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Receptor with an Active Methylene Group as Binding Site for Extraction of Inorganic Fluoride Ions from Seawater

Madhuprasad and Darshak R. Trivedi*[a]

Two new receptors **R1** and **R2** based on triphenylphosphonium salts with an active methylene group as binding site have been designed and synthesised for the detection of F^- ions. The detection limit of these receptors in organic media was found to be 0.2 ppm. Upon adding F^- ions, a $\Delta\lambda_{max}$ of 188 nm and 256 nm was observed for receptors **R1** and **R2**, respectively. The detection process followed deprotonation of the methylene proton, which has been confirmed by ^1H NMR titration. The receptors were evaluated for real-life applicability by extracting F^- ions from aqueous media and seawater into organic media. Receptor **R2** was able to extract F^- ions from seawater with 99% efficiency. The level of F^- ions present in seawater has been quantified and found to be 1.4 ppm, which is comparable to the reported literature value.

Introduction

The design and synthesis of organic receptors for the detection of anions through their optical, electrochemical and magnetic resonance response have received considerable attention owing to the vital applications of anions in various industrial, chemical, biological and environmental processes. In this regard, organic receptors with neutral binding sites for various anions have been synthesised for decades.[1] Recently, cationic receptors with ammonium, quinolinium, imidazolium and guanidinium salts were used for anion detection.[2] These cationic receptors utilise electrostatic interaction between anion and cation for anion recognition. Along with the electrostatic interactions, other weaker noncovalent interactions, such as anion–π interaction, were used for anion detection.[3]

Among the wide range of anions, the design and synthesis of an effective receptor for F^- ion detection have received considerable attention because of its vital role in industrial usage, environmental pollution and significance in clinical applications. In contrast, excess fluoride consumption is always a health concern as it can cause dental fluorosis[4] and skeletal fluorosis.[5] Acute fluoride exposure may cause collagen breakdown, depression in thyroid activity, bone cancer, immune system disturbance and anaemia.[6] Thus, the real-time monitoring of the F^- ion is most significant over other anion detection.

Receptors with well-known functionalities, such as urea/thiourea, amide, imide, pyrrole and imidazolium, as binding sites for the F^- ion have been reported in which conventional hydrogen-bond formation has been used for detection.[7] Unfortunately, the majority of them are capable of working only in absolute non-aqueous conditions for the detection of organic fluoride sources such as tetrabutylammonium fluoride (TBAF). On the other hand, only a few organic receptors have been reported for the detection of F^- ions in aqueous media.[8] To the best of our knowledge, only one report has been published so far on the selective extraction of the F^- ion from aqueous solution with measurable visual detection.[9]

Anion-binding receptors with alkyl triphenylphosphonium salts with an active/acidic methylene group as a binding site were not studied to the extent of receptors with –NH or –OH binding sites. Vicens et al. synthesised alkyl triphenylphosphonium salts attached to calix[4]arene and reported the formation of ion-pair-type complexes with a range of anions such as halides, AcO^-, HPO_4^{2-} and ClO_4^-.[10] Das et al. synthesised alkyl triphenylphosphonium salts attached to an anthraquinone skeleton, which displayed high selectivity towards F^- ions.[9] In addition, this receptor displayed a unique anion extraction from aqueous solution to organic solvent.

With this background, herein we report new receptors based on triphenylphosphonium salts that contain an active methylene (–CH_2–) group as a binding site for anion detection. The receptors were designed on the binding site–spacer–signalling unit approach, in which the binding site and signalling unit were separated by a "spacer" diazo group (Scheme 1). Receptor **R1** contains an ethoxyphenyl unit as signalling unit and receptor **R2** contains a coumarin as signalling unit. These receptors are used for the detection of F^- ions in organic media and to extract inorganic F^- ions from aqueous media into organic media. The extraction process has been visualised by an instantaneous optical change in organic media. The receptors **R3** and **R4** were synthesised to evaluate the role of the active methylene group in the detection process.

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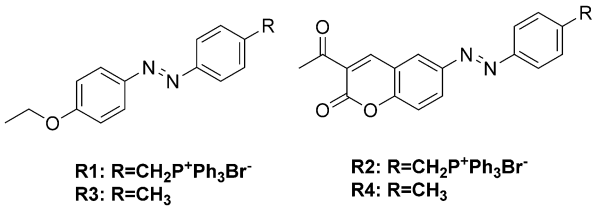


Scheme 1. Molecular structures of receptors **R1**–**R4**.

Results and Discussion

A single crystal of receptor **R3** suitable for X-ray diffraction analysis was grown by slow evaporation of an ethanol/dichloromethane (1:1) solution at room temperature. The ORTEP diagram (50% probability) of receptor **R3** is given in Figure 1. Receptor **R3** was crystallised in a monoclinic lattice. Detailed crystallographic data of receptor **R3** are given in Table 1.

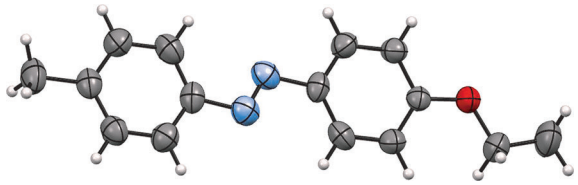


Figure 1. ORTEP diagram (50% probability) of receptor **R3**.

