A SYSTEMATIC BIBLIOGRAPHY REVIEW ON LIFE CYCLE ASSESSMENT AND CARBON UPTAKE IN CEMENTITIOUS MATERIALS

Uma revisão bibliografia sistemática sobre avaliação do ciclo de vida e absorção de carbono em materiais cimentícios

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Resumo

Enfrentando mudanças climáticas já muito perceptíveis, urge a necessidade de adotar práticas que estejam mais alinhadas com os conceitos de desenvolvimento sustentável. Avaliação de ciclo de vida (ACV) é um método adotado globalmente para avaliar indicadores de potencial de impacto ambiental para os mais diversos produtos e serviços. Na construção civil, particularmente, o método é utilizado para avaliar etapas como a extração de matérias primas, o transporte, a construção, o uso e a fase de demolição, reciclagem, reuso etc. É utilizado, também, como forma de avaliar a utilização de novos materiais e técnicas construtivas, manejo de resíduos e obtenção de certificações ambientais. A aplicação dessa ferramenta possibilita, dentro das diferentes etapas, a realização de diagnósticos para fundamentar a tomada de decisão de consumidores, companhias e governos. Nos anos recentes, alguns pesquisadores têm usado métodos de captura de carbono para diminuir o balanço de CO_2 para materiais a base de cimento. Este artigo, portanto, tem como objetivo realizar uma revisão de literatura sobre o método e sua aplicação para avaliar os benefícios da captura de dióxido de carbono em materiais a base de cimento. Com isso, é possível observar onde residem as maiores lacunas tanto nacional quanto internacionalmente. Foi possível perceber, a partir deste processo, que as lacunas residem, principalmente, nos dados de inventário, na unidade funcional e na falta de normas e padrões para essa aplicação específica.

Palavras-chave: Avaliação de ciclo de vida; Captura de CO_2; Materiais a base de cimento.

ABSTRACT

Faced with already perceptible climate changes, it is increasingly necessary to adopt practices that are more aligned with the concepts of sustainable development. Life Cycle Assessment (LCA) is a method used globally to assess potential environmental impact indicators of the most diverse products and services throughout their life cycle. In civil construction, specifically, the removal of raw material, transportation, construction, use phase, demolition, recycling, reuse, etc. It is used to study the potential of new materials and construction methods, waste management and for environmental certification of buildings and products. The application of this tool enables the diagnosis of each step involved in the process to, consequently, support the decision-making of consumers, companies, and governments. In the recent years, some researchers have been using carbon capture as a method to decrease the CO_2 balance for cement-based materials. This article aims to carry out a literature review about the method and its application to evaluate the benefits of carbon dioxide capture for cementitious materials. With this, it will be possible to observe gaps to be filled to improve the coverage at the national and international level. It was possible to perceive that the biggest gaps reside in the data for the inventory, the function unit applied and the lack of standards for this specific application.

Keywords: Life cycle assessment; CO_2 uptake; Cementitious materials.

1 INTRODUCTION

Within the current context of raw materials scarcity, environmental deterioration, production difficulties, but increasing energy consumption, it has been increasingly necessary to study the life cycle and environmental impact indicators of the most diverse types of materials, products and services. Life cycle assessment (LCA) and tools based in this method are a way to improve and understand the potential environmental impacts, supporting the decision-making process, looking for achieve more sustainable goals (Life Cycle Assessment Handbook, 2012). Four basic steps are necessary to carry out an LCA: objective and scope definition, inventory analysis, impact assessment and, finally, the interpretation of the data obtained (SANTOS et al., 2021). Such steps are common regardless of the LCA purpose. Within civil construction, the life cycle has been studied to make a choice between different materials or construction methods aiming to lower the potential impact indicators of the construction, the use phase, and the end of the life cycle (CUNHA, 2016). Despite being very important for social and economic development, buildings are among the biggest urban responsible for raw materials and energy consumption, both nationally and globally (SINGH et al., 2011). Initially, LCA was designed to reduce production costs and assess which method would have the lowest materials consumption. After that, data analysis such as land use, water use, energy consumption and emission of greenhouse gases were added. Such a mentality change was fostered by the demand of managers, consumers, legislation, banks and activists, the so-called Green Building Movement.

