A mussel-inspired coating for cost-effective and environmentally friendly CO$_2$ capture

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ABSTRACT

Nowadays, finding innovative technologies to efficiently adsorb/desorb CO$_2$ over several cycles with low energy consumption is a pressing environmental concern. In this work, a new bioinspired coating based on the copolymerization of benzene-1,2-diol and hexamethylenediamine, with a CO$_2$ uptake of 7.28 mmol/g under humidified conditions with an outstanding chemical stability and regenerability process is reported. Further functionalization with glycidyltrimethylammonium chloride increases the uptake capacity up to 9.96 mmol/g while lowering the desorption temperature down to 50 °C for 20 min. Moreover, the coating shows strong adhesion on cotton and paper, without modifying their intrinsic permeability and mechanical properties, allowing for the recycling of fully available and environmentally friendly biomass. These results demonstrate the competitive advantages of this bioinspired coating compared with current technologies to capture CO$_2$ while accomplishing the resource efficiency of bioeconomy policies.

1. Introduction

Rapid and immediate removal of anthropogenic CO$_2$ is of vital importance to achieve 1.5–2.0 °C global warming objectives [1]. In this regard, complementing reforestation and energy efficient processes, decisive actions toward emissions reduction have become critical [2]. Renewable technologies have recently seen a huge speed of maturity [3]. Despite this, most of the future energy scenarios converge in speculating that 65% of the global energy demand will still rely on fossil-based fuel (coal, natural gas and oil) by 2050 [4]. For the reason above, cutting carbon emissions from fuel-based power plants by developing carbon capture process has rocketed to the top of the agenda in the scientific and technology policies of the major economies in the world [5]. De facto, while waiting complete maturation of renewable energy technologies and definitive replacement of fossil-based fuel, carbon capture is crucial to achieve global net-zero emissions by 2025 and seriously tackle climate change [6]. Nowadays, reducing energy and financial cost associated with the carbon capture process still represents the major challenge in the ultimate implementation of CO$_2$ capture [7]. Even in the case of aqueous alkali hydroxides, which apparently offered the potential for near-term commercialization [8,9], their implementation is compromised by equipment corrosion and high energy

requirement for sorbent regeneration [10,11]. Therefore, the development of efficient CO$_2$ capture materials with low regeneration energy consumption and enhanced working capacity, i.e., systems with high adsorbate loading able to desorb CO$_2$ at lower energy, has become a major challenge in nowadays environmental technologies.

Materials containing amino groups can play an important role with this aim [12]. Decades of lab-scale development provided a plethora of solid amine-based sorbents with low energy consumption, good sorbent development and process optimization sorbents [13–16]. Still, only very few of them found successful implementation in pilot-scale tests and commercial deployments [17,18], due to their rapid oxidative degradation and high cost of production [19–22]. Another challenge to push their industrial application is their incorporation into solid substrates of a very diverse nature, always following universal approaches, easy to scale up and with remarkable thermal stability [12,23,24].

We hypothesize that these limitations can be solved with bioinspired mussel adhesive coatings using catechol and phenolic-based systems, which in addition to exhibit high thermal and chemical stability, strongly attach onto virtually any kind of surface [25–28]. On top of that, these coatings can be chemically functionalized to modify surface properties, without significantly affecting bulk features. So far, only a few examples of these materials have been reported on membranes with

high CO_2 permeability combining dopamine with epoxy functional poly (ethylene oxide) [29], coatings for metal–organic frameworks (MOFs) that favour a local environment for CO_2 reduction [30,31], the use of photo-triggered CO_2 release [32] and the coordination with iron forming film composites with high gas separation selectivity [33]. However, in spite of this pioneering studies, research on the area is still at early development stages, suffering from high CO_2 desorption energy, fabrication costs and implementation limitations. Due to its potential, further research in the area must be devoted to the development of universal coatings over different substrates incorporating amino groups that efficiently capture CO_2.

Our group recently reported effective coatings on a wide range of materials using a new cost-effective and easy to scale one-pot copolymerization of catechols with different nitrogen-based cross-linkers, under very mild basic conditions in water [34]. Interestingly, we realized that the number of exposed and reactive amino groups increased with time along the reaction procedure (Fig. 1b), as demonstrated upon functionalization with hydrophobic alkyl chains.