Table 1. Crystallographic data of receptor **R3**.

chemical formula	$C_{15}H_{16}N_2O$	α [°]	90.00
formula weight	240.30	β [°]	98.890(3)
crystal system	monoclinic	γ [°]	90.00
space group	$P2_1/n$	V [Å^3]	1337.98
a [Å]	8.1773(4)	Z	4
b [Å]	7.5454(4)	crystal size [mm^3]	0.48×0.35×0.29
c [Å]	21.9486(10)	R factor [%]	7.26

A selective anion detection study for receptors **R1**–**R4** was performed with the help of UV/Vis spectroscopy. Solutions (1.0×10^{-5} M) of receptors **R1** and **R2** in dry dichloromethane solutions were treated with two equivalents of different anions, such as fluoride, chloride, bromide, iodide, nitrate, hydrogen sulfate, dihydrogen phosphate and acetate in the form of tetrabutylammonium (TBA) salts. In the case of receptor **R1**, a significant shift in the absorbance was observed with the addition of F^- and AcO^- ions (Figure 2). The intensity of the absorption band in UV/Vis spectra for AcO^- ions was much less than that for F^- ions. This signifies that the interaction between receptor **R1** and the F^- ion is stronger and the interaction between receptor **R1** and the AcO^- ion is much weaker. All other anions did not show any change in UV/Vis spectra, which indicates that these anions either did not interact with receptor **R1** or the interaction was not enough to produce any changes in the spectra. Receptor **R2** showed similar changes

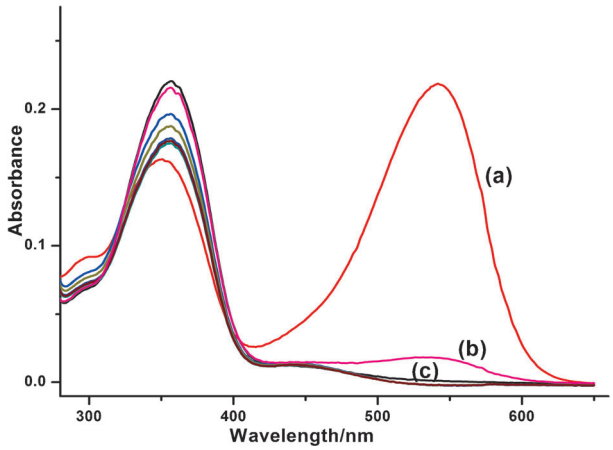


Figure 2. UV/Vis spectral change on addition of anions (2 equiv) to receptor **R1** solution (1.0×10^{-5} M) in dry CH_2Cl_2: a) F^- ions, b) AcO^- ions and c) **R1** and other anions.

with the addition of different anions (Figure S7 in the Supporting Information).

In addition, receptor **R1** was further evaluated for the colorimetric detection of anions. The receptor **R1** solution (1.0×10^{-5} M) in dry dichloromethane showed significant colour change from pale yellow to pink instantaneously with the addition of F^- ions. However, no colour change was noticed upon addition of other anions (Figure 3). The addition of AcO^-showed slight change in the absorbance of the UV/Vis spectra; however, it failed to induce any significant colour change to receptor **R1**.

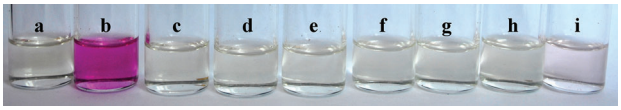


Figure 3. Change in colour after addition of different anions (2 equiv) as TBA salts to the receptor solution in dry CH_2Cl_2 (1.0×10^{-5} M). a) Receptor **R1**, b) F^-, c) Cl^-, d) Br^-, e) I^-, f) NO_3^-, g) HSO_4^-, h) $H_2PO_4^-$ and i) AcO^-.

To understand the nature of the receptor–anion interactions, a UV/Vis titration experiment was performed between receptor **R1** and TBAF (Figure 4). With the incremental addition of TBAF to receptor **R1** (1.0×10^{-5} M), the absorbance at 356 nm, corresponding to the phenyldiazene group in receptor **R1**, decreased constantly and a new absorption band at 544 nm appeared and gradually increased. This observation is owing to the formation of charge-transfer (CT) transitions involving the electron-rich methylene functionality as donor group and the phenylenediazene group as the acceptor unit. The intensity of the absorption band attained saturation after adding two equivalents of F^- ions. The bathochromic shift of 188 nm with the formation of an isosbestic point at 401 nm was attributed to the formation of a CT complex between the receptor and F^- ion. The binding stoichiometry between receptor **R1** and F^- ions was determined by the Benesi–Hildebrand method using UV spectrometric titration data at 544 nm. The linearity of the

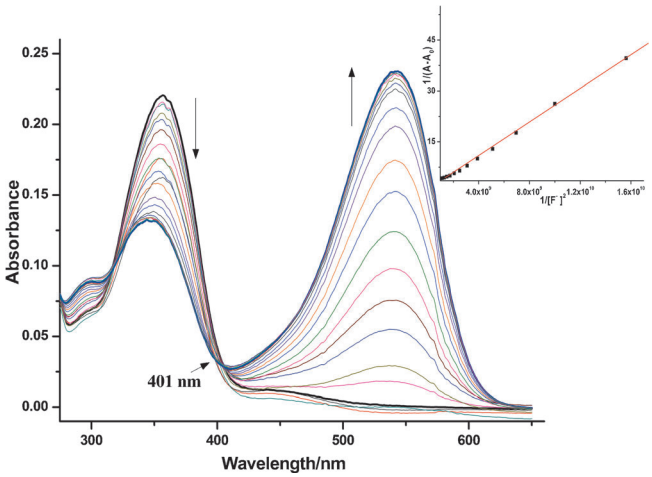


Figure 4. UV/Vis titration spectra of **R1** (1.0×10^{-5} M) with increasing concentration of TBAF (0–3 equiv) in dry CH_2Cl_2. Inset: Benesi–Hildebrand plot for **R1** at 544 nm.

