyrrole, imidazolium and boron containing receptors (Fig. 1).14

These motifs have been utilized for the construction of receptors for anions with varying selectivity. A preliminary discussion about these receptors is given below. The discovery of novel motifs for the recognition of anions is a rate limiting step in the area of anion recognition research. In the latter part of this review, we provide a brief history, detailed analysis of the origin of triazole as an anion recognition motif, and the recent developments in this area using triazole as an anion recognition motif. Most of the examples of the receptors presented here are designed for use in organic solvents.

1.1 Polyammonium-based receptors

The first synthetic anion receptor (Fig. 2) was reported by Park and Simons in 1968.15 These macrocyclic compounds, consisting of two bridgehead ammonium units, showed binding behaviour towards halide ions. However, the [8.8.8] and [10.10.10]-bridged compounds 1 and 3 showed no appreciable binding behavior towards halide ions; while the analogous [9.9.9]-bridged compound 2 binds chloride ions with an affinity of $10^2$ M$^{-1}$, with modest selectivity for chloride over bromide by a factor of eight.

Bowman-James et al. synthesized various bicyclic azacryptands (Fig. 3) containing ammonium units, for binding of anions.16 Crystal structure analysis of 4 showed the encapsulation of a single F$^-$ ion with a water molecule inside the cavity. Whereas the bicyclic azacryptand 5, having a bigger cavity than 4, accommodated two F$^-$s with a water molecule inside the cavity. The water molecule acts as bridge between the two fluoride ions and thus generates an anion-based cascade complex.

1.2 Quaternary ammonium-based receptors

Schmidtchen et al. first reported a series of quaternary ammonium-based receptors (Fig. 4) for the recognition of anions.17 The most attractive feature in such receptors is the utilization of electrostatic interaction for the recognition of anions. The discovery of novel motifs for the recognition of anions is a rate limiting step in the area of anion recognition research. In the latter part of this review, we provide a brief history, detailed analysis of the origin of triazole as an anion recognition motif, and the recent developments in this area using triazole as an anion recognition motif. Most of the examples of the receptors presented here are designed for use in organic solvents.

Mr. Praveen Kumar P. P was born in 1987 in Kerala, India. He received his Masters degree in synthetic organic chemistry from Christ College affiliated to Calicut University, Kerala, in 2009. In the same year he was honoured with CSIR-JRF, and GATE. Presently he is a PhD student in the department of chemistry, IIT Delhi, under the guidance of Dr V. Haridas. He is working on the design and synthesis of molecular receptors for various anions and cations.

Appa Rao Sapala was born in Rajahmundry, Andhra Pradesh, India (1984), received his bachelor’s degree (2005) from the same place and MSc degree (2007) in Chemistry from Gitam College, Andhra University, Visakhapatnam. He had 3 years experience in G. V. K Bio Pvt. Ltd, Hyderabad. He qualified CSIR-JRF and is currently pursuing his PhD degree at IIT Delhi under the guidance of Dr V. Haridas. His research interests are in the area of peptide design, synthesis and their applications.
anions. Receptor 6 contains four tetra-alkylammonium-bridged centres, which are connected through (CH₂)₆ alkyl linkers. Crystal structure analysis of this receptor with iodide shows that it encapsulates iodide into its tetrahedral cage by utilizing the electrostatic interactions. The receptor 7 binds to p-nitrophenolate as a result of having a higher cavity size than receptor 6.

**Fig. 4** Quaternary ammonium receptors 6 and 7 that bind I⁻ electrostatically. Quaternary ammonium receptor 8 for ATP.

Menger et al designed and synthesized a new class of quaternary ammonium-based receptors (Fig. 4) for recognition of anions. Receptor 8 showed binding with various anions: benzene sulphonate, naphthalene-2-sulfonate and naphthalene-2,7-disulphonate in aqueous solution. It also binds to ATP very strongly with an association constant of 13 300 M⁻¹.

