Physicochemical Characterization of Sodium Surfactin for Oil and Gas Industry Application

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Abstract

Introduction– Industry operators are becoming more critical of synthetic surfactants for various oil and gas operations. Principal among these concerns is the environmental degradation. As a result, there is increasing interest in the use of biosurfactant, including surfactin, in oil and gas operations. Therefore the need to improve its characteristics, hence performance becomes evident. Characteristics of cultures of surfactin (isolates) were reported. These characteristics could potentially change after synthesis and drying, hence the need for this study.

Methodology−The methodology involved characterizing surfactin in aqueous media, and sodium chloride (NaCl) salt solution of 0.1–1.5M concentrations. Properties that influence active site for adsorption (functional group), dispersion (density, foaming), amount of dissolved minerals (pH and conductivity) among others, were analyzed at various surfactin dosages of 0.025 – 1.0%.

Results−Results indicated foaming and solubility were excellent in aqueous solution, but significantly affected above 0.5M NaCl concentration. Aqueous surfactin had maximum density of 985.2kg/m^3, however increases with increasing NaCl concentration. With pH of 7.1 at 1.0% dosage, aqueous *surfactin* will pose no corrosion problem to pipelines. Additionally, both *surfactin* dosage and change in salt concentration exhibited linear relationship effect with pH and conductivity. Infrared analysis confirms cyclic nature of sodium *surfactin* with lipopeptide chain linked to an aliphatic, hydrocarbon chain.

Conclusion−These makes it suitable for use as dispersion agent, viscosity reduction for heavy crude transport, additive for drilling mud preparation, and potential candidate for surface activities, a desirable requirement for oil and gas applications.

Keywords: Sodium *surfactin*, *Bacillus subtilis*, biosurfactant, physicochemical characteristics

1 Introduction

Sodium *surfactin*s are amphiphilic surface-active molecules [1]–[3] produced by strains of *Bacillus subtilis* that are used in many industrial applications. They are class of biosurfactants composing of seven amino acids chains (peptides) linked to fatty acid [4], [5], as the hydrophilic side, and hydrophobic side comprising of hydrocarbon chain.

Surfactin is one of the most prevalent biosurfactants [6]. Unlike synthetic surfactants which are non-biodegradable, toxic prone and have less foaming and wetting properties, biosurfactants have low critical micelle concentration (CMC) [7]. This enhance their ability to greatly reduce the surface and interfacial tensions (IFT) [3], [8], [9], and endear their oil and gas application. As a result, there is increasing studies on performance of biosurfactants in recent times. A good review on applications of specific biosurfactants for particular oil and gas operations can be found in [10]. Additionally, successful experimental and numerical application of *surfactin* for enhanced oil recovery (EOR) and hydrocarbon biodegradation have been reported by [11]–[13]. These applications follow successful production and characterization, both physical and chemical, of *surfactin* as potential surfactant in oil and gas operations. Extensive reviews on method of fermentation, isolation and synthesizing of *surfactin* from various sources can be found in the work of Chen [14] and Inès [15]. Furthermore, Geissler et al., [16] established a high-performance thin-layer chromatography (HPTLC) method of identifying and quantifying cyclic lipopeptides *Surfactin*, Iturin A and Fengycin in *Bacillus* culture samples. Also, characterizations of *surfactin* for EOR have bene reported. [17] Studied effect of change in salinity, pH and temperature on performance of *surfactin* in terms of surface tension reduction. [18], [19] further studied stability of *surfactin* at different pH, salinity and temperature, in terms of solubility, surface tension and emulsification. [20], [21] compared performance of *surfactin* with that of chemical surfactant in terms of surface tension, pH and temperature stability. [22], [23] Characterizes *surfactin* from low cost agro and industrial wastes, to potentially increase spectrum of *surfactin* sources. While these studies were conducted in conditions typical of oil formation for EOR (salinity of 0 – 10%, pH of 3 – 10 and temperature of 20 – 100ºC), properties such as density and conductivity were not reported. Additionally, reported characteristics could not explain the mechanism of applications such as surfactant propagation in porous media (formation) during EOR, hydrate/paraffin/asphalt deposits control in pipelines due to dispersion, capillary and wettability effect.

