Use of a bis-1,2,3-triazole gelator for the preparation of supramolecular metallogels and stabilization of gold nanoparticles†

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In this work we have applied a double isosteric substitution of the amide groups presented in the gelator *N,N'*-((1*S*,2*S*)-cyclohexane-1,2-diyl)didecanamide (**C₁₂-Cyc**) by 1,2,3-triazole rings affording the corresponding isosteric gelator (**click-C₁₂-Cyc**). This approach enabled the preparation of different metallogels and fine-tuning their properties. In particular, **C₁₂-Cyc** was found to form stable and reversible metallogels with Pd^{II} and Au^{III} in DMSO and DMF, whereas **click-C₁₂-Cyc** formed metallogels in these solvents only in the presence of Au^{III}. Comparing the gels made of **C₁₂-Cyc** vs **click-C₁₂-Cyc** in the presence of HAuCl₄·3H₂O, the former showed higher *T_{gel}* values and 5–8 times slower gelation kinetics. Furthermore, the incorporation of Et₃N as reducing agent in the formulations facilitated the *in situ* formation of non-aggregated gold nanoparticles embedded in the viscoelastic networks made of either pure isosteres or with an equimolar mixture of **click-C₁₂-Cyc** and **C₁₂-Cyc**. So-formed NPs showed similar size distribution regardless the gold concentration and the nature of the gelator system.

Introduction

Gels have received increasing attention during the last decades^{1,2,3} due to their hierarchical molecular architectures and potential applications in various fields^{4,5} including the preparation of sensors,⁶ liquid crystals,⁷ conductive scaffolds,^{8,9} templates for cell growth¹⁰ and inorganic structures,¹¹ catalysis,^{12,13} cosmetics¹⁴ and food industries.¹⁵ Chemical gels are formed by covalent bonds,¹⁶ while physical (or supramolecular) gels^{17,18,19} are usually formed by self-assembly of low-molecular-weight (LMW) molecules into 1D nanofibers that undergo further entanglement affording a 3D scaffold. The immobilization of solvent molecules (major component) into the interstices of the 3D network via capillary forces and surface tension can increase the viscosity of the medium by factors up to 10¹⁰ and confers the solid-like appearance to the gels. Due to the non-covalent nature of the interactions (*e.g.* hydrogen-bonding, π -stacking, van der Waals), most physical organic gels display reversible *gel-to-sol* transitions that can be triggered by a variety of external stimuli (*e.g.* temperature, pH, light, ionic strength).^{20,21,22} Another important subgroup of gels are metallogels, where the main driving force for their formation is the metal-ligand coordination. Thus, the metallogels differ mainly in the metal ion used, which directly influences their functions, redox, optic, magnetic and

electronic properties.^{23,24,25,26,27}

In terms of strategies for fine-tuning the properties of physical gels, our group reported a few years ago for the first time the isosteric replacement²⁸ of amides by 1,2,3-triazole groups in LMW gelators.²⁹ In general, isosteres possess practically equal molecular shape and volume, as well as similar electronic distribution and physical properties.³⁰ As a practical concept, isosteric substitution has a long and successful history in medicinal chemistry for drug development,³¹ but it is still in its infancy in materials synthesis. In our previous work, we replaced an amide group by a 1,2,3-triazole in a glutamic acid-derived LMW gelator, where both the amide and the carboxylic acid groups played a key role on the self-assembly process via hydrogen bonds.^{29,32} Very recently, we reported the study of a more challenged scenario where 1,2,3-triazole rings replaces all the hydrogen bond centers in a LMW gelator without sacrificing its gelation capacity.³³ In particular, we carried out a double isosteric replacement of both amide groups in a known LMW gelator **C₁₂-Cyc** (*i.e.* *N,N'*-((1*S*,2*S*)-cyclohexane-1,2-diyl)didecanamide)^{34,35,36,37,38} by 1,2,3-triazole rings affording the corresponding isostere **click-C₁₂-Cyc** (Figure 1). It should be emphasized that the preservation of the gelation ability upon dual isosteric substitution is not evident because the directional amide groups constitute in this case the source of hydrogen bonds to build the 3D self-assembled network. Satisfactorily, the results of the comparison of both gelators in terms of gelation ability and gel properties demonstrated that 1,2,3-triazoles can take over all the functions derived from the amides groups offering a versatile strategy for fine-tuning the properties of the corresponding physical gels.