Two of the goals presented by the Cement Industry Technological Roadmap (WBCSD, 2020) are the partial or total replacement of clinker for cement production, given the fact that it is the raw material responsible for the largest share of emissions from the production of Portland cement-based materials, and the promotion of techniques like carbon use, storage and capture. Carbonation is one of the techniques that could be applied to achieve this goal, but it is not because of a lack of knowledge and standards to do so (PARK; TAE; KIM, 2012). This procedure can be done as industrial curing method, as a natural chemical reaction or as an aggregate preparation after demolition. Some papers have already demonstrated the potential of carbon capture in cement-based materials to decrease the amount of CO2 released in the construction industry (ANDRADE; SANJUÁN, 2018; DA SILVA; DE OLIVEIRA ANDRADE, 2017; DE OLIVEIRA ANDRADE et al., 2018; SANJUÁN et al., 2020). The FastCarb project captured 10 to 50kg CO2/t of recycled aggregate (TORRENTI et al., 2022) depending on the aggregate treatment conditions. So, this article aims to highlight the hotspots diagnosed by the authors that are researching about carbon capture in cement-based materials through life cycle assessment. This is a fundamental step to increase the knowledge about the status quo and also point to the next steps on the development on this topic.

2 CO_2 UPTAKE

Carbonation can be classified into two categories. The first of these is natural (or passive) carbonation and the second is accelerated (or active). The active method occurs through environments with high concentrations of CO2 when compared to atmospheric concentration. In addition, the process can occur both in the material already hardened and in the early ages. The passive method occurs in all cement-based materials exposed to an environment where there is an atmosphere conducive to mineralization reactions. The speed and efficiency of the process depends on internal (material) and external (exposure environment) factors. One of the main variables that influence the $CO_2\text{capture}$ potential is the material contact area the with the environment, and, for this reason, the study of coating mortars becomes interesting. It can be demonstrated, through the mathematical modeling of the $CO_2\text{capture}$, that after the structure's demolition period, the material has an exponential increase in the CO_2 absorption per m³ (POSSAN; FELIX; THOMAZ, 2016). The potential can be increased by up to five times after demolition, due to the increased material contact surface with the environment. The carbon dioxide capture through the process of natural or accelerated carbonation of cementitious materials meets criteria that make the process technically and economically viable. When talking about storage through the carbonation of calcium hydroxide, we talk about a possible reaction in a huge amount of material produced every year, in addition to being a low-cost reaction, low energy and technology mobilization, promoting chemical stability of the compounds involved in addition to improving materials microstructure (JANG et al., 2016). In addition to CO_2 capturing in hardened concrete, it is possible to perform carbonic curing of cementitious materials, promoting benefits such as: acceleration of strength, improvement in durability characteristics due to densification of the microstructure and stabilization of pre-carbonated recycled aggregates (ZHANG; LI; ELLIS, 2018).

3 SYSTEMATIC BIBLIOGRAPHIC REVIEW (SBR)

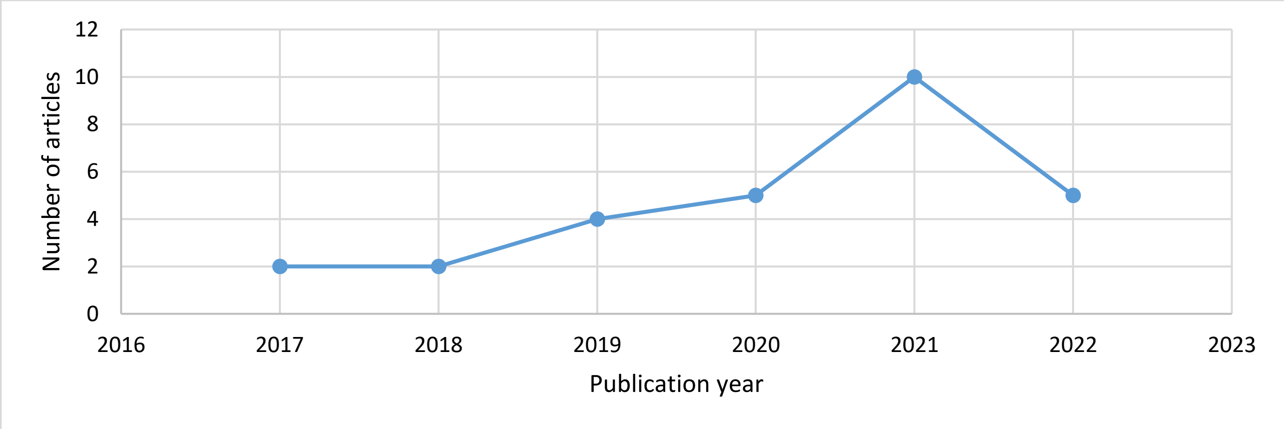
The systematic literature review (SBR) aims to be a tool for analyzing recent publications on a specific topic, in this way, it is possible to observe and verify new approaches within this pre-defined period. According to Sampaio (2013), it is necessary to determine diversified and significant research websites for science area of interest in order to encompass greater content. To carry out the SBR, when it comes to using the life cycle assessment tool, the following research websites were chosen:

