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Head group specificity of novel functionalized surfactants: synthesis, self-assembly and calcium tolerance

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A B S T R A C T

The present work describes the synthesis, characterization and application of functionalized surfactants derived through simple organic reaction steps. These surfactants have been particularly tailor made to resist hardness due to calcium ions in water. It is unique of its kind because here the surfactants have an analogous hydrophobic chain but differ structurally in the composition of the head groups in terms of the position of attachment of the chain. The effect of this small variability in the head group on the surfactant property, adsorption, self assembly and calcium tolerance behaviour has been studied in detail. This kind of phenol–keto surfactants has not been reported before. It was also found that one of the surfactants was more tolerant towards Ca^{2+} ion than the other. The individual packing behaviour of the surfactants at the air–water interface has been projected to cause this difference which is very interesting.

There is currently much interest in the properties of bio surfactants as replacements or partial replacements of conventional petrochemical-derived surfactants in a wide range of detergent-based products because of the attractions and potential benefits associated with bio sustainability and biodegradability.[1–6] These serve as an alternative to the common head group of the majority of nonionic surfactants, that is, polyoxyethylene chains. Also, anionic surfactants, which are major ingredients in many detergent-based products, are notorious for their relative intolerance to water hardness, and a number of strategies have been developed to minimize the impact of hard water conditions.[7–9]

Biosurfactants that act as replacements or partial replacements of conventional petrochemical derived surfactants are promising due to their biodegradability, low toxicity and effectiveness in enhancing biodegradation and solubilization of low solubility compounds. However, greater difficulties in large-scale production and purification have so far hampered their wider application, and as such many applications or potential applications involve their blending with conventional surfactants. Compared to conventional surfactants, biosurfactants have, in general, lower toxicity, more biodegradability, can be synthesized from sustainable sources, and have higher tolerance to pH, temperature and hardness. The higher tolerance of the biosurfactants to hard water conditions is a potentially important feature. The problem of hardness occurs due to the strong binding of multivalent counter ions and especially calcium, to form eventually insoluble precipitates. Hardness tolerance can be defined as the minimum concentration of multivalent counter ions required to cause precipitation.[5,6] Alargova et al.[10] and Petkov et al.[11] have recently demonstrated and quantified how multivalent counterions (Ca^{2+}, Al^{3+}) prior to precipitation promote micellar growth for anionic surfactants such as sodium dodecyldiethylene glycol sulfate, sodium lauryl ether sulfate (SLES). In other cases, such as the addition of Ca^{2+} to the anionic surfactant, LAS (linear alkylbenzene sulfonate), micellar growth is replaced by a transition from micellar to lamellar structures.[12] These studies[10,11] also highlight one of the frequently used strategies to improve hardness tolerance: the incorporation of a nonionic cosurfactant.[8,9] It has now been demonstrated that, in addition to the insensitivity of the ethyoxylate head group to electrolyte, the larger head group of the nonionic cosurfactant provides a steric hindrance which disrupts and ultimately prevents the formation of the anionic surfactant–ion complexes which drive the micellar growth, structural transitions and ultimately precipitation.[10–12] Furthermore, it has been demonstrated that the ability to disrupt that complex formation is directly associated with the size of the ethylene oxide head group.

Surfactants and phospholipids bearing unsaturated fatty acid chains are particularly useful in the reconstitution of membrane proteins in vitro.[12] In this respect, certain glycerophospholipids and surfactants have been synthesized by Bhattacharya et al.[13–16] Furthermore, another important application in the field of novel

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surfactants with aromatic head groups lies in gene delivery.[17–19] Researchers have also shown that multivalent cationic lipids with an aromatic backbone hold a promise for superior gene transfection activities.[20–24]

This Letter describes the synthesis of two functionalized surfactants. It is unique of its kind because here the surfactants have an analogous hydrophobic chain but differ structurally in the composition of the head groups in terms of the position of attachment of the chain. The structures of the two molecules are given in Scheme 1. The molecules were chosen such that there will be the possibility of a chelating complex between the OH group and the Ca^{2+} ion at higher (detergent relevant) pH. Thus, these surfactants have been tailored such that they become calcium tolerant in solution. Such phenol–keto surfactants which are environmentally benign and calcium tolerant have not been reported before. The effect of this variability in the head group on the surfactant property, adsorption, self assembly and calcium tolerance behaviour has been studied in detail. For convenience we have named the first compound as FS1 and the second compound as FS2.

Micelles are formed at the critical micelle concentration (CMC), which is detected as an inflection point when physicochemical/microheterogeneous properties such as surface tension or fluorescence intensity ratio are plotted as a function of concentration. In connection with a general investigation of the physicochemical properties of FS1 and FS2 we have determined their CMC in water by two independent methods: fluorescence measurements and surface tension experiments.

