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ADVANCING SUSTAINABILITY THROUGH CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS) TECHNOLOGIES: THE HYDROGEL CASE STUDY

Eduardo G. Pereira*, Alberto Fossa*, Carlos Eduardo Pellegrino Cerri*, Opeyemi Omotuyi, Hannah Hylton-Edwards***, Edmilson Moutinho dos Santos*, Alexandre Gallo*, Cylon Liaw*, & Bruna Toguedani***

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ABSTRACT

Carbon capture, utilization, and storage (CCUS) consists of several technologies that are capable of playing significant and diverse roles in the achievement of global energy and climate goals under the context of energy transition. It forms a relevant technological approach for capturing carbon and delivering a net zero energy system. Currently, CCUS projects are mainly taking place in developed countries, with some of them having specific promotion policies such as 45Q under IRA in the US. Several of the current CCUS activities take the form of enhanced oil recovery (EOR). CCS have a value chain comprising the CO_2 capture, compression and liquefaction, transportation (by pipeline or ships), and storage (e.g., underground in saline aquifer or depleted reservoirs). CCU shares some of the CCS value chain elements, except storage, as it consists of techniques and initiatives that convert captured emitted carbons into useful products. Hence, adopting a qualitative research methodology, this study explores the concept and relevancy of CCUS in achieving net zero emissions using hydrogel as a case study. This study aims for the implementation of a new CCUS value chain that involves products based on carbon sequestration in land-based carbon dioxide removal (CDR), leading to a high potential for mitigating carbon emissions. Consequently, CCUS is vital to attenuate the problems of climate change, as it plays a key role in decarbonizing and facing the challenge of anthropogenic CO_2 emissions, in addition to providing a long-term alternative compatible with sustainable development. Based on its properties and characteristics, especially as a polymeric electrolyte with a high capacity for conducting physical separation, this study proposes hydrogel as a viable technique for the maximum capture of atmospheric carbon. Such captured carbon is then utilized for various applications or stored appropriately. This study concludes with a highlight of specific lessons learned in this regard, and the major challenges observed with this CCUS technique.

Keywords: CCUS, CCU, Climate Change, Net Zero, CO_2 Reduction, Sustainable Development, Hydrogel.

1. INTRODUCTION

The existence of carbon capture, utilization, and storage (CCUS) technologies are reliable tools to attenuate the problem of anthropogenic carbon dioxide emissions that significantly influence global climate change,[1] in addition to being a well-understood and long-term sustainable technology.[2] As a commitment to the Paris Agreement and the sustainable development agenda, the deployment of net zero and negative carbon technologies for carbon dioxide capture sets an important contribution to these objectives foreseen by 2050.[3] Considering that fossil fuels' production would be extended to supply major energy needs in the global energy mix for the short and, most probably, medium term, achieving net-zero emissions will demand a progressive and fast development of CCUS technologies to pave a more sustainable way.[4] This is because aside from energy efficiency measures and a shift to lower carbon fuels in the global energy mix, CCUS is the main viable technology option that can contribute to the realization of net-zero emission reductions on the scale required by the Paris Agreement.[5] According to the United Nations, by 2050, CCUS will be responsible for almost 16% of the required carbon emission reductions and, between 2015 and 2050, for 14% of the aggregate emissions reductions.[6] The significance of CCUS technologies to the achievement of net zero goals cannot be over-emphasized. This is because it does not only contribute to the direct reduction of carbon emissions from

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1 Stephen A Montzka et al. "non-C0$_2$ greenhouse gases and climate change" (2011) Nature, 476, 43,50; Tabbi Wilberforce et al. "Progress in carbon capture technologies" (2021) Science of The Total Environment, 761.

2 Niall Mac Dowell et al. "The role of CO_2 capture and utilization in mitigating climate change" (2017) Nature, 243, 249.

3 Sam Fankhauser et al. "The meaning of net zero and how to get it right" (2021) Nature. 12, 15-21. https://doi.org/10.1038/s41558-021-01245-w accessed 25 May 2023.

4 Ibid.

5 United Nations Economic Commission for Europe "Carbon Capture and Storage: A Key to Climate Change Mitigation" (2015) https://unece.org/sustainable-energy/publications/carbon-capture-and-storage-key-climate-change-mitigation-booklet accessed 22 March 2022.

6 Ibid.

point-source capture but also provides a platform for hydrogen production from low-carbon sources, in addition to the removal of carbons to balance emissions that are unavoidable, particularly for industries with hard-to-abate emissions, such as iron and steel and cement.[7] CCUS involves the capturing of carbons directly from points of emission, particularly industrial facilities that exploit fossil or biomass fuels, or from the atmosphere.[8] Such captured carbons are used directly on-site for industrial purposes, compressed, and transported for use in relevant industrial applications, or injected into deep saline aquifers or depleted reservoirs which trap the carbon for permanent storage.[9] Other potential uses of captured carbons include its sale to oil companies for enhanced oil recovery, its usage as input for synthetic fuels, building materials, and chemicals production.[10] Thus, aside from its contribution to the global net zero emissions goals, another merit of CCUS is the use of the captured carbons for industrial purposes, which may constitute a potential revenue stream for CCUS facilities.[11] Currently, most CCUS activities take the form of enhanced oil recovery (EOR) and consequently the stored CO_2 comes from a natural CO_2 reservoir. This pattern is going to change in the near future as more CCUS projects will be implemented to store or utilize CO_2 from point-source capture.

Although an appropriate carbon capture technology for specific applications will depend on various factors ranging from the intended carbon concentration (initial and final stages) to the pressure and temperature at operations, among others, however, major internationally acceptable carbon capture technologies include chemical absorption, physical separation, membranes, and looping cycles including, chemical and calcium looping. Chemical

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7 International Energy Agency "Special Report on Carbon Capture Utilisation and Storage: CCUS in Clean Energy Transitions" IEA Energy Technology Perspec tives (2020).

8 International Energy Agency Technology Report April (2021) https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage accessed 22 March 2022.

9 International Energy Agency "Special Report on Carbon Capture Utilisation and Storage: CCUS in Clean Energy Transitions" IEA Energy Technology Perspectives (2020).

10 International Energy Agency Technology Report April (2021) https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage accessed 22 March 2022.

11 Ibid.

absorption relies on a carbon dioxide and a chemical solvent reaction, whereby carbon dioxide is absorbed by a column, while another higher temperature column releases pure carbon, finalizing with the chemical solvent regeneration for further operation.[12] This process is applied in several projects including fuel transformation, power generation, and industrial production. Physical separation is centered on the separation through absorption, adsorption, dehydration or cryogenic processes, and further compression of carbon dioxide. While physical adsorption uses solid surfaces such as metallic zeolites or oxides, a liquid solvent is used for physical absorption, such as rectisol or selexol.[13] This separation process is mainly used in hydrogen, methanol production as well as for natural gas processing. On the other hand, membrane separation focuses on inorganic or polymeric devices, that is membranes containing high-carbon selectivity that act as a gas barrier to the gaseous stream but allow carbon to pass through.[14] Chemical and calcium looping consists of a technology based on two reactors, whereby a gas stream flows by a sorbent (first reactor) which captures the carbon and then transported to another reactor to be regenerated, with a stream of pure carbon as output, later returned to the first reactor.[15]

It is noteworthy that carbon sequestration through land-based carbon dioxide removal (CDR) consists one of many efforts to reduce greenhouse gases' impact in the atmosphere. Moreover, this land-based CDR possesses have significant synergy potential in the CCUS process.[16] Hydrogel, which is noted to have many applications in various processes ranging from industrial to biological,[17] has been identified as an example of such synergic

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[12] International Energy Agency "Special Report on Carbon Capture Utilisation and Storage: CCUS in Clean Energy Transitions" (2020) IEA Energy Technology Pers pectives, p 19.

[13] Ibid, p 98.

[14] Ibid.

[15] Ibid.

[16] Research Centre for Greenhouse Gas Innovation. Hydrogel Which Stores CO_2 in the Soil will be Developed and Tested in Brazil. (16 August 2021) https://www.rcgi.poli.usp.br/hydrogel-which-stores-co2-in-the-soil-will-be-develop[ed-and-tested-in-brazil accessed 23 March 2022.