More so, the studies were conducted using isolates of *surfactin* which were not synthesized. Ease of storage and transport of wet and unsynthesized *surfactin* could difficult. Surfactant shelf-life will also be greatly disadvantaged if unsynthesized, as such could affect its performance characteristics. This is the motivation behind this study, in addition to analyzing density as a tool for CMC determination.

This study therefore is to add to results of previous investigations, and further widen the mechanism of application and performance scope of *surfactin* in oil and gas operations.

2 Materials and method

2.1 Materials

Sodium *Surfactin* (Kaneka *surfactin*) biosurfactant (CAS No.302933-83-1), $C_{55-n}H_{95.5-2n}N_7O_{13}Na1.5$, was purchased, and used as received, from Kaneka Europe Holding Company, Belgium. Aqueous solution of the *surfactin* was prepared using distilled water locally made in the Petroleum Engineering laboratory of University of Salford. Acros Organics brand (207790010/20) analytical grade univalent salt, Sodium chloride (NaCl) with 99.5% purity was purchased from Fisher Scientific, UK.

2.2 Sample preparation

Aqueous solution of surfactant was prepared by measuring and directly adding 0.025, 0.05, 0.075, 0.1 0.5 and 1.0w/v% dosages of *surfactin* into sample container. Appropriate volume of with distilled water was subsequently added. The mixture was vigorously agitated and stirred, and allowed at least for 5 hours to completely dissolve. Surfactant dosages were adopted based on the works of [24], [25].

Saline solutions of 0.05–1.5Molarity (M) concentration were as well prepared by measuring and dissolving appropriate amount of salt into 2litres of distilled water. The solution was well stirred using hotplate magnetic stirrer. Each concentration of the saline solution was then used to prepare saline solution of the surfactant, using the various dosages as stated in section 2.2.

2.3 Density measurement

The average density of aqueous sodium *surfactin* was measured by weighing each of equal volume of the surfactant samples. 50ml of each of the samples were measured in a measuring cylinder, and then poured into a container which has been tarred at zero level on weighing balance. The density value was calculated numerically using Equation (1).

$$\rho = \frac{mass\ of\ sample}{volume\ of\ sample} \tag{1}$$

Density measurement has been identified by the authors as new method of determining surfactant CMC, rather than conventional surface tension measurement. CMC is the concentration above which surfactant molecules undergoes rearrangement thereby forming aggregates, known as micelles.

2.4 FTIR spectroscopy

Fourier-transform infrared spectroscopy (FTIR) analysis of dry, powdered *surfactin* was conducted using Nicolet™ iS10 FT-IR Spectrometer. Absorption spectra were plotted using a built-in plotter. The IR spectra were collected from 500–4000 wavenumbers (cm−1). Procedure was followed as described in [26].

2.5 Conductivity measurement

Conductivity of aqueous solution of sodium *surfactin* was directly measured with RS-PRO 123-8777 conductivity meter, at average temperature of 18.5°C, with 2.1°C temperature adjustment factor. In NaCl solution, resistivity was measured using OFITE analog resistivity meter and conversion made to conductivity. Equation (2) gives the conductivity – resistivity relationship that was used for the conversion.

$$Conductivity, K = \frac{1}{resistivity} \tag{2}$$

2.6 pH measurement

Measurement of pH was made with the use of Oakton pH meter (PHTestr10). After appropriate calibration, the meter is dipped into sample, stirred and stabilized reading taken. Values were obtained at average ambient of 18.5°C.

3 Result and discussion

3.1 Foaming and solubility

Formation of aqueous solution of sodium *surfactin* in distil water comes with foaming as a consequence, shown in **Figure 1**. The foaming ability of the surfactant will enhance its utilization as foaming constituents for enhanced oil and gas recovery at sub surface using foam flooding [27]. Though, surfactant dosage and ionic concentration exhibited an inverse effect on foaming ability (**Figure 1A**). It generally decrease when salinity increased to 0.5M (**Figure 1B**), with only a very thin layer at 0.025% of 1.5M salinity (red arrow in **Figure 1C**). Figure 1 is also an indicator that the surfactant foaming is related to its solubility and salinity of the solvent. Surfactant solubility also follows same trend as foaming ability.

