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A Review on Nano-Based Technologies for Decarbonization of Chemical Industrial Processes

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Decarbonization of chemical industrial processes is a critical initiative aimed at reducing carbon emissions in the industrial sector. Decarbonization strategies encompass a spectrum of approaches.
As industries strive to the meet climate goals of the Paris agreement, decarbonization plays a pivotal role in achieving a more sustainable and eco-friendly future. In the case of the hard-to-abate industries where the production of the carbon dioxide is intrinsic in the production cycle, nanotechnology-based technologies and the use of nanoparticles for exhaust gas adsorption are gaining more and more importance in this field in the last period.The present work will critically examine some of the most promising nano-based technologies for the decarbonization of hard to abate sectors.

1. Introduction

As global economy rapidly expands and energy consumption increases, world is confronted with the growing dual difficulties of meeting both its energy supply and demand needs. In recent times, there has been a concerning rise in the levels of CO_2 emissions. Consequently, it appears imperative to take measures to decrease greenhouse gas emissions (Trinca, Rispoli, et al., 2023). According to the Paris Agreement, adopted by 196 parties in 2015, to achieve the decarbonization goals and to accelerate the transition to green energy, the main focus in the short term has to be on the current industrial system. The industrial sector is the most challenging and expensive sector to decarbonize adopting the available technologies.
To diminish the carbon footprint generated by industries, it is essential to discontinue the reliance on fossil fuels as the primary energy source (Segneri et al., 2022). The most straightforward approach to achieve this is by adopting alternative energy sources such as non-fossil fuel-derived hydrogen, the thermal treatment of waste to support a circular economy and zero-waste practices, while recovering the energy contained in the waste itself, and the utilization of e-fuels (Colelli et al., 2023).
The hardest part of this transition is due to the fact that CO_2 emissions in the hard-to-abate industries, such as cement, steel and chemical, it is not only caused by the use of fossil fuels, but also by the fact that the generation of CO_2 is intrinsic in the production processes of various commodities (such as cement, lime, steel, glass etc.). The first step towards decarbonization of this sector is the replacement of the main source of CO_2 emission in the production cycle, as an example, in the cement production the calcium carbonate ($CaCO_3$) is the main raw material in the production of the clinker, but it is also responsible for the majority of the CO_2 emission of the production site (about 60 % of the total emission); this has resulted in the need to replace limestone, clays, and shale rocks, either completely or partially, with various alternative materials (Rosa et al., 2023). These alternatives primarily consist of calcium-based substances, but also include silicates, aluminates, and iron sourced from different industrial processes.
A net zero-emission energy systems requires significant changes in the way energy is produced and used, which can only be achieved through a broad set of technologies (Falana et al., 2024). Carbon Capture, Utilization, and Storage (CCUS) is the only set of technologies that can directly reduce emissions in key sectors, as well as remove CO_2, without a direct modification of the process itself. In fact, the complete

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retrofitting of an existing plant, in particular in those sectors (hard-to-abate) may be the real bottleneck of all decarbonization processes. Usually, the CCS and CCU technologies act in the downstream of the process, without leading to any modification of the core (this is true for classical post and pre-combustion capture technologies such as physical and chemical absorption, physical and chemical adsorption, whereas it is not true in the case of oxycombustion or integrated calcium looping etc.).
This paper aims to give a brief notion about the actual CCS technologies used and then provide a systematic review of the nanofluids, in particularly amine-based, water-based, and methanol-based nanofluids, as potential enhancers for carbon capture processes.