[17] Morteza Bahram et al. "An Introduction to Hydrogels and Some Recent Appli cations" (2016) Emerging Concepts in Analysis and Applications of Hydrogels.

combination.[18] Structurally, hydrogels consist of three-dimensional crosslinked polymer meshwork, which possess the ability to absorb and bond moisture within their interstices, while maintaining the network structure in the swollen state.[19] The ability to absorb moisture is as a result of its swelling nature and its crosslinking property which also helps in maintaining its swollen state.[20] Hydrogels can be synthesized from natural or synthetic polymers, polymerizable synthetic monomers, and a combination of natural and synthetic polymers. Some of its significant properties include mechanical strength, flexibility, biocompatibility, biodegradability, swellability, and stimuli sensitivity, which have made it a viable option in various applications.[21] For instance, the adsorption of radioactive substances and heavy metals with the use of hydrogels has been posited as an optimized removal solution for toxic carbons emitted into the atmosphere. This mechanism of removing pollutants using hydrogels is carried out through the process of hydrogen bonding, physical adsorption, ion exchange, complexation, and/or chelation.[22] In other words, hydrogels offer an alternative carbon capture solution, using physical adsorption. Such adsorption of pollutants using hydrogels has been held advantageous in comparison to conventional techniques of removing pollutants. Particularly, hydrogels have high adsorption capacity and binding ability, and they can be regenerated and reused.[23]

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[18] Ibid. See also Hazem S. E. and Camele "Applications of Absorbent Polymers for Sustainable Plant Protection and Crop Yield" (2021) Sustainability 13, 3253.

[19] Shahid Bashir et al. "Fundamental Concepts of Hydrogels: Synthesis, Properties, and Their Applications" (2020) 12, 11 Polymers 2702.

[20] Lucille V Abad et al "Properties of Radiation Synthesized PVP-kappa Carrageenan Hydrogel Blends" (2003) Radiation Physics and Chemistry, 68, 901; Enas M Ahmed "Hydrogel: Preparation, Characterization, and Applications: A Review" (2015) Journal of Advanced Research 105, 121.

[21] Shahid Bashir et al. "Fundamental Concepts of Hydrogels: Synthesis, Properties, and Their Applications" (2020) 12, 11 Polymers 2702.

[22] Ljubisa B Nikolic et al. "Synthetic Hydrogels and their Impact on Health and Environment" (Cellulose-Based Superabsorbent Hydrogels, Polymers and Polymeric Composites: A Reference Series, Springer, 2018) 1, 29.

[23] Ibid.

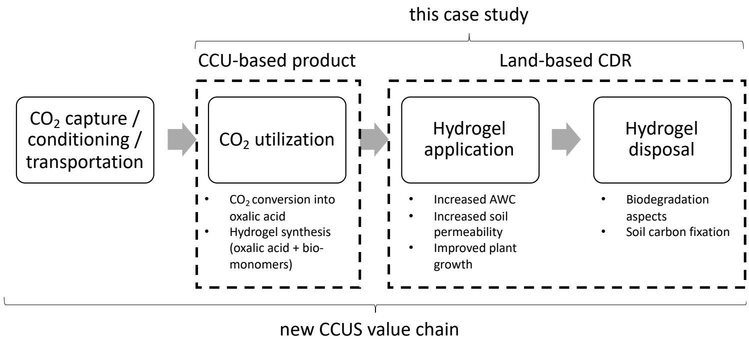

Figure 1 – Schematics of this case study's new CCUS value chain

This paper accordingly explores the implementation of a new CCUS value chain that encompasses both a CCU-based product and a land-based CDR (carbon dioxide removal) approach for mitigating carbon emissions with a particular focus on hydrogel as a viable strategy to maximize the capture of atmospheric carbon. This is explained in section two of this paper through a review of the methodology used in this study. Section three then gives a thorough background of CCUS, inclusive of its scope, its functions, the relevance of this process to the mitigation of carbon emissions, the advantage of CCUS, as well as the products that may be derived therefrom. This is followed by Section four which looks specifically at hydrogel as a viable technique for achieving the requisite reduction in emissions. In this section, both the advantages and limitations of hydrogel are analyzed with the conclusion that despite identified difficulties, hydrogel is an effective CCUS tool. To conclude, the final section presents the lessons learned in the course of this study.

2. METHODOLOGY

This study adopts a case study research methodology, which is a method "to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context".[24] The study explores the concept and relevancy of CCUS in achieving net zero carbon

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[24] Sarah Crowe et al. "The Case Study Approach" (2011) 100 BMC Medical Research Methodology, 11; Yasir Rashid et al. "Case Study Method: A Step-by-Step Guide for Business Researchers" (2019) International Journal of Qualitative Methods, 18.

emissions, using hydrogel as a case study. The case study inquiry includes several qualitative and quantitative data and comments. For instance, this study explored the use of secondary data to identify the relevance of hydrogel as a CCUS technology. It also analyses products based on oxalic acid (COOH)2 and bio-based monomers that work in natural systems (for example, agriculture, waste management, ecosystem restoration, etc.) and can be degraded and incorporated back into the natural environment. Such oxalic acid is obtained through the conversion of carbon emissions and serves as a platform molecule to produce biodegradable hydrogel. Thus, the study emphasizes hydrogel as a new CCUS solution involving products based on carbon sequestration in land-based carbon dioxide removal (CDR), thereby resulting in a high potential for mitigating carbon dioxide emissions.

Within the case study proposed, the innovation is the development of a polymeric electrolyte. This polymeric electrolyte is the hydrogel, which can conduct oxalate ions obtained by electrochemical conversion of CO_2, being potentially a product for a new CCUS chain.

Such study with different types of hydrogels evaluates the beneficial potential of hydrogels in improving physical, chemical, and biological attributes of the soil in agricultural, livestock, and forestry systems. Such systems can subsidize beneficially propositive actions for government initiatives through basic subsidies for the generation of information that will enable the establishment of targets for the reduction of greenhouse gases emissions, water use monitoring, soil fertility (macro and micronutrients) and respective impacts on plant production.

3. CARBON CAPTURE, UTILIZATION AND STORAGE

3.1 The Scope of CCUS

The United Nations Framework Convention on Climate Change (UNFCCC) has the main objective of the stabilization of greenhouse gases' concentration in the atmosphere to prevent harmful and irreversible changes to the climate.[25] This objective requires substantial cuts in carbon dioxide emissions. The third evaluation report of the Intergovernmental Panel on Climate Change (IPCC) revealed that no technological alternative would alone provide the emission reductions necessary to reach the stabilization.[26] The IPCC Special Report on Carbon Dioxide Capture and Storage labeled CCUS as a relevant choice within the portfolio of mitigation actions, especially considering the belief that fossil fuels will remain dominant for the energy supply up to at least five decades.[27] The European Commission for Climate Change also recognizes new technologies for CCUS.[28]

The technologies considered for CCUS already exist in large part and, in some cases, are fully operational.[29] However, its expansion was held back due to some hurdles, involving how costly developing technologies are, concerns with health and safety, lacking transparent carbon pricing, questions concerning its effectiveness, also unclear public perception.[30] In addition, technical regulations and standards present another obstacle on the subject due to the lack of objectivity.[31] This last hurdle can be resolved through the development of International Standards and

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25 The United Nations Framework Convention on Climate Change (1992), article 2, https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf accessed 25 March 2022.

26 Intergovernmental Panel on Climate Change "IPCC Third Assessment Report: Climate Change 2001", (2001) https://www.ipcc.ch/report/ar3/wg1/ accessed 25 March 2022.

27 Intergovernmental Panel on Climate Change "Carbon Dioxide Capture and Storage", (2005) https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/ accessed 25 March 2022.

28 European Commission "Communication from the Commission to the European Parliament and the Council: Sustainable Carbon Cycles" (15 December 2021) https:/ /ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage_en accessed 25 March 2022.

29 Liu H. J., et al. "Worldwide Status of CCUS Technologies and their Development and Challenges in China" (2017) Geofluids; Dory Gascuena "The Promise of CCUS Technologies: Slowing Down Global Warming by Recycling CO_2" (2020); Clifford C "Carbon Capture Technology has been Around for Decades- Here's Why it Hasn't Taken Off" (2021) CNBC.

30 Sara Budinis et al. "An Assessment of CCS Costs, Barriers and Potential" (2018) 22 Energy Strategy Reviews 61; Pavel Tcvetkov et al. "Public Perception of Carbon Capture and Storage: A State of the Art Overview" (2019) Heliyon 5, 12, 1.