Properties of aqueous solution of NaCl salt prepared were presented in Table 1.

Table 1 Properties of aqueous solution of NaCl salt at different ionic concentrations

Property	**Ionic Concentration (M)**					
	0.05	**0.1**	**0.25**	**0.5**	**1.0**	**1.5**
Density (kgm^{-3})	989.4	992.2	996.2	1017.3	1026.2	1039.4

pH	5.9	6	5.8	5.7	5.8	5.9
Conductivity (mS/cm)	5.07	9.24	23.697	41.667	80	111.11

Figure 1 Foaming of aqueous sodium *surfactin* when agitated at (a) 0M, (b) 0.5M and (c) 1.5M NaCl concentrations

3.2 Density, conductivity and pH

This characteristic has not been reported of *surfactin* so far, which is one motivation for this study. At room temperature, density of aqueous *surfactin* was observed to be less than that of distil water used (984kg/m^3), which increases with dosage (**Figure 2A**). Two possibilities can be attributed to the density decrease behavior; (1) increase in size of *surfactin* molecules in solution which, despite been physically soluble, are not able to completely occupy the intermolecular empty spaces, (2) the solution expands which caused an increase in volume that neutralizes the mass addition. The density characteristics will be of significance in enhancing performance of *surfactin*; (a) for asphalt, wax, and hydrate deposition control thereby enhancing oil and gas transport through dispersion, (b) viscosity reduction for heavy oil transport, (c) rheology reduction during drilling mud preparation [27], [28], (d) promoting imbibition process/wettability alteration during EOR [29] and hydraulic fracking [30]. In addition, an interesting density characteristics was exhibited at 0.075–0.1%, where the density remained constant at 983.6kg/m^3. Surfactant saturation must have been reached at this point, leading to attainment of CMC. This indicates that density measurement can as well be employed to ascertain saturation point/CMC of surfactant.

As the case with density, **Figure 2B** showed that pH of the surfactant increases with increasing dosage, with maximum 7.1 pH value at 1.0% surfactant dosage. This is to say that sodium *surfactin* is itself either basic or neutral, since it tilts the pH of distil water (5.9) toward neutral value.