- Engineering Village – Features the search, analysis and navigation tools engineers need to efficiently generate research and assess the impact and relevance of critical information (ENGINEERING VILLAGE, 2020);
- Science Direct – It has more than 16 million articles and is one of the largest search tools for articles in different areas of knowledge. (SCIENCE DIRECT, 2020);
- Scopus – Combines a comprehensive database of citations and abstracts with enriched data and linked academic content (SCOPUS, 2020).

The review was performed using keywords in English so that it was possible to obtain results with origins in several different countries. The terms used were (LCA OR Life cycle assessment) AND (CO2 capt* OR CO2 uptake OR carbon capt*) AND (Const* OR Build* OR Material). A fixed period was defined for the searches from 2017 to 2022. To manage the selected articles with greater agility, the Mendeley Desktop Software and the Parsifal website were used. In addition, filters related to the knowledge areas were applied: “Environmental Science”, “Engineering” and “Materials Science”. By excluding duplicate articles, a total of 222 were found, which were selected, firstly, through the content of the title, the abstract and, finally, the total content. The final selection of this stage totaled 36.

However, it was found out that 10 of the 36 articles did not have the full document available so the snowball approach was applied, and the final selection ended with 28 articles. This method is recommended for subjects with difficult or private access. It works by reference lines and recommendations. Given the research, the journal that publishes the most articles on the subject is the Journal of Cleaner Production, responsible for approximately 1/5 of the publications. It is also possible to perceive a constant and growing interest on the subject as shown in Figure 1.

Figure 1: Number of published articles in the final selection of the last 6 years



The selected articles are geographically distributed according to the map presented in Figure 2. It can be noticed a strong presence in several countries of Europe and in the Asian east. Papers were also selected from Brazil, United States and Australia. The carbon capture has been aborded in eastern Asia to figure it out how to deal with the great amount of CO_2 released (specially in China) and how to improve the residues management.

Using Vosviewer software it was possible to produce co-citation networks to analyze which articles are been co-citated by the others. The result showed three groups of papers that are citing each other. Only 19 articles were cited more than 4 times by the others in the selected portfolio. The three more cited had 7 citations. Arrigoni *et al.* (2017) was the one that appears the most and it’s a paper that worked with a life cycle assessment in hempcrete considering transportation distance. The authors concluded that choosing between construction materials is key information.