31 Natalia Romasheva and Alina Ilinova "CCS Projects: How Regulatory Framework Influences Their Deployment" (2019) 8 Resources 181.

must be resolved immediately,[32] since governments and industries have showed that CCUS stands as a priority alongside associated projects that should be started immediately.[33]

Essentially, the CCU process includes at least four steps, three of them shared with CCS, until the carbon-rich product is ready for use or disposal (see figure 2).

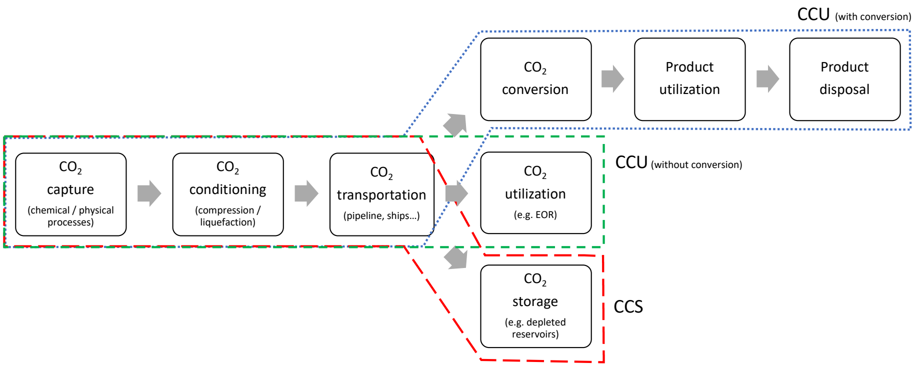

Figure 2 – Schematics of CCUS systems

Firstly, the CCUS system depends on CO_2 being captured from flue gas (industrial exhaust stream) or directly from the air. The second step accounts for the conditioning of CO_2 to be then transported, the third step. This conditioning may involve compression or liquefaction, depending upon the transportation mode, such as pipeline and ships. Up until this step, CCUS chain is common for both storage and utilization routes. For CCS, the next step involves the injection of CO_2 into deep saline aquifers or depleted reservoirs which trap the carbon for permanent storage. CCU might include CO_2 conversion process or not. EOR is a typical case of CCUS where no conversion is performed. CCU involving chemical processes to convert CO_2 usually aims to

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32 Such international standards may be developed through the environmental and qua lity management standards of the International Organization for Standardization.

33 International Energy Agency "Special Report on Carbon Capture Utilisation and Storage: CCUS in Clean Energy Transitions" Energy Technology Perspectives 2020.

produce a high-carbon chemical product. As a result of CO_2 conversion, following steps involve the utilization of C-rich product/service leading to product disposal, if not permanently stored.

SAPEA (2018)[34] stated the following rationale to CCU, though it might be extended to CCUS matters, concerning a competitive scenario with renewable energy sources (RES), which, in conclusion, are a prerequisite for CCU to thrive:

> "(…) the argument that CCU may compete for RES on a large scale, at times where RES is required to substitute fossil power more directly is contradicted by the timescale foreseen for CCU systems. All EU planning for the roll-out of RES in the power sector foresees a level above 50% RES in the power system by 2050. At this level, storage and transport of RES will be critical and all the flexibilization measures will have to be in place. CCU is expected to be a complementary technology (at least locally) rather than a competitor for RES. At the present level of RES penetration, this would not be the case and thus high levels of RES are unconditionally a prerequisite for CCU implementation beyond demonstrators."

3.2 Why is it relevant?

Though technology plays an important role in CCUS development,[35] has pointed out that regulatory and commercial barriers stand in the front row as primary concerns in the short run. At least one CCUS technology has already reached mature or early adoption levels in every stage of the process (except in the transportation stage), however, the majority is yet to be developed in the long run, especially with the support of incentives and policies. According to IEA (2020)[36], though CO_2 has been used in industrial processes for decades, i.e., ammonia and urea production and enhanced oil recovery, many of the potential

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[34] Science Advice for Policy by European Academies "Novel Carbon Capture and utilisation technologies", SAPEA (2018) https://www.sapea.info/wp-content/uploads/CCU-report-May2018-3.pdf accessed 25 May 2023.

[35] International Energy Agency "The role of CCUS in low-carbon power systems", License: CC BY 4.0 (Paris, 2020) https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems accessed 25 May 2023.

[36] Ibid.

products are still in a demonstration or an early commercial stage for large scale. This includes building materials and feedstock for synthetic fuels, both temporarily trapping CO_2 for the time being.

As reported by ZHANG *et al.* (2020), regarding every potential CO_2 market and thus the beneficial side of CCUS, it is expected a very particular result for each country. Figure 3 shows the potential CO_2 utilization in 2050 compared to global CO_2 emissions, indicating a representative market for CO_2 use. The authors recommend that some categories of CO_2 utilization markets should deserve a special attention: polymers, fuels (i.e., methane), building materials (i.e., carbonate aggregates and concrete); chemical intermediates (i.e., methanol, and syngas).

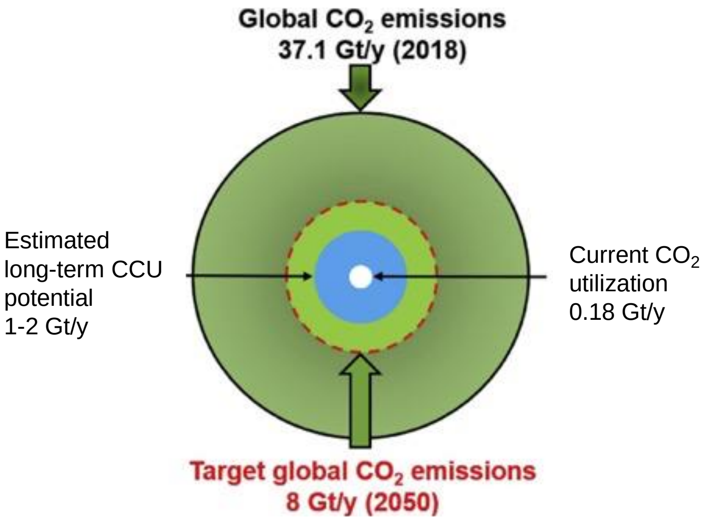

Figure 3 – Comparison between CO_2 emissions and utilization potentials. Source: ZHANG *et al.* (2020).

According to IEA (2019), in the short term, the CO_2 market for utilization will not soar, but some opportunities are on the run, such as building materials and related ones. To widely contribute to climate change concerns, CCUS technologies have to go beyond traditional uses, such as EOR (enhanced oil recovery) and the food and beverages sector, expanding its uses to more diversified pathways as technology evolves (See figure 4).

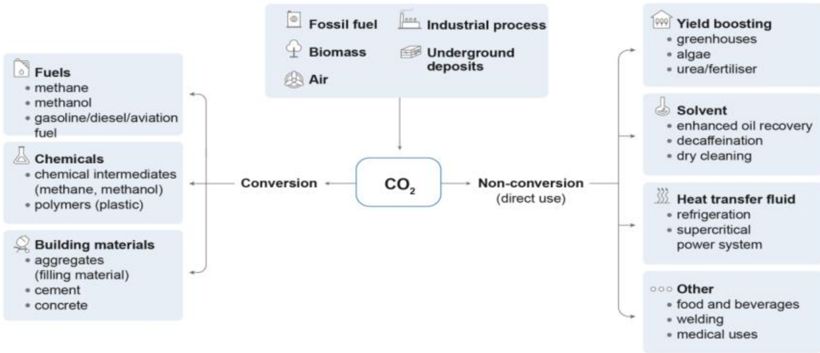

Figure 4 – Simple classification of pathways for CO_2 use.
Source: IEA (2019)

Product development is subject to several challenges and market entry barriers, which include location matter.[37] As mentioned by DOE (2017):

> "Areas that contain the greatest CO_2 capture opportunities in the vicinity of utilization sites could provide critical mass for the development of pipeline network hubs. These hubs could, in turn, guide the identification of regional and national corridors for CO_2 transportation."

In this sense, Ramirez et al. (2019) describe an alternative for optimized production *in loco* of high-value-added products to be developed in integrated processes, combining an electrochemical conversion unit with a compatible CO_2 capture process. The IEA (2019) report states that transport-related costs and emissions can be greatly minimized whenever a location unites favorable conditions to thrive, such as the low-cost rich supply of CO_2, availability of raw materials, such as cement and water, an existing CO_2 infrastructure as well as low-carbon energy (such as heat and electricity).