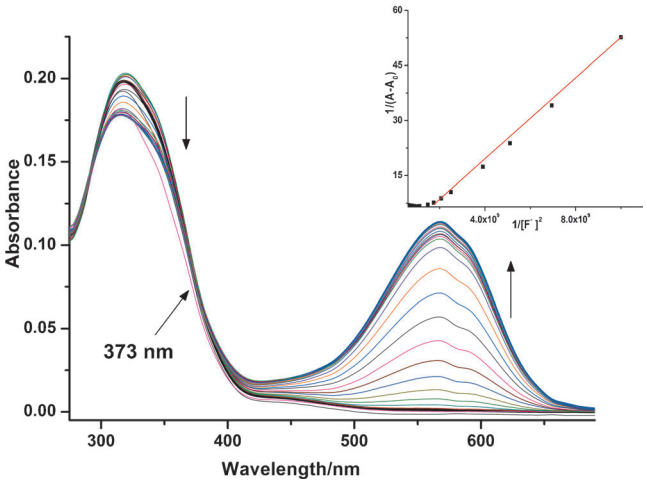


Figure 6. UV/Vis titration spectra of **R2** (1.0×10^{-5} M) with increasing concentration of TBAF (0–3 equiv) in dry CH_2Cl_2. Inset: Benesi–Hildebrand plot for receptor **R2** at 573 nm.

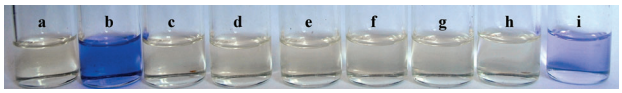


Figure 5. Change in colour after addition of different anions (2 equiv) as TBA salts to the receptor solution in CH_2Cl_2 (1.0×10^{-5} M). a) Receptor **R2**, b) F^-, c) Cl^-, d) Br^-, e) I^-, f) NO_3^-, g) HSO_4^-, h) $H_2PO_4^-$ and i) AcO^-.

graph confirms the formation of a stable 1:2 receptor/F^- ion stoichiometric complex (Figure 4, inset).

Further, the colorimetric investigation was extended to receptor **R2**. The receptor **R2** (1.0×10^{-5} M) was treated with two equivalents of different anions in dry dichloromethane (Figure 5). The addition of F^- ions resulted in a significant colour change from pale yellow to dark blue, whereas AcO^- ions showed slight variation in colour from pale yellow to light blue. This difference in the colour intensity indicated a stronger binding interaction between receptor **R2** and F^- ions and a significantly weaker interaction between receptor **R2** and AcO^- ions. On the other hand, other anions either did not interact or interacted feebly with receptor **R2** and did not show any visual colour change.

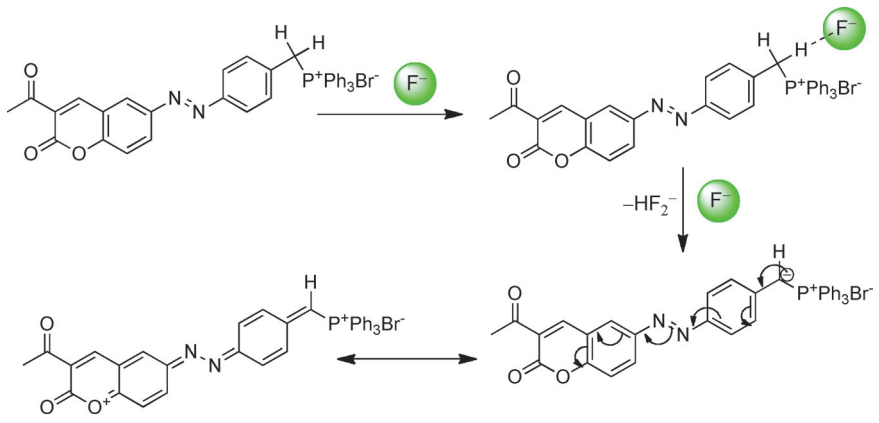
Receptor **R2** was further analysed quantitatively with UV/Vis spectroscopic titration by adding TBAF to dry dichloromethane solution (Figure 6). The addition of TBAF resulted in the generation of a new absorption band at 573 nm. With the incremental addition of F^- ions to the receptor **R2** solution, the absorbance band at 317 nm, corresponding to the phenyldiazene chromenone unit, decreased gradually and simultaneously the absorption band at 573 nm increased progressively owing to the development of CT transitions between the electron-rich methylene functionality, which it acts as an electron donor, and the phenylenediazene chromenone group, which acts as an electron acceptor unit. The intensity of this new absorption band attained saturation after the addition of two equivalents of TBAF. The stoichiometric complexation ratio was determined with the Benesi–Hildebrand method. The Benesi–Hildebrand plot was obtained by using UV spectrometric titration data at 573 nm. The plot showed linearity only at the square of the concentration of F^- ions. This clearly indicates the formation of a 1:2 stoichiometric complex between receptor **R2** and F^- ions (Figure 6, inset).