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Fig. 1 Isosteric LMW gelators **C₁₂-Cyc** and **click-C₁₂-Cyc** used in this work for the preparation of metallogels.

Herein, we have extended our study to the formation of metallogels and *in situ* preparation of gold nanoparticles embedded in the gel-phase networks formed by **C₁₂-Cyc** and/or **click-C₁₂-Cyc**.

Experimental

Materials

Unless otherwise indicated, all chemicals, reagents and solvents were of analytical grade, purchased from commercial sources (Sigma-Aldrich, TCI Europe, Alfa Aesar) and used as received without further purification. Double-distilled water was purified additionally using a Millipore water-purifying system (Merck) prior usage. Isosteric gelators *N,N'*-((1*S*,2*S*)-cyclohexane-1,2-diyl)didodecanamide (**C₁₂-Cyc**) and (1*S*,2*S*)-1,2-bis(4-decyl-1*H*-1,2,3-triazol-1-yl)cyclohexane (**click-C₁₂-Cyc**) were prepared and characterized as we have previously described.³³

Characterization of metallogels

Critical gelation concentration (CGC) values (defined as the minimum concentrations of compound where gelation is observed) were estimated by continuously adding aliquots of solvent (0.02–0.1 μL) into vials containing the desired mixture of [gelator + metal salt] and performing a typical heating-cooling protocol for gel-formation until no gelation was observed. The starting point for CGC determinations was 120 g L⁻¹ in most of the cases. No further experiments were made if gelation was not achieved at 200 g L⁻¹. Non-gel containing vials (*i.e.* clear solution after 7 days) were frequently left at RT and visually monitored for possible gelation/crystallization over time.

Thermal *gel-to-sol* transition temperature (T_{gel}) values were determined using a custom made set-up where the sealed vial containing 100 μL of the metallogel was placed into a mold of an alumina block and heated up at 1 °C/5 min using an electric heating plate equipped with a temperature control couple (Figure S1). So obtained values were verified by DSC measurement of a model organogel (40 g L⁻¹ **C₁₂-Cyc** in cyclohexane). Herein, the temperature at which the gel started to break was defined as T_{gel} . Gel stability was controlled by taking the vial out of the heating block and turning it upside down to find gravitational flow. Each measurement was made at least by duplicate and the average value reported. T_{gel} values were found almost unaltered within a difference of 1–2 °C after several heating-cooling cycles.

Oscillatory rheology was performed with an AR 2000 Advanced rheometer (TA Instruments) equipped with a Julabo C cooling system. A 1000 μm gap setting and a torque of 5×10^{-4} N/m at 25 °C were used for the measurements in a plain-plate (40 mm, stainless steel). The following experiments were carried out

for each sample, using *ca.* 2 mL total gel volume: a) Dynamic Strain Sweep (DSS): variation of G' (storage modulus) and G'' (loss modulus) with strain (from 0.01 to 100%); b) Dynamic Frequency Sweep (DFS): variation of G' and G'' with frequency (from 0.1 to 10 Hz at 0.1% strain); c) Dynamic Time Sweep (DTS): variation of G' and G'' with time keeping the strain and frequency values constant and within the linear viscoelastic regime as determined by DSS and DFS measurements (strain = 0.1% strain; frequency = 1 Hz).

Fourier transform infrared (FT-IR) spectra were recorded at room temperature using an Excalibur FTS 3000 FT-IR spectrometer (Biorad) equipped with a single reflection ATR (attenuated total reflection) accessory (Golden Gate, Diamond).

X-Ray Diffraction spectroscopy (XRD) was performed on a STOE STADI P powder diffractometer (StartFragment Transmission mode, flat samples, Dectris MYTHEN 1k microstrip solid-state detector) with CuK α radiation operated at 40 kV and 40 mA. Conditions were 0.015°, time 600 s per step, 2 theta range 0–90°.

Field Emission Scanning Electron Microscopy (FESEM, resolution 0.8 nm) images of xerogels were obtained with a Carl Zeiss Merlin, Field Emission Scanning Electron Microscope equipped with a digital camera and operated at an accelerating voltage of 10 kV. For visualization, samples were prepared by the freeze-drying (FD) method: An Eppendorf tube containing the corresponding gel-material (100–200 μL) was frozen in liquid nitrogen or dry ice/acetone and the solvent was immediately evaporated under reduced pressure (0.6 mmHg) for 2 days at RT. The so obtained fibrous solid was placed on top of a tin plate and shielded by Pt (40 mA during 30 s; film thickness $\approx$ 5 nm).

