Amino Acid-Containing Phase-Selective Organogelators: A Water-Based Delivery System for Oil Spill Treatment

Jun Chen, Charlotte E. Boott, Lev Lewis, Andrew Siu, Renad Al-Debasi, Veronica Carta, Amanda A. Fogh, Daniel Z. Kurek, Lilo Wang, Mark J. MacLachlan,* and Gabriel Hum*

ABSTRACT: The simple structural modification of replacing a terminal carboxylic acid with a primary amide group was found to lower the minimum gelation concentration (MGC), by at least an order of magnitude, for a series of N-lauroyl-l-amino acid phase-selective organogelators in decane. The amide-functionalized analogue N-lauroyl-l-alanine-CONH₂ was demonstrated to gel a broad range of solvents from diesel to THF at MGCs of 2.5% w/v or less, as well as to produce gels with a higher thermal stability (ca. 30 °C) and enhanced mechanical properties (5 times increase in complex modulus), compared to the carboxylic acid analogue, N-lauroyl-l-alanine-COOH. These improved properties may be due to the additional hydrogen bonding in the primary amide analogue as revealed by SCXRD. Most significantly for this study, the introduction of the primary amide functionality enabled N-lauroyl-l-alanine-CONH₂ to form a self-assembled fibrillar network in water. The aqueous network could then actively uptake and rapidly gel decane, diesel, and diluted bitumen (“dilbit”) with MGCs of 2.5% w/v or less. This aqueous delivery method is advantageous for oil-remediation applications as no harmful carrier solvents are required and the gel can be easily separated from the water, allowing the oil to be recovered and the gelator recycled.

INTRODUCTION

Low-molecular-weight organogelators (LMOGs) are compounds that can form supramolecular gels in an organic solvent. In these systems, the LMOGs self-assemble to form long fibrillar structures (i.e., fibers, rods, and ribbons), when an external trigger is applied, such as heat, increased concentration, or solvent.¹ The fibers then entangle to form a self-assembled fibrillar network (SAFiN), which has a high void volume that can trap organic solvents (Figure 1) at relatively low concentrations of LMOGs (i.e., <2% w/v). LMOGs have many attractive properties, including facile synthesis, tunable functionality, and low minimum gelation concentrations (MGCs), which make them attractive materials for applications such as drug delivery,² chemical sensing,³ and environmental remediation.⁴

Despite the utility of LMOGs, their de novo design is still a challenge. While there are very general design principles,⁵ the ability to predict whether a particular liquid will be gelled by a specific molecule remains elusive.⁶ Seemingly small changes in the structure of LMOGs can result in significant changes in the gel-forming behavior.⁷ The lack of guidelines for the design and discovery of molecular gelators serves to make the exploration of phase-selective organogelators (PSOGs), a specialized subset of LMOGS, an even greater challenge. In one strategy, a number of analogues are prepared based upon a known gelator⁷−⁹ and the members of the library are screened.
PSOGs are capable of gelling organic solvents in the presence of a second, immiscible liquid phase, which is typically water, and they are being explored for a range of environmental remediation applications, including oil spill containment.10,11 Using a PSOG to selectively gel the oil phase in water would provide spill responders with a measure to control the spreading of the oil spill. The gelled oil would remain buoyant and can be efficiently separated from the water phase by mechanical methods such as filtration and skimming.12–14 This approach is a promising strategy to increase the amount of oil that can be recovered in order to minimize environmental damage. The use of PSOGs also allows for the possibility that the recovered oil can be separated and reused, and the PSOG can be recycled.

Early research into PSOGs for oil spill applications confirmed the feasibility of this approach, but required relatively high MGCs (ca. 5% w/v).15–17 It took until 2001 for Bhattacharya and Krishnan-Ghosh to report an amino acid-based PSOG, N-lauroyl-l-alanine (1a) (Figure 2), that could gel petroleum at a lower MGC of 1.2% w/v.18 For this system, SAFiN formation was confirmed by scanning electron microscopy (SEM) and the presence of the carboxylic acid group was found to be key to gelation. When the carboxylic acid was replaced with a methyl ester group, gelling behavior was lost, which the authors attributed to the inability of the ester to form hydrogen bonds. Since this discovery, many other PSOGs have been prepared for oil remediation, generally relying on sugar, amino acid, or peptide amphiphiles with rigid hydrophilic groups and long flexible hydrophobic groups.19–23

The main barrier to the use of PSOGs in oil spill remediation is their deployment. The majority of PSOGs require a high-temperature trigger or the presence of an organic cosolvent, which means neither of these methods are feasible for an oil spill in open water. However, in recent years, several strategies have been developed to overcome these issues, including dissolution of LMOGs in a carrier solvent but at much higher concentrations,24 application of the PSOG in its xerogel form,25 and direct application of the solid phase by mechanical methods such as filtration and skimming.26–28 This approach is a promising strategy to increase the amount of oil that can be recovered in order to minimize environmental damage. The use of PSOGs also allows for the possibility that the recovered oil can be separated and reused, and the PSOG can be recycled.