Fluorescence spectra were taken with stock solutions of both FS1 and FS2 using a common fluorescent probe coumarin 153 (C153). C153 absorbs at ~440 nm and emits at ~545 nm in pure aqueous solution. Addition of different concentrations of FS1 and FS2 leads to a substantial increase in fluorescence intensity with an appreciable blue shift of ~30 nm in case of FS1 and ~50 nm in case of FS2 (Fig. 1). Increase in fluorescence intensity as well as extent of blue shift was found to be significantly higher in case of interaction of C153 with FS2 as compared to FS1 (Fig. 2). This shows that the probe partitions better inside the micellar environment of FS2 and experiences a more non-polar environment. It can therefore be assumed that FS2 is a more non-polar surfactant as compared to FS1.

A plot of relative fluorescence intensity and concentration leads us to accurately determine the CMC value of the two surfactants from the emission studies as shown in Figure 3. The CMC is found out to be 0.27 mM for FS1 and 0.45 mM for FS2. A slightly lower value of CMC in case of FS1 compared to FS2 indicates that the head group indeed plays a role in the micellization process, in spite of having similar hydrophobic chain length.

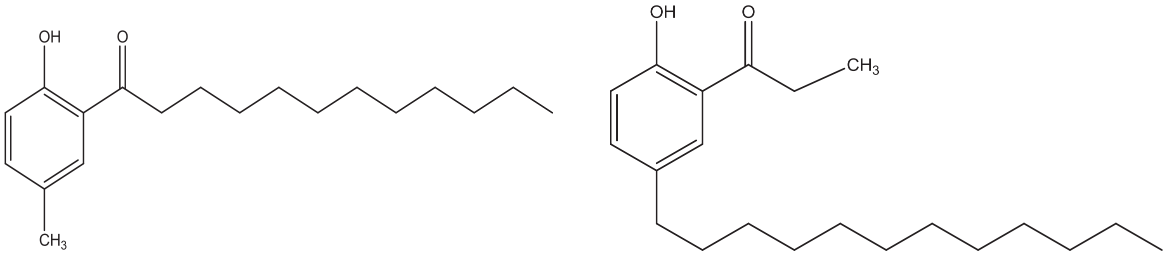
The Gibb's free energy of micellization was also found from the following equation:

$$\Delta G^0_{\mathrm{mic}} = RT \ln \mathrm{CMC} \tag{1}$$

This was found to be $-20.36\ \mathrm{kJ\ mol^{-1}}$ for FS1 and $-19.09\ \mathrm{kJ\ mol^{-1}}$ for FS2 indicating that the process of micellization is highly favourable.

A greater lowering of surface tension was found in case of FS2 as compared to FS1. This difference is expected considering the higher CMC of the former species. The relationship between surface tension and the logarithm of the concentration of the surfactants is shown in Figure 4. The breakpoint allows the ready evaluation of the CMC for both the surfactants.

The CMC as calculated from surface tension measurement are found to be 0.33 mM for FS1 and 0.50 mM for FS2. This is in good agreement with those derived from the fluorescence studies. Also it is evident that the micellization occurs at lower concentration for FS1 as compared to FS2.



Scheme 1. Structures of FS1 and FS2, respectively.