### 1.3 Amide-based receptors

Pascal et al. first reported abiotic amide-based receptor (Fig. 5) for recognition of anions by utilizing amide –NHs as hydrogen-bonding donor groups. The crystal structure analysis of cyclophane 9 offers a cylindrical cavity of approximately 4 Å in length and 3 Å in diameter, due to the presence of two facial aromatic rings that are connected through three bridging arms. The crystal structure revealed that three amide–NHs are inclined by 47, 54, and 68° to radii drawn from the central axis through the nitrogen atoms.

**Fig. 5** Amide receptors 9–11.

Choi and Hamilton reported a series of amide-containing rigid macrocycles and acyclic compounds (Fig. 5). These compounds bind to various anions as follows: I⁻, Cl⁻, NO₃⁻, pTsO⁻, HSO₄⁻, and H₂PO₄⁻ with varying ability. Binding studies showed that macrocycle 10 is a better binder towards anions than the acyclic 11. The receptor 10 showed 1 : 1 binding with a tosylate anion, whereas 11 binds to I⁻, Cl⁻, and NO₃⁻ in 2 : 1 stoichiometry.

Bowman-James et al. designed and synthesized a polyamide-based cryptand (Fig. 6) to investigate the binding behaviour for various anions. The receptor 12 showed promising binding behaviour for the fluoride ion in DMSO-d₆ with a log K value of 5.0 followed by Cl⁻ (log K = 3.47), CH₃COO⁻ (log K = 3.38), H₂PO₄⁻ (log K = 3.30), NO₃⁻ (log K = 1.93), HSO₄⁻ (log K = 1.83), and Br⁻ (log K = 1.6) with the formation of 1 : 1 complexes.

**Fig. 6** Polyamide cryptand receptor 12 for F⁻.

### 1.4 Urea and thiourea-based receptors

Wilcox et al. reported urea and thiourea-based synthetic receptors for recognition of various oxo-anions. The binding behavior of receptor 13 (Fig. 7) with various oxo-anions a–d in chloroform was examined by UV/vis titration experiments. The thiourea-based receptor 14 is a better binder than 13 for oxo-anions a–d.

**Fig. 7** Urea and thiourea-based receptors 13 and 14.

Reinhoudt et al. designed and synthesized various urea- and thiourea-based molecules (Fig. 8) for recognizing anions. The cleft-like acyclic urea-based receptor 15 binds to H₂PO₄⁻, in a 2 : 1 stoichiometry with an association constant of 5 × 10⁷ M⁻¹. It showed very poor binding affinity towards Cl⁻, Br⁻, NO₃⁻, and HSO₄⁻. The thiourea-based receptor 16 binds similarly to 15. The rigid macrocycles 17 and 18 offered a 1 : 1 binding stoichiometry toward H₂PO₄⁻ with association constants of 4 × 10³ and 2.5 × 10³ M⁻¹, respectively.
Gale et al. proposed an acyclic, urea-based receptor 19 (Fig. 9) to acknowledge anions.24 The bis-urea containing receptor 19 binds to the acetate ion more selectively with a binding constant of $K_b = 3.2 \times 10^9 \text{M}^{-2}$ over $\text{Cl}^-$, $\text{Br}^-$, $\text{H}_2\text{PO}_4^-$, and $\text{HSO}_4^-$. The receptor 19 binds to acetate more strongly than receptors 20 and 21.

1.5 Guanidinium-based receptors

Since the beginning of anion co-ordination chemistry, the guanidinium moiety was used for design of anion receptors, as the guanidinium moiety has two key major features for the creation of abiotic anion receptors: (1) its high basic nature, which helps in sustaining a wide pH range; (2) its ability to donate two parallel hydrogens for hydrogen bond donors. Because of these unique features, guanidinium-based receptors show high affinities and selectivities for oxyanions. Taking advantage of this moiety, Lehn et al. reported a series of novel guanidinium-based cyclophanes (Fig. 10).25 The binding studies of these macrocycles 22, 23, and 24 showed 1 : 1 binding with trianionic phosphate ($\text{PO}_4^{3-}$) in methanol–water (9 : 1) solution with $\log K_a = 3.1, 3.4$, and 4.3 respectively.