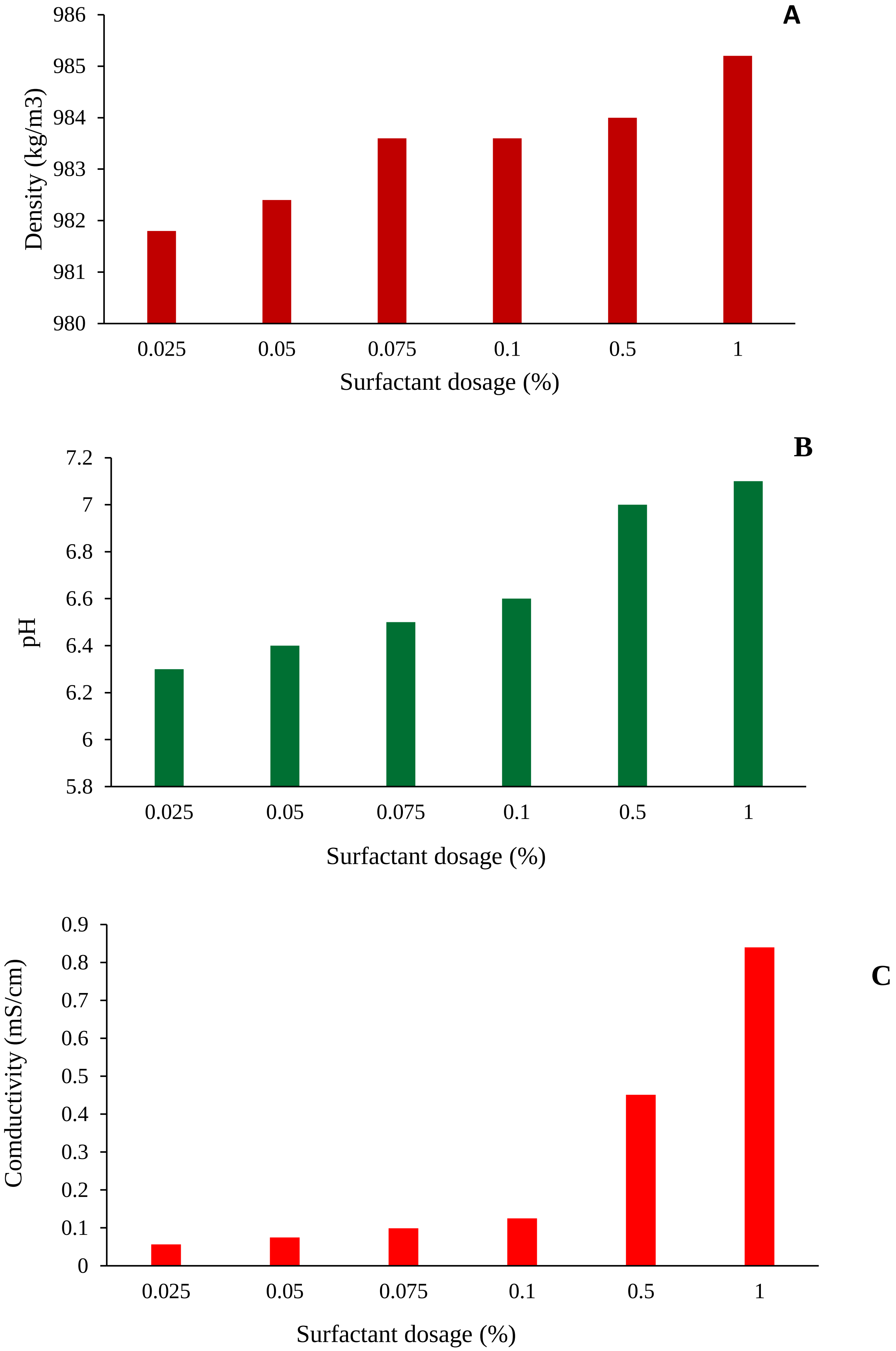

Figure 2 (a) Density, (b) pH, and (c) Conductivity of aqueous *surfactin* at different dosages

The result indicates that increasing *surfactin* dosages tend to increase the pH towards neutral and/or basic value. This in line with reports of [18], [31]–[33] which indicated best performance of *surfactin* from strain of *Bacillus,* in terms of interfacial tension (IFT) reduction, in the range of 6–10 pH. Sodium *surfactin* is therefore, at this pH, inferred to reduce IFT between oil-water and or gas–water. Additionally, use of sodium *surfactin* will pose no corrosion problem in pipelines.

Similar to other *surfactin* characteristics, conductivity of the surfactant increases with increase in dosage (**Figure 2C**). Conductivity and pH of *surfactin* depicted a linear relationship, across all dosages.

However, dissolution of sodium *surfactin* in saline solution results in general increase in density and conductivity as shown in **Figure 3** and **Figure 4**. Mass of NaCl salt contained in the solution must have contributed to the overall increase in density and conductivity. Nevertheless, the trend was dosage-dependent, especially with surfactant dosages 0.05–0.1% at 1.0 and 1.5M salinity. It indicates incompatibility of sodium surfactin in NaCl solution of above 0.5M concentration. Though [3], [25], [34] reported optimal IFT reduction using aqueous *surfactin* dosages of 0.075–0.1%, use of *surfactin* in saline solution of 1.0M concentration and above was observed to pose solubility problem (**Figure 5**). Scaling in well bore and walls of pipelines are some of the consequence of partial solubility of surfactants. [12], [35] however reported stability and performance of *surfactin* from *Bacillus subtilis* in NaCl solution in the range of 0–0.5M, which is in line with this study.