Correspondingly, the UV/Vis spectroscopic titration was performed by adding tetrabutylammonium acetate to the receptors **R1** and **R2** in dichloromethane. The spectral pattern displayed similar changes to that of TBAF (Figure S12 for receptor **R1** and Figure S13 for receptor **R2**). However, the intensity of the new absorption band was much less than that of TBAF. This is perhaps a result of weaker interactions between receptors and AcO^- ions.

The coumarin moiety is a well-known fluorophore, so it was interesting to study fluorescence changes upon F^- ion binding to receptor **R2**. Therefore, a fluorescence titration was performed by adding TBAF to receptor **R2** in dichloromethane (Figure S16). As expected, upon increasing the concentration of F^- ions the quenching of fluorescence was observed owing to the deprotonation of receptor **R2**.

The binding constant for both receptors (**R1** and **R2**) was calculated using the Benesi–Hildebrand equation and found to be $(4.58\pm0.02)\times10^7\ M^{-2}$ for receptor **R1** and $(7.5\pm0.03)\times10^7\ M^{-2}$ for receptor **R2**. This result shows that the F^- ion binds more strongly to receptor **R2** than receptor **R1**. This sensitivity is perhaps because of the presence of the coumarin unit in receptor **R2**, which is a strong signalling unit when compared with the ethoxyphenyl group in receptor **R1**.

Further, the binding mechanism of receptor **R2** to F^- ions was proposed by evaluating the results obtained from UV/Vis titration and the Benesi–Hildebrand method. On compiling the results of UV/Vis experiments, it is evident that the colorimetric detection of the F^- ion with receptor **R2** is a two-step process. Initially, the F^- ion binds to the active methylene ($-CH_2-$) group of receptor **R2** through hydrogen bonding, which results in a 1:1 adduct to form the **R1**···F^- complex. A second F^- ion leads to deprotonation of the active methylene group to



Scheme 2. Proposed binding mechanism of F^- ions with receptor **R2**.

form **R2**$^-$ (Scheme 2).[11] As a result, the electron density of receptor **R2** increases, which leads to intramolecular CT interaction between the electron-rich phenyldiazene chromenone functionality and the electron-deficient $[PPh_3]^+$ group. Thus, receptor **R2** shows intense colour change instantaneously upon addition of F^- ions.

The binding mechanism was further confirmed by ^{1}H NMR titration (Figure 7) of receptor **R2** performed in deuterated dimethyl sulfoxide ([D_6]DMSO) solution. The ^{1}H NMR signal at $\delta = 5.32$ ppm corresponds to two protons of the methylene (–CH_2–) group of receptor **R2**. The splitting pattern of this signal appeared as a doublet because of coupling with the adjacent phosphorus.[12] Upon adding 0.5 equivalents of F^- ions, a slight downfield shift from $\delta = 5.32$ to 5.33 ppm and $\delta = 5.35$ to 5.36 ppm was observed. This downfield shift resulted from the formation of a hydrogen bond between the methylene proton and F^- ion. Upon increasing the concentration of F^- ions to one equivalent, the signal corresponding to this methylene group disappeared completely, which indicated a fast proton exchange between the methylene proton and the F^- ion. Further, the addition two equivalents of F^- ions resulted in the deprotonation of receptor **R2** to form **R2**$^-$ and simultaneously the electron density over the receptor molecule increased. Therefore, the signal corresponding to the protons of the –CH_2– group shifted downfield from $\delta = 5.32$ to $\delta = 5.76$ ppm. Concurrently, the splitting pattern disappeared because of the fast proton exchange within the receptor. The multiplet signals for aromatic protons experienced a downfield shift (from $\delta = 7.24$–7.63 to $\delta = 7.54$–7.64 ppm) and merged together to form two major signals with multiple splitting. This result further confirms the increase in electron density over receptor **R2**. In addition, upon adding two equivalents of F^- ions to the receptor **R2** solution, the active methylene group undergoes deprotonation. This deprotonation process was confirmed from the appearance of the ^{1}H NMR signal at $\delta = 16.1$ ppm (Figure 7, inset), which corresponds to HF_2^-.[13]

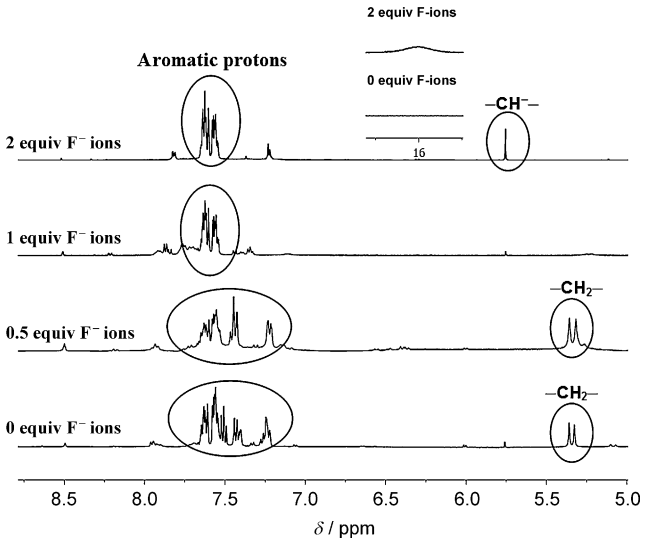


Figure 7. Partial ^{1}H NMR titration spectrum of receptor **R2** in [D_6]DMSO after the addition of F^- ions. Inset: Appearance of the ^{1}H NMR signal at $\delta = 16.1$ ppm corresponding to HF_2^- upon adding 2 equivalents of F^- ions.