RESULTS AND DISCUSSION

Molecular Design and Synthesis. The basic scaffold of 1a, previously reported by Bhattacharya,18 is an attractive structure because it offers four potential sites for molecular modification that can be altered to optimize the gelator for oil spill remediation: the alkyl chain length, the secondary amide bond, the α-amino acid R group, and the carboxylic acid group. For this study, we focused on the effect of changing the α-amino acid R group and the carboxylic acid group. We selected four amino acids (alanine, valine, leucine, and phenylalanine) and chose to introduce a primary amide in place of the carboxylic acid terminus (Figure 2). In addition, we also modified the enantiopurity of the amino acids as it had been previously reported that the enantiopurity of LMOGs can influence their gelling behavior.29,30

All compounds were prepared beginning with an accessible and high-yielding substitution reaction. A second step to convert ester groups to either the corresponding free acid or amide was carried out as necessary (see Supporting Information for more details). Briefly, compounds 1a–4a were synthesized using the l-amino acid methyl ester hydrochloride, which was reacted with lauroyl chloride. Deprotection of the methyl ester group was performed by hydrolyzing with sodium hydroxide followed by acidification with HCl to yield the carboxylic acid. Compounds 1b–4b were synthesized from the l-amino acid amide hydrochloride and lauroyl chloride. Compounds 1c and 1d were prepared from the d- and dl-alanine methyl ester hydrochloride, respectively, with lauroyl chloride. The resulting ester intermediate was then reacted with ammonia to produce the primary amide product. All compounds were recrystallized from methanol/water (9:1) to yield the pure material and characterized using nuclear magnetic resonance (NMR), elemental analysis (EA), and high-resolution mass spectrometry (see Supporting Information for more details).

Determination of MGCs. To assess the gelation behavior of our compounds, we used the inversion test (Figure S1 and Table S1). The gelation study (Table 1) revealed that changing the carboxylic acid to a primary amide improved (reduced) the MGC of all of the compounds tested, with the exception of the leucine-based compounds, 3a and 3b. Unlike the analogous lauroyl amides of ala (1b), val (2b), and phe (4b), which all produced opaque gels with decane, the leu

![Figure 2. Chemical structures of N-fatty acid amino acid amide PSOGs 1–4.](https://dx.doi.org/10.1021/acsomega.0c01821)
amide (3b) suffered from solubility issues. At 5% w/v, it was not possible to solubilize 3b in decane even with the application of heat. After solubilization with heating at 2.5%/w/v, 3b precipitated from solution upon cooling to room temperature. These results demonstrate that the nature of the α-amino acid R group substituent affects the solubility and gelling behavior of the LMOG.

For this series of compounds, the most striking results for the impact of substituting a primary amide for the carboxylic acid moiety were observed for the phenylalanine analogue (4b). The carboxylic acid version of this compound (4a) did not gel at 5% w/v; however, the primary amide analogue (4b) had a MGC of 0.16% w/v. This is more than a 30-times improvement in the MGC value of all the compounds tested. The efficiency of trapping solvent molecules per molecule of a gelator is critical for successful SAFiN formation.

We also investigated the influence of the enantiopurity of the gelators on the MGC, by preparing the d and d/L analogues of 1b. Both enantiomers 1b (l) and 1c (n) had the same MGC values (measured as 0.18 and 0.19% w/v, respectively). The racemate (1d), however, performed appreciably poorer with a MGC of 2.5% w/v. This result highlighted that the use of optically pure compounds is essential for lowering the MGC.

In this study, we found that compound 4b had the lowest MGC value of all the compounds tested. The efficiency of 4b as a gelator became even more pronounced when its gelation number,\(^{30}\) was compared to that of the alanine analogue (1b). The gelation number is defined as the molar ratio of an entrapped solvent to a gelator, that is, the maximum number of solvent molecules trapped per molecule of a gelator.\(^{32}\) Compound 4b immobilized 1100 molecules of solvent per molecule of the gelator, which is 30% more efficient than 770 molecules trapped by 1b.

**Thermal and Mechanical Properties of the Organogels.** The gelation study identified that the primary amide-based compounds were more efficient gelators than the carboxylic acid variants. To investigate how this chemical modification influenced the thermal and mechanical properties of the gels, they were studied by DSC and rheology measurements. For these studies, we focused on C12-L-ala-COONH\(_2\) (1b) because it is the direct analogue of the parent compound 1a first reported by Bhattacharya.\(^{18}\)

The decane gels of 1a and 1b were prepared at a concentration of 5% w/v for DSC measurements. This study revealed that the amide version was ca. 30 °C more thermally stable than the acid analogue (Table S1). Furthermore, the gels are thermoreversible; melting and reformation of the gel by heating and cooling cycles can be repeated multiple times without any observable deterioration in the thermal properties.

The rheological properties of the organogels were investigated using frequency and amplitude sweeps at 25 °C. Figure 3 shows the frequency sweep for decane gels of 1a (5.0% w/v) and 1b (2.5% w/v). The storage modulus, \(G'\), was greater than the loss modulus, \(G''\), over all frequencies tested, characteristic of a gel.\(^{6}\) The complex modulus of 1b (~94 kPa) was five times higher than that of 1a (~17 kPa), at a frequency of 1 Hz, and formed a more robust gel compared to 1a at a lower concentration (2.5 vs 5% w/v).