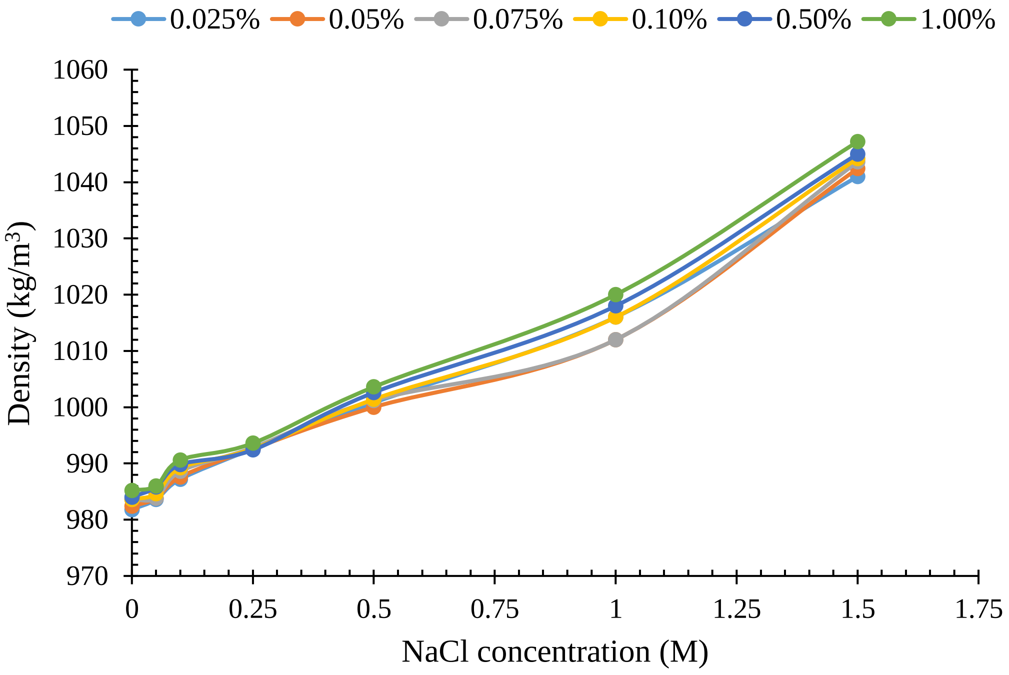

Figure 3 Density of sodium *surfactin* in NaCl solution at different dosages

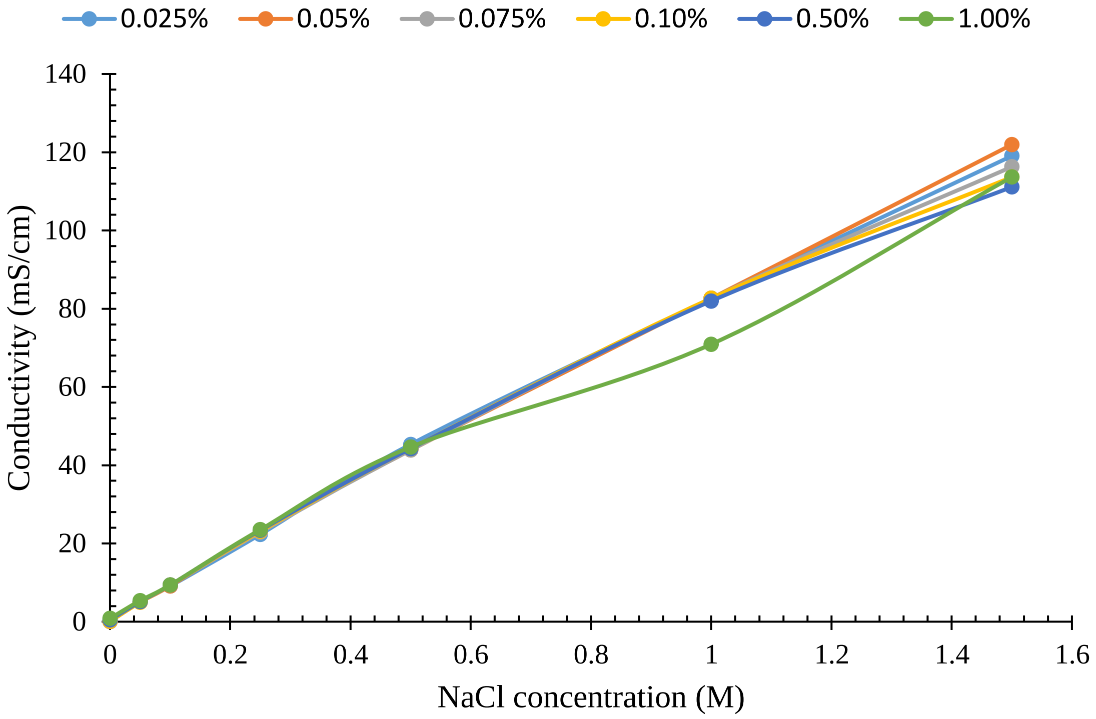

Figure 4 Conductivity of sodium *surfactin* in NaCl solution at different dosages