As evidence for the deprotonation mechanism, UV/Vis spectroscopic titration was performed by adding tetrabutylammonium hydroxide (TBAOH) to dry dichloromethane solutions of receptors **R1** and **R2** (Figure S14 for receptor **R1** and Figure S15 for receptor **R2**). The UV/Vis spectra of TBAOH for both the receptors showed similar changes to that of TBAF, which clearly indicates the detection process follows the deprotonation mechanism.

Receptors **R3** and **R4**, which do not contain an active methylene group, were studied for their anion detection ability in dichloromethane. As expected, these receptors neither showed any colour changes (Figures S8 and S9) nor displayed any UV/Vis spectral changes (Figures S10 and S11) even with the addition of 20 equivalents of anions. This finding clearly suggests that the active methylene group is responsible for the F^- ion detection.

Inorganic fluoride such as NaF is an essential nutrient for living organisms; however, at higher concentrations it is hazardous to health. Therefore, the World Health Organization has restricted the F^- ion concentration level to 1 ppm in drinking water.[14] Keeping this fact in mind, the real-life applicability of extraction of F^- ions from aqueous media with receptors **R1** and **R2** has been evaluated. Standard solutions of NaF at different concentrations were prepared in water and used as inorganic F^- ion source for the extraction study. These standard solutions were treated with receptor **R1** and **R2** solutions in dichloromethane. Upon vigorous shaking of these organo-aqueous mixtures, the receptor solutions were able to extract F^- ions from aqueous media. As a result, the colour of receptors **R1** and **R2** changed from yellow to pink and yellow to

deep blue, respectively. Further, these receptors were tested for the extraction of F^- ions from seawater collected from the Arabian Sea (latitude 13° 0′ 33.99″, longitude 74° 47′ 17.23″) to examine the practical applicability.

The extraction experiment was performed by treating standard solutions of NaF (1–4 ppm) and seawater (1.5 mL each) with dichloromethane solutions of receptor **R2**, in glass vials. The organo-aqueous solutions were shaken well to extract the F^- ions. The vials containing above 1 ppm NaF solution showed significant colour change from yellow to blue, which clearly indicates that the receptor is capable of extracting F^- ions from water (Figure 8). The instantaneous colour change (blue) observed in the organic layer during extraction experiments suggests that receptor **R2** can extract F^- ions efficiently

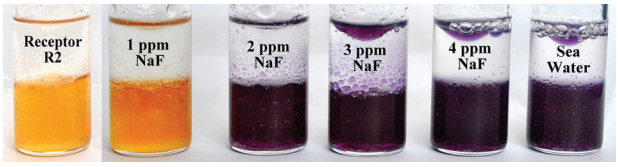


Figure 8. Extraction process of F^- ions from aqueous solutions and seawater using receptor **R2** solution in CH_2Cl_2.

from seawater, and thus confirms that other competing anions, such as chloride, bromide, iodide, phosphate and so forth, present in seawater did not interfere in the detection/extraction process. Further, the experimental studies revealed that receptor **R2** was able to extract F^- ions from aqueous NaF solution and seawater with 99% efficiency.

The extraction study was further quantified by UV/Vis spectroscopy. Standard solutions of NaF with varying concentrations from 1 to 4 ppm were prepared in water. Portions (1 mL) of these standard solutions were subjected to extraction (three times for each NaF solution) using receptor **R2** dissolved in dichloromethane. The organic phases of each solution were separated, diluted four times and the UV/Vis spectrum was measured. The same procedure was repeated for seawater. A calibration curve of absorbance versus concentration of F^- ions (in ppm) was plotted (Figure 9), from which the concentration of F^- ions in seawater was found to be 1.4 ppm. This result was comparable with the previously reported literature value.[14b]

Similar extraction experiments were performed for receptor **R1**, which showed a significant colour change in the organic medium only with organo-aqueous solutions that contained a minimum 1.5 ppm of NaF. Therefore, receptor **R1** was unable to extract the F^- ions from seawater (Figure 10). This is perhaps owing to the less extended conjugation as the ethoxyphenyl group is not participating in the detection process.

Conclusion

Two new receptors with an active methylene group as binding site have been designed and synthesised for the selective detection of F^- ions. On adding F^- ions, the receptors **R1** and **R2** displayed a colour change from pale yellow to pink and pale

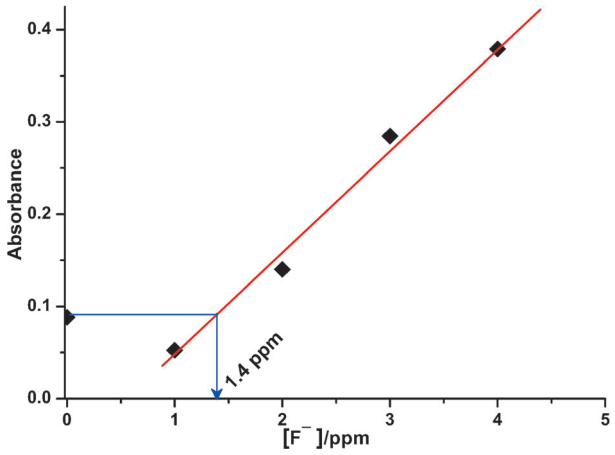


Figure 9. Calibration curve for quantitative determination of F^- ions in seawater and samples.