2. State of the art

The CCS method is based on the separation of CO_2 from a flue gas, biogas or a syngas and its transfer, after compression and liquefaction, by pipeline to an onshore or offshore storage location (Trinca, Bassano, et al., 2023). The most important CCS technologies that are being already used are: post-combustion, oxy-combustion and pre-combustion. The post-combustion capture (PCC) is a technology that capture CO_2 from the flue gas of a plant. PCC has many requirements that can affect both the CapEx (Capital Expenditures) and OpEx (Operational Expenditures). The solvent is sensitive to impurities, so additional equipment is needed and lots of energy is required to regenerate the solvent that will be recycled to the absorption process. The main reasons for the use of this technology are the readiness of the technology at the required scale (TRL9) and the fact that the current structures are fully capable of being updated by this feature (Paltsev et al., 2021). Other type of PCC technologies are adsorption-based and membrane-based processes. They are characterized by relatively simple process schemes, they don’t have flowing liquid phase, and have fewer auxiliary streams and fewer pieces of equipment, which make them cost-competitive at smaller scales. On the other hand, adsorption column components and membrane modules are normally limited in their maximum size and benefit less than the absorption processes from the economies of scale. Furthermore, the sensitivity of these technologies to impurities in the flue gas, such as water vapor, may vary depending on the material used. Oxy-combustion is a technology in which the fuel is burnt in high purity oxygen, instead of air. The exhaust gases obtained by combustion are mainly CO_2 and water vapor, with limited amount of SO_x, NO_x and particulates. The purification of these gases is a lot less expensive operation than the one in the PCC process; the high purity CO_2 stream can be processed for transport and storage after water condensation. The drawback of this process is the large amount of energy required for the production of high purity oxygen stream through an ASU and the necessity to operate on the combustion chamber or on the process core. In the pre-combustion capture systems, syngas fuel is purified from CO_2 usually by physical absorption. Since the syngas is usually obtained at higher pressure with respect to post-combustion case. A key benefit of this method is the high concentration of CO_2 in the output stream. However, this technology, like other technologies, may require great amount of energy for the regeneration of the absorbent used for the CO_2 capture, and also other energy to work at lower temperature than 0 °C in some cases. The last problem is the difficulty to update existing industrial structures with this system (Raza et al., 2019).

3. Nanoparticles for CO_2 chemical absorption

The high capital costs and substantial energy requirements associated with absorption processes have prompted extensive research into methods for improving CO_2 mass transfer while simultaneously reducing capital expenses (Trinca et al., 2023). Researchers commonly recommend two primary categories for enhancing absorption: active and inactive approaches. Active methods involve applying external forces, such as an external magnetic field, to the absorber system. Inactive methods, on the other hand, refer to mechanical and chemical approaches aimed at improving absorption performance (Hoseini et al., 2019). Nanofluids, a novel type of absorbent, are produced using an inactive method for the enhancement of the absorption performance by dispersing nanosized materials in base fluids. Nanofluids can be categorized based on the type of nano-additive that is added to the base solvent or based on the base solvent, the most important solvents used for nanofluids are amine solvents, distilled water and methanol (Tavakoli et al., 2022). Nanofluids are being explored in the field of carbon capture for their potential to enhance the efficiency of various processes involved in capturing and storing carbon dioxide (CO_2). The unique properties of nanofluids can be advantageous in addressing some challenges associated with traditional carbon capture methods. Nanofluids, with their enhanced thermal conductivity and surface area, can potentially improve the absorption and desorption rates of CO_2 in solvents used for carbon capture processes. This can lead to more efficient capture and release of CO_2. Also, nanofluids, by improving heat transfer efficiency, can help manage temperature changes more effectively, optimizing the performance of absorption and desorption units and consequentially they can reduce the duty needed to for the regeneration of the solvents leading to a decrease

of the OpEx of the carbon capture process. Another important characteristic of nanoparticles dispersed in the absorbent solutions is that they can enhance the stability of the absorbents, preventing their degradation over time; furthermore, functionalized nanoparticles can be designed to enhance the selectivity of absorbents, making them more specific in capturing CO_2 while minimizing the capture of other gases.
Due to their characteristics the nanofluids are suited to upgrade the post combustion technologies, enhancing the CO_2 absorption rate and reducing the energy requirement of this type of technologies. In some studies, to assess the reusability and reactivation of nanofluid, some tests were carried out by performing five cycles of CO_2 absorption and desorption. After the five cycles in the various tests depending on the nanoparticles typology, the adsorption capacity of the nanofluid decreased of only 4 - 8 % of its initial value, this implies that the solvents were able to retain, recover, and regenerate almost completely. It was also observed a decrease in the regeneration time of the solvent when the nanoparticles were added to the solvent(Lee et al., 2011).