Herein we demonstrate that these coatings can be now successfully used as energy-efficient, chemically stable, scalable and cost-effective solid amine-based CO_2 sorbents with fully reversible desorption at 100 °C (Fig. 1c). Further functionalization with glycidyltrimethylammonium chloride (GTMAC) increases the capture capacity while decreasing the temperature desorption down to 50 °C and, therefore, the required energy. As proof-of-concept, to demonstrate the viability of our approach, we have selected two highly abundant and easily accessible materials such as cotton and paper. The selection was mainly based on the fact that paper and cotton: i) are accessible and low cost, ii) they can be part of composite-type structures to form simple or multilayer filters, iii) are easily recyclable once their cycle of life is over and iv) allows for its coating in large quantities, optimizing the synthesis process. These low-cost bioinspired materials, in addition to exhibit low toxicity and adsorption heats, address nowadays concerns of life cycle and waste management. The possibility to use recycled materials, showing competitive working capacity compared to existing technologies, keep waste down and has a minimal impact on the environment.

2. Results and discussion

2.1. Synthesis and coating characterization

The coating (from now on pyroHMDA) was obtained following the procedure reported elsewhere (see Supporting Information, Experimental Section) [34,35]. Briefly, benzene-1,2-diol (pyrocatechol) and hexamethylenediamine (HMDA) were dissolved in MilliQ® water with a HMDA/pyro ratio of 1.5. Thereafter, the substrate (cotton or paper) was placed in the primer solution and the reaction flask was covered with pierced Parafilm® in order to allow the entrance of oxygen into the reaction mixture. The coating time ranged between 8 and 96 h. The resulting coated samples were washed several times with Milli-Q® water, dried under vacuum and characterized.

Compositional changes were first analyzed by FT-IR (see Supporting Information, Fig. S1). The broad band around 3240 cm^{-1} was attributed to the presence of NH_2 while the shoulder at higher wavenumbers (around 3400 cm^{-1}) may be assigned O–H vibrations from catechol. The bands observed in all the spectra at 3050 cm^{-1}, and between 1540 and 1585 cm^{-1} can be respectively assigned to C = C–H and C = C vibrations from the catecholic/quinonic rings. The presence of HMDA is also confirmed by observing the methylene C–H bonds from the alkyl chain of the HMDA at around 2849 and 2932 cm^{-1}. The intense bands present in all the spectra around 1575 cm^{-1}, and between 1620 and 1710 cm^{-1} could be assigned to C = O quinonic groups. Finally, the peak observed in all the spectra at around 1260 cm^{-1} could be assigned to a secondary amine bridging an alkyl and an aromatic ring. Time-dependence FT-IR experiments also showed that the peaks corresponding to the reduced state (catechol) decrease with time, whereas those assigned to oxidized state (quinone) species increase, indicating an over-oxidation of catechol moieties for longer reaction times for both substrates (cotton and paper). In parallel, $–NH_2$ signals increased for longer reaction times, indicating that pyroHMDA coating has a high content in amino terminal groups. High-resolution XPS curve-fitting was used to study the surface exposed functional groups and the environment bonding of the coating after 8 h and 24 h (see Supporting Information, Fig. S2). Briefly, the N1s spectra indicated an increase of both aliphatic and aromatic amine-related species for longer reaction times. Additionally, C–N aromatic contributions could be assigned to two amino group types: i) directly bonded to the catechol rings and ii) C–NH aliphatic, confirming the presence of unreacted amine tail ends. The fitted C1s spectra confirm the coexistence of catechol with its oxidized quinone state as can be noted by the C–OH signals at around 286 eV and the C = O signals at around 288 eV. The analysis of the O1s spectra confirmed the coexistence of these two species.