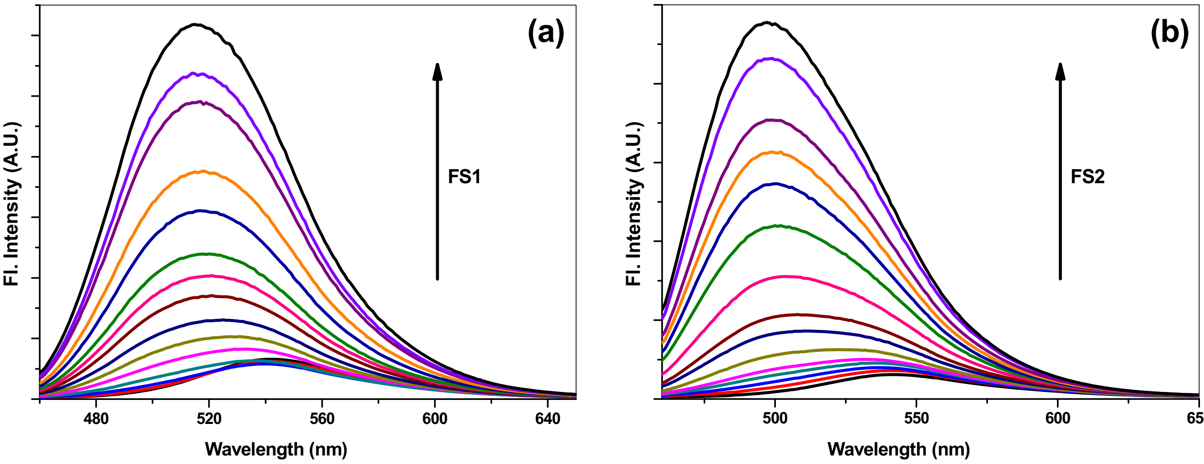


Figure 1. Emission spectra of 5 μM C153 with increasing concentrations of FS1 and FS2. The concentration of both the surfactants varies from 0 mM to 2 mM.

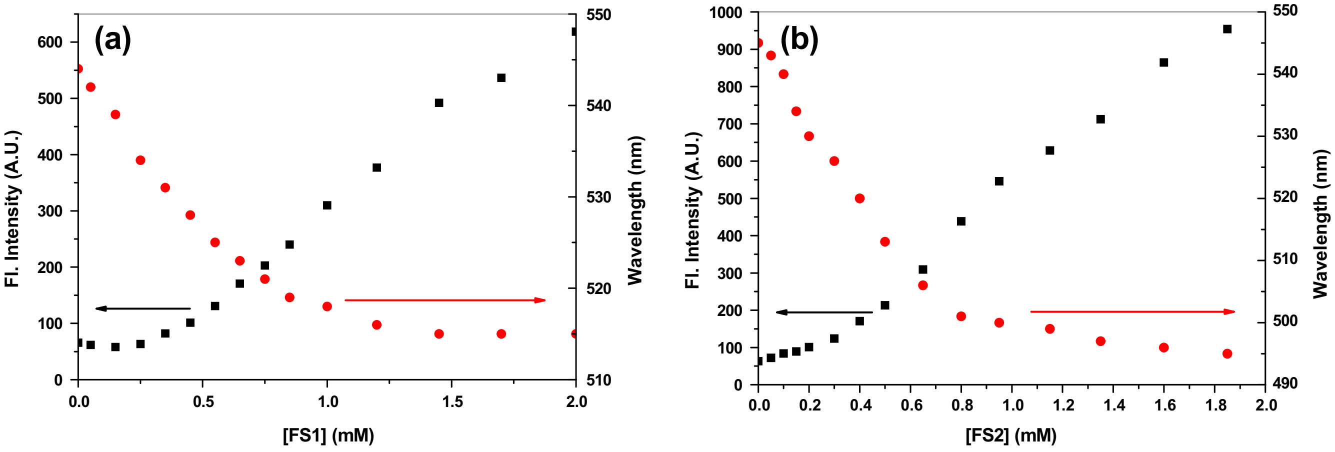


Figure 2. Variation of fluorescence intensity and wavelength of 5 µM C153 with increasing concentrations of FS1 and FS2.

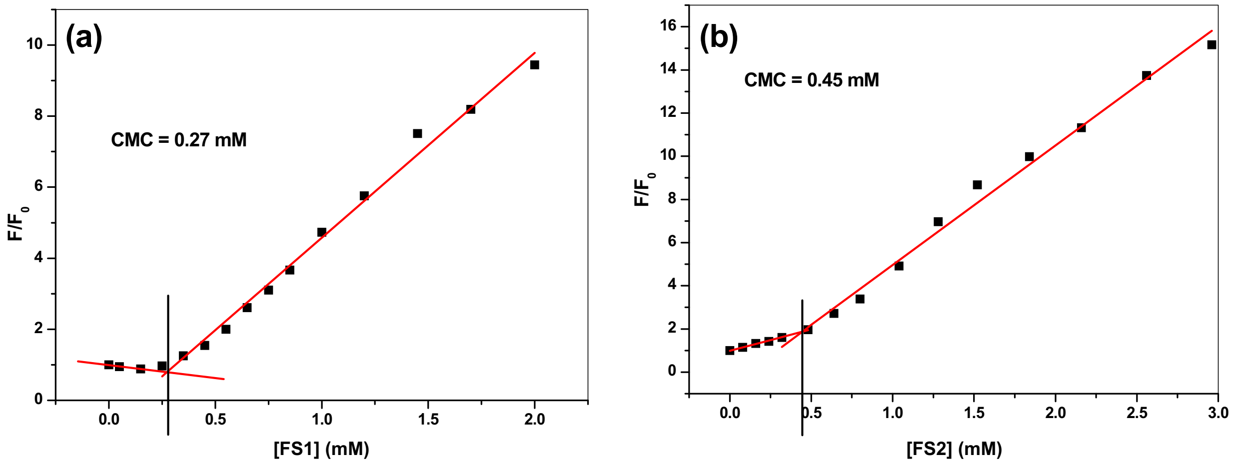


Figure 3. Plot of relative fluorescence intensity vs. concentration of surfactants.