Yield stress is defined as the minimum stress at which irreversible deformation occurs. This can be determined by plotting \(G'\) and \(G''\) against the oscillation stress and recording the onset values of each plot (Figure S2). At a fixed frequency of 1 Hz, a yield stress of 24 ± 7 Pa was obtained for the decane gel of 1a (5.0% w/v), while the yield stress of 1b (5.0% w/v) was nearly twenty times higher at 600 ± 50 Pa at the same concentration. Once again, the amide analogue 1b exhibited superior properties to the acid analogue 1a.

**Organogel Morphology.** In an attempt to understand the difference in MGCs observed for the acid and amide analogues, we used SEM to probe the microstructure of the organogels of 1a, 1b, 1d, 4a, and 4b (Figure 4). Samples were prepared by air drying the organogel (at 0.5–10% w/v depending on the gelator) to the corresponding xerogel on aluminum sample holder stubs for imaging.

SEM images of the xerogels of 1a and 1b both showed the presence of a dense network of fibers (Figure 4a,b) with fiber dimensions of over 100 μm in length and 100–400 nm in diameter. There was no discernible difference in the SAFiN structures that could account for the order of magnitude difference in the MGC values between 1a and 1b.

While the SEM of the enantiopure 1b xerogel revealed a fibrous network (Figure 4b), the SEM of racemate analogue 1d showed the presence of crystalline sheets (Figure 4c). These sheets may not be as effective in trapping solvent molecules compared to the entangled fibrous network, and thus, resulted in 1d having a higher MGC of 2.5% w/v compared to 0.18% w/v for 1b. This result demonstrates how the enantiopurity of the gelator is critical for successful SAFiN formation.

In the case of the phenylalanine-based compounds, 4a and 4b, the acid to amide substitution resulted in a noticeable
difference in fiber morphology (Figure 4d,e). Acid 4a formed short needle-like structures (ca. 10−20 μm in length), while amide 4b formed long fibers (>100 μm in length). For this pair of compounds, the distinctive change in the morphology may account for the observed differences in MGC for 4a (>5% w/v) and 4b (0.16% w/v) in decane. The shorter needle-like structures in the decane gel of 4a likely form a weak SAFiN structure because of their limited ability to entangle, whereas the longer fibers in 4b are more likely to form an entangled fibrous network and immobilize more solvent.

To confirm that the SEM samples were representative of the structure present in the solvated state,33 we also obtained confocal laser scanning microscopy (CLSM) images of the organogel of 1b. In order to visualize the decane gel using this technique, we doped the system with Nile Red, a fluorescent dye that has been used to study lipids and other hydrophobic structures in cellular systems.34,35 The CLSM images revealed a fibrous network similar to what was observed in the SEM images (Figure 4f and Video S1). However, unlike the SEM images, the fibers in the unperturbed decane gel are loosely packed with high void volumes that are occupied by the solvent. The samples prepared for SEM show a collapsed structure after solvent evaporation.

There are few reports in the literature on the ability to visualize SAFiNs in an organogel via the interaction of a dye with the gelator assembly.36 While this method has been used to study supramolecular fiber structures in hydrogels,37,38 visualization of SAFiNs in organogels has typically relied upon the fluorescence of the gelator.39,40 This technique by which a nonfluorescent SAFiN is illuminated using a dye may prove useful for the study of other organogel systems.

**Intermolecular Bonding in the SAFiNs.** From the SEM and CLSM data, we know that both compounds 1a and 1b are able to form SAFiNs, which enables them to form organogels. However, the MGCs of the two compounds are an order of magnitude apart. To explore the origin of this phenomenon, we tried to determine the difference in the intermolecular bonding of the two compounds using FT-IR spectroscopy and SCXRD.

We recorded the FT-IR spectra of 1a and 1b in solution (in dimethyl sulfoxide) and their corresponding decane gels. When comparing the two spectra, we focused on the carbonyl stretch peaks as these can provide information on the extent of hydrogen bonding. For both sets of spectra (Figures S3 and S4), we observed a shift in the carbonyl stretching frequencies to lower wavenumbers in the decane gelled state. This shift is indicative of participation of the carbonyl groups in hydrogen bonding (Figure 4d,e). Acid 4a formed short needle-like structures (ca. 10−20 μm in length), while amide 4b formed long fibers (>100 μm in length). For this pair of compounds, the distinctive change in the morphology may account for the observed differences in MGC for 4a (>5% w/v) and 4b (0.16% w/v) in decane. The shorter needle-like structures in the decane gel of 4a likely form a weak SAFiN structure because of their limited ability to entangle, whereas the longer fibers in 4b are more likely to form an entangled fibrous network and immobilize more solvent.

To confirm that the SEM samples were representative of the structure present in the solvated state,33 we also obtained confocal laser scanning microscopy (CLSM) images of the organogel of 1b. In order to visualize the decane gel using this technique, we doped the system with Nile Red, a fluorescent dye that has been used to study lipids and other hydrophobic structures in cellular systems.34,35 The CLSM images revealed a fibrous network similar to what was observed in the SEM images (Figure 4f and Video S1). However, unlike the SEM images, the fibers in the unperturbed decane gel are loosely packed with high void volumes that are occupied by the solvent. The samples prepared for SEM show a collapsed structure after solvent evaporation.