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[37] International Energy Agency "Putting CO2 to Use" (Paris, 2019) License: CC BY 4.0. https://www.iea.org/reports/putting-co2-to-use accessed 25 May 2023; Licheng Sun et al. "Carbon emission transfer strategies in supply chain with lag time of emission reduction technologies and low-carbon preference of consumers" (2020) 264, https://doi.org/10.1016/j.jclepro.2020.121664 accessed 25 May 2023.

In addition to a prosperous policy and incentives-driven scenario, a possible placement within industrial clusters is recommended due to the combined effect of enhanced demand for input products and the infrastructure for transportation, also aiming for a CCS integration. CCUS synergies from CO_2 use and CCS deliver a potential source of revenue (i.e., CO_2-EOR), technology refinement, economies of scale, and shared infrastructures.[38] Table 1 presents an overview of mature CO_2-derived products and services, gathering suitable candidates for early markets.

	Fuels / chemical intermediates	Polymer chemicals	Building materials	Stabilising waste	Yield boosting
Mature application	Methanol; methane	Poly-carbonates	CO_2-cured concrete	Aggregates from waste	Greenhouses
Energy inputs	High	Low	Low, but depends on transport distances	Depends on carbonation process and transport distances	Low, but depends on transport distances
Willingness to pay for CO_2	Low (fuels); high (chemicals)	High	High	Low	Low
Source of revenues (other than normal product sale value)	None	Cheaper feedstock	Lower cement use; extra market value of superior product	Avoided waste disposal cost	Avoided natural gas use
Main source of potential climate benefits	Displacement of fossil fuel	Displacement of fossil feedstock	Lower cement use; permanent retention of CO_2	Permanent retention of CO_2	Displacement of natural gas
Early opportunities	Areas with low-cost CO_2 and renewable energy	Industrial sites with excess polymer production capacity	Areas with minimum transport distances Target market segments receptive to product	Areas with minimum transport distances and high waste disposal costs	Areas with minimum transport distances and existing CO_2 and heat infrastructure

Table 1— Overview of mature CO_2-derived products and services
Source: IEA (2019).

As reported by IEA (2019)[39], the CO_2 use to support climate goals is possible whenever it unites a scalable application with low-carbon energy use and the displacement of a higher life-cycle emission product. In this sense, the greatest climate change mitigation potential comes from fuels and building materials markets, mainly due to their current size and also for their low energy requirements and permanent carbon retention (Figure 5).

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[38] Ibid.
[39] Ibid.

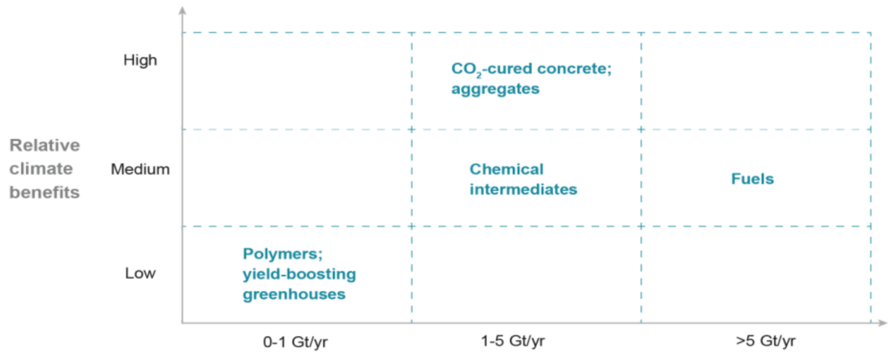

Figure 5 – Theoretical potential and climate benefits of CO_2-derived products and services. Source: IEA (2019).

Some aspects in assessing the climate benefits of CO_2 use should be considered, according to IEA (2019):

- the source of CO_2 (from natural deposits, fossil fuels, industrial processes, biomass, or air)
- the type of product or service the CO_2-based product or service is displacing
- how much and what form of energy is used to convert the CO_2
- how long the carbon is retained in the product (temporary or permanent)
- the scale of the opportunity for CO_2 use

Moreover, a life-cycle assessment (LCA) is yet necessary to quantify these benefits, represented by cradle-to-grave analysis, as seen in Figure 6, covering the upstream, CO_2 use, and downstream stages.

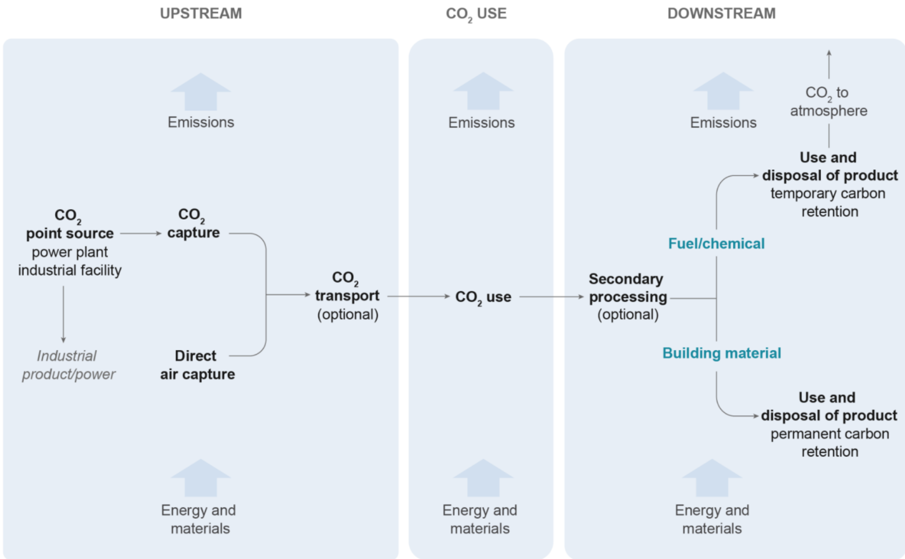

Figure 6 – Life cycle of CO_2-derived products and services.
Source: IEA (2019).

However, there is currently limited knowledge built around LCA and potential climate benefits from CO_2 use, since LCA shows considerable variations in its findings and conclusions, due to the carbon source, the carbon intensity of the input energy, and the conversion technology. As such, these uncertainties directly impact policy makers' and consumers' perceptions, of whether CO_2 use represents a viable and efficient climate mitigation tool (IEA, 2019)[40].

Notwithstanding the above-mentioned challenges concerning LCA and the adequate climate benefits measurement, there is an opportunity for improvement in updating such understanding, which is currently not provided by the ISO 14000 series. The International Organisation for Standardization (ISO) lacks sufficient guidance for assessments of CO_2 use applications, therefore, as a spearhead institution dedicated to products and services technical standards elaboration, ISO is expected to further contribute to this matter. As stated by Zhang *et al.* (2020),

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40 International Energy Agency "Putting CO2 to Use" (Paris, 2019) License: CC BY 4.0. https://www.iea.org/reports/putting-co2-to-use accessed 25 May 2023.

standards-setting organizations and governments should work together to ease the market entry of these products and develop an innovative agenda for CO_2 use. As stated by the IEA (2019), worldwide institutions are leading several attempts to set a common ground for LCA analysis for CO_2 use, i.e., the Global CO_2 Initiative consortium, and the U.S. National Energy Technology Laboratory.[41]

For IEA (2019), the barriers to short-term scale-up of CO_2 use are commercial and regulatory, instead of technological. Within this outlook, there is a growing interest in CO_2-based products, which is seen directly in the growing support from diverse stakeholders, such as governments, industries, and investors. Governments have a particular interest in the potential gains while stimulating industrial innovation, technological leadership, and enabling the circular economy. However, within the current market and in the absence of a developed policy framework and economy-driven incentives, most conversion processes and CO_2-derived products and services are unable to thrive, since their technological development stages are yet in their infancy.[42] In this sense, Zhang *et al.* (2020) stated that "a stable regulatory framework is needed to help companies reduce and avoid the negative impacts of failure and increase the financial return from the investment. Therefore, well-designed policies for CO_2 utilization are very important to start and build markets".

To develop a substantial CO_2-derived products and services market, IEA (2019) recommends a variety of policy instruments (see Table 2), which would lead, for instance, to a leveraged public and manufacturer procurement expenditure towards the attendance of a minimum percentage of products and services derived from CO_2. Another example of policy involves raising

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[41] Lorenzo Cremonese et al. "Making Sense of Techno-Economic Assessment & Life Cycle Assessment Studies for CO2 Utilization: A guide on how to commission, understand, and derive decisions from TEA and LCA studies" (2020) https://deepblue.lib.umich.edu/handle/2027.42/146529 accessed 22 March 2022; National Energy Technology Laboratory (2019) Carbon Dioxide Utilization Life Cycle Analysis Guidance for the U.S. DOE Office of Fossil Energy www.netl.doe.gov/lca accessed 22 March 2022.