UV-Vis spectra of nanoparticle-containing gels were recorded using an Ocean Optics Flame Miniature Spectrometer equipped with an Ocean Optics DH-2000-BAL light source and an Ocean Optics 1 cm cuvette holder. For measurements using 1 mm quartz glass cuvettes, nanoparticle-containing gels were diluted 1:1 (v/v) or more when noted to minimize light scattering.

General procedure for the preparation of metallogels

A weighed amount of the solid gelator (**C₁₂-Cyc** or **click-C₁₂-Cyc**) was placed into a 2 mL screw-capped vial (4 cm length and 1 cm diameter). Then, the corresponding metal salt was added in its crystalline form. After the addition of the solvent, the vials were closed with the cap and gently heated with a heat-gun until the solid material was completely dissolved. Cooling the mixtures to RT induced the formation of the metallogels. No control over temperature rate during the heating-cooling process was applied. The material was preliminarily classified as “gel” if it did not exhibit gravitational flow upon turning the vial upside-down at RT. The state was further confirmed by rheological measurements. Gelation time was checked by repeatedly moving the gel-containing vial until no gravitational flow was observed anymore.

General procedure for *in situ* formation of Au nanoparticle-containing gels

C₁₂-Cyc, **click-C₁₂-Cyc** or a mixture of both compounds was weighed in a screw-capped vial (4 cm length and 1 cm diameter). After the subsequent addition of solid HAuCl₄·3H₂O, the

corresponding solvent was added using a microliter syringe. Thereafter, Et₃N was added in one portion immediately leading to a color change, which was enhanced as the suspensions were heated and cooled down to RT affording opaque gels with dark red-brown colors as described in the main text.

Photochemical reactions were performed under UV light ($\lambda = 245$ nm; light power = 8 W) using a Rayonet RMR-600 Photochemical reactor at 35 °C (chamber temperature).

Results and discussion

In a recent study, we have reported a comparative study of the gelation ability of the isosteres **C₁₂-Cyc** and **click-C₁₂-Cyc**.³³ Briefly, both gelators are able to form rapidly opaque and thermo-reversible organogels in various non-polar (e.g. cyclohexane, hexane, oils) and polar-protic (e.g. ethylene glycol, methanol, nitromethane) solvents after a heating-cooling cycle. Furthermore, theoretical simulations revealed that **click-C₁₂-Cyc** can adopt a wide variety of interacting patterns, whose relative stability depend on the polarity of the environment, being in agreement with the experimental gelation data.³³

Other important features of **click-C₁₂-Cyc** for potential applications are its non-cytotoxic character and its phase-selective gelation of water-oil mixtures. In addition, triazole ring offers the versatility to bridge several metal centers and obtain unique polynuclear compounds. Thus, in this work we have investigated and compared the formation of metallogels with both isosteres (**C₁₂-Cyc** and **click-C₁₂-Cyc**), as well as the *in situ* formation and stabilization of gold nanoparticles embedded in the gel-phase network.

Formation of metallogels

The formation of metallogels using different transition metals and LMW ligands has a long history in supramolecular chemistry.^{39,40,41,42,43,44} Many of these metallogels have been used as matrices for the *in situ* formation of metal nanoparticles, mainly silver^{45,46,47,48,49} and gold nanoparticles.^{50,51,52,53,54,55,56,57,58,59}

In this study, both **C₁₂-Cyc** and **click-C₁₂-Cyc** yielded precipitates in the absence of metal ions in polar aprotic solvents such DMSO. However, stable opaque metallogels were obtained in these solvents via a heating-cooling cycle upon incorporation of some metals. Materials that did not show gravitational flow upon turning the vial upside-down were initially classified as stable gels. The viscoelastic nature of some selected gels was later confirmed by oscillatory rheological experiments (*vide infra*). Specifically, **C₁₂-Cyc** enabled the formation of metallogels with Pd^{II} and Au^{III} in DMSO and DMF, whereas **click-C₁₂-Cyc** formed metallogels in these solvents only in the presence of Au^{III} (Figure 2). The exact reason for such different behavior remains unclear at the moment. Experiments incorporating Cu^{II}, Co^{II} or Ni^{II} yielded viscous solutions instead of stable gels. At this point, we selected DMF and Au^{III} as model solvent and metal ion to perform additional studies.