Figure 2: Geographical distribution of final selected articles

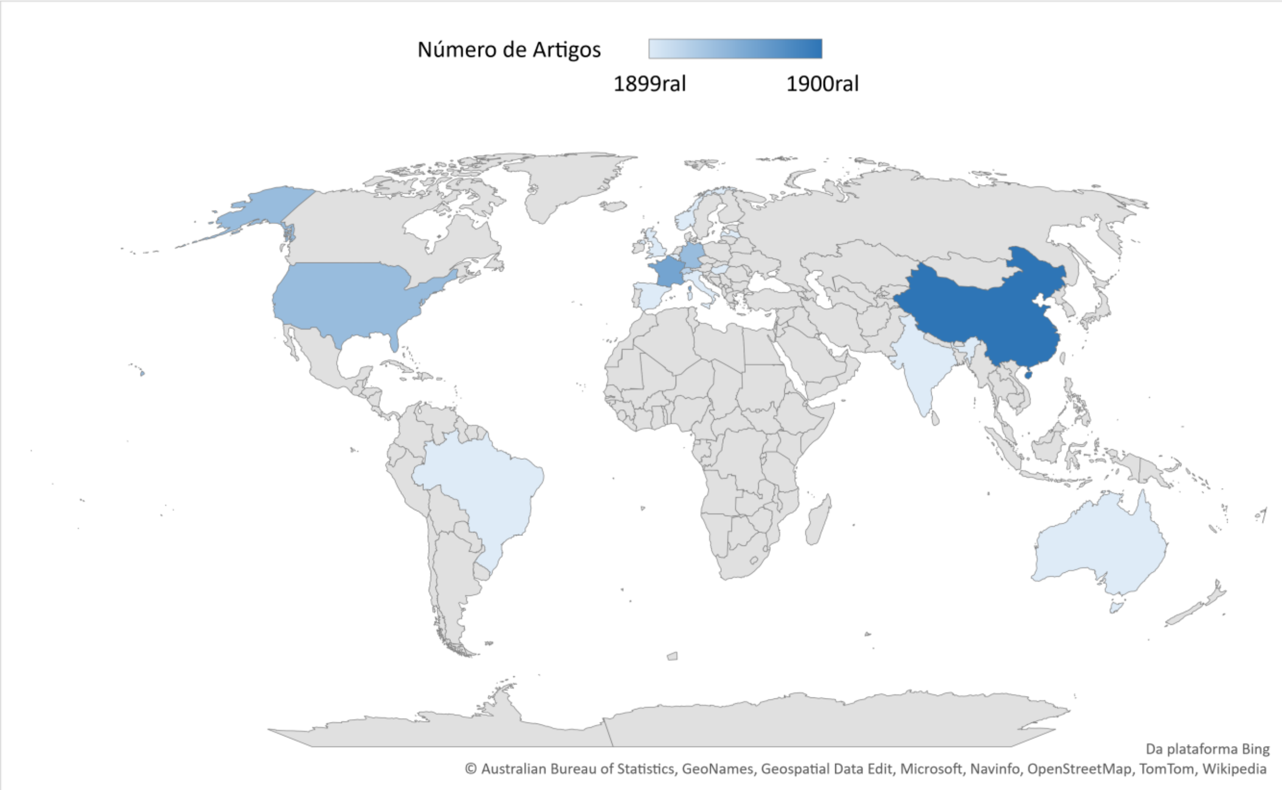
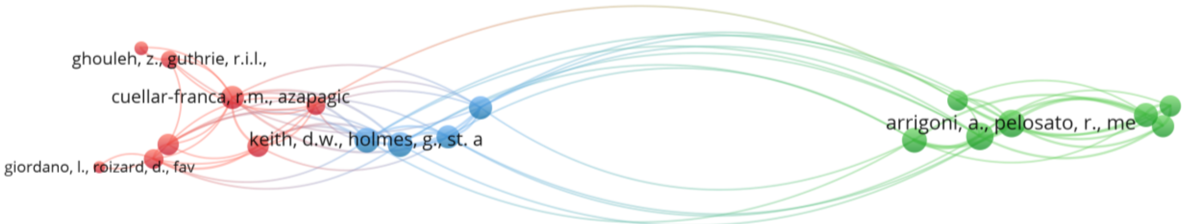
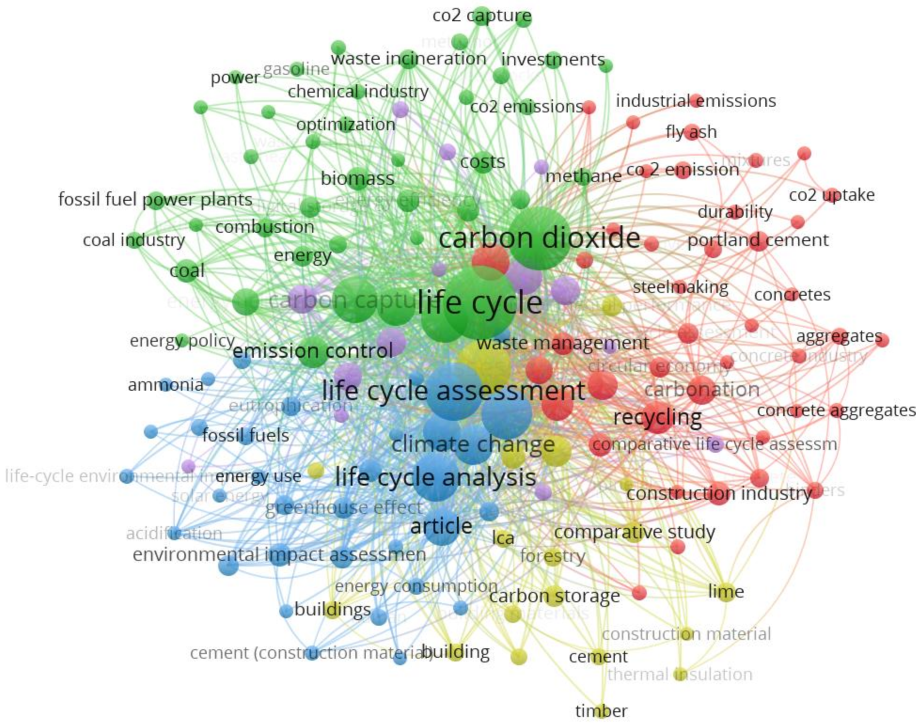


