Towards the implementation of Circular Economy in Engineering Education: A systematic review

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Abstract— **Nowadays, companies, governments, and designers are concerned about the environmental impact derived from the development of new products. In light of this trend, the concept of Circular Economy (CE) is gaining relevance since CE enables a set of strategies to avoid and reduce resource consumption, energy, and emissions derived from transforming raw material into functional products. These strategies also imply extending product lifespan, keeping their value as long as possible, and closing the loop of materials involved in such products. Future engineers will face the CE model, which involves a radical shift from the current linear model based on throw-away practices. Therefore, there is a need to educate professionals with knowledge in the topic and advance the research in the field. However, CE has not been yet globally introduced in the engineering curriculum in many parts of the world, and the research in the field has also been limited. CE has not been widely adopted yet as a strategy for the sustainable development of new products. Consequently, this article reviews and summarizes the research work and some implementation initiatives on CE in learning activities for engineering students during the last 10 years following a systematic approach.**

Results of the study provide a broad viewpoint in terms of where the research work is taking place and the means of disseminating the results. Additionally, an analysis based on the content reflects the methodological approaches used to introduce CE in the curriculum. Finally, the literature review also identifies the focus areas of the CE research and the emphasis during the lifecycle of the products. This work also reflects on some challenges for implementing CE in the engineering curriculum. The analysis presented in this article serves as a keystone for educators, lecturers, and researchers in engineering education to include and implement CE strategies and methodological tools in the curriculum of engineering and advance the research work in this area.

Keywords—Learning, Curriculum, Education, Circular Economy, Sustainability

I. Introduction

Sustainability issues like pollution, resource depletion, and climate change are pushing the transition towards a more sustainable consumption pattern, not only for the industrial sector but also for daily human activities. It is estimated that in 2030, two planets will be necessary to sustain the current consumption patterns derived from human activities [1]. Nowadays, production and consumption patterns built on linear economic models and based on discarding of products after use demand more resources than the earth can generate [2]. Therefore, such models must be transformed into ones more sustainable where the regeneration of material is necessary.

The concept of Circular Economy (CE) appears as an alternative to compensate and reduce environmental burdens promoting the recirculation of materials and extension of the useful life of products [3]. However, such implementation requires industry, academia, and government participation as key actors to guarantee a rapid and successful transition towards a more sustainable production and consumption system.

From the perspective of engineering education, universities have a key role in consolidating the incorporation of sustainability issues in future professionals who will lead the required changes for the next generations in production and consumption patterns, since they are considered stakeholders and role models in their communities in the field of social and environmental responsibility [4]. Besides, the future generation of engineers must be educated with solid knowledge on sustainability issues to create new products and systems minimizing environmental, economic, and societal impacts [5]. Therefore, universities have the responsibility and ability to promote CE transition through curriculum education activities [6]. Thus, education in engineering should focus on teaching students to solve real problems considering sustainability and the circular economy [7].

This article studied the implementation of CE in engineering education during the last decade, identifying trends, research gaps, and opportunities for academics, university boards, and industrial partners interested in contributing to training future engineers and related professionals in the field of CE. The main research questions addressed in this review are: i) How has the implementation of the CE concept in engineering education been? ii) What are the main trends and challenges in CE related to engineering education?

II. Method

A. Literature search methodology

The literature search was conducted using the PRISMA approach [8], which provides a transparent and reproducible method to filter and identify relevant works about any research topic. This study covered the SCOPUS database using as keywords "Circular economy," "engineering education," "curriculum," "course," "learning," "project," and "teaching." Additional filters included language (English), type of publication (Journal and Proceeding articles), and "Circular Economy" as the indexed keyword to reduce the number of records, the observation period covered from 2010 to early 2021. The full search query employed was: *[TITLE-ABS-KEY ("Circular Economy" AND ("Engineering Education" OR "Education" OR "Curriculum" OR "course" OR "learning" OR "project" OR "teaching")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cr")) AND (LIMIT-TO (EXACTKEYWORD , "Circular Economy")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))].* All literature filtering and analysis were performed by the two authors of this article.

Fig 1. Shows the steps followed during the implementation of the PRISMA approach. An additional literature search was performed using academic google and analyzing relevant works related to CE in engineering education.

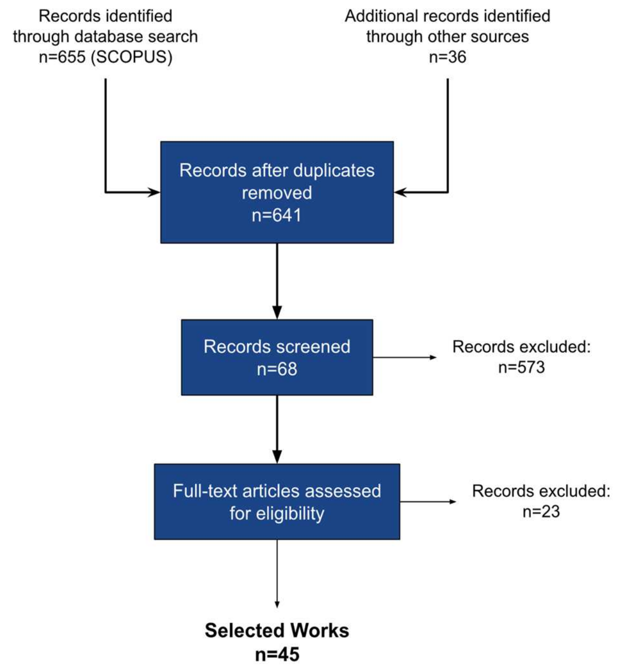

Fig. 1. Literature review methodology (PRISMA approach)

B. *Filtering and Selected Works*

After applying the search query, 655 records were obtained from the SCOPUS database, and they were complemented with 36 records from other sources. Thus 691 records were obtained from the literature search. After removing duplicates, 50 records were eliminated from the primary list. Then a screening based on title and abstract (overall revision) reviewing allowed to reduce the number of records to 68. Such records were then reviewed in detail (full article revision), and, finally, 45 records were identified as selected works. Attributes employed to determine selected works are described in the next subsection.