Fig. 2 Pictures of metallogels prepared from **C₁₂-Cyc** and **click-C₁₂-Cyc**.
 Left: **C₁₂-Cyc** in DMSO ($c = 24$ mmol L⁻¹), 12 mol% PdCl₂. Middle: **C₁₂-Cyc** in DMF ($c = 41$ mmol L⁻¹), 90 mol% HAuCl₄·3H₂O. Right: **click-C₁₂-Cyc** in DMF ($c = 43$ mmol L⁻¹), 89 mol%.

In order to optimize the gelator:metal molar ratio we investigated the evolution of both T_{gel} and gelation time values with gelator and metal salt concentrations for both **C₁₂-Cyc** and **click-C₁₂-Cyc** in DMF (Figure S2, ESI). In all cases, the gelator concentration was found to have a much higher influence on the gel stability than the concentration of HAuCl₄·3H₂O. At high concentrations (> 40 mmol L⁻¹) of **C₁₂-Cyc**, both T_{gel} and gelation kinetics increased with increasing gold concentrations whereas this influence was less pronounced at lower gelator concentrations (Figure S2, ESI). Regarding **click-C₁₂-Cyc**, T_{gel} increased with the metal concentration at high gelator concentrations, while it decreased at low gelator concentrations (Figure S2, ESI). However, the gelation time was only influenced by the metal concentration at very high amounts of gelator (Figure S2, ESI). Concerning a nearly optimal gelator concentration of 40 mmol L⁻¹, all trends could be considered linear and flat leading to a free variability of the gold concentration without decreasing the gel stability. Comparing the gels made of **C₁₂-Cyc** vs **click-C₁₂-Cyc** in the presence of HAuCl₄·3H₂O, the former showed higher T_{gel} values (62 °C compared to 41 °C in presence of 60 mmol L⁻¹ gelator and 40 mmol L⁻¹ Au) and 5–9 times shorter gelation times (110 s compared to 950 s in presence of 30 mmol L⁻¹ gelator and 40 mmol L⁻¹ Au). Table 1 outlines the CGC, T_{gel} and gelation time values for the gels made of **C₁₂-Cyc** and **click-C₁₂-Cyc** with a 1:1 molar ratio of gelator and gold. It is worth mentioning that the CGC of **C₁₂-Cyc** in DMF in the presence of HAuCl₄·3H₂O was ca. 40 % lower than in the absence of the metal salt (*i.e.* 12 mM = 6 g L⁻¹ vs 10 g L⁻¹, respectively).

Table 1 CGC, T_{gel} and gelation time values of metallogels made of **C₁₂-Cyc** and **click-C₁₂-Cyc** with HAuCl₄·3H₂O (100 mol%). Molar ratio gelator: Au = 1:1.

Gelator	CGC (mmol L ⁻¹)	Gelation time (min)	T_{gel} (°C)
C₁₂-Cyc	12 ± 2	2.5 ± 0.5	37 ± 2
click-C₁₂-Cyc	29 ± 2	13 ± 3	32 ± 1

FT-IR and XRD spectroscopic studies of the metallo-xerogels revealed similar aggregation patterns and the presence of crystalline domains as observed with the metal-free organogels (Figures S3-S4, ESI). As shown in Figure 3, these metallogels also responded to a variety of external stimuli.

The metallogels prepared from both isosteres showed full thermal reversibility and remained stable over at least one month. The addition of NaOH (1 M) led to partial collapse of the