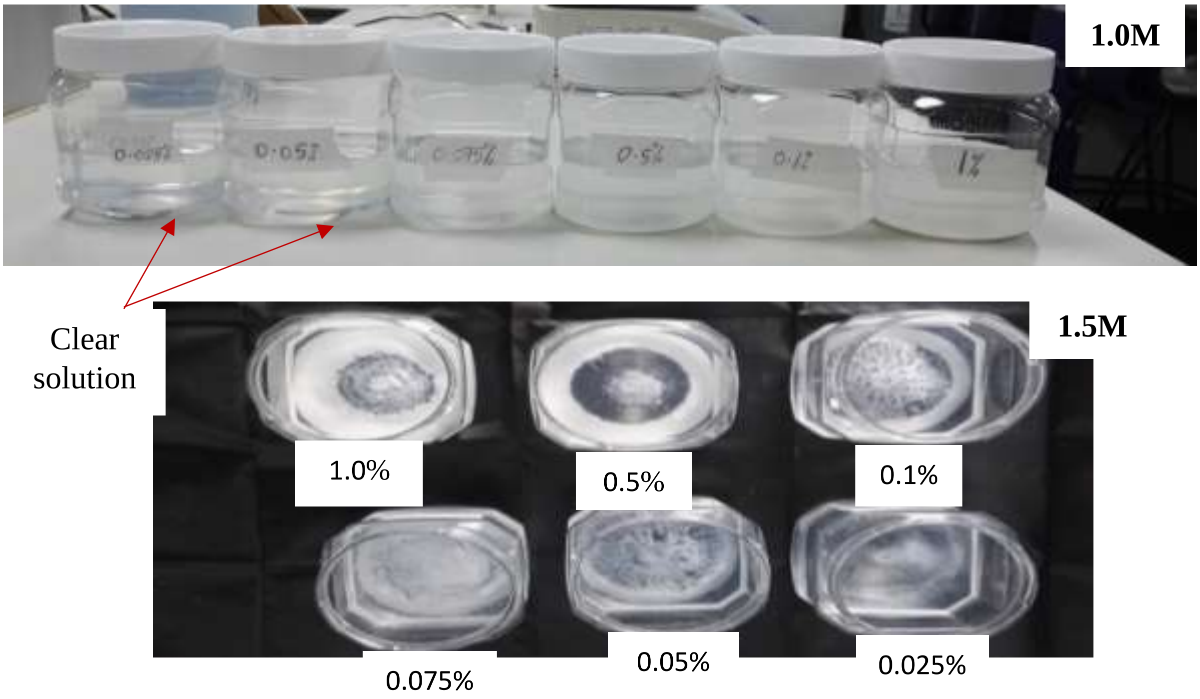

Figure 5 Solubility of sodium *surfactin* in 1.0 and 1.5M NaCl solution

Change in ionic concentration affect surfactant pH in monotonic pattern, except at 1.0% dosage shown in **Figure 6**, indicating that pH is both salinity and dosage dependent.