Schmidten designed and synthesized a bis-guanidinium-based acyclic molecule (Fig. 11) for the binding of anions.26 The two-guanidinium moieties in 25 converged in the presence of tetrahedral anions, such as thymidine-5'-phosphate (e) and thus provided a suitable geometry for binding. The NMR titration experiment showed a 1 : 1 complex of 25 with e, having a binding constant of $10^6 \text{M}^{-1}$ in water. The compound 25 displayed no binding for simple $\text{HPO}_4^{2-}$ anions.

Lavigne and Anslyn reported on a guanidinium-based receptor (Fig. 11) for detecting tartrate anions.27 The receptor 26, containing two guanidinium moieties, provides a suitable geometry with the correct cavity size for binding of tartrate. It also responded to other analytes: ascorbate, L-malate, succinate, lactate, and sugars. It binds strongly to tartrate as compared to other analytes in 1 : 1 stoichiometry and with a binding constant of $5.5 \times 10^4 \text{M}^{-1}$ towards tartrate.

1.6 Pyrrole-based receptors

The first pentapyrrolic macrocyclic receptor (Fig. 12) was reported by Sessler et al. in the late 1990s.28 The crystal structure analysis showed the complex as a diprotonated macrocycle with fluoride residing inside the cavity. Solution phase studies showed that the diprotonated sapphyrin (expanded porphyrin containing five pyrrole units) 27 binds to fluoride 10^3 fold more than chloride and bromide. This finding opened up a new direction for the exploration of anion co-ordination chemistry of pyrrole-containing systems.
A new type of calixpyrrole (Fig. 13) was synthesized for binding towards anions. The crystal structure analysis of 28 showed a wing-like architecture with a benzoate ion between the two wings. It showed a strong affinity for acetate in 1:1 stoichiometry with binding constant value of 229 000 M$^{-1}$.

Fig. 13 Pyrrole-based receptor 28, 29 with controlled cavity size for anions.

Lee et al. designed and synthesized a new class of calix[4]pyrrole containing a flexible strap on one side of the molecule (Fig. 13) for controlling the cavity for better selectivity and affinity toward various anions. The receptor 29 showed significant binding behaviour for fluoride and chloride. It showed better binding ability for fluoride and chloride than the simple calix[4]pyrrole moiety. However, it does not show any appreciable binding ability with bromide, iodide, sulphone, and phosphate. The smaller cavity of these molecules disfavoured the accommodation of larger anions for binding.

1.7 Imidazolium-based receptors

Welton et al. designed and synthesized imidazolium-based (Fig. 14) compound 30. The $^1$H NMR study of 30 with halide ions (Cl$^-$, Br$^-$, and I$^-$) showed significant interaction to the C2H group of imidazolium located between the two nitrogen atoms. This result demonstrated that the imidazolium –CH could be exploited for binding towards halides. Later, Sato et al. investigated the binding event of 31 with halide ions (Cl$^-$, Br$^-$, and I$^-$). The binding constant values of 31 with chloride, bromide, and iodide ions were 78, 59, and 29 M$^{-1}$, respectively. Taking the structural benefits of the imidazolium moiety, Sato et al. designed and synthesized receptors 32–34. These receptors showed better binding ability for halides than mono-imidazolium 31.

Kim et al. reported a cyclic imidazolium receptor 35 (Fig. 15) and discussed its binding behaviour toward various anions. $^1$H NMR studies showed that receptor 35 binds to fluoride more strongly than to other anions, such as chloride, bromide, iodide, and hydrogen sulphate ions. Crystal structure analysis, as well as Job’s plot, supported the formation of a 1:1 complex of 35 with a fluoride ion, whereas for other anions, it was a 1:2 binding stoichiometry. The binding constant value of 35 with the fluoride ion was found to be 28900 M$^{-1}$.

Fig. 14 Imidazolium-based receptors 30–34.

1.8 Boron-based receptors

Boron in the trisubstituted state with sp$^2$ hybridization has a vacant p orbital that can easily accommodate nucleophiles (Fig. 16) and therefore can act as good receptors for anions. In 1985, Katz studied the binding affinity of receptor 36 (Fig. 17) and utilizing $^{19}$F,$^{1}$H, $^{19}$F,$^{13}$C and $^{11}$B NMR, and found that the B-B distance becomes shorter after binding with F$^-$.

