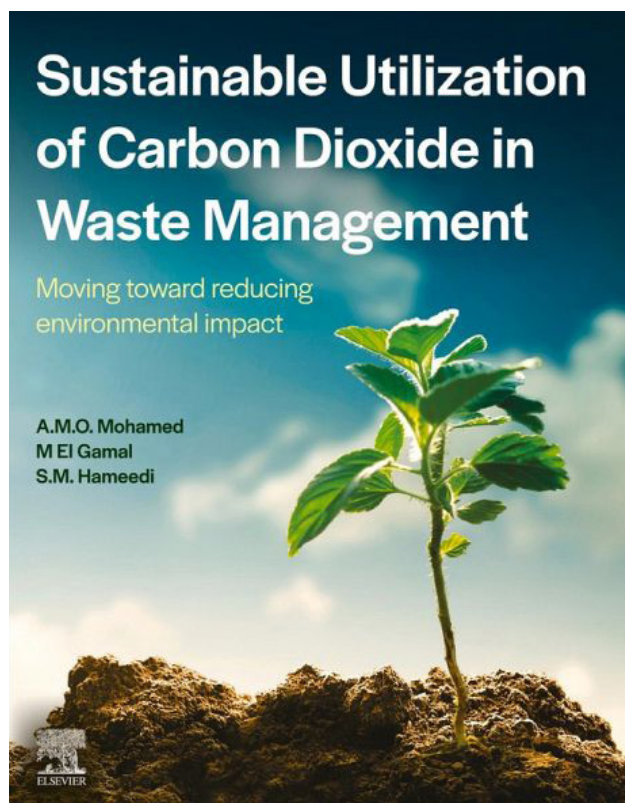


## BOOKS REVIEW



### SUSTAINABLE UTILIZATION OF CARBON DIOXIDE IN WASTE MANAGEMENT

Edited by: A.-M. O. Mohamed, M. El Gamal, S. Hameedi and E.K. Paleologos

The book "Sustainable Utilization of Carbon Dioxide in Waste Management" illustrates several options for the sustainable use of carbon dioxide (CO<sub>2</sub>) in the waste management sector. The authors highlight the main environmental impacts of waste generation and demonstrate the importance of applying carbon capture (CC) methods to improve the level of sustainability of waste management. They also provide the readers with the best available practices for CC, carbon storage (CS) and carbon utilization (CU) through the treatment of a wide range of waste types to improve the lifecycle benefits of waste treatments, with particular regard to the carbon footprint.

More specifically, the book is divided into 14 chapters. The first chapters introduce basic CC principles, with a critical view on their level of sustainability and the need for improvements, and present the methods to assess the benefits of CC following a Life Cycle Thinking approach. The

second half of the book is a detailed survey on carbonation techniques that can be applied to a large variety of waste: from residues of industrial processes and air pollution control technologies to waste coming from extraction sites, construction and demolition activities and desalination processes.

Chapter 1 starts with an overview of carbon emissions worldwide by sector and the expected trend for the next future. The authors discuss the opportunities given by available markets for CC and CU, i.e. CO<sub>2</sub> reuse after sequestration, for instance in the beverage industry, in greenhouses, as a feedstock to produce value-added products, such as polymers, reprocessed aggregates, slags, ashes, chemicals, and synthetic fuels. The chapter also introduces basic principles related to the waste hierarchy, sustainable development, circular economy and end-of-waste concepts, showing the importance of defining appropriate end-of-waste criteria involving waste characterization, an assessment of technical, market, environmental and health impacts and the procedures for waste reprocessing. The authors present case studies on three waste streams to show the complexity behind the development of end-of-waste criteria: construction and demolition waste, industrial waste, and CC products. The end-of-waste status of the latter is particularly important to mitigate global warming and it depends on the related environmental impacts and the presence of an available end market.

Chapter 2 enters the details of carbon capture and storage (CCS) and CU processes. Both concepts require the separation of CO<sub>2</sub> from a waste gaseous stream originating from post-conversion (e.g., combustion), pre-conversion (e.g., syngas formation) or oxy-fuel combustion (which increase CO<sub>2</sub> concentration in the waste gas) processes. Despite the significant reduction in the global warming potential thanks to CC, the authors underline an increase in other environmental impacts (eutrophication, acidification, photochemical oxidant formation, human toxicity and ecotoxicity), stressing the need for cleaner technologies. In addition, the costs are related to the level of purity of the CO<sub>2</sub> emitted, which is the highest in fermentation processes and the lowest in oil refining. After separation, CO<sub>2</sub> is compressed, transported and injected into deep geologic formation and seabed or into oilfields for enhanced oil recovery (EOR). The chapter then presents the main applications of CU: carbonation/acidification of drinks and food, production of polymers, chemicals and fuels by chemical, biological and electrochemical conversion, and fixation in inorganic compounds, which is the main subject of the book. The authors then review examples of large-scale applications of CU projects worldwide and provide a list of

products with the largest estimated potential in terms of economic value in the European Union (EU), proteins from microalgae and synthetic fuels showing the highest values. Overall, CCS and CU are expected to contribute to 20–25% of the CO<sub>2</sub> emission reduction needed to comply with the 2050 targets of the International Energy Agency to halve energy-related CO<sub>2</sub> emissions. The chapter ends with an overview of the EU policies supporting CCS and CU, such as the Emission Trading System (EC/410/2018), the Renewable Energy (2018/2001/EU) and the Energy Efficiency (2012/27/EU) Directives.