There are few reports in the literature on the ability to visualize SAFiNs in an organogel via the interaction of a dye with the gelator assembly.36 While this method has been used to study supramolecular fiber structures in hydrogels,37,38 visualization of SAFiNs in organogels has typically relied upon the fluorescence of the gelator.39,40 This technique by which a nonfluorescent SAFiN is illuminated using a dye may prove useful for the study of other organogel systems.

**Intermolecular Bonding in the SAFiNs.** From the SEM and CLSM data, we know that both compounds 1a and 1b are able to form SAFiNs, which enables them to form organogels. However, the MGCs of the two compounds are an order of magnitude apart. To explore the origin of this phenomenon, we tried to determine the difference in the intermolecular bonding of the two compounds using FT-IR spectroscopy and SCXRD.

We recorded the FT-IR spectra of 1a and 1b in solution (in dimethyl sulfoxide) and their corresponding decane gels. When comparing the two spectra, we focused on the carbonyl stretch peaks as these can provide information on the extent of hydrogen bonding. For both sets of spectra (Figures S3 and S4), we observed a shift in the carbonyl stretching frequencies to lower wavenumbers in the decane gelled state. This shift is indicative of participation of the carbonyl groups in hydrogen bonding (Figure 4d,e). Acid 4a formed short needle-like structures (ca. 10−20 μm in length), while amide 4b formed long fibers (>100 μm in length). For this pair of compounds, the distinctive change in the morphology may account for the observed differences in MGC for 4a (>5% w/v) and 4b (0.16% w/v) in decane. The shorter needle-like structures in the decane gel of 4a likely form a weak SAFiN structure because of their limited ability to entangle, whereas the longer fibers in 4b are more likely to form an entangled fibrous network and immobilize more solvent.

To confirm that the SEM samples were representative of the structure present in the solvated state,33 we also obtained confocal laser scanning microscopy (CLSM) images of the organogel of 1b. In order to visualize the decane gel using this technique, we doped the system with Nile Red, a fluorescent dye that has been used to study lipids and other hydrophobic structures in cellular systems.34,35 The CLSM images revealed a fibrous network similar to what was observed in the SEM images (Figure 4f and Video S1). However, unlike the SEM images, the fibers in the unperturbed decane gel are loosely packed with high void volumes that are occupied by the solvent. The samples prepared for SEM show a collapsed structure after solvent evaporation.
bonding and has been seen in other alanine-based organogel systems. The FT-IR spectra confirmed that both the primary and secondary amide are involved in hydrogen bonding, and that the primary amide functionality in 1b means that it can form one additional hydrogen-bonding interaction in the gel state, when compared to 1a (Figure S5). This may be the origin of the difference in the gelling behavior of the acid and amide analogues, but this needs to be explored further.

We used SCXRD to explore the difference in crystal packing between acid and amide analogues and provide insights into the observed differences in gelling ability. We tried to grow single crystals of all pairs of compounds (acid and amide) but were only successful in producing crystals of the phenylalanine analogues, 4a (acid) and 4b (amide).

Compound 4a has two hydrogen bonding motifs. One motif is a chain that extends along the crystallographic axis c, where the hydrogen bond is between the NH group and the carbonyl group of the carboxylic acid (Figure 5a). This motif can be described with the primary graph set notation C(S), where C = chain and S = number of bonds in the pattern (or degree of the pattern). A second chain (Figure 5b) extends along the crystallographic axis a and can be described by the graph set notation C(7). The hydrogen bonding for this chain is between the −OH group and the amide carbonyl. The combination of the two hydrogen bonding motifs generates a ring (Figure 5c) with second level graph set R2(20), where R = ring, 4 is the number of hydrogen bond donors and acceptors, and 20 is the number of bonds in the ring.

Compound 4b has two hydrogen-bonding motifs generated by the combination of two hydrogen bond acceptors (carbonyl functionalities) and three donors (NH2 and NH groups). One motif is a ring described by the primary graph set notation R3(8), where R = ring, 8 = number of bonds in the pattern, 2 = number of acceptors, and 3 = number of donors. Three hydrogen bonds between two NH2 groups and two carbonyl groups are present in the ring. Two hydrogen atoms in a NH3 group are involved in two hydrogen bonds, and only one hydrogen atom in another NH3 group is involved in the third hydrogen bond. Ring R3(8) combines with the hydrogen bond between the amide NH donor and the amide carbonyl, generating a bigger ring R2(12), with 12 bonds in the pattern, two acceptors and two donors (Figure 5d). Packing along the crystallographic b and c axes is shown in Figures S6 and S7, respectively.

It is also worth noting that in the crystal structures of both 4a and 4b, the slippage between the phenyl rings, at 4.02 and 3.89 Å, respectively, is too big to state that there is a π−π stacking interaction (see Supporting Information page S27 for more details). This does not mean that π−π stacking interactions are not present in the gel form, but we do not have any specific evidence to support that. Although the crystal packing may not be representative of the gel structure, the information from the SCXRD does offer insight into how the molecules can interact with each other. The ability of 4b to form more hydrogen bonds than the acid analogue 4a may account for the lower MGC, more robust rheological properties, and higher thermal stability of the gel.