Fig. 15 Cyclic imidazolium-based receptor 35 for the selective recognition of F$^-$.

Fig. 16 Coordination of boron with nucleophiles.

Fig. 17 Boron-based receptor for F$^-$. 

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A mixed Lewis system (Fig. 18) containing boron and silicon centers on an \(o\)-phenylene backbone showed stronger binding toward \(\text{F}^-\) than the monodentate boron analogues. 35

\[
\begin{align*}
\text{SiR}_2\text{F} & \xrightarrow{\text{KF/L}} \text{Toluen, RT, 5h} \\
\text{BF}_{\text{Mes}} & \xrightarrow{\text{[KL]}^-} \lbrack \text{[F]}^{-}\rbrack
\end{align*}
\]

\(\text{a R = Me} \quad \text{b R = Ph} \quad \text{L = 2.2.2|cryptand or 18-crown-6} \quad \text{Mes = 2,4,6-trimethylphenyl} \)

\[37, \text{F}^-\]

**Fig. 18** Mixed Lewis system for \(\text{F}^-\) recognition.

### 1.9 Triazole-based receptors

The examples illustrated above delineate some of the developments in the anion receptor design. The majority of anion binding motifs make use of strong hydrogen bond donor groups like NH and OH. The proton transfer and strong binding affinity are attributes of such moieties. The untapped potential of the non-conventional hydrogen bonding interaction could be exploited in the receptor design, in order to craft a truly reversible system with good binding affinity and selectivity. Therefore, novel motifs utilizing a variety of less explored non-covalent interactions for binding to the guest are much sought after. Design and synthesis of neutral receptor molecules for the anion are more difficult, because they mainly make use of the hydrogen bond, which is weaker than the coulombic interaction utilized in charged anion receptors. The maximum use of hydrogen bond donor units and the preorganized cavity are the typical design criteria for neutral anion receptors. The triazole moiety is one of the recent examples that showed good promise for the design of various neutral receptors. The testimony to that is the fairly good number of receptors that appeared in the literature in a short period of time.

**Why triazoles.** The majority of the synthetic receptors designed have a strong binding affinity towards anions; therefore, the release of anions is a real issue. The \(\text{CH} \cdots \text{X}\) interaction, though weaker than the conventional H-bond, could be utilized for binding to neutral as well as charged guests.

The \(\text{H}\)-bonding ability of triazole \(\text{CH}\) could be modulated by substituents (\(R_1\) and \(R_2\)) and thereby provide an additional benefit for making truly reversible systems. The high yield and chemoselective nature of the click reaction makes the introduction of triazole an easier task, and thus this reaction provides a better future for the design of receptors for neutral as well as charged guest molecules (Fig. 19).

In 2008, our group reported a neutral triazolophane that can bind to an acetonitrile molecule (Fig. 20). 37 Compound 38 showed a unique type of binding with acetonitrile because of non-classical hydrogen-bonding interactions. The only available hydrogen bond donor in 38 was the \(\text{CH}\) of triazole, and the macrocycle could bind the acetonitrile molecule by the non-classical hydrogen bonds and \(\text{CH} \cdots \pi\) interactions.

**Fig. 19** Synthesis of a triazole moiety and the interaction of the \(\text{CH}\) of triazole with an anion.

In the same year, Li and Flood designed and synthesized a series of shape-persistent preorganized triazolophanes (Fig. 21) by exploiting the click reaction for the recognition of anions. 38 Macrocyle 39 binds the chloride ion with a high affinity and selectivity over all halide ions. This is due to its ideal cavity size with cumulative binding effects of all the triazole CHs, and the endocyclic benzene CHs, which are oriented inwards in the cavity. The triazolophane 39 showed a very strong binding affinity value \((K = 1.1 \times 10^7 \text{ M}^{-1})\) with the chloride ion in dichloromethane.