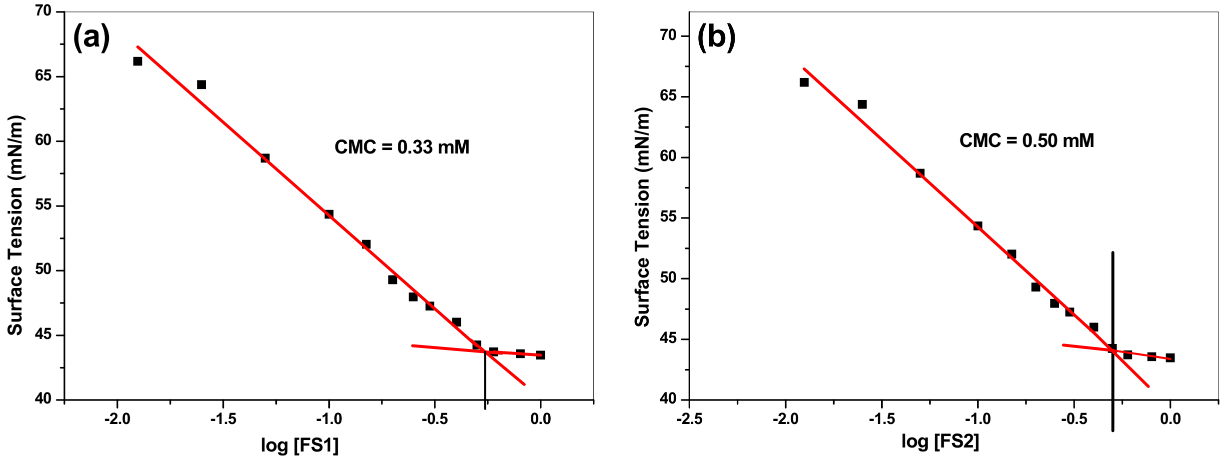


Figure 4. Plot of surface tension against log of the surfactants for FS1 and FS2, respectively.

The HLB values[25–28] represent an empirical numerical correlation of the emulsifying and solubilizing properties of different surface active agents. Table 1 illustrates the various ranges of HLB values.

Davies[29] found that HLB values for surface active agents can be consistently calculated directly from the chemical formulae, using *group numbers*. The group number for our surfactant system was collected from ref [17] from which the HLB values were calculated for FS1 and FS2, using the relation,

$$\mathrm{HLB} = \sum(\text{hydrophilic group numbers}) - n(\text{group number per } \mathrm{CH_2} \text{ group}) + 7 \qquad (2)$$

Table 1
Classification of emulsifiers according to HLB values

Range of HLB values	Application
3.5–6	W/O emulsifier
7–9	Wetting agent
8–18	O/W emulsifier
13–15	Detergent
15–18	Solubilization

Here, *n* is again the number of –CH_2– groups in the molecule of emulsifying agent. It must be emphasized that the HLB system is not concerned with the stability of the emulsion once formed: it is only a correlation of function, not of efficacy.[27,28] The HLB value was found out to be ~4 for FS1 and ~3 for FS2. It shows that the surfactants are essentially lipid soluble surfactants and can act as water-oil emulsifiers. These surfactants should also have a property of acting as anti-foaming agents.[29]

Static light scattering measurements were employed for the determination of the aggregation number of the surfactants. Typical Zimm plots[30] of FS1 and FS2 aqueous solution at different concentrations above the CMC were used for the estimation of the molecular weight of the aggregated states in the micellar solutions as well as the radius of gyration and the second virial coefficient. The aggregation number was calculated by simply dividing the relative molar mass of the aggregated states by that of the monomeric state. It is interesting to see that the aggregation number of FS2 is higher than that of FS1, though the area/molecule is lesser in the former. This implies a closer packing of the surfactant molecules in the air–water interface. The evaluated values are tabulated in Table 2.

In the concentration range studied, angular dissymmetry, $Z_{60} = R_{60}/R_{120}$, for a micellar solution of the surfactants was found to range ~1.04 for FS1 and ~0.91 for FS2. For spherical micelles the value is close to unity and for rigid rods the value is $\sqrt{3}$, that is, 1.73. It can therefore be concluded that the micelles formed are typically spherical in nature.[31] The calculated radius of gyration was 33 ± 2 nm for FS1 and 67 ± 2 nm for FS2 which is compatible with spherical bodies. The ratio of the radius of gyration to that of the hydrodynamic radius (R_G/R_H) has been evaluated to be close to $\sqrt{(3/5)}$. This is the value for spherical micelles.[32] This further supports the presence of spherical micelles in the system. The plot of hydrodynamic radius (at angle 90°) versus intensity for the two surfactants is given in Figure 5.