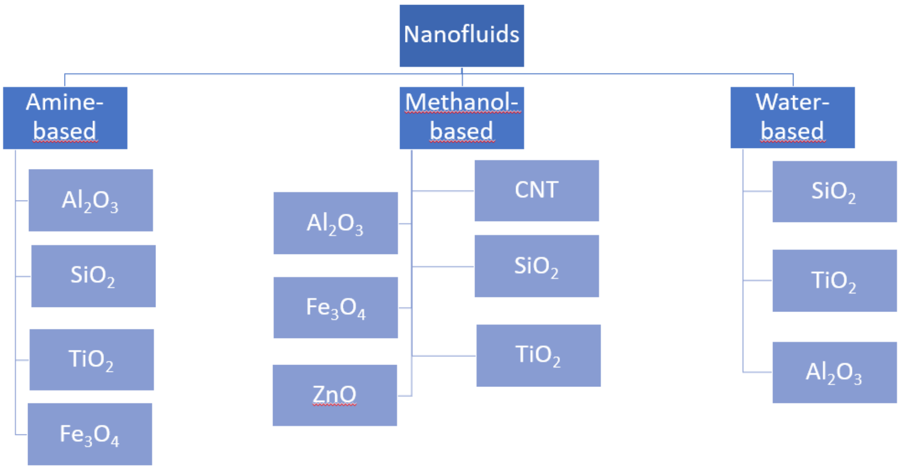

Figure1 Overview of different nanoparticles used and specific solvent

3.1 Amine-based nanofluids

CO_2 exhibits solubility in aqueous solutions containing alkanolamines (Trinca, Patrizi, et al., 2023). The effectiveness of this absorption can be enhanced by introducing PZ (Piperazine) as an activator, and similarly, additives have the potential to accelerate CO_2 absorption. However, due to the presence of diverse species in various amines, the chemical stability and corrosive nature of the resulting products from CO_2 absorption can differ. Corrosion poses challenges for the overall process, leading to a reduction in equipment lifespan. Moreover, the robust chemical bonds formed between amine solvents and CO_2 necessitate significant energy for the desorption process. The substantial energy requirements for solvent recovery and the corrosion issues associated with scrubbers used in CO_2 capture, prompted the exploration of solid sorbents as an alternative approach. Amine-modified nanomaterials have proven to be an effective solution for CO_2 chemical adsorption, due to their low energy consumption, chemical stability, and reversible nature. (Segneri et al., 2023).
Wang et al., (2016) conducted experimental research to explore the impact of nanoparticles on the absorption and release of CO_2 in aqueous MEA solutions. In the stage of diffusion-controlled mass transfer, nanoparticles demonstrate a noticeable improvement in mass transfer efficiency. Specifically, SiO_2, Al_2O_3, and TiO_2 nanoparticles exhibit an enhancement of over 10% in CO_2 absorption, with the maximum increase of the capture effect with the TiO_2 nanoparticles. The bubble breaking effect has the most significant role in overall mass-transfer improvement. Additionally, they investigate the enhancement of CO_2 desorption from rich MEA solutions with nanoparticles under various input heat fluxes. The performance ranking of the three particles is the same of the one for the increase of absorption with the TiO_2 leading and the SiO_2 and Al_2O_3 following. When regenerating the rich solvent from 0.4 mol CO_2/mol MEA to 0.25 mol CO_2/mol MEA, the solution containing TiO_2 nanoparticles demonstrates a time savings of approximately 42% in the desorption process.
Jiang et al., (2014), tested two different amine solvent, made of MEA and MDEA; from this study it is observable that the addition of the majority of nanoparticles can markedly enhance the CO_2 absorption rate. It is also shown that the most efficient nanoparticle is the TiO_2. It, also, can be highlighted that the higher absorption rate is obtained with the MEA and not with the MDEA nanofluids, this is due to the higher reactivity that leads to the higher absorption rate of the base solvent, but it can be observed a higher increase in