**Fig. 20** Structural representation (a) and acetonitrile mediated assembly in the solid state of triazolophane 38 (b).

**Fig. 21** Shape-persistent preorganised triazolophane 39 binds \(\text{Cl}^-\) selectively.
A new class of triazolophanes (40 and 41) containing pyridine rings (Fig. 22) were synthesized.\(^{39}\) This generated a negative electrostatic potential due to the presence of a nitrogen lone pair in the pyridyl ring; thus, the cavity became oval, which favoured a 2:1 binding towards various halide ions. The receptor 40 showed the highest binding towards I\(^-\), followed by Br\(^-\) and F\(^-\). However, it shows a negative cooperative effect with the Cl\(^-\) ion. The receptor 40 showed relative values of \(K_1\) and <3200 M\(^{-1}\) and >32 000 000 M\(^{-1}\), respectively, with the iodide ion. These results clearly indicate that the presence of pyridyl units in the ring destabilizes the formation of 1:1 triazolophane complexes due to N…X \(\pi\) electron pair repulsion; rather, it favours 2:1 sandwich complexes.

The receptor 42, which has two hydroxy groups on the central phenylene ring, makes an intramolecular hydrogen bond with the N3 of the triazole ring, and thus brings about a preorganised structure (Fig. 23). Because of preorganisation, it binds the chloride ion with \(\sim 50\) fold greater affinity compared to non-preorganised pentad receptor 43.\(^{40}\)

In 2008, Meudtner and Hecht demonstrated the design and synthesis of a novel class of triazole-based clickamers (Fig. 25), via the click reaction, and their folding behavior under various conditions.\(^{42}\) The clickamer 47, which contains two complete turns with a number of \(\pi-\pi\) stacking units, showed very insignificant folding behavior in acetonitrile. The population of the helical conformation was observed upon the addition of substantial amounts of water. The helicity with addition of water is due to the intramolecular chirality transfer from the chiral side chains to the backbone, which is evidenced from temperature dependent circular dichroism (CD) as well as dynamic light-scattering (DLS) and UV/Vis absorption spectroscopy studies. The shorter oligomer 46 also exists in a helical conformation. The foldamer 47 showed very unusual folding behavior toward various halides. The size of the halide ion plays a major role in helix inversion by transforming intramolecular chirality from the chiral side chain to the backbone, thus establishing an equilibrium between left- and right-handed helices.

Sanotoyo-Gonzalez et al. synthesized various calixarene based cavitands (48–50) using the click reaction. Interestingly, compound 50 showed binding affinities towards various anions (Fig. 26).\(^{43}\)
Molina et al. synthesized ferrocene-pyrene dyad 51 (Fig. 27) by coupling the terminal alkyne of pyrene with that of ferrocenyl azide via a click reaction. The receptor 51 displays a highly selective binding event for trianionic $\text{H}_2\text{P}_2\text{O}_{7}^{3-}$ over various anions such as $\text{F}^-$, $\text{Cl}^-$, $\text{AcO}^-$, $\text{NO}_3^-$, $\text{HSO}_4^-$, and $\text{H}_2\text{PO}_4^-$. A fluorescence titration experiment of 51 with $\text{HP}_2\text{O}_7^{3-}$ shows a 2 : 1 complex formation.

Sessler et al. discussed a pyrrolyl-based triazolophane (Fig. 28), which displays highly selective binding affinity for the pyrophosphate anion, followed by $\text{HSO}_4^-$, $\text{H}_2\text{PO}_4^-$, $\text{Cl}^-$ and $\text{Br}^-$.

The receptor 52 binds to trianionic pyrophosphate with a 10-fold greater affinity and selectivity as compared to hydrogen sulphate. However, the binding constant was found to be $(2.30 \pm 0.40) \times 10^9 \text{M}^{-1}$ for pyrophosphate. The X-ray crystal structure analysis shows that all the pyrrole NH, triazole CH, and the endocyclic benzene CH protons are involved in stabilizing a pyrophosphate molecule in its cavity.

In 2012, Beer et al. synthesised Zn containing porphyrin-cages (Fig. 29) for the recognition of anions with the aid of click chemistry. The $^1$H NMR and UV/vis spectroscopic titration experiments showed that the receptor can bind with $\text{Cl}^-$ with a binding constant of $10^4 \text{M}^{-1}$ in a 1 : 1 stoichiometry.