[42] International Energy Agency "Putting CO2 to Use" (Paris, 2019) License: CC BY 4.0. https://www.iea.org/reports/putting-co2-to-use accessed 25 May 2023.

consumer awareness of the sustainability aspects of low-carbon products through labeling, certification, and testing procedures.

Policy instrument	Examples of existing policies / support
Public procurement	Public procurement rules in Canada and the Netherlands that favour material inputs with low-carbon footprints for construction projects
Mandates	Renewable Energy Directive (RED II) (EU) and Low Carbon Fuel Standard in California, both favouring low-carbon transport fuels, including CO_2-derived fuels
Economic incentive	US 45Q tax credit that encourages the capture and conversion of CO_2 into useable products
Product labelling	Environmental labelling of numerous products, including household appliances and packaging materials
Certification and testing	Certification and testing of wide range of product markets, including electronics and food.
RD&D support	International level: Mission Innovation – coalition of countries that pledged to double R&D budgets on clean energy, which offers an opportunity to expand R&D on CO_2 use as well. National level: EU's Horizon 2020 programme, US DOE's Carbon Use and Reuse R&D portfolio, National Key R&D programmes on CO_2 use in the Chinese 13th Five-Year Plan

Table 2 – Policy instruments for the creation of a market for CO_2-derived products and services
Source: IEA (2019).

As stated by IEA (2019), carbon pricing instruments, such as carbon tax or a cap-and-trade system, may overcome the scarcity of policies supporting CO_2 use. Its impact may vary per product type, depending on the transferability of regulatory responsibility, CO_2 sale price, and the percentage of CO_2 that is permanently stored in the product. According to the World Bank (2020), some governments have embraced carbon pricing to reduce emissions. As of November 2020, there were 64 carbon pricing initiatives – comprising both emissions trading systems (ETS) and carbon taxes—implemented or scheduled for implementation worldwide that address 12 gigatons of CO_2 equivalent, or 22.3% of global GHG emissions per year. A recent example of policy to incentivize the development of CCUS is the 45Q under IRA in the US. This tax credit provides on the lower end 60 USD/tCO_2 for EOR and industrial uses of CO_2, 80 for CO_2 permanently stored (CCS), going up to 130 for used CO_2 (CCU) and 180 for direct air capture (DAC) projects.[43]

4. CASE STUDY: HYDROGEL

4.1 How does it work?

The objective of the study is to implement a new CCUS value chain that involves products based on carbon sequestration in land-based carbon dioxide removal (CDR), leading in general to a high potential for mitigating CO_2 emissions. In this context, it is noteworthy that carbon dioxide is the most significant greenhouse gas and CO_2 emissions generate complications in the context of the environment. Therefore, there is a need to develop additional, and potentially noble, destinations for CO_2 from underground storage to useful products. Hence, this study proposes the production of oxalate from industrial CO_2 emissions using the reverse fuel cell concept. The conversion of CO_2 to oxalate (in salt (COOM)2 form) is advantageous, as it is the product with the greatest power to reduce emissions.[44] In that context, the study proposes firstly the development of active and selective catalysts (electro and photo) to produce oxalate skirt from the electrochemical and/or photo-electrochemical reduction of CO_2. Secondly, the preparations of solid polymer electrolyte with properties directed to the purpose. Finally, combining the previous developments into electrode membrane assemblies to test catalysts in real conditions which equals to reverse fuel cell type (electrochemical reactors), optimized to maximize the conversion of CO_2 into the product of interest (oxalate).

Among these proposals, what matters the most in terms of CCU normalization is the production of a reverse fuel cell, because its

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43 International Energy Agency Technology Report (April 2021) https://www.iea.org /fuels-and-technologies/carbon-capture-utilisation-and-storage accessed 22 March 2022.

44 Maria Murcia Valderrama et al. "The potential of oxalic – and glycolic acid based polyesters (review). Towards CO2 as a feedstock (Carbon Capture and Utilization – CCU)" (2019) European Polymer Journal, 119, 445–468; Raja Angamuthu et al. "Electrocatalytic CO2 conversion to oxalate by a copper complex" (Jan 2010) Science. 15;327(5963):313-5.

production is the base stage for the development of the hydrogel with maximized atmospheric CO_2 capture. The reverse fuel cell consists of an electrochemical cell with a solid electrolyte, that is, a cationic or anionic membrane (cation and anion conductors, respectively) resulting in "electrochemical reactors" that will act as a CO_2 to oxalate converter. The more CO_2 has been converted to oxalate, the better the cell's efficiency in capturing atmospheric CO_2. The main advantages related to the choice of this concept, when compared with conventional cells based on liquid electrolytes are:

1) with the use of a solid electrolyte the solubility of the reagents becomes redundant.
2) product separation is highly superior.
3) photons (light) can be used to promote the anode and cathode reactions aiming at a lower overall energy consumption of the system.

The proposed concept is based on a process to study the reduction of CO_2 by electrochemistry and photo electrochemistry and the effect of its chemical environment on the selectivity and efficiency of this reaction. The CO_2 molecule is reduced to activated CO_2 species (that is CO_2^-), which are organized into products aided by parametric optimization of the electrochemical and photo-electrochemical reactor, to maximize the conversion of CO_2 into the desired reduction product, that is, hydrogel.

Hence, the study further:

1) Assesses the side effects of hydrogels in natural systems (forestry, agriculture, livestock, and horticulture);
2) Evaluates the use of hydrogel in closed systems;[45]
3) Evaluate effects of the use of hydrogel in soil clays;[46]
4) Evaluate the effect of the rhizosphere microbiota[47] (close to the roots) on the potential for carbon sequestration in the soil.

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[45] CLOSED SYSTEMS: they are a simplification of open space systems, it is expected that the extrapolation of the main parameters is applicable. As a greenhouse, underground systems controlled by the biosphere (tunnels, residential, others).

[46] SOIL CLAYS: clays are part of the mineralogical constitution of the physical particles of the soil, originating from the degradation of feldspar rocks by chemical or physical attack. In addition, with an intelligent selection of clays, they can be considered as active in soil fertility, as they maintain valuable cationic components for balanced soils, increasing their cation exchange capacity (CTC).

Among the potential side effects of applying the hydrogel application, the following can be highlighted:

- potential increase in H2O infiltration rates;
- improve soil structure;
- reduce soil compaction[48] and improve aggregate stability;
- increased cation exchange capacity in the soil (potential negative charges from the hydrogel);
- greater probability of absorption of macro and micronutrients by mass flow (transport of substances at equal rates; xylem and phloem transport)[49], diffusion and root interception (root grows against the element in the soil);
- greater plant resistance to water stress;
- less susceptibility to contamination by pathogens and diseases;
- potential increase in plant phytomass production and increase in plant root vigor due to the presence of the hydrogel;
- establishment of an attractive niche for soil microbiota, with a potential increase in biodiversity in the rhizosphere.

These effects may result in a carbon sequestration increase, since greater plant biomass will be deposited in the soil during the microbial decomposition process. The study has the central objective of developing products based on oxalic acid (COOH)2 and bio-based monomers that work in natural systems (for example, agriculture, waste management, ecosystem restoration, etc.) and can be degraded and incorporated back into the natural environment. The oxalic acid will be obtained through the conversion of CO_2 to a platform molecule to produce biodegradable hydrogel. In this context, it should be noted that the properties of hydrogel or other synthetic polymers can make them resistant to microorganisms and other natural degradation

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47 RHIZOSPHERE MICROBIOTA: set of microorganisms (bacteria, fungi, protozoa) that inhabit the region where roots and soil come into contact. Studies show that this habitat has a greater diversity of microorganisms when compared to root-free soil.

48 SOIL COMPACTION: defined as an increase in the density of the soil in the same volume with a reduction in its porosity. One of the main consequences of extensive livestock, leading to the destruction of pasture soils for planting.