Figure 3: Co-citation network



Applying the same technique to visualize keywords networks Figure 2 were obtained, showing the relevance of the keywords “life cycle” with 132 occurrences, “carbon dioxide” with 99, and “life cycle assessment” with 83. One of the main subjects analyzed by the authors are the so-called green concrete, this material is characterized by a concrete that uses waste components in substitution of at least one raw material, does not lead to environmental destruction or it has high performance and life cycle sustainability (DACIC; FENYVESI, 2022). Dacic and Fenyvesi (2022) compared the life cycle assessment of different design methods for green concrete and figured that one of the main problems to apply LCA in this case is the functional unit. For several years it was used just the volume but now it would be better to apply a functional unit based on volume, compressive strength, and durability. Other difficulty is the allocation process for sub-products that were considered waste for a long time. For recycled aggregate (AR) of construction and demolition waste (CDW) the orientation is to apply allocation by mass for the different particle size distribution that can be achieved in the production process of AR of CDW. For several design methods for green concrete, the authors suggest using the one who brings the best performance in durability because it tends to have the lower impact since the life cycle is longer. The authors also considered the CO_2 uptake calculated by equations available in the literature. However, some projects have already concluded that these equations do not represent the CO_2 uptake performance of concretes with recycled aggregate since the equation was made for standard concrete (RIGO, 2019).

Figure 4: Keywords network



Muller et al. (2020) produced a document called "A guideline for life cycle assessment of carbon capture and utilization" made by 40 building experts upon existing guidelines to help allocate resources and time in more efficient technologies for climate chance mitigation. This study aimed to enhance transparency, comparability, and reliability of LCA studies for CCU technologies and point out that the prediction of future developments can introduce another source of uncertainty. The authors concluded by analyzing materials and methods that the decision making should be made according to the chemical structure and the functional unit used (energy, mass and/or technical performance). One of the main gaps are the data that could be filled with second-law analysis, gate-to-gate inventory estimation and artificial neural networks. The method should be different for temporary or permanent storage, in the case of cement-based materials the storage is permanent because the chemical reactions result in stable compounds. After all, the article brings a guideline to reduce the ambiguity in methodological choices, making recommendations for LCA according to different products and objectives.