Jiang et al. demonstrated a light-induced triazole-based foldamer, containing a photoresponsive azo-benzene in between the two phenyl-triazole oligomer units (Fig. 30). The compound 54 adopts two conformations, 54trans and 54cis, with respect to azo-linkage. The 54cis isomer predominates upon irradiation of UV light; however, it binds anions more strongly than the 54trans conformer. This behavior is expected due to its scissor-like conformation, which results in assembling all the binding sites ideally for the recognition of ions. The 54trans conformer predominantly exists in the presence of visible light, and it binds weakly as compared to 54cis to various anions, due to the extended conformation of the azo-benzene core. The receptor 54cis binds the chloride ion strongly with a binding constant of $290 \text{M}^{-1}$, which is approximately a 4-fold excess compared to the 54trans conformer.

In 2011, Kim synthesised a neutral ferrocene appended aryl triazole receptor 55 that can bind strongly with phosphate (Fig. 31). Ferrocene, being an electrochemical sensor, enabled detection of phosphate using cyclic voltammetry (CV) and...
differential pulse voltammetry (DPV). All of the triazole CHs, phenyl CH, and ferrocene CH, take part in binding with phosphate. These interactions induce a large shift in CV and DPV and thus act as an electrochemical sensor.

Fig. 31 Ferrocene appended redox neutral receptor for $\text{H}_2\text{PO}_4^-$.

Hua and Flood addressed the photoisomerisation behavior leading to foldamer and its binding ability towards the chloride ion of a triazole-based azo-benzene molecule (Fig. 32). The compound 56 exists in three isomeric forms: 56trans–trans, 56cis–trans, and 56cis–cis. Among them, the 56trans–trans isomer prefers the helical form under visible light (436 nm) and is more preorganised for chloride binding. Owing to its ideal arrangement of H–bonding donor sites, the 56trans–trans isomer binds chloride more strongly than 56cis–trans and 56cis–cis isomers. The binding constant value of receptor 56trans–trans with the chloride ion under dark conditions was found to be 3000 M$^{-1}$.

Jiang et al. investigated the anion-induced folding behavior with binding properties of novel oligo(phenyl-amide-triazoles) (Fig. 33) in great detail. The NMR titration experiments of chloride, bromide, and iodide ions (TBACl, TBABr and TBAI) with oligomer 57 showed a 1 : 1 binding stoichiometry, with association constants of 350, 80 and 15 M$^{-1}$, respectively. However, the longer oligomers 58 and 59 showed 1 : 2 complexes with both the chloride and bromide ions, and both of the oligomers bind to the chloride ion more strongly than to the bromide ion. Stepwise association constants for oligomer 57 with the chloride ion were found to be $K_1 = 4.9 \times 10^3$ M$^{-1}$ and $K_2 = 13$ M$^{-1}$, indicating a negative cooperative effect for folding.

Similar results were observed for oligomer 59 in the presence of the chloride ion, but it showed a better binding ability than oligomer 58.

Fig. 32 Photoswitchable triazole-based receptor.

Fig. 33 Oligo(phenyl-amide-triazoles) 57–59 and the chloride assisted folding of 57.