Table 2
Surfactant relevant properties of FS1 and FS2 in aqueous solutions

Surfactant	CMC (mM)	Area (Å^2/molecule)	M_w	*N*
FS1	~0.3	117.2	2.85×10^4	~85 ± 2
FS2	~0.5	85.7	4.25×10^4	~135 ± 5

Furthermore, the second virial coefficient evaluated from the Zimm plots for an aqueous solution of the surfactants in aqueous solution was 1.25×10^3 mol cm^3 g^{-2} for FS1 and 2.12×10^3 mol cm^3 g^{-2} for FS2. The value is positive and close to that usually found for spherical micelles.[32] All these results suggest symmetry in the micellar structure, pointing to a spherical shape of the micelles. This is further evidenced by the polydispersity index of the micellar solutions which has been calculated as 0.107 which is very low indicating a fairly monodisperse solution.

The plots of surface tension as a function of concentration for both FS1 and FS2 (Fig. 4a) show an effective reduction in the surface tension. This is consistent with the efficient positive adsorption at the air/water interface. The lowering of surface tension with increasing concentration of the surfactants can be explained in terms of surface activity. It is well known that for surfactants, the amphiphilic molecules orient at the air/water interface with the hydrophobic part above the interface and the chains residing in the aqueous phase. The relative ease with which a surfactant molecule migrates to the interface depends on the solubility in the bulk phase.

The Gibbs adsorption isotherm was used for the estimation of the limiting area occupied by one molecule of FS1 and FS2 at the air/water interface. The simplified Gibbs adsorption equation in terms of concentration can be expressed as:

$$\Gamma_{ex} = -(1/RT)(d\gamma/d \ln c) \quad (3)$$

where Γ_{ex} is the excess concentration of surfactant molecules at the interface, that is, the amount of surfactant adsorbed per unit area (mol/cm^2), γ is the surface tension of the solution, *c* is the concentration of the surfactant in the bulk of the solution, *T* is the temperature and *R* is the gas constant.

The slope of the surface tension versus log concentration plot (Fig. 3b and c) (below the CMC) was used to estimate Γ_{ex}. The limiting area per molecule (A_{min}) was then calculated from the equation

$$A_{min} = 1/(N\Gamma_{ex}) \quad (4)$$

where *N* is Avogadro number.

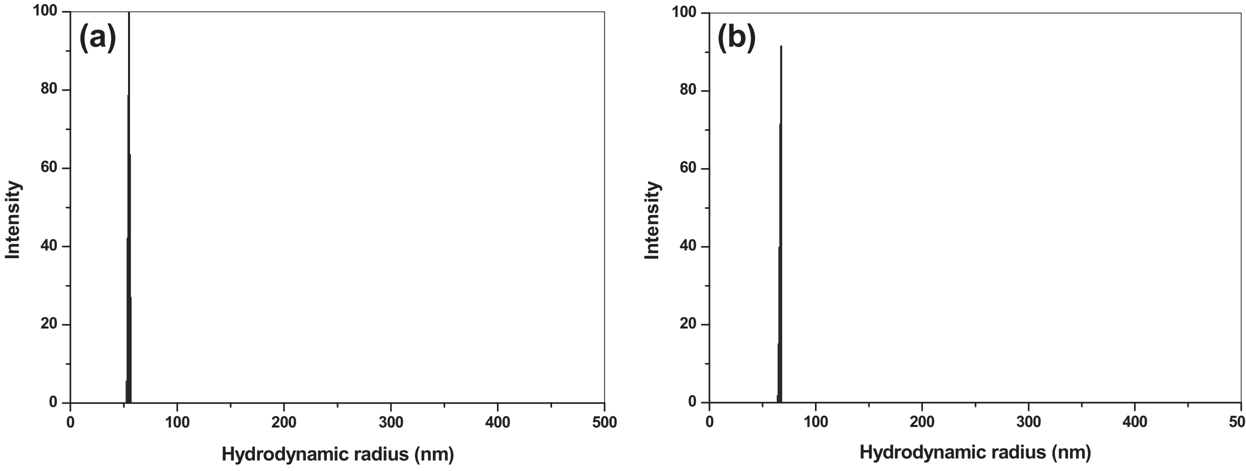


Figure 5. Plot of hydrodynamic radius vs. intensity for (a) FS1 and (b) FS2. [FS1] = 0.5 mM and [FS2] = 1 mM.