yellowish gels, which became blackish presumably due to the reduction of Au^{III} to Au^0 (Figure 3). Mechanical agitation caused partial dissolution only of the metallogel made of **click-C₁₂-Cyc**. Moreover, the addition of concentrated acetic acid, water, PBS (0.1 M, pH 7.0) and HCl (1 M) led to partial dissolution of both gels, albeit the process was faster in the case of **click-C₁₂-Cyc**. This observation differed from the metal-free experiments, where only acetic acid among these additives showed an impact on the gel stability. The consistence of the gels remained upon addition of solid additives such as FeCl_3 , PdCl_2 and $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$. These salts slowly diffused through the gel network, which could be visually monitored by color change of the bulk gels (Figure 3). The gels remained stable in consistence and visual appearance under sonication and after the addition of other additives such as NaCl and MeOH. Interestingly, UV irradiation ($\lambda = 254 \text{ nm}$) over a period of 6 h caused initial discoloration of the gels. After 30 min the gel made of **click-C₁₂-Cyc** became colorless and was thereafter found to develop a blackish brown appearance with increasing intensity over time (Figure S5, ESI). The same behavior was found for the gel made of **C₁₂-Cyc**, albeit the process was much slower leading to full discoloration after 120 min and a final dark yellow color after 6 h. These observations were in agreement with the generation of gold nanoparticles of different sizes as confirmed later by plasmonic resonances (*vide infra*).⁶⁰ These results suggest that both isosteres display intrinsic and significant reduction potentials.

observed in the case of the metallogel made of **C₁₂-Cyc** upon treatment with NaOH (picture not shown).

In terms of flow properties, dynamic oscillatory rheological experiments (*i.e.* DFS, DSS, DTS) confirmed the viscoelastic nature of selected metallogels and revealed a storage modulus G' higher than the loss modulus G'' . The difference between G' and G'' is much higher in the case of **C₁₂-Cyc** metallogel. Overall, the results showed a higher mechanical strength of the **C₁₂-Cyc** metallogel compared to the **click-C₁₂-Cyc** metallogel, as indicated by higher absolute G' and lower $\tan \delta$ values (Table 2; Figure S6, ESI). However, the yield stress (γ) was higher for the gel made of **click-C₁₂-Cyc** (*i.e.* 2.2 % vs 1.8%). The same trends were in agreement with those observed in the metal-free experiments. The most important effect of the incorporation of the metal into the gels was observed in the damping properties of the material, making the metallogel made of **click-C₁₂-Cyc** less elastic compared to its metal-free version. The opposite behavior was observed in the case of **C₁₂-Cyc**, where the potential to store the load increased upon incorporation of the metal.

Table 2 Rheological data of metallogels made of **C₁₂-Cyc** and **click-C₁₂-Cyc** ($c = 40 \text{ g L}^{-1}$) in DMF incorporating $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ ($c = 40 \text{ g L}^{-1}$).

Gelator	G' (kPa)	G'' (kPa)	$\tan \delta$	γ (%)
C₁₂-Cyc	12	1.4	0.12	1.8
click-C₁₂-Cyc	3.5	1.4	0.4	2.2

Formation of gold nanoparticles-containing gels

Other metallogels have been already used for catalytic purposes¹² as well as for the formation and stabilization of metal nanoparticles (NPs).⁶¹ Within this context, we decided to check also the possibility to generate gold NPs by intragel reduction of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$. First of all, we investigated the solubility properties of the metal salt in various solvents and the stability of bulk gels in the presence of the metal salt (Table S1-S2, ESI). From these preliminary experiments, propan-2-ol, acetone, NMP and DMF yielded stable opaque gels, suggesting their potential use as solvent for metal reduction. A brown appearance of the gel was observed directly in the case of propan-2-ol presumably due to its intrinsic reductive character.⁶²

Although UV irradiation was found to induce metal reduction, the method was slow and less reproducible than using external reducing agents such as NaBH_4 , Et_3N or hydroquinone (Table S3, ESI). These reducing agents showed solubility in DMF both at RT and 80 °C, in contrast to other common reducing agents such as sodium citrate or sodium ascorbate. The metal reduction was investigated using a fixed gelator concentration ($c = 40 \text{ mmol L}^{-1}$), which previously demonstrated to support a consistent gel stability under varying concentrations of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$. Thus, the concentration of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ was varied between 20 and 60 mmol L^{-1} during the experiments. Before the application of a heating-cooling cycle, Et_3N was added to the suspension of gelator and $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ (*i.e.* $[\text{Et}_3\text{N}] = 10 \times [\text{Au}]$). Immediately thereafter, a reddish color was developed in all samples containing the metal salt. Subsequent application of a heating-cooling cycle yielded the formation of stable dark reddish-brown gels as expected due to the formation of the corresponding gold