Chapter 3 describes the basic principles of Life Cycle Thinking, with a focus on the necessary steps to perform a Life Cycle Assessment (LCA) of CO<sub>2</sub> utilization technologies and processes, in particular the aim and scope definition, the definition of boundaries, the inventory analysis, the Life Cycle Impact Analysis, the sensitivity analysis and the interpretation of the results. The authors point out the need for improvements in the LCA approach, specifically the need for a uniform LCA framework allowing the direct comparison between different technologies/processes and reducing the effect of the evaluator's choice.

In Chapter 4, the authors enter the technical details of waste carbonation, presenting carbonation reaction kinetics. More specifically, the chapter focuses on the factors that limit the reaction rates between an alkaline waste and CO<sub>2</sub>, such as the diffusion of CO<sub>2</sub> and alkaline ions through the liquid film, diffusion through the boundary layer (product layer) and diffusive processes slowed down by changes in porosity.

Chapter 5 deals with mineral carbonation, i.e. the production of calcium- and magnesium-based carbonated as partial substitutes for Portland cement and aggregates. In particular, the accelerated carbonation (AC) process is described, which is characterized by low cost (due to the exothermic nature of the reactions involved), stability of the precipitated materials, high carbon fixation rates, ability to immobilize heavy metals, the pH neutralizing potential of the products and their possible use in the construction sector or in the chemical industry. Contrarily to natural carbonation, AC lasts from a few minutes to a few hours due to the higher concentration and purity of the CO<sub>2</sub> stream. The authors distinguish between direct and indirect AC, the latter involving the extraction of alkaline metals from the solid matrix. The chapter then describes the principles of mineral carbonation, showing the main chemical reactions involved, and the main parameters that influence the process: the type of surface activation (through grinding, heat/steam application, acidification, application of magnetic fields or sonication), the characteristics of the CO<sub>2</sub> stream, the reactor used, the reacting media (including process parameters like temperature, pH, liquid-to-solid ratio and pressure), and the product's nature. Finally, the main products and the several possible uses are described.

In Chapter 6, the authors discuss specific carbonation processes and related stages, with the available technologies ready for implementation from laboratory scale to industrial scale. In particular, the chapter focuses on multi-process aqueous processes, considered as more efficient than single-stage processes. Technologies for natural

serpentine carbonation range from TRL3 to TRL7, while technologies for alkaline waste carbonation vary from TRL3 to TRL6. One of these processes, developed by some of the authors of the book for alkaline waste carbonation based on fluidized bed and CO<sub>2</sub> recirculation, is discussed with reference to case studies of potential implementation to process steel slags, to produce sewerage pipes from carbonated Ladle furnace slag and carbonated ground granulated blast furnace slag. The authors present the results of tests carried out in real underground sewerage systems and in saline and acidic environments.

The focus of Chapter 7 is on laboratory-scale methods, in particular fluidized-bed reactor, spouted-bed reactor, high-gravity rotating bed reactor and the use of ultrasound. The authors highlight that the fluidized-bed reactor is particularly advantageous compared to conventional methods because of the enhanced mass transfer and carbonation reactions, and the continuous detachment of the product layer from the reactive material bed. In the spouted-bed reactor, the inert particles enhance the gas-liquid interfacial area and mixing between the two phases. However, the best type of inert particles, the interaction with the gas stream, the degree of separation from carbonated materials and energy optimization strategies must be still investigated in detail. Similar benefits can be achieved with the high-gravity rotating bed reactor, but difficulties in modeling this process were pointed out. Ultrasound works by continuously removing the diffusion limiting layers and breaking up the particles through cavitation and enhanced turbulence. The main drawbacks are related to energy efficiency issues and to the reduced break-up of microparticles caused by cushioning effects related to high solid concentration. Some experimental methods to evaluate the CO<sub>2</sub> uptake are also reviewed.

The authors dedicate Chapter 8 to the carbonation of fly ashes. Different types of combustion fly ashes are reviewed: coal fly ashes, municipal solid waste incineration ashes and modern ashes, i.e. ashes produced with modern technologies such as oxy-fuel combustion. Direct (dry, semi-dry and aqueous) and indirect routes for carbonation are presented and their respective main fields of application: the construction industry and the production of valuable and high-purity precipitated calcium carbonates. Sequestration rates with these methods were reported to range between 50 and 100 g of CO<sub>2</sub> per kg of fly ash.