Coating weight adaptation along the reaction time, which represents a crucial feature for CO_2 capture (vide infra), was also studied and
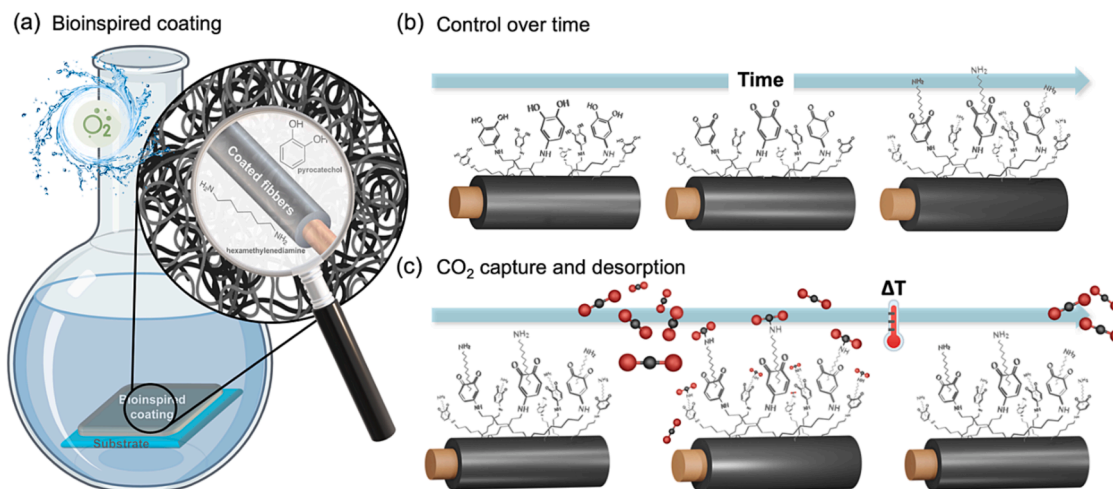
Fig. 1. (a) Schematic synthetic protocol for the bioinspired coating formation on substrates. Both pyrocatechol and hexamethylenediamine are polymerised under mild conditions, presence of oxygen and using water as a solvent. In this study, fibber-based substrates were selected (cotton and paper). (b) The composition of the coating can be controlled with the reaction time. For shorter times, the amount of hydroxyl (–OH) groups is higher than for longer reaction times (>12 h), where the presence of quinones (=O) and amino (–NH_2) groups is increased. (c) The bioinspired coating with the higher amount of exposed amino groups is employed for CO_2 capture by forming covalent bonds. Additionally, the CO_2 molecules can be easily desorbed by increasing the temperature.

adjusted. As can be seen in Fig. 2a, there is a marked tendency of the coating to increase with reaction time, slightly higher for cotton than for paper. To analyze the influence of the coating on the mechanical properties of the substrate, a representative cotton-based sample was further analysed by Dynamic Mechanical Analysis (DMA) to study the stress–strain behaviour (tensile strength (TS) and the elongation at yield (EY)). Pristine cotton behaves as a soft and tough material (TS = 26.42 MPa and EY = 1.66%), but the coating with the pyroHMDA acts as mechanical reinforcement (Fig. 2b). De facto, the sample obtained after 24 h of coating (from now one cC-24) exhibits superior mechanical resistance, higher tensile stress (*ca.* 58 MPa) and elongation at yield (more than 2%), which typically relates to a hard and strong behaviour. This suggests that the coating promotes favourable interactions between the cotton fibres, enabling a more efficient stress dissipation, and therefore a higher mechanical stress resistance. The same outcome was also observed for the paper substrate (see Supporting Information, Fig. S3). Finally, scanning electron microscopy (SEM) images reveal that the coating is strictly formed around the fibbers (see Supporting Information, Fig. S4) with no relevant differences before and after coating (Fig. 2c,d).

2.2. CO2 adsorption performance

The maximum CO_2 adsorption capacity of the coated substrates under 1 atm of 4% dry CO_2 (equilibrated with N_2) at 25 °C was measured and the results normalized to the percentage of the pyroHMDA coating. As shown in Fig. 3a, the capture ability of both cotton- and paper-based samples sharply increases, and almost superimpose for both substrates, reaching a maximum uptake of 3.73 mmol/g after 24 h for the cotton substrate. Such value is close to the track record found for solid sorbents operating under the same experimental conditions [36,37]. After 24 h the capture ability decreases, most likely due the progressive increase of

the coating thickness, i.e. the volume to surface ratio, and its detrimental effect on the capture capacity effectiveness. The cC-24 CO_2 adsorption kinetics are represented in Fig. 3b. The pyroHMDA exhibits a two-stage adsorption, with a sharp linear weight gain just after exposition to the CO_2 stream followed by a much slower adsorption process, which is a typical behavior of amine-based sorbents [38–40], and can be ascribed to the progressive increase in CO_2 diffusion resistance during adsorption [38,41].

Cotton samples coated for 24 h (from now on cC-24) were further investigated under simulated flue gas conditions (pre-humidified 4% of CO_2, 18% RH) at 25 °C and ambient pressure [42]. Due to the hydrophilic character of the pyroHMDA coating and its likeliness to rapidly absorb moisture from humid gases, coating performance under typical operating conditions for amine-based sorbents may be disrupted. For this, the sorbent was first equilibrated at 25 °C in pre-humidified N_2 (same moisture level of the CO_2) until a constant weight is achieved. This already resulted in a weight gain of about 6.7 wt% and 7.2 wt% for pure cotton and cC-24, respectively (see Supporting Information, Fig. S5). The feeding gas was then switched to the humid CO_2 at 25 °C and the weight gain used to calculate the adsorption capacity. As can be seen in Fig. 3b, the presence of water molecules favors CO_2 diffusion within the sorbent, enhancing the reaction between the amino functionalities and the gas molecules. This results in a higher carbon capture capacity, showing that the normalized adsorption capacity under humid conditions reached the impressive value of 7.28 mmol/g, among the highest reported for amine sorbents [43,44] and almost 6-fold higher than current benchmark found for amine-scrubbing solutions (~1.25 mmol g^{-1} for 30% monoethanolamine solution, MEA) [45].