Fig. 3 Stimuli responsive map of metallogels made of (A) **C₁₂-Cyc** and (B) **click-C₁₂-Cyc** (bottom) in the presence of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ in DMF (gelator:metal = 1:1 molar ratio; $c = 40 \text{ g L}^{-1}$). Abbreviation: H = heating; C = cooling. [PBS] = 0.1 M; [HCl] = 1 M; [NaOH] = 1 M. Note: Partial gel with a blackish appearance was also

NPs (Figure 4). The intensity of the dark color increased gradually with the concentration of metal salt. Both **C₁₂-Cyc** and **click-C₁₂-Cyc** were tested individually and also as a 50:50 mixture (molar ratio) in order to study the influence of the surrounding gelator network on the resulting nanoparticles. In general, both gelation kinetics and gel strengths were visually enhanced by the presence of gold in the formulations. Importantly, all gels remained stable after the reduction process was complete; indicating the robustness of the formulations for the *in situ* formation of NPs embedded in the viscoelastic networks. It is worth mentioning that other metallogels have also been used for the synthesis of NPs in both apolar organic solvents⁵¹ and in water.^{54,57,58}

Fig. 4 Formation of gold nanoparticles embedded in stable gel matrices made of **C₁₂-Cyc**, **click-C₁₂-Cyc** and an equimolar mixture of both gelators ($c = 40 \text{ g L}^{-1}$) with different concentrations of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ and Et_3N (10 equiv with respect to metal salt). Samples in the absence of metal salt were also treated with Et_3N ($c = 400 \text{ g L}^{-1}$) as control. The mixture 50:50 corresponds to an equimolar mixture of both gelators (50 mol% each).

Finally, in order to gain information about the size distribution of the formed nanoparticles, we carried out UV-vis studies of the NPs-containing gels and electron microscopy imaging of the corresponding xerogels. The plasmon resonance band centered at ca. 520 nm was observed in the UV-vis spectra of all metallogels made of pure isosteres or an equimolar mixture of **click-C₁₂-Cyc** and **C₁₂-Cyc**, suggesting the formation of NPs with similar size distribution regardless the gold concentration and the nature of the gelator system. The plasmon resonance was particularly pronounced in the samples with $[\text{Au}] = 60 \text{ mmol L}^{-1}$ (Figure 5; Figure S7, ESI). These results are in good agreement with previous studies reported in the literature.⁶³

Fig. 5 UV-vis spectra of Au NPs dispersed in the gel matrix made of **click-C₁₂-Cyc** ($c = 40 \text{ mmol L}^{-1}$). The NPs were obtained using different concentrations of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ and Et_3N as described in Figure 4.

FESEM images of the xero-metallogel made of **click-C₁₂-Cyc**, $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ and Et_3N after the reduction was complete showed a band-structure morphology (Figure 6A-D; Figure S8, ESI) that reminded those previously observed for the metal-free xerogel prepared in nitromethane. The formed gold NPs dispersed through the gel network were clearly visualized by TEM imaging (Figure 6E-J; Figures S9-S11, ESI). Non-aggregated NPs were equally distributed over the ordered template networks regardless the gelator system, albeit they were polydisperse in nature. The gel made of an equimolar mixture of **C₁₂-Cyc** and **click-C₁₂-Cyc** allowed for the formation of gold NPs with the smallest size distribution centered around 4 nm (Figure S12, ESI). Similar particle sizes with a resonance band centered at 520 nm have been also reported with steroidal-based network.⁶³ The average particle sizes of the three gelators systems were $4.7 \pm 2.3 \text{ nm}$ (**C₁₂-Cyc**), $4.0 \pm 1.7 \text{ nm}$ (50:50, **C₁₂-Cyc**:**click-C₁₂-Cyc**), and $4.6 \pm 2.3 \text{ nm}$ (**click-C₁₂-Cyc**). In general, these NPs are ca. 1-2 times larger in diameter than those obtained with metallogels made of gelators bearing thiol^{50,51} or disulfide⁵³ moieties. However, much larger Au NPs have been also fabricated using urea-based gelators^{52,56} and hydrogels.⁵⁴ In addition, monodispersed Au NPs of ca. 5 nm with icosahedral geometry have been reported using bis-imidazolium amphiphile-based hydrogels.⁵⁸ In many cases, NaBH_4 is used as reducing agent, while we used Et_3N that can be easily removed by evaporation during the preparation of the xerogels. Importantly, the gels containing non-agglomerated NPs could be restored by simple addition of DMF to the xerogel and applying a heating-cooling cycle. Further characterization of the 50:50 mixture is still necessary in order to understand the effect of the co-assembly process in the formation of the NPs. In addition, we confirmed the laser-triggered degelation of a gold NPs containing gel made of **click-C₁₂-Cyc** ($c = 40 \text{ g L}^{-1}$) in DMF incorporating $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ (molar ratio gelator: Au = 1:1). Finally, in agreement with previous studies,⁶⁴ the bulk gel with a T_{gel} of ca. 40°C collapsed after 35 min of green laser exposure ($\lambda = 532 \text{ nm}$, 50 mW/cm^2) due to the photothermal properties of the Au NPs. As expected, the gel-phase was slowly reformed when