absorption rate from the base solvent in the case of MDEA, which indicates the chemical reaction is an important factor and the enhancement effect becomes weak with the increase in the chemical reaction rate.
Komati & Suresh, (2008) highlighted that with the use of a nanofluid with a magnetic nanoparticle, such as Fe_3O_4, dissolved in it, its absorption rate can be enhanced with the application of a magnetic field; results showed that with the introduction of 0.39 vol% of nanoparticles, it can be obtained an increase in absorption capacity of 92.8 % compared to the base fluid alone, this is possible with the use of nanoparticles with a diameter inferior of 15 nm, in this way the single nanoparticles can act as single-domain magnetic particles.
The efficacy of Al_2O_3 and SiO_2 nanoparticles in improving absorption was evaluated by dispersing them in three distinct base fluids: MDEA, PZ, and MEA. The mass transfer coefficient, measured on the liquid side, demonstrated a notable improvement in the absorption kinetics of the PZ absorbent following the addition of nanoparticles. It is interesting that the value of increased ratio of absorption kinetics by nanoparticle, as said before, follows the same order with solvent reaction rate with CO_2, which is PZ, then MEA and last DMEA. Results indicated that the enhancement of nanoparticle concentration reduces the absorption rate due to the solution's elasticity(Wang et al., 2016). In a different investigation, Ashrafmansouri & Nasr Esfahany, (2014) examined how the introduction of colloidal nanosilica to the 2-amino-2-methyl-1-propanol (AMP) solvent affects CO_2 absorption performance within a stirred vessel. Their findings revealed that with an increase in nanoparticle concentration the absorption rate increases and the volumetric mass transfer coefficient on the liquid side decreases. In general, it can be concluded that absorption capacity increases by increasing nanoparticle concentration in the base fluid.

3.2 Water-based nanofluids

As a non-toxic and natural absorber, water can form physical bonds with both CO_2 and H_2S. Distilled water (DW) offers certain advantages as an absorber, such as its high surface tension and suitable capacity for CO_2 absorption. However, it exhibits weak performance in CO_2 recovery and has a relatively low absorption rate. Consequently, numerous researchers have proposed the dispersion of nanoparticles in untreated water as a means to significantly enhance gas absorption in the resulting nanofluid (Elhajj et al., 2014).
An appropriate mathematical model was developed by Darabi et al., (2017)., on the carbon dioxide adsorption by hollow fiber membranes using two different solutions of SiO_2/water and CNT/water; in this work the Brownian motion and Grazing effect were considered as the main reasons of mass-transfer enhancement. In these conditions, an increase of 32 % in the CO_2 absorption rate was observed using a nanofluid with a 0.05 wt % of CNT nanoparticles, instead the increase with the use of the silica nanoparticles was only of the 16 % in the CO_2 absorption rate. The reason is the lower adsorption capacity of SiO_2 nanoparticles compared to CNT nanoparticles. In their work Samadi et al., (2014), studied the mass transfer performance of CO_2 absorption in a wetted-wall column using various nanofluids, made of water and different nanoparticles, these studies were conducted using magnetic nanoparticles, in fact part of the tests were carried out under the effect of a magnetic field. Through this study they highlighted that the increase in liquid flow rate led to higher mass transfer flux and mass transfer coefficient and that the formation of small eddies, due to the elevated liquid flow rate, significantly improved mass transfer characteristics through their rapid movements. Adding γ-Al_2O_3 nanoparticles to water enhanced absorption performance, and adding greater nanoparticles content in the nanofluid result in improved absorption. For instance, using Al_2O_3/water nanofluid with 1 vol % alumina particles increased the mass transfer rate by about 40–55 % compared to the solvent without nanofluid. Similarly, the mass transfer rate increased with the volume fraction of nanoparticles in Fe_3O_4/water nanofluid. However, under all conditions, the mass transfer rates and coefficients were lower than those of the base fluid (water). The use of TiO_2/water nanofluid decreased mass transfer coefficients and mass flux. At a volume fraction of 0.05 %, the reductions in mass transfer coefficient and rate were 16% and 5%, respectively.
The impact of a magnetic field on CO_2/water absorption depended on its direction. Experiments showed that a magnetic field with the same direction as the falling film strengthened CO_2/water absorption, while a field against the direction weakened it. In the presence of a magnetic field (1.5 A electric current with the same direction as the falling film), mass transfer flux and coefficient increased by 22.35 % and 59 %, respectively, compared to experiments without a magnetic field. The effectiveness of magnetic mixing can be attributed to the direct transfer of movement energy to particles by the magnetic field. This prompt particle movement increases the relative velocity between the particle surface and the surrounding medium, enhancing absorption performance. Instead, Haghtalab et al., (2015) studied the absorption rate of CO_2 in pure water and the absorption rate enhancement in nanofluid composed of water and nanoparticles of SiO_2 or ZnO. They highlighted that using a 0.1 wt % of ZnO nanofluids presented a higher absorption rate enhancement than the SiO_2 nanofluids at the same weight of nanoparticles, for this nanofluids composition the absorption enhancement is respectively 14 % for the zinc monoxide and 7 % for the silica dioxide. Furthermore, they measured the different solubility of CO_2 in the ZnO nanofluids for a range of composition of the nanofluid itself,