Finally, the CO_2 capture ability of the pristine substrates was measured and found to be practically zero even in the presence of moisture (see Supporting Information, Fig. S6), confirming that the CO_2 adsorbtion mostly arises from the pyroHMDA coating.
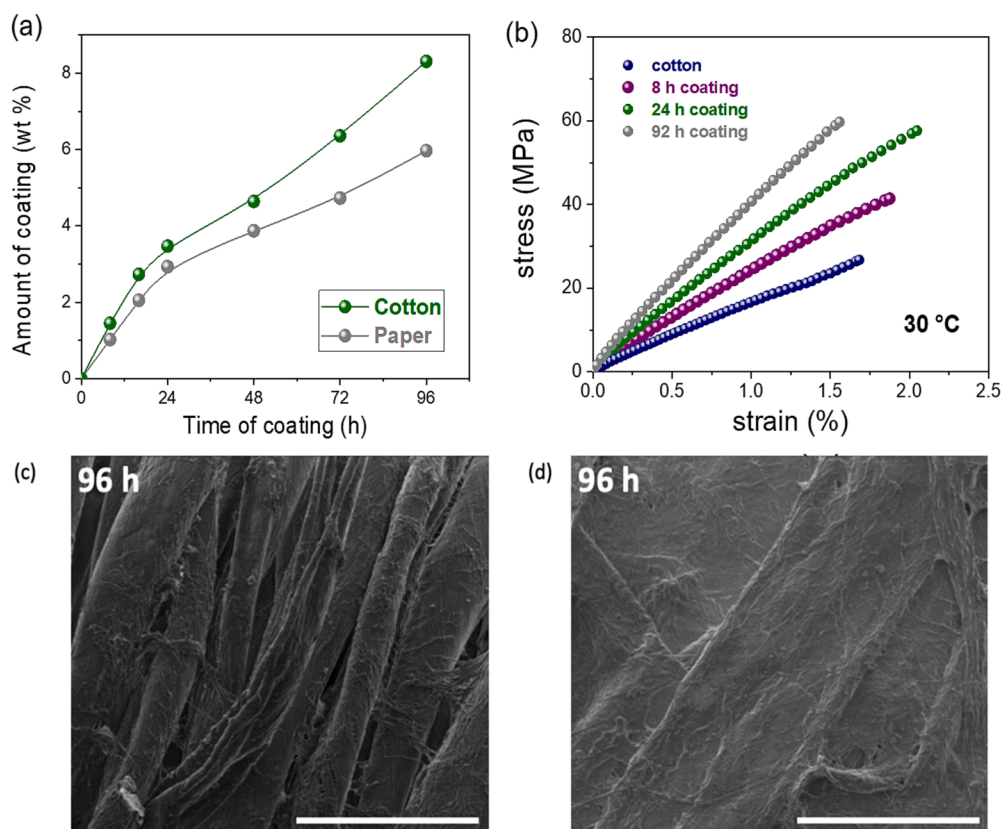
Fig. 2. (a) Percentage of coating (weight) vs. the reaction time for cotton and paper. (b) Stress − strain curves conducted at 30 °C for cotton-based sorbents. Scanning electron microscopy (SEM) micrographs for (c) cotton and (d) paper. Scale bar: 40 μm.
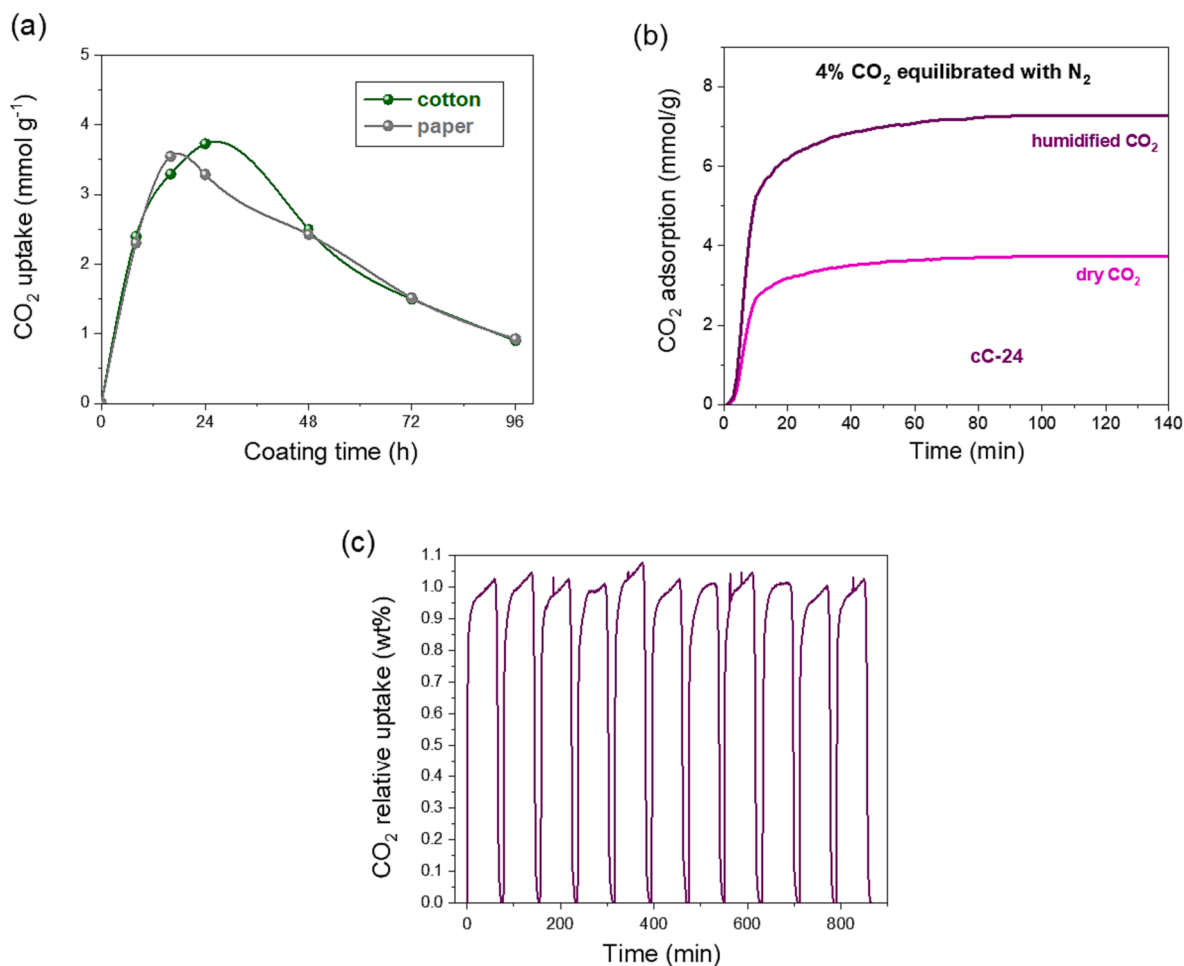
Fig. 3. (a) Normalized CO_2 uptake for coated samples as a function of the coating time. (b) CO_2 adsorption kinetics of cC-24 under dry and humidified (18% RH) 4% CO_2. (c) Cyclic performance for cC-24 sorbent over multiple adsorption/desorption cycles. Sorption conditions = 40 mL/min humid CO_2 at RT for 60 min, and desorption conditions = 40 mL/min humid N_2 at 110 °C for 20 min.