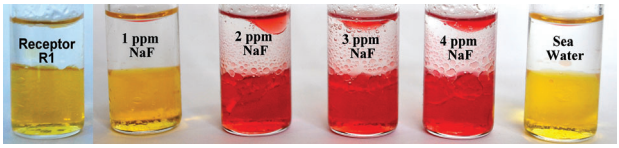


Figure 10. Extraction process of F^- ions from aqueous solutions and seawater using receptor **R1** solution in CH_2Cl_2.

yellow to dark blue along with a significant bathochromic shift of 188 nm and 256 nm, respectively. This colour change and bathochromic shift resulted from the charge-transfer transitions in the receptors on adding F^- ions. These receptors were able to detect F^- ions even at concentrations as low as 0.2 ppm in organic media, which is much less than the World Health Organization permissible level. In addition, these receptors were able to extract F^- ions from aqueous media into organic solutions with a substantial colour change. The real-life applicability of the receptors was evaluated by extracting F^- ions from seawater. Receptor **R2** was able to extract F^- ions from seawater with 99% efficiency. In addition, the level of F^- ions present in seawater was determined by using receptor **R2** and was found to be 1.4 ppm, which is in good agreement with literature reports. Currently, we are concentrating on the design and synthesis of new and more efficient receptors for the extraction of F^- ions from industrial wastes.

Experimental Section

General information

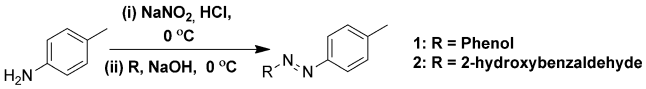
All chemicals were purchased from Sigma–Aldrich, Alfa Aesar or Spectrochem and used without further purification. All the solvents were procured from SD Fine, India, were of HPLC grade and used without further distillation.

The ^1H NMR spectra were recorded on a Bruker Avance II (500 MHz) instrument using TMS as internal reference and [D_6]DMSO as solvent. Resonance multiplicities are described as s (singlet), d (doublet), t (triplet) and m (multiplet). Melting points were measured on a Stuart SMP3 melting-point apparatus in open

capillaries. Infrared spectra were recorded on a Thermo Nicolet Avatar-330 FTIR spectrometer; signal designations: s (strong), m (medium) and w (weak). UV/Vis spectroscopy was performed with an Analytikjena Specord S600 spectrometer in standard 3.5 mL quartz cells (two optical windows) with 10 mm path length. Fluorescence spectroscopy was performed with a JASCO FP-6200 spectrofluorometer in standard 3.5 mL quartz cells (four optical windows) with 10 mm path length. Elemental analyses were done using a Flash EA1112 CHNS analyser (Thermo Electron Corporation).

Synthesis of (*E*)-4-(*p*-tolyldiazenyl)phenol (1) and (*E*)-2-hydroxy-5-[(p-tolylimino)methyl] benzaldehyde (2; Scheme 3)

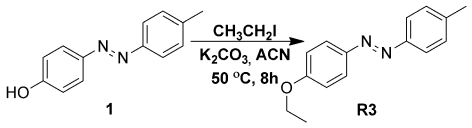
The diazonium salt of *p*-toluidine was prepared by adding sodium nitrate (3.5 mmol) to a stirred solution of *p*-toluidine (2.33 mmol) in concd HCl (2 mL) at 0 °C. A mixture of **R** (phenol, 2.33 mmol or 2-hydroxybenzaldehyde, 2.33 mmol) and NaOH (4.66 mmol) was added slowly to the diazonium salt at 0 °C and stirred for 10 min. The reaction mixture was then stirred at room temperature for 30 min and the pH was adjusted to 6 to obtain the solid product. The solid was isolated by filtration, washed with water and dried to obtain the desired products **1** (0.446 g) or **2** (0.5 g).



Scheme 3. Synthesis of intermediates **1** and **2**.

Synthesis of (*E*)-1-(4-ethoxyphenyl)-2-*p*-tolyldiazene (R3; Scheme 4)

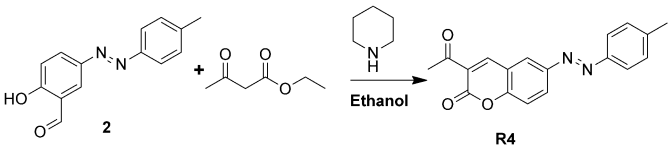
Anhydrous K_2CO_3 (0.488 g, 3.53 mmol) and ethyl iodide (0.231 g, 1.48 mmol) were added to a solution of **1** (0.25 g, 1.18 mmol) in dry acetonitrile (ACN). The reaction mixture was stirred at 50 °C for 8 h. The completion of reaction was checked by thin-layer chromatography (TLC). Excess of K_2CO_3 was removed by filtration and the filtrate was evaporated under reduced pressure to yield pure brown product **R3** (0.226 g).



Scheme 4. Synthesis of receptor **R3**.