Arehart et al. (2021) made a review of carbon sequestration and storage in the build environment in the past decade with 180 articles. The authors placed that carbon sequestration in the build environment could be achieve in materials and methods with focus in cement-based and bio-based concrete and mortar. Carbon sequestration, or uptake, refers to the active process of removing carbon in the form of carbon dioxide. In the other hand, carbon storage refers to the construction material keeping the carbon for a defined period. For bio-based materials it occurs storage and for cement-based, uptake or sequestration. It is also figured in this review that there are three ways of analyzing the carbon storage and uptake. The first one is the material flow analysis by mass transference, the second is the static LCA and the final is the dynamic LCA. Flow analysis should be applied for initial studies of carbon capture balance, static LCA as a second phase and dynamic LCA as more reliable and complex method (but very important for bio-based materials that sequestrate carbon for a defined period). According to the articles reviewed, a reinforced concrete column could sequestrate up to 19% of the initial emissions released (ANDERSSON *et al.,* 2019). Using recycled aggregate, through second generation carbonation, can offset 55-65% of total emission for a structure (COLLINS, 2013). Caldas *et al.* (2021) associated wood waste in bio-based concrete and concluded that wood can be considered a good CO_2 sink and a pathway for the low-carbon and circular construction industry. Another important observation made by the authors is that the main limitations for the diffusion of circular economy are the regulatory and policy barriers (SHI; ZHOU; ZHU, 2019).

Pittau *et al.* (2019) applied carbon capture in a study of the potential in retrofit as a carbon sink in the European Union. The focus was to store CO_2 in the walls by using biogenic materials and studying its potential through a dynamic LCA between 2018 and 2218. It was studied only residential buildings that represent 76% of the

European building stock and are responsible for 67% of the total primary energy demand (EUROSTAT, 2018). Retrofit was planned based in the building age. The functional unit applied was 1m² of retrofitted wall with the U-value necessary to achieve the thermal isolation standard, identical fire safety and a 60-year lifespan. It can be seen and important difference between articles that applied only volumetric functional unit and the articles that applies multifactorial units. In the dynamic approach it was analyzed two-time horizons, 50 years for short-term impacts and 200 years for long-term effects. The authors also analyzed the recycling potential of all materials used and considered that mortar had no recycling potential. The carbon capture was calculated using Fick's first law of mono-direction diffusion. It could be concluded that biogenic materials combined with Portland-cement-based have a high potential do act as a carbon sink. Until 2050, it could compensate 80% of all carbon emitted in the production and construction process.

Some other papers achieved a negative carbon emission by using sub-products combined with OPC. Li *et al.* (2021) produced steel slags blocks through two production methods. (1) blocks with steel slag as an artificial aggregate and (2) pure steel slag blocks in an activation by carbon dioxide. The pure steel slag block achieves negative emissions and one with artificial aggregate almost achieved it. Carbon capture was calculated according to some recommendations for TGA analysis. The LCA was performed with a static method and using data from Ecoinvent. The mid-point impact was adopted based on the well-known CML 2001 (Centre of Environmental Science in Leiden University). Some interesting conclusions are that the electricity necessary in the carbonation chamber contributes to 74% of GWP and CO_2 gas cylinder production contributes in 12% for steel slag aggregates and for steel slag block these number are 20% and 50% respectively. So, the GWP is associated not only with the material itself but with the production process also. For negative-balance-material the production process has its importance increase when compared to other life cycle periods. The gas cylinder production, according to the authors, is always neglected but it cannot be overlooked.

Transportation distance was one of the main topics of the article wrote by Arrigoni *et al.* (2017), which analyzed the impact of transport and carbonation in the environmental impacts of hempcrete blocks. The functional unit was 1m² of hempcrete wall. The boundaries were gate-to-gate with only the carbonation being analyzed in the use phase. It was concluded, by DRX analysis that the natural carbonation of the wall in the use phase was non-existent. However, the high amount of hemp in the mixture allowed blocks to store a great quantify of carbon. One problem faced by the authors was the difficulty in comparing results because other projects had great differences between the hempcrete wall performance. Although, every project had negative GWP balance, going from -36.08 to -1,6 $kgCO_2$/ FU. Differences can be seen in the transportation distance and the binder component, binder that is the major issued, followed by the truck's diesel. In this situation, the lower the distance the better, however, distances inferior to 100km are considered acceptable. The transport arises the importance of making environmental science a problem not only of engineering but also of public policy. Chicaiza *et al.* (2021) pointed the importance of the technical solutions in engineering CCU to be accompanied by legal regulations, policies and socio-cultural considerations.