**Broad Spectrum Gelling Abilities.** The effect of the primary amide substitution on the range of solvents that could be gelled was evaluated using compounds 1a and 1b. In Table 2, fifteen solvents with different polarities, ranging from nonpolar hydrocarbons to polar alcohols, were selected and evaluated for organogel formation with the gelators 1a and 1b. It was found that the carboxylic acid analogue, 1a, could only form a gel in hexanes at 2.5% w/v. Conversely, the amide analogue, 1b, could effectively gel a diverse range of solvents at 2.5% w/v, including alkanes (both straight-chain and cyclic), chloroform, aromatic solvents, and even polar aprotic solvents such as acetonitrile and tetrahydrofuran (THF). In alcohols, however, the gelators precipitated from solution as dense aggregates upon cooling and no gels were formed, as the polar protic solvents disrupt the intermolecular hydrogen bonding of 1b (Figure S8). Gelator 1b was particularly effective at gelling alkanes and food oils, as well as diesel and dibit, making it a good candidate for oil spill remediation. This is because of the high solubility of the dodecyl aliphatic chain of 1b in these solvents, coupled with the fact that intermolecular hydrogen bonding between the alanine amide groups is promoted in these solvents, which is critical for SAFiN formation and hence successful gelation.

**Deployment Method for Phase-Selective Organogelators.** Because the heating-cooling method we have used to assess the gelators is not feasible to use in a real open-water oil spill, we tried to develop a suitable deployment method for gelator 1b. Gelator 1b could be dissolved in isopropanol and the resulting formulation efficiently gelled decane, diesel, and dibit (dilute bitumen, i.e., crude oil) at 1.25% w/v (Figure S9). However, this delivery method still required a significant amount of organic solvent, so we investigated using water as the delivery solvent. We found that heating a 0.5% w/v suspension of 1b in water gave a homogeneous solution that, when cooled, yielded a fibrous network that spanned the entire volume of the suspension (Figure 6a). When the same protocol was used on gelator 1a, instead of forming a stable aqueous network, 1a dissolved in hot water and yielded dense ribbons suspended in the water upon cooling (Figure 6a). When dibit was added to the water suspensions of 1a and 1b, 1b successfully formed the organogel, while 1a failed to immobilize any of the dibit (Figure 6b,c). This control experiment indicated that the primary amide functionality is critical to the unique water solubility of 1b. The aqueous network of 1b was found to form stable oil gels at 1.25, 1.25, and 2.5% w/v for diesel, decane, and dibit, respectively.

### Table 2. Range of Solvents Gelled by 1a and 1b

| Solvent | 1a Concentration (%) | 1b Concentration (%) |
|---------|----------------------|----------------------|
| Hexane  | G NG NG NG            | G NG NG NG           |
| n-Octane| NG G G G             | NG G G G             |
| n-Nonane| NG G G G             | NG G G G             |
| Cyclohexane| NG G G G | NG G G G         |
| Chloroform| NG G NG             | NG G NG             |
| Benzene | NG G G             | NG G G             |
| Toluene | NG G G NG           | NG G G G           |
| Acetonitrile | NG G G G   | NG G G G         |
| THF     | NG G G             | NG G G             |
| Methanol| NG NG             | NG NG             |
| Sunflower oil | NG G G G   | NG G G G         |
| Diesel  | NG G G             | NG G G             |
| Canola oil | NG G G G   | NG G G G         |
| Dibit   | NG G G             | NG G G             |

*G: gel formation, NG: no gel formation.*
corresponding decane gel (Figure 7a,c,e). For the aqueous to probe the morphology of the aqueous network and the molecular level, we used SEM, optical microscopy, and CLSM to explain the self-assembly phenomenon of 1b fi packed network, optical microscopy and CLSM revealed long, loosely-packed fibers in the decane gel (Figure 4b). While it is still hard to explain the self-assembly phenomenon of 1b in water at a molecular level, we used SEM, optical microscopy, and CLSM to probe the morphology of the aqueous network and the corresponding decane gel (Figure 7a,c,e). For the aqueous network, optical microscopy and CLSM revealed long, loosely-packed fibers, while the SEM image of the xerogel showed more densely packed fibers. These data confirmed that the self-assembly process of 1b still occurs in the presence of water, but qualitatively the fibers appear to be thicker (Figure 7a) than the fibers in the decane gel (Figure 4b).

When decane is added to the aqueous network, the network visibly shrinks and a gel is obtained. When the resulting gel was imaged using SEM, optical microscopy, and CLSM (Figure 7b,d,f and Video S2), a densely packed fibrous network was revealed and SEM images showed ribbon-like structures that are microns thick. The morphology of this decane gel is significantly different to the decane gel obtained through the heating and cooling method, which we attribute to the reduced solubility of 1b in water. This leads to a kinetically trapped structure for the SAFiN network instead of the more thermodynamic structure from the heating-cooling method. When oils come into contact with the network, it behaves like an oleophilic sponge; the water that is initially present is displaced with oil molecules and the network contracts (Video S3). The ability of 1b to form SAFiNs in both organic and aqueous phases makes it an exciting candidate for oil spill remediation.