the percentage in weight of the ZnO ranged from 0.05 to 1 wt %, and they obtained that the solubility was enhanced by increasing ZnO weight percent, in the same temperature and pressure conditions.

3.3 Methanol-based nanofluids

Methanol-based nanofluids represent a unique category of absorbents that enhance CO_2 absorption in synthetic natural gas (SNG) systems. The absorbent's high selectivity, cost-effectiveness, and suitability for high-pressure natural gas streams make it a promising option for these applications. Additionally, its advantage lies in the lower temperatures required for the regeneration process compared to aqueous solutions, attributed to its smaller latent heat and lower boiling point. Consequently, non-aqueous alkanolamines emerge as favorable choices for improving CO_2 absorption performance. However, adherence to Henry's law of solubility dictates maintaining the absorbent temperature at approximately -20 °C to increase absorption rates, necessitating substantial energy consumption to sustain methanol at such low temperatures. Incorporating nanoparticles into the base fluids proves to be an effective strategy for enhancing CO_2 absorption in this context (Budzianowski, 2017). Lee et al., (2011) in their work obtained an evaluation of the dispersion stability for Al_2O_3/methanol and SiO_2/methanol nanofluids at different concentrations; the authors discovered that the optimum concentration for both the nanoparticles of silica and alumina range from 0.01 to 0.05 vol %in methanol based nanofluids. It is, also, noticeable that the CO_2 absorption rate is enhanced up to 4.5% at 0.01 vol % of Al_2O_3/methanol nanofluids at 20 °C, and 5.6 % at 0.01 vol % of SiO_2/methanol nanofluids at -20 °C, and also that the pH variation is closely related with the absorption enhancement by the particles dissociation. Instead, Pineda et al., (2014), worked on a rotating annular contactor with trays to test the CO_2 absorption rate of pure methanol and Al_2O_3, SiO_2 and TiO_2 methanol-based nanofluids, all tested in both co-current and counter-current; from this they highlighted that the performance of all the solvents were better in a counter-current flow system; the addition of trays enhances the absorption rate up to 9 %, 10 %, 6 % and 5 % for pure methanol, alumina, silica and titania, respectively, for counter-current flow. Furthermore, the rotation effectiveness is greater for Al_2O_3 and TiO_2 with an increase of the absorption rate for the CO_2 of 24.2 % and 14.4 %, respectively. The reason for the enhance of the absorption rate is the increased contact time between the liquid and the bubble due to the use of trays. From this study it is, also, discovered that SiO_2 nanofluids do not enhance their mass transfer any further when the liquid is put in motion.