Synthesis of (*E*)-3-acetyl-6-(*p*-tolyldiazenyl)-2*H*-chromen-2-one (R4; Scheme 5)

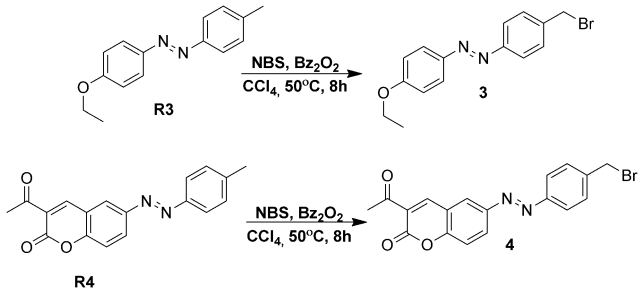
Ethyl acetoacetate (0.135 g, 1.04 mmol) was added to a mixture of **2** (0.25 g, 1.04 mmol) and piperidine (0.018 g, 0.21 mmol) in ethanol, and stirred for 5 h at room temperature. The completion of reaction was confirmed by TLC. The solid obtained was isolated by filtration, washed with ethanol and dried to obtain a yellow pure product **R4** (0.316 g).



Scheme 5. Synthesis of receptor **R4**.

Synthesis of (*E*)-1-[4-(bromomethyl)phenyl]-2-(4-ethoxyphenyl)diazene (3) and (*E*)-3-acetyl-6-{[4-(bromomethyl)phenyl]-diazenyl}-2*H*-chromen-2-one (4; Scheme 6)

N-Bromosuccinimide (NBS; 0.162 g, 0.91 mmol for **R3** and 0.183 g, 1.03 mmol for **R4**) and a catalytic amount of dibenzoyl peroxide (Bz_2O_2) were added to a solution of **R3** or **R4** (0.2 g, 0.83 mmol or 0.288 g, 0.94 mmol) in CCl_4 (20 mL). The resulting mixture was heated at reflux for 8 h. The decomposed product of NBS was then separated by filtration and the filtrate was evaporated to dryness to afford a yellow solid. The solid was triturated with diethyl ether to yield pure product **3** (0.24 g) or **4** (0.343 g).



Scheme 6. Synthesis of intermediates **3** and **4**.

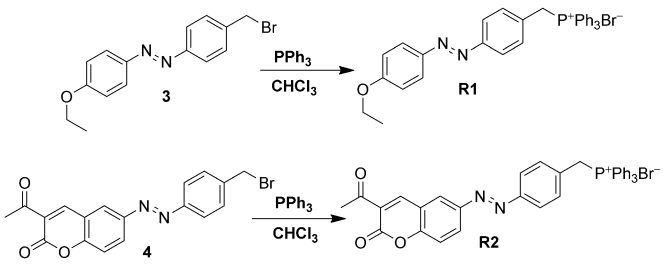
Synthesis of (*E*)-1-(4-ethoxyphenyl)-2-{4-[(triphenylphosphino)methyl]phenyl}diazene bromide (R1) and (*E*)-3-acetyl-6-({4-[(triphenylphosphino)methyl]phenyl}diazenyl)-2*H*-chromen-2-one bromide (R2; Scheme 7)

A solution of **3** or **4** (0.2 g, 0.63 mmol or 0.3 g, 0.78 mmol) and triphenylphosphine (0.182 g, 0.693 mmol for **3** and 0.225 g, 0.858 mmol for **4**) in dry chloroform (20 mL) was heated at reflux for 4 h and then stirred at room temperature for 8 h. The reaction mixture was evaporated under reduced pressure to afford a hygroscopic residue, which was stirred with diethyl ether until it formed a solid residue. The solid was isolated by filtration and dried to give the pure product **R1** (0.34 g) or **R2** (0.47 g).

Characterisation data

(*E*)-4-(*p*-Tolyldiazenyl)phenol (**1**): Yield: 90%; m.p. 135–136 °C; FTIR: $\tilde{\nu}$ = 3356.9 (br m), 3040.3 (m), 2936.4 (m), 1601.2 cm^{-1} (s); elemental analysis calcd (%) for $C_{13}H_{12}N_2O$: C 73.56, H 5.70, N 13.20; found: C 73.59, H 5.66, N 13.19.

(*E*)-2-Hydroxy-5-[(*p*-tolylimino)methyl] benzaldehyde (**2**): Yield: 89%; m.p. 119–121 °C; FTIR: $\tilde{\nu}$ = 3364.9 (br m), 3072.3 (w), 2835.7 (w), 1698.9 (s), 1602.3 cm^{-1} (s); elemental analysis calcd (%) for $C_{14}H_{12}N_2O_2$: C 69.99, H 5.03, N 11.66; found: C 70.02, H 5.06, N 11.69.



Scheme 7. Synthesis of receptors **R1** and **R2**.

(*E*)-1-(4-Ethoxyphenyl)-2-*p*-tolyldiazene (**R3**): Yield: 80%; m.p. 126–127 °C; ^{1}H NMR (500 MHz, [D$_6$]DMSO, 25 °C): δ = 7.88 (d, ^3J(H,H) = 7 Hz, 2H; Ar-H), 7.77 (d, ^3J(H,H) = 8 Hz, 2H; Ar-H), 7.39 (d, ^3J(H,H) = 8 Hz, 2H; Ar-H), 7.13 (d, ^3J(H,H) = 7 Hz, 2H; Ar-H), 4.15 (q, ^3J(H,H) = 7 Hz, 2H; -CH$_2$-), 1.38 ppm (t, ^3J(H,H) = 7 Hz, 3H; -CH$_3$); FTIR: $\tilde{\nu}$ = 3041.4 (m), 2940.3 (m), 1602.4 cm^{-1} (s); elemental analysis calcd (%) for $C_{15}H_{16}N_2O$: C 74.97, H 6.71, N 11.66; found: C 74.95, H 6.69, N 11.69.