Recoverability and Recyclability. Having developed a water-based delivery system for 1b, we next focused on the recovery and recyclability of the organogel. Although the decane gel resulting from the aqueous network delivery method was found to be notably weaker than the decane gel yielded from the heating-cooling method, its storage modulus, $G'$ ($\sim$1300 Pa), was still greater than its loss modulus, $G''$ ($\sim$400 Pa), in the linear viscoelastic region of amplitude sweeps (Figure S10). Compared to some common viscoelastic materials, the $G'$ of the decane gel of 1b obtained from the aqueous network delivery was found to be between that of typical toothpaste ($G' \sim$ 150 Pa) and that of peanut butter ($G' \sim$ 4000 Pa) (Figure S10). This moderate viscoelasticity allows us to harvest the decane gel of 1b with a nylon screen filter. We then used two different methods to recover the oil from the harvested gel: distillation and filtration. While 48% of decane was recovered by distillation (Figure S11), 79% of the decane was recovered by filtration with a syringe filter (Figure S12). Moreover, the 1H NMR spectrum of the gelator residue left from the distillation showed no obvious chemical decomposition, suggesting a high possibility to recycle these gelators after oil gelation (Figure S13).

Conclusions

In summary, the substitution of an acid group with a primary amide in a PSOG brought a series of improvements in its gelation in a broad range of solvents and the properties of the resulting gels. More importantly, the primary amide function-
alility allowed gelator 1b to be soluble in hot water and self-assemble into an aqueous network upon cooling. The resulting network can subsequendy absorb and immobilize oils including diesel, decane, and dilbit at 1.25, 1.25 and 2.5% w/v, respectively. The oleophilic nature of an aqueous network can subsequently absorb and immobilize oils assemble into an aqueous network upon cooling. The resulting gelator self-assembles in the presence of water. Oil spill applications aiming to enhance the gelation efficiency allowed gelator 1b to be soluble in hot water and self-assemble into an aqueous network upon cooling. The resulting network can subsequently absorb and immobilize oils including diesel, decane, and dilbit at 1.25, 1.25 and 2.5% w/v, respectively. The oleophilic nature of an aqueous network may open the door to new strategies for oil spill remediation. In future work, we plan to study the structure–activity relationship of this new class of primary amide gelators toward oil spill applications aiming to enhance the gelation efficiency as well as the detailed mechanistic insights of how such an amphiphile self-assembles in the presence of water.

**ASSOCIATED CONTENT**

1. **Supporting Information**
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c01821.

Experimental details, synthetic procedures, images comparing MGC evaluation methods, DSC data for decane gels of 1a and 1b, rheology data for decane gels of 1a and 1b, FT-IR spectra of decane gel of 1a and 1b, crystal packing data for 4b, and HR(MS) and 1H and 13C NMR for all reported compounds and SCXRD data. CCDC 1959468 and CCDC 19195969 (PDF) CLSM Z-stack of the decane gel of 1b (MP4) CLSM Z-stack of the aqueous network of 1b (MP4) Addition of oil blue-dyed decane (1 mL, 2.0% w/v) to the aqueous network of 1b (MP4) Crystal structure of 4a (CCDC 1959468) (CIF) Crystal structure of 4b (CCDC 1959469) (CIF)

**AUTHOR INFORMATION**

**Corresponding Authors**

Mark J. MacLachlan – Department of Chemistry, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada; orcid.org/0000-0002-3546-7132; Email: mmaclach@chem.ubc.ca

Gabriel Hum – BC Research Inc., Richmond BC V6V 1M8, Canada; Email: gabrielhum@gmail.com

**Authors**

Jun Chen – BC Research Inc., Richmond BC V6V 1M8, Canada

Charlotte E. Boott – Department of Chemistry, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

Lev Lewis – Department of Chemistry, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

Andrew Siu – BC Research Inc., Richmond BC V6V 1M8, Canada

Renad Al-Debasi – BC Research Inc., Richmond BC V6V 1M8, Canada

Veronica Carta – Department of Chemistry, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

Amanda A. Fogh – BC Research Inc., Richmond BC V6V 1M8, Canada

Daniel Z. Kurek – BC Research Inc., Richmond BC V6V 1M8, Canada

Lilo Wang – BC Research Inc., Richmond BC V6V 1M8, Canada

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c01821

**Author Contributions**

J.C., A.S., and R.A. synthesized the compounds. J.C., A.S., and D.K. performed the M.G.C. experiments. C.B. and L.L. characterized the compounds (HR-MS, EA, melting points) and gel morphology (SEM, IR, SCXRD). Rheology was performed by J.C., A.S., and A.A.F. DSC was done by A.A.F. and L.W. SCXRD was performed by V.C. CLSM was done by J.C. Biphasing activity tests and recovery studies were performed by J.C. and C.B. The manuscript was written by J.C., C.B., L.L., M.M., and G.H. with input from V.C. The project was supervised by M.M. and G.H.

**Notes**

The authors declare no competing financial interest. The technology described here was submitted for a patent application: PCT/CA2019/050785.