4. Conclusions

The urgent challenge of contemporary society lies in the escalating problem of global climate change, primarily driven by excessive carbon dioxide emissions. This review elucidates recent progress in employing nanofluids for the absorption of CO_2. From this work it can be highlighted the unique properties of nanoparticles, such as enhanced thermal conductivity, surface area, and stability, offer promising avenues for improving the efficiency of carbon capture and reducing operational costs.

Notably, the discussion on amine-based nanofluids highlights their effectiveness in chemical adsorption, with studies demonstrating significant enhancements in CO_2 absorption rates, particularly with the inclusion of nanoparticles like TiO_2. Water-based nanofluids, despite challenges in mass transfer rates, showcase potential improvements in absorption performance, with magnetic fields proving to be a contributing factor. Meanwhile, methanol-based nanofluids present a distinctive category with applications in synthetic natural gas systems, showcasing promise in high-pressure natural gas streams.

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References

Ashrafmansouri, S.-S., & Nasr Esfahany, M. (2014). Mass transfer in nanofluids: A review. *International Journal of Thermal Sciences*, *82*, 84–99. https://doi.org/10.1016/j.ijthermalsci.2014.03.017

Budzianowski, W. M. (Ed.). (2017). *Energy Efficient Solvents for CO2 Capture by Gas-Liquid Absorption*. Springer International Publishing. https://doi.org/10.1007/978-3-319-47262-1

Colelli, L., Segneri, V., Bassano, C., & Vilardi, G. (2023). E-fuels, technical and economic analysis of the production of synthetic kerosene precursor as sustainable aviation fuel. *Energy Conversion and Management*, *288*, 117165. https://doi.org/10.1016/j.enconman.2023.117165

Darabi, M., Rahimi, M., & Molaei Dehkordi, A. (2017). Gas absorption enhancement in hollow fiber membrane contactors using nanofluids: Modeling and simulation. *Chemical Engineering and Processing: Process Intensification*, *119*, 7–15. https://doi.org/10.1016/j.cep.2017.05.007

Elhajj, J., Al-Hindi, M., & Azizi, F. (2014). A Review of the Absorption and Desorption Processes of Carbon Dioxide in Water Systems. *Industrial & Engineering Chemistry Research*, *53*(1), 2–22. https://doi.org/10.1021/ie403245p

Falana, J., Osei-Kyei, R., & Tam, V. W. (2024). Towards achieving a net zero carbon building: A review of key stakeholders and their roles in net zero carbon building whole life cycle. In *Journal of Building Engineering* (Vol. 82). Elsevier Ltd. https://doi.org/10.1016/j.jobe.2023.108223

Haghtalab, A., Mohammadi, M., & Fakhroueian, Z. (2015). Absorption and solubility measurement of CO2 in water-based ZnO and SiO2 nanofluids. *Fluid Phase Equilibria*, *392*, 33–42. https://doi.org/10.1016/j.fluid.2015.02.012

Hoseini, N., Esfahany, M. N., Etesami, N., Afarani, H. T., & Fadaie, E. (2019). INVESTIGATION OF THE EFFECT OF ELECTRIC FIELD ON CO2 ABSORPTION IN WATER/Fe3O4 NANOFLUID. *Brazilian Journal of Chemical Engineering*, *36*(3), 1333–1342. https://doi.org/10.1590/0104-6632.20190363s20180478

Jiang, J., Zhao, B., Zhuo, Y., & Wang, S. (2014). Experimental study of CO2 absorption in aqueous MEA and MDEA solutions enhanced by nanoparticles. *International Journal of Greenhouse Gas Control*, *29*, 135–141. https://doi.org/10.1016/j.ijggc.2014.08.004

Komati, S., & Suresh, A. K. (2008). CO_2 absorption into amine solutions: a novel strategy for intensification based on the addition of ferrofluids. *Journal of Chemical Technology & Biotechnology*, *83*(8), 1094–1100. https://doi.org/10.1002/jctb.1871

Lee, J. W., Jung, J.-Y., Lee, S.-G., & Kang, Y. T. (2011). CO2 bubble absorption enhancement in methanol-based nanofluids. *International Journal of Refrigeration*, *34*(8), 1727–1733. https://doi.org/10.1016/j.ijrefrig.2011.08.002