49 MASS FLOW: it is the movement of substances at equal rates or as a single body. For example, blood circulation, water transport, and assimilate in xylem and phloem plants. This is based on the cohesion of the water molecules to each other and the adhesion to the vessel wall by hydrogen bonds.

processes. This can cause them to remain in the environment after disposal. Moreover, depending on its properties, the hydrogel can cause problems such as environmental pollution (e.g., soil contamination with microplastics if the hydrogel biodegradation route leads to this kind of subproduct), waste management and problems associated with scarcity of area for the proper management of solid waste. Due to these problems, there is a growing concern regarding the use of biodegradable polymeric materials as a solution for environmental safety, savings, and solid waste management. In addition, hydrogel can play an important role in the agriculture, livestock, and forestry sectors, by improving soil conditioning and its physical, chemical, and hydraulic properties.[50]

4.2 What are the best practices?

Hydrogel is a generic term for hydrogels utilization in different applications, including cleaning and water treatment,[51] oil recovery,[52] sewage sludge treatment,[53] food processing,[54] laboratory and medical materials,[55] and its important use in agriculture.[56]

A hydrogel is a three-dimensional network structure composed of cross-linked polymer chains (Figure 7), which can absorb a large

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[50] Carlos Cerri et al. "Quantifying soil carbon stocks and greenhouse gas fluxes in the sugarcane" (2013) Scientia Agricola, v.70, n.5.

[51] Malcon P Stevens "Polymer Chemistry: An Introduction" (3rd ed, Oxford University Press, USA, 1999) 78.

[52] Emesih, G. C et al. "Evaluation of modified starches for improved oil recovery" (1999) Applied Engineering in Agriculture 15(3), 237,242.

[53] Zhihui Pan "Sewage sludge ash-based thermo-responsive hydrogel as a novel drawagent towards high performance of water flux and recovery forforward-osmosis" (2021) Desalination, 512, 115147.

[54] Malcon P Stevens "Polymer Chemistry: An Introduction" (3rd ed, Oxford Unive rsity Press, USA, 1999) 78.

[55] Frank W Barvenik "Polyacrylamide characteristics related to soil applications" (1994) Soil Science 158(4), 235,243; Kousaku Ohkawa et al. "Biodegradation of ornithine-containing polylysine hydrogels" (1998) Biomaterials 19, 1855,1860.

[56] Jahangir Abedi-Koupai et al "Evaluation of Hydrogel Application on Soil Water Retention Characteristics" (2008) Journal of Plant Nutrition 31:2, 317,331; Gonçalvez, L. "Biodegradable hydrogels for agriculture". (Coimbra.Portugal, 2014) 140; Neethu, T.M et al. "Prospects and Applications of Hydrogel Technology in Agriculture" (2018) Int.J.Curr.Microbiol.App.Sci 7(5), 3155,3162.

volume of solution.[57] This can be attributed to hydrophilic residues, which are found on the monomer chains or as lateral terminal chains, or to counter-ions in the network, resulting in an associated osmotic pressure.[58] A large variety of chemicals are being added to enhance hydrogel efficiency, such as hydrophilic functional groups.[59]

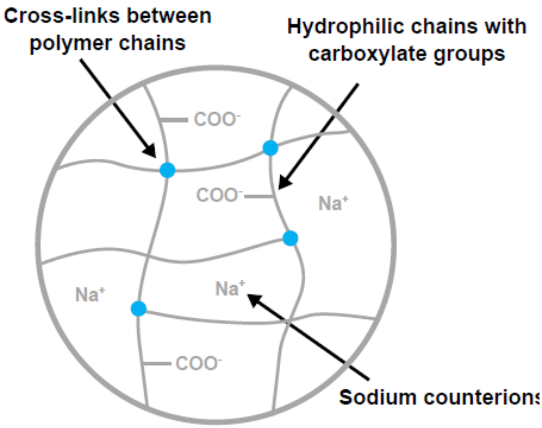

Figure 7 – Material structure of a super-absorbent polymer (sodium neutralized polyacrylic acid).
Source: Fennell and Huyghe (2019).

According to Frachini et al. (2019), it is possible to characterize hydrogels (Figure 8) based on 3 key aspects for gels. The hydrogel shall be a coherent colloid disperse system of a minimum of 2 components displaying mechanical attributes of the solid state and its dispersed component and continuous medium extent themselves continuously throughout the whole system. In addition, according to the same authors, two important conditions are necessary to create a hydrogel from solutions: first, the solid substance should separate from the solution in a finely dispersed "colloidal" state, and second, the separated solid particles should

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57 Eanna Fennell et al. "Chemically Responsive Hydrogel Deformation Mechanics: A Review" (2019) Molecules, 24, 3521.

58 Malcon P Stevens "Polymer Chemistry: An Introduction" (3rd ed, Oxford University Press, USA, 1999) 78; Ebewele, R.O., 2000. Polymer Science and Technology. 2000: Copyright, CRC Press LLC. 210p.

59 Zhihui Pan "Sewage sludge ash-based thermo-responsive hydrogel as a novel drawagent towards high performance of water flux and recovery forforward-osmosis" (2021) Desalination, 512, 115147.

not precipitatenor remain as individual moving particles, but they should form a coherent framework throughout the volume.[60]

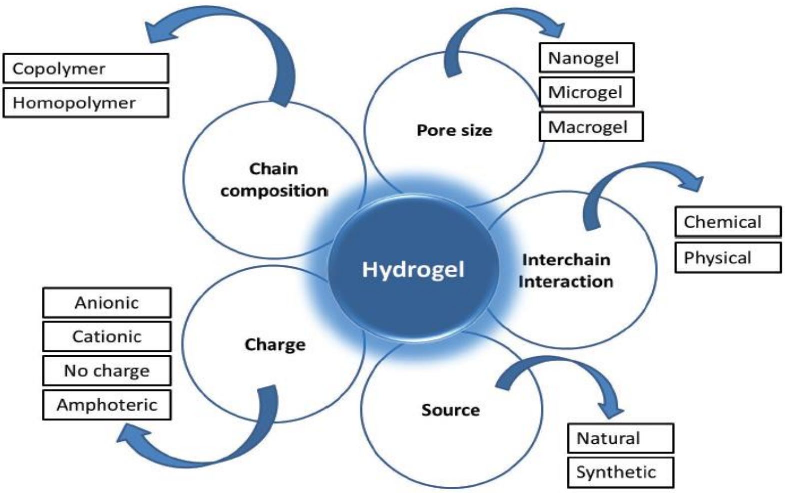

Figure 8 – Chemical and physical aspects for the classification of polymer hydrogels. Source: Frachini et al. (2019).

When the application of a hydrogel focuses on agricultural use, it is essential to apply polymers super-absorbents, which can absorb large amounts of water and other fluids (i.e., ideally more than 1000 times its dry weight) in shorter periods of time.[61] When correctly used in the agricultural sector, hydrogel can enhance soil quality/soil health, because it may improve not only soil physical attributes (for instance: macro and microporosity, soil bulk density, water infiltration permeability, compaction, water

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[60] Emilli C G Frachini et al. "Magneto-Responsive Hydrogels: Preparation, Charac terization, Biotechnological and Environmental Applications" (2019) J. Braz. Chem. Soc., Vol. 30, No. 10, 2010,2028.

[61] Jahangir Abedi-Koupai et al "Evaluation of Hydrogel Application on Soil Water Retention Characteristics" (2008) Journal of Plant Nutrition 31:2, 317,331; Gonçalvez, L. "Biodegradable hydrogels for agriculture". (Coimbra.Portugal, 2014) 140; Neethu, T.M et al. "Prospects and Applications of Hydrogel Technology in Agriculture" (2018) Int.J.Curr.Microbiol.App.Sci 7(5), 3155,3162; Zhihui Pan "Sewage sludge ash-based thermo-responsive hydrogel as a novel drawagent towards high performance of water flux and recovery forforward-osmosis" (2021) Desalination, 512, 115147.

holding capacity, and other soil attributes and properties) but also improving biological/microbial activities in the soil, which enhanced the air accessibility in the root zone of plants.[62]

The presence of water in the soil is key for vegetation development. Thus, hydrogel application is gaining acceptance from scientists because it provides solutions for the shortage of water for agriculture by increasing soil health.[63] As a consequence, the hydrogel application may cause an increase in seed germination rates, time of seedling emergence and survival and best conditions for root establishment and growth.[64] Polymers hydrogel influences soil structure (compaction, permeability, density), evaporation and infiltration of water into the soils.[65] Therefore, the hydrogel has the capacity to release water and added macro/micronutrients to the plants when the soil conditions around the plant root systems get dry. This process is a great advantage compared to the soil without hydrogel application because not only provides nutrients for plant uptake but also releases water that may guarantee plant survival under drought events.[66]

According to Kumar et al. (2018), several studies have focused on the efficacy of hydrogel use in sandy soils and in soils of desert areas. Hydrogel prolongs the plant nutrient and water uptake by releasing the water slowly over a longer period. It decreases water usage and improves the physical properties of the soil. Moreover,

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62 Frank W Barvenik "Polyacrylamide characteristics related to soil applications" (1994) Soil Science 158(4), 235,243; Shahid B Dar et al. "Hydrogel: To enhance crop productivity per unit available water under moisture stress Agriculture" (2017) Env. Pharmacol. Life Sci. 6(10), 129,135; Lawrence Ekebafe et al. "Polymer applications in agriculture" (2011) Biokemistri. 23(2), 81,89.