The sources and characteristics of different types of steel slags are presented at the beginning of Chapter 9. In general, steel and iron slags are depicted as excellent candidates for CO<sub>2</sub> sequestration because of their high amount of CaO. Slags are considered as attractive secondary materials especially for cement manufacturing, aggregate materials for concrete and asphalts. However, possible leaching of heavy metals and slag expansion due to free and unreacted CaO and MgO have slowed down their applications. Regarding the preferred carbonation methods, the authors suggest that dynamic systems (e.g., fluidized, rotating or ultrasonic beds) would increase the CO<sub>2</sub> uptake than static beds because of the increased mass transfer, breaking of the aggregated particles and the continuous detachment of the product layer.

Chapter 10 deals with the carbonation of calcium carbide residues, originated from the production process of acetylene, which is the raw material for polyvinyl chloride. The authors review the potential applications of calcium carbide residues and then focus on the applicable carbonation processes. Direct carbonation (especially the fluidized-bed process developed by two of the authors) and indirect carbonation to produce pure calcium carbonate are discussed. Finally, hydration, thermal pretreatment, material modification, and incorporation of inert materials are discussed as possible processes to apply for the production of effective CaO-based sorbents for CO<sub>2</sub> capture.

The carbonation of concrete cement waste, originating from hydrated or non-hydrated cement paste and particles from coarse sand aggregates, is the subject of Chapter 11. The authors focus on the cycle of absorption and release of CO<sub>2</sub> in the process of limestone calcination using concrete cement waste: the carbonation of hardened cement paste may be carried to uptake CO<sub>2</sub> and, meanwhile, produce calcite, which is the main ingredient in limestone production. The CO<sub>2</sub> released during limestone calcination can be recovered and supply again for the carbonation of cement waste. However, the authors stress the need for further studies on concrete production from cement waste, especially to improve the quality of the final products.

In Chapter 12, the authors present the possible strategies for the carbonation of mine tailing waste residues, namely the single-step direct aqueous carbonation and the two-stage carbonation. The chemistry of accelerated carbonation varies slightly depending on the dominant alkaline metal (Ca, Mg and Na). The authors then explain the carbonation processes for different residues (anorthosite, brucite, chrysotile and ophiolitic complexes). The carbonates and high-surface area silica can be used to produce cement and clinker. However, the processes involved are still not competitive on the market.

Chapter 13 provides interesting insights into possible ways to manage brine waste from desalination or the oil/gas industry. As a matter of fact, the discharge of brine waste into the environment has adverse impacts in terms of salinity and presence of heavy metals. Carbonation is applicable to brine waste too, allowing a two-fold opportunity: CO<sub>2</sub> sequestration and reduced impacts on water and soils. The authors present some available carbonation processes for brine waste: the Solvay process (aiming at the production of sodium bicarbonate and sodium carbonate from sodium chloride), methods involving alkanolamine liquefied absorbents or mixed metal oxides, and electro-dialysis for absorption of CO<sub>2</sub> onto alkaline hydroxides to form bicarbonates and carbonates. Possible end products are cementitious construction materials and chemicals.

The last chapter (Chapter 14) deals with cement kiln dust and the applicable carbonation processes. Cement kiln dust composition is strongly related to the fuel used and the feeding material and is classified as hazardous waste with caustic properties. Cement kiln dust can undergo carbonation, whose reactions were modeled by the authors, who evaluated the effect of the many parameters involved. The carbonation degree and its efficiency also

depend on the carbonation process: the authors discuss the use of fluidized-bed, ultrasonic, batch, column, rotating-tube and indirect processes, which may achieve > 70% carbonation efficiency.

Overall, the book provides detailed information on CCS methods and CU strategies for the simultaneous management of different waste types and the mitigation of carbon emissions from human activities. The book is directed to a specialized audience, i.e. environmental and sustainability scientists, engineers and academics in the field. Though mainly focused on mineral carbonation, the book provides insights into the application of other CCS and CU as well as a comprehensive overview of how these techniques fit in the general framework of waste management and the circular economy.

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Suhaib Hameedi gained his BSc. in chemical engineering from Mutah University-Jordan in 2005. His graduation training was in Jordanian phosphate mines company. He joined industries through chemicals manufacturing application in Jordan until 2010, and water treatment application until 2013 in United Arab Emirates. He earned his MSc. degree in chemical engineering from the United Arab Emirates University in 2016 with a thesis about CO<sub>2</sub> capture by steel-making residues. During his masters, he had duties as research assistant in CO<sub>2</sub> capture using industrial wastes. In addition, he was a teaching assistant to thermodynamics for a engineering students course. He joined Zayed University (ZU) in 2016 as a Researcher in environ-

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#### **Book Info:**

*Editors:* Abdel-Mohsen O. Mohamed, Maisa M. El-Gamal, Suhaib Hameedi  
*Imprint:* Elsevier  
*Year of publication:* 2022  
*Page Count:* 606  
*Paperback ISBN:* 9780128234181