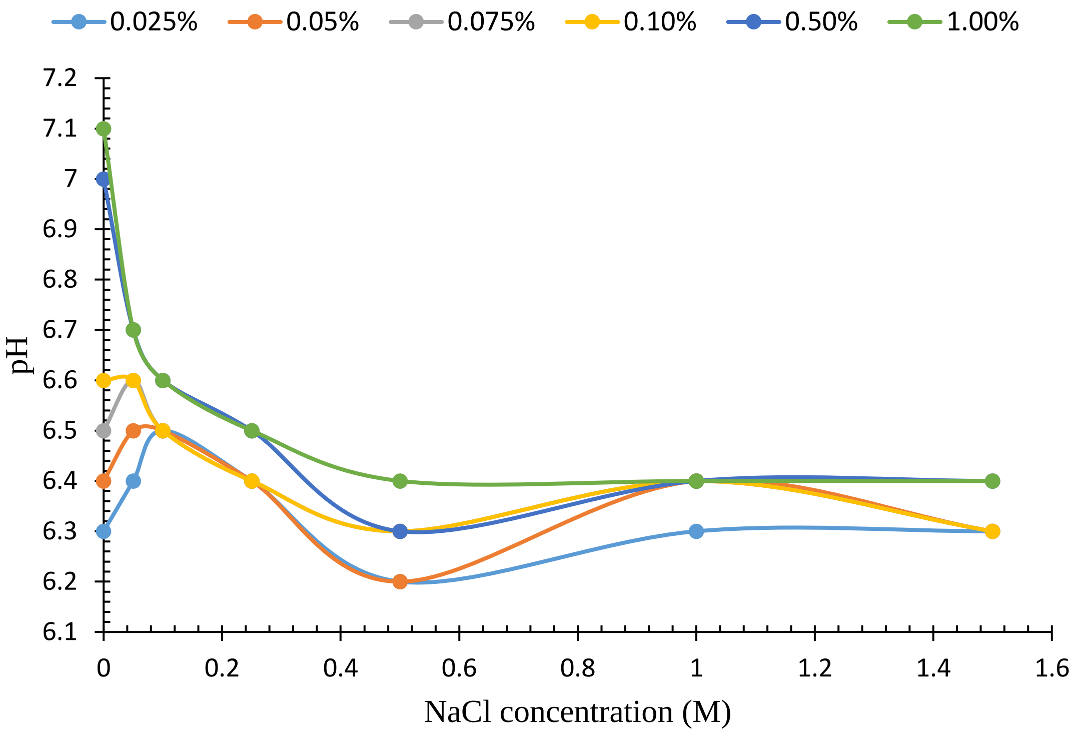

Figure 6 Effect of NaCl concentration on pH at various *surfactin* dosages

As mentioned earlier, the pH of aqueous *surfactin* particularly at dosages 0.075 – 1.0% will pose less or no threat to corrosion in pipes since the pH value is greater than 6.5. Similarly, *surfactin* in low saline solution of concentration up to 0.1M will pose no corrosion threat. However, increasing the NaCl concentration beyond 0.1M decreases the pH value towards acidic, though it became surfactant dosage – dependent. Nonetheless, care must be taken especially when dealing with a system containing high concentration of carbonate ions.

3.3 IR spectroscopy

Figure 7A showed the IR spectra obtained for sodium *surfactin*. It clearly indicated characteristic of peptides (NH-stretching mode) at 3293cm^{-1} and 1528 peaks. Furthermore, peaks 2956–2870cm^{-1} and 1467–1368cm^{-1} are representative of C–H group confirming the presence of aliphatic chains (–CH_3; –CH_2–) with symmetric stretching at 2870cm^{-1} [36] ; and 1735 cm−1 band is a characteristics of C=O (carbonyl group). 1648cm^{-1} band result from the stretching mode of the CO–N bond. The pattern of the IR analysis is a confirmation of the cyclic nature of sodium *surfactin*, and characteristics of lipopeptide biosurfactant previously described by [18], [37]. A characteristic that is desirable for adherence of surfactants for surface activities in oil and gas industry. Additionally, it also validate result of analysis by Kaneka Corporation (**Figure 7B)**.