2.3. Cycling stability and sorbent regeneration

To assess the chemical stability and regeneration energy of this novel effective coating, repetitive adsorption/desorption CO_2 cycles of cC-24 were carried out under simulated flux gas conditions. For each cycle, the coated sample was first exposed to a humid flow of 4% CO_2 (18% RH) at 25 °C for 60 min, followed by desorption in dry N_2 RH at 110 °C for 20 min.

As can be seen in Fig. 3c, the cC-24 sorbent can be thermally regenerated by N_2 flow and heating at 110 °C for only 20 min (see Supporting Information, Fig. S7). Moreover, the maximum adsorption capacity was regenerated for at least 50 cycles, demonstrating the full reversibility of the process.

Differential scanning calorimetry (DSC) was used to monitor heat evolution along the CO_2 adsorption/desorption process [42]. The DSC thermogram exhibits a sharp positive heat-flow peak followed by a quite broad shoulder after CO_2 exposure, which could be attributed to the rapid exothermic reaction of the amino groups with the CO_2 (see Supporting Information, Fig. S8). Peak integration gave an adsorption heat value of $\Delta H = 83.4$ kJ/mol, comparable to those found for other amine sorbents (45–95 kJ mol^{-1}) [12,20,37,46,47]. Moreover, a broad endothermic peak (130.8 kJ mol^{-1}) was obtained upon switching the purge gas from humid CO_2 at 25 °C to dry N_2 at 110 °C. Such value, associated to sorbent regeneration, is lower than the energy for stripping a 30% MEA solution (209 kJ mol^{-1}) [48].