Some researchers defend the presence of carbon capture in the United Nations Framework Convention on Climate Change (UNFCCC) and, in order to do that, made a massive review on the potential of carbon uptake. For European Union was established a 10-year national energy and climate plan from 2021 to 2030 to ensure consistent reporting under this framework and the Paris agreement. So, it is necessary to ask for the carbon uptake to be included in the framework. Andersson et al. (2019) compiled 100 years of cement consumption data, 60 years of distribution and detailed knowledge of how structures are distributed to estimate the stock of concrete. That was concluded in previous studies that CO_2 uptake during use stage and end-of-life can amount to 10-15% of corresponding annual emissions (considering fuel and calcination) for cement production. For 2021 data, it was achieved 23%. Only natural carbonation was considered for both use phase and end-of-life. This study is important because the European Trading System (ETS) does not currently allow consideration of CO_2 uptake for cement and concrete industry.

In another project, the CO_2 is used to produce nanoparticles of calcium carbonate for use in cement as filler (BATUECAS *et al*., 2021). An increase in 2% in weight of $CaCO_3$ nanoparticles enable a decrease in 60% of emitted CO_2 of cement production. The CO_2 is obtained in the flue gas from cement industry that usually presents itself in concentrations of 14-33%. The benefit lies in the stability of $CaCO_3$. The carbon dioxide can be disassociated from the other gases using ionic liquids. LCA applied in this project was consequential with expanded system and the FU was 1m² of cement with 2% $NanoCaCO_3$. For the climate change indicator was achieved a 2.12 $kgCO_{2-eq}$ compared to 4.88 $kgCO_{2-eq}$ for the production without the use of ionic liquids. For 1kg of cement, ordinary Portland cement presented 0.96 $kgCO_{2-eq}$ and 2%$NanoCaCO_3$ an amount of 0.29 $kgCO_{2-eq}$. Even with the author claiming a consequential LCA, themselves pointed that the limitation is the lack of economic data available for complex analysis.

4 CONCLUSIONS

This review compiled concepts, research articles and its conclusions when the subject is carbon capture, storage and utilization applied in cement-based materials, using LCA as a tool. The use for evaluation of new materials, the study of construction methods, and waste management are just some of the functions of LCA. From the scientific data collected, it was possible to reach the following conclusions:

- A significant quantity of articles talks about green concrete that, in general, is hempcrete or some other alternative with recycled aggregate from subproducts of other industries. For this topic, dynamic LCA is the most applied method because it allows to analyze the non-permanent storage promoted by hemp. Applied as blocks or as an aggregate, hemp seems like a good solution to achieve a negative emissions balance, a good thermal performance and satisfactory compressive strength. The hotspot is usually the transportation distance, the carbon dioxide curing energy demand and the binder production.
- Another topic well aborded was the functional unit that usually was related just to volume or mass. However, several articles pointed FU with information like compressive strength, thermal performance and lifespan. This happens because two mortars or concretes can significantly differ when changing characteristics. Also, materials with divergent physical, chemical and mechanical properties have different applicability. And since the functional unit is based on the function it is necessary to point more than just the amount of concrete used in a block, or the mass of hemp blocks applied in a wall. The complete FU allows researchers to compare projects based in the global performance.
- For many projects the most promising carbon capture technology is the uptake after the demolition due to the increase in surface area in contact with carbon dioxide. Some authors pointed the inefficiency of natural carbonation since more than the atmospheric CO2 concentration is needed to increase significantly the carbon capture in the use phase. However, carbon curing seems interesting since it was a higher sequestration in early ages and help the micro and macrostructure evolution, filling the pores with calcium carbonate. For carbon curing, the energy demand and the infrastructure necessary to the process are the two hotspots pointed by the review.
- Cement-based materials carbonation could be used in geology solutions and as a method to produce aggregates or filler materials. And, in this case, usually are stable and permanent. This conclusion shows the variability of methods and materials that can benefit from carbonation.
- The application of TGA, Fick's law, static LCA and dynamic LCA were observed of different analysis and objectives. For material characterization is usually done TGA and Fick's law analysis combined with models presented in the literature. For construction methods with stable CO2 capture, static LCA seems satisfactory but, however, materials that benefits from temporary storage need a dynamic LCA to point the chances along time.
- For several articles in the final selection, the lack of standards and guidelines for carbon capture and storage makes it easier for the researchers to compare projects and results and makes harder to apply the method in a larger scale. The collab work between researchers, costumers, industry, and policy makers is a good way to think about the process and develop some standards and guidelines.

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