The limiting areas calculated for FS1 and FS2 were 117.2 and 85.7 Å^2/molecule, respectively. The values match well with the commercially available spherical surfactants. It is interesting that the area per molecule at the air–water interface is smaller for FS2 than for FS1. It seems that more favourable intra- or intermolecular hydrogen bonding leads to better packing of the FS2.

The oil–water interfacial tension was measured using KRUSS spinning drop tensiometer. The surfactant concentrations were chosen well above CMC, 1.0 mM for both FS1 and FS2. The oil taken was *n*-heptane with a density of 0.684 gm/cm^3. The IFT was found to be 0.5167 mN/m for FS1 and 0.8460 mN/m for FS2. Detergency of oily soil is a complex kinetic process that includes contributions from the wash system physical properties, time and temperature of wash, and the hydrodynamic forces exerted during the wash process. Generally, surfactant mixtures that exhibit a low oil–water interfacial tension are considered to provide superior oily soil detergency. A quantitative understanding of detergency will be imperative in robust formulation design. There have been attempts to correlate oily soil removal with easily measurable physical property of the wash system. In particular, the oil–water interfacial tension is one property that has been used to correlate oily soil detergency.[33–37] A preliminary look at correlating a complex kinetic process like detergency with a thermodynamic parameter like interfacial tension appears to be flawed. The works of Verma and Kumar[38] indicate that a general correlation of oil–water interfacial tension with oily soil removal does not exist. Detergency of oily soils is a complex kinetic phenomenon, which can be described by the mass transfer process, which includes surfactant adsorption at various interfaces, detachment of oil from the surface and suspension of these molecules in surfactant micelles, or as emulsified drops. It is also obvious that the soil removal/suspending capacity of the wash liquor is defined and intimately related to various thermodynamic quantities such as the oil–water interfacial tension. Also, the spinning drop tensiometer is only useful for measurement of the oil–water interface on the hydrophilic side of the phase inversion temperature for nonionic surfactants. Above this temperature, the surfactant will be relatively more oleophilic and will try to form a water-in-oil emulsion in an agitated state. This implies that the curvature will be concave towards the oil phase. In the spinning drop tensiometer, this will just cause the oil droplet to spread along the length giving misleading results for interfacial tension. Therefore, instead of attempting to predict the detergency of these surfactants, we can just say that the values are comparable to the commercially available EO group of surfactants.[38] Actual study with formulations and soil will be required to understand the detergency of these surfactants which is underway.

The effect of calcium ion on the behaviour of the two surfactants was studied to understand the Ca^{2+} resistivity of the surfactants. This method has been previously exploited by Bordes et al. and is a very well known method for determining calcium resistivity of a particular surfactant.[39] CaCl$_2$ solutions of increasing concentrations were progressively added to a stock surfactant solution of FS1 and FS2 well above their CMC concentrations. The effect of precipitation (of absence of it thereof) was monitored through studying their physicochemical properties to estimate the Ca^{2+} resistivity of the surfactants. This was studied using two methods: (i) turbidimetry and (ii) surface tensiometry. The results have been discussed in the following section:

Turbidimetry

The effect of addition of Ca(II) ions on the precipitation behaviour of FS1 and FS2 was studied by monitoring the turbidity of the solutions with progressively increasing concentration of Ca(II) ions. The results are given in Figure 6. The results depict that both the surfactants have high level of Ca(II) tolerance. Up to ~40 mM for FS1 the turbidity does not change significantly indicating resistance of the surfactants to Ca^{2+} precipitation. At higher concentration however, Ca^{2+} start precipitating leading to higher turbidity of the solutions as shown in Figure 6. However, it is interesting to see that FS2 seems to be even more Ca^{2+} tolerant compared to FS1. The turbidity of the solutions hardly changes within the experimental limits of our study. This shows that the effectivity of FS2 as a Ca(II) tolerant surfactant is highly potential. This is probably happening because the packing of the FS2 molecules are much better than FS1 as we found out from our light scattering studies. In other words, the steric crowding at the carbonyl oxygen which helps in forming stable complexes with Ca(II) ions, is lesser in case of FS2 as compared to FS1. Perhaps the presence of a long hydrophobic tail attached with the carbonyl oxygen in case of FS1 leads to effective binding with Ca2+ ions and better packing of surfactants. This ultimately results in reduction in the precipitation of Ca2+ ions and therefore increases the Ca^{2+} ion tolerance of FS2 compared to FS1.