Paltsev, S., Morris, J., Kheshgi, H., & Herzog, H. (2021). Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. *Applied Energy*, *300*, 117322. https://doi.org/10.1016/j.apenergy.2021.117322

Pineda, I. T., Choi, C. K., & Kang, Y. T. (2014). CO2 gas absorption by CH3OH based nanofluids in an annular contactor at low rotational speeds. *International Journal of Greenhouse Gas Control*, *23*, 105–112. https://doi.org/10.1016/j.ijggc.2014.02.008

Raza, A., Gholami, R., Rezaee, R., Rasouli, V., & Rabiei, M. (2019). Significant aspects of carbon capture and storage – A review. *Petroleum*, *5*(4), 335–340. https://doi.org/10.1016/j.petlm.2018.12.007

Rosa, D., Segneri, V., Di Palma, L., & Vilardi, G. (2023). Synthesis and CO2 Adsorption Capacity of Biomass Waste Functionalized by Nanoparticles. *Chemical Engineering Transactions*, *101*, 127–132. https://doi.org/10.3303/CET23101022

Samadi, Z., Haghshenasfard, M., & Moheb, A. (2014). CO_2 Absorption Using Nanofluids in a Wetted-Wall Column with External Magnetic Field. *Chemical Engineering & Technology*, *37*(3), 462–470. https://doi.org/10.1002/ceat.201300339

Segneri, V., Ferrasse, J. H., Trinca, A., & Vilardi, G. (2022). An Overview of Waste Gasification and Syngas Upgrading Processes. *Energies*, *15*(17), 6391. https://doi.org/10.3390/en15176391

Segneri, V., Trinca, A., Libardi, N., Colelli, L., Micciancio, M., & Vilardi, G. (2023). Nanoparticles used for CO2 Capture by Adsorption: a Review. *Chemical Engineering Transactions*, *101*, 133–138. https://doi.org/10.3303/CET23101023

Tavakoli, A., Rahimi, K., Saghandali, F., Scott, J., & Lovell, E. (2022). Nanofluid preparation, stability and performance for CO2 absorption and desorption enhancement: A review. *Journal of Environmental Management*, *313*, 114955. https://doi.org/10.1016/j.jenvman.2022.114955

Trinca, A., Bassano, C., Verdone, N., Deiana, P., & Vilardi, G. (2023). Modelling and economic evaluation of CCS/PtX technologies integrated into biomass MTG plants. *Journal of Environmental Chemical Engineering*, *11*(1), 109184. https://doi.org/10.1016/j.jece.2022.109184

Trinca, A., Patrizi, D., Verdone, N., Bassano, C., & Vilardi, G. (2023). Toward green steel: Modeling and environmental economic analysis of iron direct reduction with different reducing gases. *Journal of Cleaner Production*, *427*, 139081. https://doi.org/10.1016/j.jclepro.2023.139081

Trinca, A., Rispoli, A. L., Sapone, V., Bubbico, R., & Vilardi, G. (2023). Combined clean hydrogen production and bio-active compounds recovery from spent coffee grounds. A multi-perspective analysis. *Process Safety and Environmental Protection*, *173*, 1–12. https://doi.org/10.1016/j.psep.2023.03.005

Trinca, A., Segneri, V., Ferrasse, J. H., Parisi, M., Patrizi, D., & Verdone, N. (2023). Nanocatalysts Used for Tar Cracking Present in the Syngas from Gasification of Municipal Solid Waste. *Chemical Engineering Transactions*, *101*, 139–144. https://doi.org/10.3303/CET23101024

Wang, T., Yu, W., Liu, F., Fang, M., Farooq, M., & Luo, Z. (2016). Enhanced CO2 Absorption and Desorption by Monoethanolamine (MEA)-Based Nanoparticle Suspensions. *Industrial and Engineering Chemistry Research*, *55*(28), 7830–7838. https://doi.org/10.1021/acs.iecr.6b00358