2.4. Gtmac-functionalized sorbents

To improve the adsorption/desorption efficiency, the exposed amino groups were transformed into quaternary ammoniums by reaction with Glycidyltrimethylammonium chloride (GTMAC) (see Fig. 4a and Experimental Section in Supporting Information). Previous developments with anion exchange membranes demonstrated that quaternary ammonium groups can rapidly and reversibly trap CO_2 upon a nucleophilic attack of the carbon and interconversion of the hydroxides into bicarbonate ions [49,50]. Moreover, the equimolar stoichiometry between CO_2 and the quaternary ammonium group (see Supporting Information, Scheme 1), ensures higher CO_2 uptakes and lower regeneration temperatures than aqueous MEA.[46].

The successful quaternization of a coated cotton sample (from now on cCQ-24) was confirmed by FT-IR, showing the characteristic peak of $H_3C–N^+–$ at around 2980 cm^{-1} (for more information see Supporting Information, Fig. S9). On top of that, SEM and DMA characterization revealed that the post-functionalization does not alter the morphology nor its mechanical performance (see Supporting Information, Figs. S10 and S11, respectively). The new CO_2 adsorption kinetics of cCQ-24, together with those of pristine cotton and cC-24, are represented in Fig. 4b. Interestingly, the adsorption rate is remarkably higher for the quaternized cCQ-24 system, confirming the faster reaction between quaternary ammonium groups and CO_2. Moreover, the peak adsorption capacity of CO_2 uptake reaches a normalized CO_2 adsorption of 4.46 mmol/g, which represents a 20% improvement with respect that found
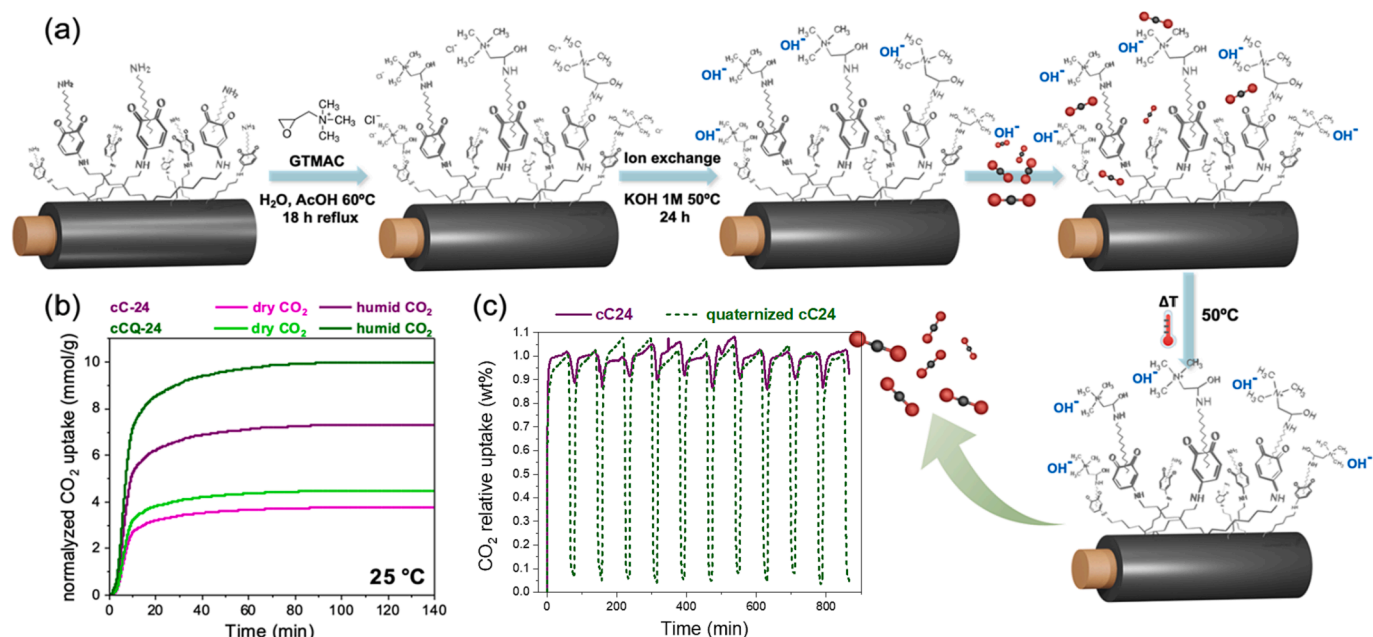
Fig. 4. (a) Schematic representation of the sample functionalization with GTMAC and subsequent CO_2 capture (b) CO_2 capture performance of cC-24 and cCQ-24 sorbents under dry and humid 4% CO_2 and (c) regenerability test for CO_2 adsorption on cCQ-24 sample under sorption conditions = 40 mL/min humid CO_2 at RT for 60 min, and desorption conditions = 20 mL/min humid N_2 at 50 °C for 20 min.