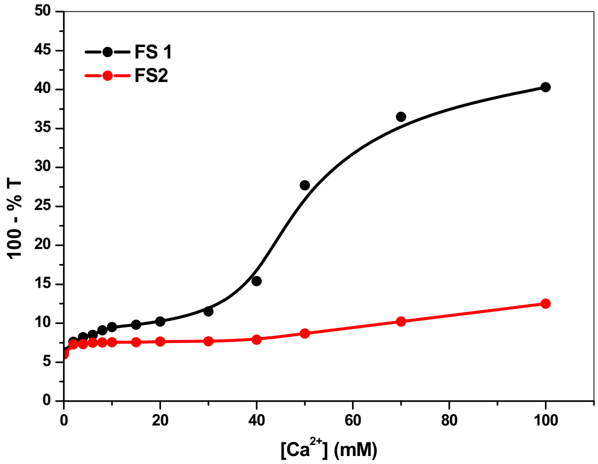


Figure 6. Turbidimetric plots for interaction of FS1 and FS2 with Ca^{2+} ions. [FS1] = 0.5 mM and [FS2] = 1 mM.

Surface tensiometry

CaCl$_2$ was added to an aqueous solution of the surfactants at a concentration much higher than the CMC and the surface tension was monitored. The results are shown in Figure 7. The surface tension remained approximately constant up to a CaCl$_2$ concentration of ~40 mM for FS1, after which it rapidly increased. The strong increase is most likely due to precipitation of the surfactant as the calcium salt. Similarly the surface tension of FS2 with increasing Ca(II) concentration was found to remain almost constant within our experimental range. The results comply with those obtained from the turbidimetric studies and confirm high tolerance of these synthesized surfactants towards Ca(II), especially for that of FS2.

NMR studies

NMR was used to determine quantitatively the amount of surfactant remaining in solution as the CaCl$_2$ concentration was increased. The results, shown in Figure 8, confirm that the FS2 surfactant is more calcium tolerant than the two other surfactants.

A tentative explanation for the difference is the following. These surfactants should be capable of forming intramolecular chelates with the divalent calcium ion, leading to stable membered rings. However, the steric crowding for forming this in case of FS1 > FS2,

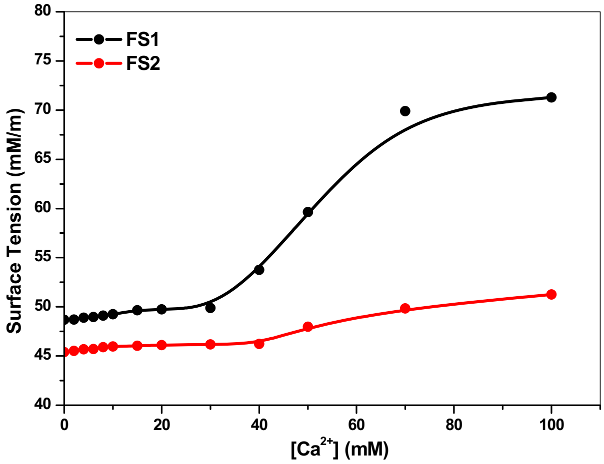


Figure 7. Surface tension plots for interaction of FS1 and FS2 with Ca^{2+} ions. [FS1] = 0.5 mM and [FS2] = 1 mM.

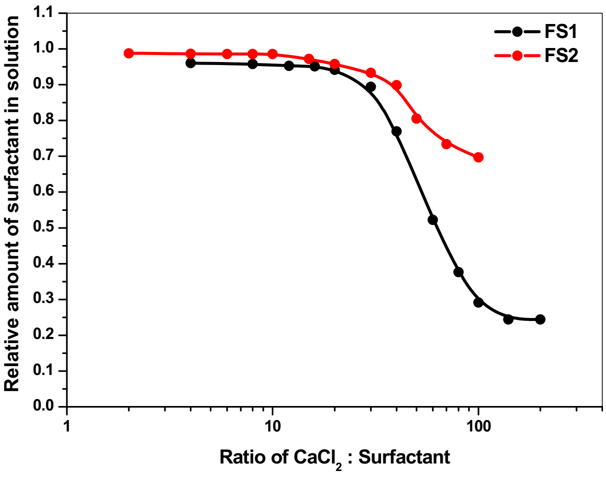
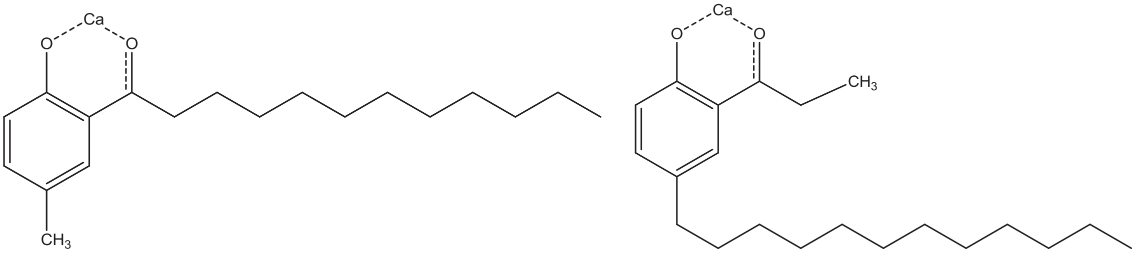