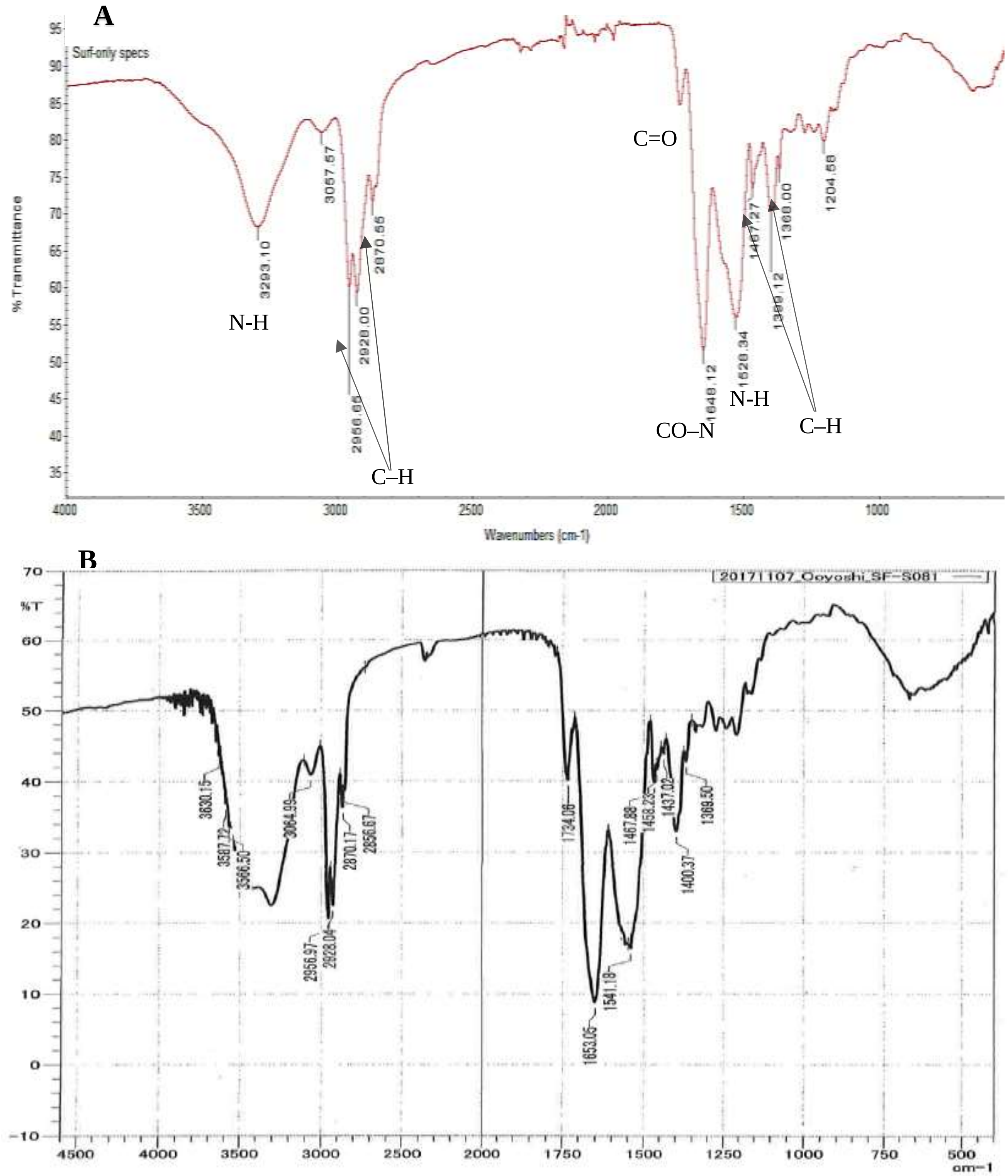

Figure 7 IR spectra of dried sodium *surfactin* powder (A) this study; (B) from Kaneka

4 Conclusion

The physicochemical characteristics of sodium *surfactin* have been presented in the body of this report. Foaming, density and pH characteristics indicated that the surfactant is a good candidate for deposit control in oil and gas pipelines, EOR, drilling mud preparation. It will also serve as good foaming agent in foam preparation for EOR, enhanced gas recovery, hydraulic fracking using foam, and potentially as hydrate formation inhibitor. Though solubility was excellent at zero or low NaCl salt concentration (up to 0.5M), it is significantly affected at 1.0M concentration and above. Furthermore, the solubility and foaming at 1.0M were concentration and dosage dependent. IR analysis confirms sodium *surfactin* to be a biosurfactant with a cyclic lipopeptide chain linked to an aliphatic, hydrocarbon chain. This makes it a potential candidate for surface activities.

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Author's contribution

Suleiman M. Salihu conducted the experimental work on the course of his PhD study, Abbas J. Abubakar and Babaei M. supervised and co-supervised the work respectively, and Ghasem G. Nasr proof read and review the manuscript.

Conflict of interest

The authors declare no conflict of interest regarding this publication.

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