(*E*)-3-Acetyl-6-(*p*-tolyldiazenyl)-2*H*-chromen-2-one (**R4**): Yield: 95%; m.p. 177–178 °C; ^{1}H NMR (500 MHz, [D$_6$]DMSO, 25 °C): δ = 8.82 (s, 1H; Ar-H), 8.50 (s, 1H; Ar-H), 8.22 (d, ^3J(H,H) = 9 Hz, 1H; Ar-H), 7.85 (d, ^3J(H,H) = 8.5 Hz, 2H; Ar-H), 7.66 (d, ^3J(H,H) = 8.5 Hz, 1H; Ar-H), 7.44 (d, ^3J(H,H) = 8 Hz, 2H; Ar-H), 2.61 (s, 3H; -COCH$_3$), 2.43 ppm (s, 3H; -CH$_3$); FTIR: $\tilde{\nu}$ = 3042.4 (m), 2885.9 (m), 1699.4 (s), 1684.4 (s), 1601.5 cm^{-1} (m); elemental analysis calcd (%) for $C_{18}H_{14}N_2O_3$: C 70.58, H 4.61, N 9.15; found: C 70.54, H 4.58, N 9.18.

(*E*)-1-[4-(Bromomethyl)phenyl]-2-(4-ethoxyphenyl)diazene (**3**): Yield: 90%; m.p. 156–158 °C; FTIR: $\tilde{\nu}$ = 3056.9 (m), 2986.4 (m), 1601.4 (s), 1247.3 cm^{-1} (m); elemental analysis calcd (%) for $C_{15}H_{15}BrN_2O$: C 56.44, H 4.74, N 8.78; found: C 56.49, H 4.76, N 8.80.

(*E*)-3-Acetyl-6-{[4-(bromomethyl)phenyl]diazenyl}-2*H*-chromen-2-one (**4**): Yield: 91%; m.p. 188–190 °C; FTIR: $\tilde{\nu}$ = 3040.2 (w), 2889.3 (m), 1700.3 (s), 1687.4 (s), 1602.5 cm^{-1} (m); elemental analysis calcd (%) for $C_{18}H_{13}BrN_2O_3$: C 56.12, H 3.40, N 7.27; found: C 56.17, H 3.46, N 7.29.

(*E*)-1-(4-Ethoxyphenyl)-2-{4-[(triphenylphosphino)methyl]phenyl}diazene bromide (**R1**): Yield: 92%; m.p. 146–147 °C; ^{1}H NMR (500 MHz, [D$_6$]DMSO, 25 °C): δ = 7.62–7.94 (m, 23H; Ar-H); 5.30 (d, J = 16 Hz, 2H; P-CH), 4.16 (q, J = 7 Hz, 2H; -CH$_2$-), 1.38 ppm (t, J = 7 Hz, 3H; -CH$_3$); FTIR: $\tilde{\nu}$ = 3462.3 (m), 3045.6 (m), 2985.7 (m), 1604.3 cm^{-1} (s); ESI-MS: *m*/*z*: calcd: 581.5; found: 581.1; elemental analysis calcd (%) for $C_{33}H_{30}BrN_2OP$: C 68.16, H 5.20, N 4.82; found: C 67.53, H 5.58, N 4.86.

(*E*)-3-Acetyl-6-({4-[(triphenylphosphino)methyl]phenyl}diazenyl)-2*H*-chromen-2-one bromide (**R2**): Yield: 92%; m.p. 159–161 °C; ^{1}H NMR (500 MHz, [D$_6$]DMSO, 25 °C): δ = 7.24–7.64 (m, 23H; Ar-H); 5.36 (d, J = 16 Hz, 2H; P-CH), 2.42 ppm (s, 3H; -CH$_3$); FTIR: $\tilde{\nu}$ = 3462.3 (m), 3045.6 (m), 2985.7 (m), 1604.3 cm^{-1} (s); ESI-MS: *m*/*z*: calcd: 647.5; found: 648.5; elemental analysis calcd (%) for $C_{36}H_{28}BrN_2O_3P$: C 66.78, H 4.36, N 4.33; found: C 66.23, H 4.68, N 4.73.

CCDC 985440 (**R3**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Extraction efficiency measurement of receptor R2

A solution of TBAF (1.0×10^{-4} M, 1 mL) was treated with receptor **R2** solution (1.0×10^{-5} M, 19 mL) in absolute dry CH_2Cl_2 (20 mL total volume). The absorbance was recorded by a UV/Vis spectrometer. An aqueous NaF solution (1.0×10^{-4} M) was prepared and extracted three times with receptor **R2** solution in CH_2Cl_2. The extracted non-aqueous solutions were combined, diluted to 20 mL and the absorbance recorded. The absorbance of both solutions at 573 nm was compared to obtain the extraction efficiency and the receptor was found to be 99% efficient.

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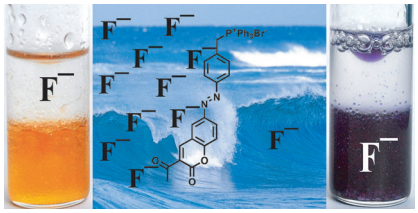
Watercolors: A receptor based on a triphenylphosphonium salt that contains an active methylene group has been designed and synthesized for the colorimetric detection and extraction of F^- ions from seawater with 99% efficiency. The process results in an instantaneous color change (see figure).



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Receptor with an Active Methylene Group as Binding Site for Extraction of Inorganic Fluoride Ions from Seawater