**ACKNOWLEDGMENTS**

This work was supported by Natural Resources Canada (NRCan) through the Oil Spill Response Science (OSRS) program and the Natural Sciences and Engineering Research Council (NSERC) of Canada (CREATE NanoMat grant; Discovery grant). C.E.B. thanks Banting Postdoctoral Fellowships and Killam Postdoctoral Fellowships for funding. L.L. thanks the University of British Columbia for financial support (4VF).

**REFERENCES**

(1) Draper, E. R.; Adams, D. J. Low-Molecular-Weight Gels: The State of the Art. Chem. Soc. Rev. 2015, 115, 13165–13170.

(2) Skilling, K. J.; Citossi, F.; Bradshaw, T. D.; Ashford, M.; Kellam, B.; Marlow, M. Insights into Low Molecular Mass Organic Gelators: A Focus on Drug Delivery and Tissue Engineering Applications. Soft Matter 2014, 10, 237–256.

(3) Du, X.; Zhou, J.; Shi, J.; Xu, B. Supramolecular Hydrogelators and Hydrogels: From Soft Matter to Molecular Biomaterials. Chem. Soc. Rev. 2015, 115, 13165–13170.

(4) Okesola, B. O.; Smith, D. K. Applying Low-Molecular Weight Supramolecular Gelators in an Environmental Setting – Self-Assembled Gels as Smart Materials for Pollutant Removal. Chem. Soc. Rev. 2016, 45, 4226–4251.

(5) van Esch, J. H. Can Design Molecular Gelators, But Do We Understand Them? Langmuir 2009, 25, 8392–8394.

(6) Weiss, R. G. The Past, Present, and Future of Molecular Gels. What Is the Status of the Field, and Where Is It Going? J. Am. Chem. Soc. 2014, 136, 7519–7530.

(7) Awhida, S.; Draper, E. R.; Mcdonald, T. O.; Adams, D. J. Probing Gelation Ability for a Library of Dipeptide Gelators. J. Colloid Interface Sci. 2015, 455, 24–31.

(8) Ren, C.; Chen, F.; Zhou, F.; Shen, J.; Su, H.; Zeng, H. Low-Cost Phase-Selective Organogelator for Rapid Gelation of Crude Oil at Room Temperature. Langmuir 2016, 32, 13510–13516.

(9) Ren, C.; Ng, G. H. B.; Wu, H.; Chan, K-H.; Shen, J.; Teh, C.; Ying, J. Y.; Zeng, H. Instant Room-Temperature Gelation of Crude Oil by Chiral Organogelators. Chem. Mater. 2016, 28, 4001–4008.

(10) Ohseda, Y. Low-Molecular-Weight Organogelators as Functional Materials for Oil Spill Remediation. Polym. Adv. Technol. 2016, 27, 704–711.

(11) Motta, F. L.; Stoyanov, S. R.; Soares, J. B. P. Application of Solidifiers for Oil Spill Containment: A Review. Chemosphere 2018, 194, 837–846.

(12) Prathap, A.; Sureshan, K. M. A Mannitol Based Phase Selective Supergelator Offers a Simple, Viable and Greener Method to Combat Marine Oil Spills. Chem. Commun. 2012, 48, 5250–5252.

(13) Vibhute, A. M.; Muvvala, V.; Sureshan, K. M. A Sugar-Based Gelator for Marine Oil-Spill Recovery. Angew. Chem., Int. Ed. 2016, 55, 7782–7785.
(14) Sakamoto, K. Development Of Gelling Agent For Spilled Oils. In Oil Spill Remediation: Colloid Chemistry-Based Principles and Solutions; Somasundaran, P., Patra, P., Farinato, R. S., Papdopoulos, K., Eds.; John Wiley & Sons, 2014; pp 231−245.

(15) USEPA, Water quality office. Gelling Crude Oils to Reduce Marine Pollution from Tanker Oil Spills; Water Pollution Control Research Series; U.S. government printing office, Washington D.C. 20402, 15080DJN 1/71, 1971.

(16) Saito, T.; Matsuzawa, Y.; Ninagawa, S.; Honna, M.; Takesada, M.; Takehara, M. U.S. Patent 3,969,087 A, 1976.

(17) Kobayashi, T.; Kawashima, Y.; Yoshimura, M.; Sugiuara, M.; Nobe, T.; Fujimoto, S. U.S. Patent 4,502,975 A, 1985.

(18) Bhattacharya, S.; Krishnan-Ghosh, Y. First Report of Phase Selective Gelation of Oil from Oil/Water Mixtures. Possible Implications toward Containing Oil Spills. Chem. Commun. 2001, 185−186.

(19) Oda, R. Safin Gels with Amphiphilic Molecules. In Molecular Gels: Materials with Self-Assembled Fibrillar Networks; Weiss, R. G., Terech, P., Eds.; Springer Netherlands, 2006; pp 577−609.

(20) Dastidar, P. Supramolecular Gelling Agents: Can They Be Designed? Chem. Soc. Rev. 2008, 37, 2699−2715.

(21) Datta, S.; Bhattacharya, S. Multifarious Facets of Sugar-Derived Molecular Gels: Molecular Features, Mechanisms of Self-Assembly and Emerging Applications. Chem. Soc. Rev. 2015, 44, 5596−5637.