63 Waleed Abobatta "Impact of hydrogel polymer in agricultural sector" (2018) Adv Agr Environ Sci,1(2), 59,64.

64 Gehring, J. M. and A. J. Lewis "Effect of hydrogel on wilting and moisture stress of bedding plants" (1980) Journal of American Society of Horticultural Science 105(4), 511,513.

65 Lawrence Ekebafe et al. "Polymer applications in agriculture" (2011) Biokemistri. 23(2), 81,89; Huttermann, A. et al. "Addition of hydrogels to soil for prolonging the survival of Pinus halepensis seedlings subjected to drought" (1999) Soil and Tillage Research. 1999;50(3-4),295,304.

66 Sri Laxmi et al. "Effect of hydrogel on soil moisture stress" (2019) Journal of Pharmacognosy and Phytochemistry SP5, 316,320.

this may be providing accurate entry to essential nutrients for plant growth and the improvement of biomass production.[67]

Hydrogel and other alternative water-holding amendments (e.g., biochar) and irrigation methods are becoming extremely relevant in the past years, especially in semi-arid and arid regions of the world in which water availability is rather scarce.[68] Hydrogels and biochars are also key technological options for the recuperation of degraded lands, especially in conditions where the plants are rain feed because there will not be opportunities for plant irrigation.[69]

Furthermore, hydrogels have the capacity to absorb and retain water hundreds/thousands of times their own weight.[70] Table 3 illustrates hydrogel's capacity to store water in different soil textures.[71] A soil's available water content (AWC) is the quantity of water released between its field capacity (FC) and its permanent wilting point (PWP). Field capacity is the quantity of water retained by a soil after it has been sufficiently saturated, and drainage is not relevant. Permanent wilting point of a soil is the soil moisture level below which plants wilt permanently. AWC is determined by subtracting PWP from FC, indicating the available water that can be utilized by plants. Therefore, soil and hydrogel combined can provide increased water held (AWC) for plant uptake during drought periods and enhance the potential of plant survival in water stress conditions.

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[67] Adem Gunes et al. "Evaluation of effects of water-saving superabsorbent polymer on corn (Zea mays L.) yield and phosphorus fertilizer efficiency" (2016) Turkish J. Agric. For. 40, 365,378.

[68] Jahangir Abedi-Koupai et al "Evaluation of Hydrogel Application on Soil Water Retention Characteristics" (2008) Journal of Plant Nutrition 31:2, 317,331; Shahid B Dar et al. "Hydrogel: To enhance crop productivity per unit available water under moisture stress Agriculture" (2017) Env. Pharmacol. Life Sci. 6(10), 129,135.

[69] Eikhof, R H et al "Control of wilting in potted plants" (1994) Ohio Flor. Assoc. Bul. 532; Jahangir Abedi-Koupai et al "Evaluation of Hydrogel Application on Soil Water Retention Characteristics" (2008) Journal of Plant Nutrition 31:2, 317,331.

[70] Ibid.

[71] Jahangir Abedi-Koupai et al "Evaluation of Hydrogel Application on Soil Water Retention Characteristics" (2008) Journal of Plant Nutrition 31:2, 317,331.

			Amount of hydrogel addition (g/kg)			
Water content (%)	Type of hydrogel	Control	2	4	6	8
		Sandy loam				
AWC	PR3005A	3.17	5.31	7.01	8.15	10.06
	TarawatA100		5.28	5.90	7.49	8.32
		Loam				
AWC	PR3005A	4.27	5.39	5.04	8.11	9.55
	TarawatA100		5.53	5.90	7.49	8.32
		Clay				
AWC	PR3005A	4.65	5.55	6.77	8.05	8.39
	TarawatA100		4.78	5.23	7.91	8.29

Table 3 – Volumetric water content at AWC in sandy loam, loamy and clay soils compared to the control.
Source: Abedi-Koupai et al. (2008).

As it is well known, the phases of seed germination and seedling establishment are essentials for any vegetation development. Thus, plant growth is totally dependent on nutrient uptake and water availability, which may be limited in several parts of the globe, notably in sandy soils from arid and semi-arid regions.[72] In order to minimize those limitation effects on plant development, a hydrogel can be used to promote an increase in the water-holding capacity of the soil to enable the prolonged time before it reaches wilting point thereby increasing plant's survival under water stress, decreasing fruit drop ratio, and may leading to expanded total yield and fruit weight under various severity conditions.[73]

In addition, according to Abobatta (2018), adding hydrogel to the soil increased the plant circumference; this may be due to increasing the amount of available water in the root zone, which infers longer irrigation intervals. Moreover, the application of hydrogel polymer is used to create a water reservoir near the root zone of plants, decrease osmotic moisture of soil, improve the capacity of plant available water, enhance plant growth, and increase the whole yield and decrease production costs of crops. Other uses of hydrogels include improving plant viability, seed germination, ventilation, and root development mainly under arid

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72 Waleed Abobatta "Impact of hydrogel polymer in agricultural sector" (2018) Adv Agr Environ Sci,1(2), 59,64.

73 Ibid.

environments. Additionally, concerning plant growth, it is noteworthy that there is a significant increase in the growth of plants with the usage of hydrogel.[74]

Another environmental problem in the agricultural sector is the common application of agrochemicals to soils and plants. To mitigate this drawback modern solutions are emerging, such as the use of controlled-release formulations, whereby active compounds are encapsulated in a slow-release matrix prior to soil application.[75] According to Minet et al. (2013) the expected advantages of this approach include: prolonged activity in soil (protection from microbial degradation until release), reduced number of applications, reduced costs (due to single application), and reduced environmental loss.[76]

Moreover, according to Abobatta (2018), hydrogel polymers play a vital role in agricultural uses such as constituting structural materials for creating a climate beneficial to plant growth. It could be used in different forms as follow:

- Seed additives to support seed germination or seed coatings;
- Dipping of seedling roots before establishment;
- Immobilizing plant growth substances;
- Coating protecting agents (herbicides and pesticides) for slow release;
- Polymeric Biocides and Herbicides;
- Water-insoluble polymers;
- Polymers for soil remediation.

Agricultural hydrogels can change the different soil properties through various mechanisms[77] such as:

- Implement water–holding capacity of the soil;
- Increasing soil permeability;
- Improving water retention on different soil types;

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[74] Ibid.

[75] Eddy P Minet et al. "Slow delivery of a nitrification inhibitor (dicyandiamide) to soil using a biodegradable hydrogel of chitosan" (2013) Chemosphere 93, 2854,2858.

[76] Ibid.

[77] Waleed Abobatta "Impact of hydrogel polymer in agricultural sector" (2018) Adv Agr Environ Sci,1(2), 59,64.

- Increasing the water use efficiency;
- Increasing irrigation intervals due to increasing the time to reach a permanent wilting point;
- Minimizing soil erosion and water runoff;
- Implement soil penetration and infiltration;
- Decrease soil compaction tendency;
- Improve soil drainage;
- Support crop growth performance under reduced irrigation conditions;
- Enhance nutrient retention as a result of solute release from hydrogel polymer particles and delay the dissolution of fertilizers

As presented here, it is possible to list a series of benefits associated with using hydrogel in agricultural systems. Among the potential secondary effects can be highlighted the potential increase in water infiltration rates, improve soil structure, reduce soil compaction and improve aggregate stability; increased capacity for exchanging cations in the soil (potential negative charges from the hydrogel); greater probability of absorption of macro and micronutrients by mass flow, diffusion and root interception; greater plant resistance to water stress, less susceptibility to contamination by pathogens and diseases; potential increase in the production of plant mass and increase and vigor of the plant root system due to the presence of the hydrogel; establishment of an attractive niche for soil microbiota, with the potential to increase biodiversity in the rhizosphere. These effects may result in more significant carbon sequestration in the soil since greater plant biomass will be deposited in the soil during the microbial decomposition process.