for cC-24 (3.73 mmol/g). Even a higher increase of 37% was obtained under pre-humidified 4% CO_2 (18% RH) at 25 °C conditions. In this case, the quaternized cCQ-24 sorbent achieves a normalized CO_2 uptake of 9.96 mmol/g, in comparison to the 7.28 mmol/g capacity previously found for cC-24. Additionally, such value equals capacity records reported to date for amine sorbents operating under similar conditions [51]. To point out the astonishing potential of the mussel-inspired coating, a performance comparison of cC-24 and cCQ-24 with several earlier published solid-supported amine sorbents has provided in Table 1. Higher CO_2 capture, namely 12 mmol/g, were reported by Qi et al. in the case of silica-based sponges with covalently tethered amines [37]. However, their production required a complex, time-consuming and costly multi-step synthetic approach which also involved the use

of toxic concentrated acid solution (i.e., 5 M HCl). On the other side, E-VER-TEPA-2% is an inexpensive sorbent prepared by supporting tetraethylenepent-amine (TEPA) onto natural abundant vermiculite (E-VER) nanosheets [52]. Such amino-based sorbent was able to achieve and impressive adsorbing capability under high pressure conditions, i.e., 29.5 mmol/g at 45 bar, whilst the capture performance under diluted partial pressure of CO_2, were very poor. De facto, only the mussel-inspired coating combines true cost-effective and scalable features with high performance into diluted conditions.

Finally, regeneration of cCQ-24 was almost completed by heating at 50 °C, sixty degrees lower than the temperature required for cC-24 (110 °C). This implies less energy consumption, as corroborated by analysis of the heat evolution during CO_2 adsorption/desorption (see

Table 1

Performance comparison of cC-24 and cCQ-24 sorbents with state-of-the-art materials for CO_2 Capture.

Materials	Atmosphere Condition	Temperature (°C)	CO_2 adsorption (mmol CO_2/g sample)	Method	Stability	Ref
cC-24	4% CO_2 in N_2 18% RH	25	7.28	TGA[a]	No efficiency loss in 50 cycles	This work
cCQ-24			9.96		No efficiency loss in 50 cycles	
LeZIF8-PhIm	120 kPa CO_2	0	4.05	VOL[b]		[55]
Functionalized Silica sponges	8% CO_2 in N_2 18% RH	25	12	TGA	Robust after 50 cycles	[37]
CNF-x-a-CNC	10% CO_2/N_2	30	2.11	IR[c]	–	[56]
CNF-Ph(1:1.5)	500 ppm CO_2	25	5.2	VOL	–	[57]
MgSepP-50	60% CO_2/N_2	75	2.48	TGA	Robust over 10 cycles	[58]
MWCNT-20 %PEI	0.15 %CO_2/N_2	25	2.28	TGA	Loss 10% in 10 cycles	[59]
SiO_2CNT-20 %PEI	15 %CO_2/N_2	30	1.92	TGA	–	[60]
50 %PEI/SBA-15	400 ppm CO_2/N_2	25	1.3	TGA	Robust over 10 cycles	[51]
PEI@BN	2% CO_2/N_2	75	3.12	TGA	Loss 6.3% after 10 cycles	[61]
54.9 wt% PEIPNC-1	101 kPa CO_2	25	2.5	VOL	Robust over 10 cycles	[62]
SH800	40% CO_2/H_2	25	6.77	PB[d]	Robust over 5 cycles	[63]
(FBNNs)/ZnO	100 kPa CO_2	0	2.83	PRE	Loss 7.63% in 10 cycles	[64]
polyHIPE/nano-TiO2/PEI-50	CO_2/H_2O/N_2 (1:1:8)	75	5.6	TGA	Loss 9% in 50 cycles	[65]
20 wt% MgO-RHA	10% CO_2/N_2	–	4.56	IR	Loss 7.68% in 10 cycles	[66]
0.52 wt% PEI@AOMC	100% CO_2	30	2.58	TGA	Robust after 11 cycles	[67]
MgO/C-550	15% CO_2/N_2	27	4.77	TGA	–	[68]
Solid-supported amines sorbents operating in the high-pressure range						
NOHM-c-5	25 bar CO_2	25	4.08	TGA	No efficiency loss in 10 cycles	[69]
E-VER-TEPA-2%	45 bar CO_2	25	29.5	VOL	Loss 3.3% after 6 cycles	[52]
MWCNT/SiO_2 NOHM	50 bar CO_2	25	6.1	PRE[e]	Robust over 10 cycles	[70]