(22) Lombardo, D.; Kiselev, M. A.; Magazu, S.; Calandra, P. Amphiphiles Self-Assembly: Basic Concepts and Future Perspectives of Supramolecular Approaches. Adv. Condens. Matter Phys. 2015, 1, 1−22.

(23) Abdellatif, M. M.; Ibrahim, S.; Nomura, K. Efficient and Eco-Friendly Low-Molecular-Weight Gelators Based on L-Phenylalanine as Promising Remediation Tool for Oil Pollution. J. King Saud Univ. Sci. 2020, 32, 946−951.

(24) Li, J.; Huo, Y.; Zeng, H. Combinatorial Identification of a Highly Soluble Phase-Selective Organogelator with High Gelling Capacity for Crude Oil Gelation. J. Mater. Chem. A 2018, 6, 10196−10200.

(25) Zhang, B.; Chen, S.; Luo, H.; Zhang, B.; Wang, F.; Song, J. Porous Amorphous Powder Form Phase-Selective Organogelator for Rapid Recovery of Leaked Aromatics and Spilled Oils. J. Hazard. Mater. 2020, 384, 121460.

(26) Datta, S.; Samanta, S.; Chaudhuri, D. Near Instantaneous Gelation of Crude Oil Using Naphthalene Diimide Based Powder Gelator. J. Mater. Chem. A 2018, 6, 2922−2926.

(27) Ren, C.; Shen, J.; Chen, F.; Zeng, H. Rapid Room-Temperature Gelation of Crude Oils by a Wetted Powder Gelator. Angew. Chem., Int. Ed. 2017, 56, 3847−3851.

(28) Pathak, N. P.; Rajkamal; Yadav, S. A Gelator−Starch Blend for Dry Powder Based Instant Solidification of Crude Oil at Room Temperature. Chem. Commun. 2020, 56, 2999.

(29) Prathap, A.; Sureshan, K. M. Organogelator-Cellulose Composite for Practical and Eco-Friendly Marine Oil-Spill Recovery. Angew. Chem., Int. Ed. 2017, 56, 9405−9409.

(30) Pal, A.; Ghosh, Y. K.; Bhattacharya, S. Molecular Mechanism of Physical Gelation of Hydrocarbons by Fatty Acid Amides of Natural Amino Acids. Tetrahedron 2007, 63, 7334−7348.

(31) Pal, A.; Patra, T.; Dey, J. Physical Gelation of Organic Liquids by Achiral Amino Acid Based Amphiphilic Gelators: Effect of Chirality. Chem. Phys. Lett. 2013, 556, 245−250.

(32) Pal, A.; Dey, J. Water-Induced Physical Gelation of Organic Solvents by N- ( n-Alkylcarbamoyl ) - L-Alanine Amphiphiles. Langmuir 2011, 27, 3401−3408.

(33) Adams, D. Does Drying Affect Gel Networks? Gels 2018, 4, 32.

(34) Greenspan, P.; Mayer, E. P.; Fowler, S. D. Nile Red: A Selective Fluorescent Stain for Intracellular Lipid Droplets. J. Cell Biol. 1985, 100, 965−973.

(35) Prifti, E.; Reymond, L.; Umeyabashi, M.; Hovius, R.; Riezman, H.; Johnsson, K. A Fluorescent Probe for SNAP-Tagged Plasma Membrane Proteins Based on the Solvatochromic Molecule Nile Red. ACS Chem. Biol. 2014, 9, 606−612.

(36) D’Aleo, A.; Guerzo, A. D.; Fages. Confocal Laser Scanning Microscopy: A Versatile Spectroscopic Tool for the Investigation of Molecular Gels. In Analytical Methods in Supramolecular Chemistry; Schalley, C. A., Ed.; Wiley-VCH Verlag GmbH & Co. KGaA, 2012; pp 607−627.

(37) Kyonaka, S.; Sada, K.; Yoshimura, I.; Shinkai, S.; Kato, N.; Hamachi, I. Semi-Wet Peptide/Protein Array Using Supramolecular Hydrogel. Nat. Mater. 2004, 3, 58−64.

(38) Onogi, S.; Shigemitsu, H.; Yoshii, T.; Tanida, T.; Ikeda, M.; Kubota, R.; Hamachi, I. In Situ Real-Time Imaging of Self-Sorted Supramolecular Nanofibres. Nat. Chem. 2016, 8, 743−752.

(39) Giansante, C.; Raffy, G.; Schäfer, C.; Rahma, H.; Kao, M.-T.; Olive, A. G. L.; Del Guerzo, A. White-Light-Emitting Self-Assembled NanoFibers and Their Evidence by Microspectroscopy of Individual Objects. J. Am. Chem. Soc. 2011, 133, 316−325.

(40) Chen, J.-Y.; Komely-Nia, Z.; Fan, L.-P.; Li, Z.-Y.; Yuan, B.; Tang, B.; Li, J.-L. Manipulating the Fractal Fiber Network of a Molecular Gel with Surfactants. J. Colloid Interface Sci. 2018, 526, 356−365.

(41) Luo, X.; Liu, B.; Liang, Y. Self-Assembled Organogels Formed by Mono-Chain. Chem. Commun. 2001, 1556−1557.