4.3 What are the main gaps & challenges?

The hydrogel is directly associated with CO2 Abatement Technology approaches. In this sense, the hydrogel may promote benefits in improving soil physical, chemical and biological attributes in agricultural, livestock and forestry systems. Such systems can subsidize beneficially purposeful actions for government initiatives (such as the Low Carbon Agriculture Program ("Progama ABC") or even the National Biofuels Policy, among others) through basic subsidies for the generation of information that will make it possible to establish targets for reducing greenhouse gas emissions, monitoring water use, soil fertility (macro and micronutrients) and the respective impacts on plant production. However, one of the main gaps and challenges are related to the potential side effects of applying hydrogel in soil-plant interaction in natural systems. Therefore, it is key to better understand a few aspects, including assessing the secondary effects of hydrogels on natural systems (forestry, agriculture, livestock, and horticulture), evaluating the use of hydrogel in closed systems, appraising the effect of hydrogel use on soil clays, and analyzing the effect of rhizosphere microbiota on soil carbon sequestration potential. Thus, consistent and robust results need to be generated that will support the decision-making about the potential of using hydrogel in agrosystems.

Among the potential side effects, the following can be highlighted: potential increase in water infiltration rates, improve soil structure, reduce soil compaction and improve aggregate stability; increased cation exchange capacity in the soil (potential negative charges from the hydrogel); greater probability of macro and micronutrient absorption by mass flow, diffusion and root interception; greater plant resistance to water stress, less susceptibility to contamination by pathogens and diseases; potential increase in the production of plant phytomass and increase and vigor of the root system of plants due to the presence of the hydrogel; establishment of an attractive niche for soil microbiota, with a potential increase in biodiversity in the rhizosphere. These effects may result in greater carbon sequestration in the soil since greater plant biomass will be deposited in the soil during the microbial decomposition process. However, hydrogel application and its properties might induce side effects, making it resistant to biodegradation or degrading into undesired products causing waste management issues.[78] Therefore, using biodegradable monomers and adequate choice of properties and chemical composition are fundamental to achieve a product environmentally friendly.

Hydrogels (and biochars) have drawn attention in the agricultural and forestry sectors as potential delivery devices for applications that require controlled release (water, nutrients, xenobiotics or

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[78] Saruchi, N et al. "Biodegradation of Gum tragacanth acrylic acid based hydrogel and its impact on soil fertility" (2015) Polymer Degradation and Stability 115, 24,31.

other agrochemicals). One of the constraints of the traditional application of chemicals in the agricultural sector is the use of large amounts of pesticides, probably for a period of time longer than necessary to achieve its goal (e.g. reduce the population of a pest, insect or disease or even to eliminate an invasion plant species etc.), which leads to crop damage and environmental contamination. The controlled release of agrochemicals is the solution to this problem; Controlled release is a mechanism in which agrochemical is released to plants at predefined rates.[79] Different hydrogels can be used to release agrochemicals in an effective and controlled manner once we understand in-depth and mitigate any possible negative side effects to the environment.

5. LESSONS LEARNED

Although a lack of technological innovation and advancement could inhibit this CCUS technique, this study, however, identifies inadequate commercial and regulatory policies as the major inhibitors to carbon use and application. Thus, governments through appropriate and adequate policies and other regulatory frameworks need to stimulate industrial innovation and enable the circular economy in this regard. In other words, governments should engage the public, industries, investors, etc. to encourage a scale-up of carbon use and carbon-based products and services.

Second, this study identifies a stable regulatory framework as essential to increase the returns on investment in CCUS technologies. This is because in the absence of an optimum policy framework, carbon-based products and services will be unable to compete profitably in the market, especially since their technological development is still preliminary. For instance, this study identifies that the production costs of carbon-based fuels and chemicals are several times higher than conventional fuels. However, the study further identifies that polymers such as hydrogel derived from carbon can be produced at lower costs than their fossil counterparts although the market for such products is relatively small. Thus, well-developed policies for carbon utilization are significant to enhance markets for carbon-based products and services. Such policy framework may include a

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[79] Ibid.

prescribed minimum percentage of carbon-based products and services for manufacturers and industries, as well as for public procurement expenditure. It may also include a regulatory framework that raises consumer awareness and promote responsible consumerism through policies such as labeling, certification, and testing of low-carbon products. Governments may also adopt incentive driven CCUS implementation and technological advancement through economic incentives such as *inter alia*, tax credits for the capture and conversion of carbon into useable products, and carbon taxes or emission levies for industries.

Third, this study identifies hydrogel as a viable technique for the maximization in the capture of atmospheric carbon, also known as direct air capture (DAC). Carbon dioxide is the most significant greenhouse gas and consequently results in negative ramifications for the environment. As such, it has become increasingly important to develop a noble destination for carbon dioxide. In pursuit of this goal, it was determined that an effective way to meet mitigation requirements was the production of oxalate from industrial carbon dioxide emissions using the reverse fuel concept. This concept presents several advantages inclusive of the redundancy of reagents owing to the use of solid electrolytes, the superiority of product separation and the use of photons to promote anode and cathode reactions. Through polymerization and other synthesis processes, oxalate and other bio-monomers are combined into hydrogel.

This study evaluates the beneficial potential of hydrogels in improving physical, chemical and biological attributes of the soil in the agricultural, livestock and forestry system. It demonstrates that there are many potential side effects for applying hydrogel application including a potential increase in water infiltration rates, an improvement in the soil structure, a reduction in soil compaction, greater resistance to water stress and a severely decreased susceptibility to contamination by pathogens and diseases. Despite the many advantages of hydrogel, this process isn't without obstacles. From this study, it is apparent that hydrogel can have significant adverse environmental impacts such as environmental pollution, and waste management challenges. These hurdles make it imperative for the international standardization of CCUS techniques or land-based carbon dioxide removal (CDR), as well as the development of an international standard to guide the life-cycle assessment of carbon use and applications.

As such, with the ever-growing need to mitigate greenhouse gas emissions, the only way to achieve the goals within the set timeline is to implement CCUS technologies. Unfortunately, owing to financial restraints, market restraints and governmental resistance among States, the effective implementation of these technologies is becoming increasingly challenging. Therefore, in analyzing mechanisms available to increase carbon sequestration for the use of manufacturing carbon-based products, a viable option is the use of hydrogels. This technique presents a plethora of advantageous side effects and benefits, not simply for carbon sequestration but also the improvement of population health and water quality. Notwithstanding the potential challenges inclusive of waste management, environmental impacts, and variability in different weather environment conditions, the hydrogel is a demonstrably beneficial approach for the maximum absorption of atmospheric carbon.

6. CONCLUSION

It is indisputable, as demonstrated by the significant research and data on the subject, that carbon capture, utilization and storage are imperative in the reduction of greenhouse gases in the atmosphere and are crucial to realize the objectives outlined in the Paris Agreement. It has been proven that CCUS is the one of the main viable technology options that can contribute to the realization of net emission reductions on the scale required by the Paris Agreement. The technology contemplated for CCUS already exists and has, in some cases, already been implemented for commercial use. However, its widespread implementation has not yet occurred owing to some difficult barriers including exorbitance, health and safety concerns, lack of pricing and skepticism from the public. Notwithstanding this, however, it has been shown herein how these technologies for the reduction of CO2 are currently utilized and have been developed. Accordingly, this paper demonstrated how these technologies have been implemented and the products which have derived therefrom the life cycle of these products, and the alternative options. Most importantly, the focus was placed on the question of hydrogel, to implement a new CCUS value chain that involves products based on carbon sequestration in land-based carbon dioxide removal (CDR), leading generally to a high potential for mitigating carbon dioxide emissions. It was consequently important to analyze how these technologies worked as well as the side effects of the hydrogel application. It was demonstrated that the hydrogel application showed numerous advantageous benefits including many benefits to soil quality and agricultural production. However, it was also demonstrated that the hydrogel could cause problems such as environmental pollution, waste management and problems associated with scarcity of area for the proper management of solid waste. Whilst there are still a few gaps and difficulties to overcome, this paper shows that owing to its properties and characteristics, especially as a polymeric electrolyte with a superior capacity for conducting physical separation, a hydrogel is a viable technique for the maximum capture of atmospheric carbon.

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