[a] TGA, thermogravimetric analysis; [b] VOL, volumetric method; [c] IR, infrared analyser; [d] PB, packed bed; [e] PRE, pressure method.

Supporting Information, Fig. S12). Indeed, both adsorption ($\Delta H_a = 51.7$ kJ/mol) and desorption ($\Delta H_d = 89.6$ kJ/mol) heats are remarkably lower than the ones of cC-24 ($\Delta H_a = 83.4$ kJ/mol and $\Delta H_d = 130.8$ kJ mol^{-1}) and one of the lowest regeneration energy penalties among previously reported supported-amines sorbents [15,37]. On top of that, repetitive adsorption/desorption cycles under simulated flue gas conditions confirmed that the post-functionalization of cC-24 does not impact on the remarkable cycling stability of the sorbent, as the maximum adsorption capacity is maintained even after 50 adsorption/desorption cycles (Fig. 4c and Supporting Information, Fig. S13).

3. Conclusions

We have demonstrated how a bioinspired thin coating, synthesized through the reaction of pyrocatechol and HMDA, can transform cotton and paper substrates into efficient CO_2 sorbents. The selection of paper and cotton as scaffold materials is because they are: i) fully accessible in tons-scale with low cost, ii) they can be part of composite-type structures to form simple or multilayer devices that can be easily implemented in buildings and common air filtering systems, iii) they are easily recyclable once their life cycle is over, iv) allows its coating in large quantities, optimizing the synthesis process and v) last but not least, fulfil resource efficiency of nowadays bioeconomy policies.

The coating thickness can be adjusted to optimize CO_2 adsorption within 24 h or even less, considering that any commercialization would require further optimization of the upscaling process, all of this without compromising the intrinsic properties (stress, porosity and permeability) of the substrate.

Under these adjusted conditions, an optimized CO_2 uptake of 7.28 mmol/g (normalized to the coating percentage) was achieved under 4% humidified CO_2 at 25 °C, which raises up to 9.96 mmol/g upon quaternization with GTMAC. What is even more relevant, the functionalization also decreases the regeneration temperature down to 50 °C for less than 20 min with an energy penalty of only 89.6 kJ/mol. Considering the cost of energy consumed during CO_2 release mostly determines the capital expenditure of the CO_2 capture process [53], the implementation of our bioinspired functionalized coating holds promise for massive reduction of the capture cost with respect to processes based on MEA (62 $/ton) [54], mesoporous silica (75–105 $/ton) [54] and MOF (80–150 $/ton) [53] sorbent materials. Moreover, in both cases, with or without GTMAC, no adsorption/desorption capacity loss is detected for at least 50 cycles. Once the end of the life cycle is reached, the coated materials can be easily recycled without causing added contamination thanks to the biodegradable nature of both the polymeric compound and the chosen substrates. This ensures its integration into a circular economy with lowering costs and low energy or pollution impact.

For commercial purposes, the synthesis process is carried out using cost-effective and fully scalable technologies in water, with the presence of oxygen and soft chemical mixing (can be mechanical). This ensures a process that does not require large amounts of energy or the use of organic solvents or any other difficult-to-obtain compounds that can hinder its large-scale production at an industrial level. On top of that, large amounts of material can be coated within a single batch, or even more, the polymeric coating can be synthesized, stored, and later applied to the target substrate.

Finally, and thanks to the versatility and robustness of the described polymeric coating, its application can also be extended to other specific substrates depending on the final application, ensuring its adhesion thanks to the bioinspired chemical nature of catechol molecules. All in all, our coating holds promise in amino-based sorbents for highly performing low-energy consuming carbon sequestration technology and therefore in the circular economy of carbon.

CRediT authorship contribution statement

Salvio Suárez-García: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Isabella Nicotera:** Resources, Writing – review & editing, Funding acquisition. **Daniel Ruiz-Molina:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Cataldo Simari:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi. org/10.1016/j.cej.2023.145280.

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