Sanchez et al. described the self-assembly behavior of aryl triazole molecules (Fig. 34), with their anion binding properties leading to disruption of the molecular self-assembly due to the conformational changes in the molecules. Molecular self-assembly of aryl triazole 60 resulted in flat lamella-like architectures, while 61 was organized into spheres, which was confirmed by scanning electron microscopy (SEM) studies. NMR studies of 60 and 61 indicated the existence of “anti” conformations, which are switched over to “syn” conformations in the presence of bromide ions, resulting in disorder of the structural morphologies. The receptor 60 binds to bromide in 1 : 1 stoichiometry with a binding constant of 15 M$^{-1}$, which is higher than 61.
Our group successfully used triazole in conjunction with an amide unit as a excellent moiety for anion recognition (Fig. 35). Various receptor systems (63–67) were synthesised and validated for anion binding. Since the triazole moiety can mimic an amide bond, the triazole with amide could be compared with two peptide linkages.52 Interestingly, the dialkyne precursor 62 showed less binding compared to the amide-triazole version, thus underscoring the usefulness of this moiety in anion recognition.53 Increasing the acidity of triazole CH is another way to modulate the binding affinity. The introduction of phenyl substituents on the triazole rings showed higher binding ability compared to the benzyl substituents. Receptor 65 binds F− with a high binding constant ($K \sim 10^5 \text{ M}^{-1}$). Receptor 67 showed a color change from pale yellow to orange upon adding F−.52 Various triazole based receptors (64 and 66) containing a phenolic group were designed and synthesized in order to provide extra binding sites for anions (Fig. 36). Interestingly, in most of the cases, proton exchange was observed between the F− and the phenolic –OH. All other anions showed less binding to phenolic receptors. These results further emphasize the challenge in anion receptor design. Li et al. replaced one of the amide NH of urea with a triazole to generate various receptors (Fig. 37).54 The amide-triazole combines the characteristics of urea and triazole. The ease of synthesis, coupled with better solubility for the amide-triazole compounds compared to urea-based compounds, is a factor that enhances the utility of this moiety in the future.

![Fig. 34](image_url) Molecular self-assembly and binding behaviour of 60 and 61.

Fig. 35 Comparison of amide-triazole and peptide linkages.

Interestingly, the dialkyne precursor 62 showed less binding compared to the amide-triazole version, thus underscoring the usefulness of this moiety in anion recognition.53 Increasing the acidity of triazole CH is another way to modulate the binding affinity. The introduction of phenyl substituents on the triazole rings showed higher binding ability compared to the benzyl substituents. Receptor 65 binds F− with a high binding constant ($K \sim 10^5 \text{ M}^{-1}$). Receptor 67 showed a color change from pale yellow to orange upon adding F−.52 Various triazole based receptors (64 and 66) containing a phenolic group were designed and synthesized in order to provide extra binding sites for anions (Fig. 36). Interestingly, in most of the cases, proton exchange was observed between the F− and the phenolic –OH. All other anions showed less binding to phenolic receptors. These results further emphasize the challenge in anion receptor design. Li et al. replaced one of the amide NH of urea with a triazole to generate various receptors (Fig. 37).54 The amide-triazole combines the characteristics of urea and triazole. The ease of synthesis, coupled with better solubility for the amide-triazole compounds compared to urea-based compounds, is a factor that enhances the utility of this moiety in the future.

![Fig. 36](image_url) The dialkyne precursor 62 and triazole receptors 63–67 for anion binding.

![Fig. 37](image_url) Comparison of urea and the amide-triazole moieties.

Various acyclic receptors were synthesized and they showed good binding affinities for tetrahedral oxyanions (Fig. 38). Receptor 68, containing OH, NH and CH motifs at the binding site, showed good colorimetric response in the presence of
fluoride. Various acrylic receptors, such as 69 and 70, were synthesized, and they showed significant binding affinities for tetrahedral oxanions.

Conclusion

The use of non-conventional hydrogen bonding makes the binding to anions weaker and more reversible and therefore useful for a variety of biological applications. The use of the CH⋯X interaction is relatively new and is not much exploited in the anion receptor design. The moderate binding ability of CH⋯X in isolation or in conjunction with other hydrogen bonding moieties will expand the repertoire of receptors. The last four years witnessed the utilization of the acidic –CH of triazole for non-conventional hydrogen bonding with guest molecules. Notably, many receptors were found to utilize non-conventional hydrogen bonding interactions that were unknown a few years back. The explosive developments in this area of molecular recognition using the triazole motif are expected to flourish further because of the clean and high yielding nature of this reaction, along with other attributes. A combination of conventional and non-conventional hydrogen bonding in the receptor design using this reaction will enhance the power of organic chemists in designing compounds with high binding and good release rates of guest molecules.

Most of the anion receptors are designed for binding in organic solvents. The design and synthesis of receptors for binding anions in the aqueous environment is an additional challenge to chemists. The chemoselective nature of the click reaction will be a useful attribute for the synthesis of water soluble receptors.

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