Figure 8. Relative amount of dissolved surfactant as a function of molar ratio of added $CaCl_2$ to surfactant. [FS1] = 0.5 mM and [FS2] = 1 mM.

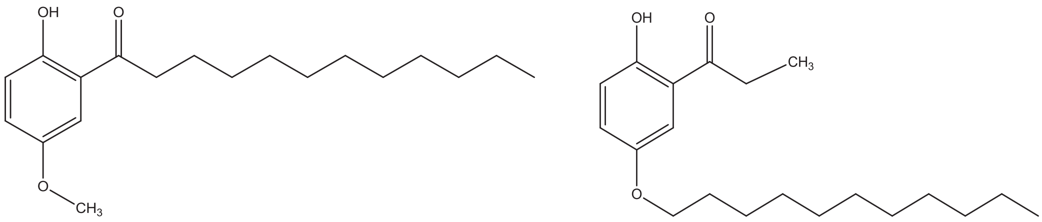
which is perhaps why this is less favourable for FS1. The intramolecular binding is likely to be less effective in terms of surfactant packing at the interface than the intermolecular binding where the calcium ions trigger closer packing of the anionic surfactants. Precipitation seems to be favoured by the intramolecular binding 350 of calcium ions, which is not surprising since calcium soaps of divalent acids are known to precipitate readily. The intermolecular binding is likely to be less effective in terms of surfactant packing at the interface than the intramolecular binding where the calcium ions trigger closer packing of the surfactants. The intramolecular chelating of calcium ions is assisted by interaction between the carbonyl oxygen and the cation (Scheme 2). Such interactions have been observed before for similar chelating agents and divalent cations.[27–30] Between FS1 and FS2, we find that FS2 is more effective in terms of both surfactant packing at the air-water interface as well as its Ca^{2+} ion resistant property. This has been explained by the higher degree of steric crowding at the carbonyl oxygen in case of FS1, which helps in forming stable complexes with Ca(II) ions, due to the presence of a long hydrophobic tail attached with the carbonyl oxygen. This perhaps leads to effective binding with Ca^{2+} ions and better packing of surfactants that lead to reduction in the precipitation of Ca^{2+} ions and therefore increase the Ca^{2+} ion tolerance of FS2 compared to FS1. Such interactions have been observed before for similar chelating agents and divalent cations.[40–42] Close packing of all the surfactants may also be favoured by formation of hydrogen bonds aligned at the interface.[38]

We also synthesized and extracted two derivatives of FS1 and FS2, with $-OCH_3$ groups substituted as shown in Scheme 3, naming it as FS3 and FS4. The surface active properties of both the compounds as well as their Ca^{2+} tolerant behaviour were characterized. It was found that FS1 and FS3 had analogous properties while FS2 and FS4 had analogous properties. This conclusively shows that the difference of property between FS1 and FS2 is mainly because of the packing behaviour of the head groups at the air–water interface which is governed by the steric crowding at the carbonyl oxygen.

This Letter describes the synthesis of two unique functionalized surfactants, FS1 and FS2 having an analogous hydrophobic chain but differing structurally in the composition of the head groups in terms of the position of attachment of the chain. The molecules were chosen such that there will be possibility of a chelating



Scheme 2. Intramolecular complex between Ca(II) and FS1 and FS2.



Scheme 3. Structures of FS3 and FS4, respectively,

complex between the OH group and the Ca^{2+} ion. These molecules are therefore tailor-made to suit our purpose and this kind of phenol–keto surfactants has not been reported here before. The effect of this variability in the head group on the surfactant property, adsorption, self assembly and calcium tolerance behaviour has been studied in detail. The Ca^{2+} ion resistivity of both the surfactants was monitored and preliminary results have been presented, which seem to be promising. Comparing the surfactants it was found that FS2 was more Ca^{2+} ion tolerant than FS1. The individual packing behaviour of the surfactants at the air-water interface has been projected to cause this difference which is interesting. The higher tolerance of these surfactants to hard water conditions poses a potentially important feature and opens a new vista towards development of further such surfactants.

Acknowledgments

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2014.08.111.

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