laser irradiation was stopped, and no-gel phase transition was

observed in control experiments in the absence of NPs.

Fig. 6 A-D) Representative FESEM pictures of xerogels obtained by freeze-drying the corresponding metallogels made of **click-C₁₂-Cyc** ($c = 40 \text{ mmol L}^{-1}$), $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ ($c = 40 \text{ mmol L}^{-1}$), and Et_3N ($c = 400 \text{ mmol L}^{-1}$) in DMF. E-F) Representative TEM photographs of the gel prepared from **C₁₂-Cyc** ($c = 40 \text{ mmol L}^{-1}$), $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ ($c = 40 \text{ mmol L}^{-1}$), and Et_3N ($c = 400 \text{ mmol L}^{-1}$) in DMF. G-H) Representative TEM photographs of the gel prepared from **C₁₂-Cyc** ($c = 20 \text{ mmol L}^{-1}$) and **click-C₁₂-Cyc** ($c = 20 \text{ mmol L}^{-1}$), $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ ($c = 40 \text{ mmol L}^{-1}$), and Et_3N ($c = 400 \text{ mmol L}^{-1}$) in DMF. I-J) Representative TEM photographs of the gel prepared from **click-C₁₂-Cyc** ($c = 40 \text{ mmol L}^{-1}$), $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ ($c = 40 \text{ mmol L}^{-1}$), and Et_3N ($c = 400 \text{ mmol L}^{-1}$) in DMF. See ESI for additional pictures. Note: Differences observed between SEM and TEM images with respect to the morphology of the matrix (*i.e.* microscale crystalline tapes vs nanoscale fibers) could be due to modifications occurred during the preparation of the samples such as partial crystallization of the gelator.

Conclusions

In conclusion, the isosteric substitution of the two amide groups presented in the LMW gelator *N,N'*-((1*S*,2*S*)-cyclohexane-1,2-diyl)didodecanamide (**C₁₂-Cyc**) by 1,2,3-triazole rings afforded the corresponding isosteric gelator (**click-C₁₂-Cyc**). This approach allows for fine-tuning the properties of the corresponding organo- and metallogels. The foregoing results demonstrate that **C₁₂-Cyc** can form stable and reversible metallogels with Pd^{II} and Au^{III} in DMSO and DMF, whereas **click-C₁₂-Cyc** forms metallogels in these solvents only in the presence of Au^{III} . Comparing the gels made of **C₁₂-Cyc** vs **click-C₁₂-Cyc** in the presence of $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$, the former showed higher T_{gel} values and 5–8 times shorter gelation times. Furthermore, the incorporation of Et_3N as reducing agent in the formulations facilitated the *in situ* formation of gold NPs embedded in the viscoelastic networks. The plasmon resonance band centered at ca. 520 nm was observed in the UV-vis spectra of all metallogels made of pure isosteres or an equimolar mixture of **click-C₁₂-Cyc** and **C₁₂-Cyc**, suggesting the formation of NPs with similar size distribution regardless the gold concentration and the nature of the gelator system. The formed gold NPs dispersed through the gel network were clearly visualized by TEM imaging, showing non-aggregated NPs equally distributed over the ordered template networks. It is important to highlight that both the solvent (DMF) and the reducing agent (Et_3N) used in these experiments could be evaporated during the preparation of the xerogels by freeze-drying for 5 h under reduced pressure. This process afforded a non-toxic and chemically inert network template in which Au NPs were equally distributed. Subsequent addition of DMF to the xerogels following by heating enabled again a dark-red isotropic solution without agglomeration of the NPs.

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