C. *Attributes of selected works*

Selected works in this study fulfill at least one of the following issues: a) relation between CE and engineering education; b) implementation and validation of learning activities to include, measure, or analyze CE in courses or curriculums; and c) analysis of educational initiatives in countries or regions concerning CE. Selected works were analyzed to identify trends regarding the characterization of research efforts, type of interventions (course-based / project-based), practical applications, curriculum adaptations, and gaps regarding the cutting-edge research in circularity. An in-deep description of this analysis is included in the following section.

III. Results

This section includes the analysis and characterization of the 45 selected works and summarizes trends, gaps, and research opportunities in engineering education for CE. From such selected works, it was possible to identify a wide variety of approaches and contributions to implement and promote CE in the education of engineers and related careers. Interesting interventions were identified, like the proposed by Venugopal et al. [9], which was oriented to measure the degree of familiarity of CE in engineering students as a diagnostical tool to generate more adequate interventions in the classroom. Another type of works was focused on measuring and diagnosing the CE implementation under a broader scope, covering curriculum interventions in entire regions or countries. For example, Qu et al [6] analyzed the implementation of CE in China's universities during the last 15 years. Other work, proposed by Rodriguez-Chueca et al [7], analyzed the implementation of CE using flipped Classroom and Challenge-Based Learning in Spain. Similarly, other researchers, like Rokicki et al [10] covered high education initiatives focused on the energy sector from the perspective of CE in EU countries.

Other works propose using new methods, like Game-based approaches, using innovative tools to facilitate the understanding and application of CE concepts. For example, [11] employed a board game name "Katch up" to motivate and assist students to generate solutions based on sustainability and CE to business challenges. Similarly, [12] explored implementing the serious game "In the loop" to analyze how students understand and apply CE concepts in an experiential learning situation. Other interesting contributions were oriented to define or establish which competencies for engineering education are required nowadays to face the challenges of Sustainable Development Goals [13, 14, 15].

Contributions were also identified in the development and monitoring of inter-institutional educational projects. Like the proposed by Rajeb and Zwolinski [16], which was oriented to implement CE in Europe through the RemanPath (Workshop), aimed to develop Remanufacturing learning contents; the WM-CRM (MOOC and short course) associated with critical raw materials, end of life products, and CE; and the INNOMAT (Short course) which was oriented to introduce the methodology of Life cycle assessment.

To consolidate systematically the information obtained from the analysis of the selected works, this section has been divided into two main subsections. The first one related to a brief bibliometric analysis focused on the characterization of works in terms of evolution in the last decade, identifying research efforts in terms of countries or regions and sources. The second subsection includes a content-based analysis describing the methodological approach, the type of intervention (learning approach), the CE strategies studied and, the lifecycle stage analyzed in the selected works.

A. Bibliometric analysis

After comparing the existing literature related to CE and the literature about CE in engineering education, it is noticeable an important gap. From this analysis, it is identified that per every 100 articles on CE published, one article related to its implementation or measurement in education is published. (See Fig. 2)

Analyzing the distribution of regional contributions in CE in engineering education demonstrates a domain of Europe (The Netherlands, Portugal, and the UK) with 77% of research works. Other regions like Asia (11%), Latin America (8%), and North America (4%) have minimum participation in selected works. (See Fig. 3). Reviewing the distribution of research per journal or conference proceeding. There are six main sources: i) SEFI conference (Societé Européenne pour la Formation des Ingénieurs) with 13% of selected works, ii) Journal of Cleaner Production with 9%, iii) Resources, Conservation & Recycling with 9%, iv) Sustainability, representing the 5%, and, v) ICED conference (International Conference on Engineering Design) and vi) EDUCON conference (Global Engineering Education Conference) with 4% each one. Other individual contributions represent 56% of selected works. (See Fig. 4).

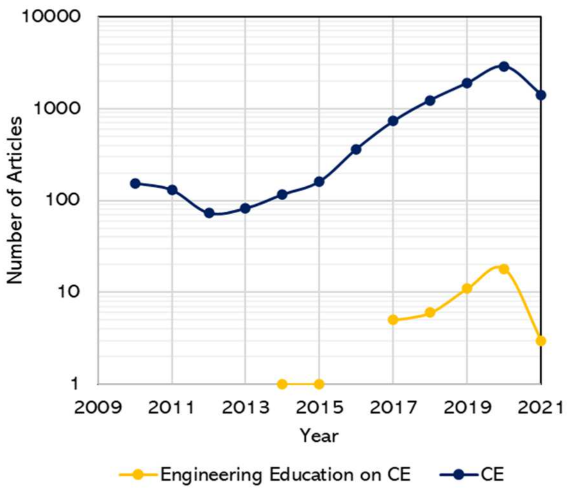

Fig. 2. Comparison of research efforts for Circular Economy and Engineering Education on CE.

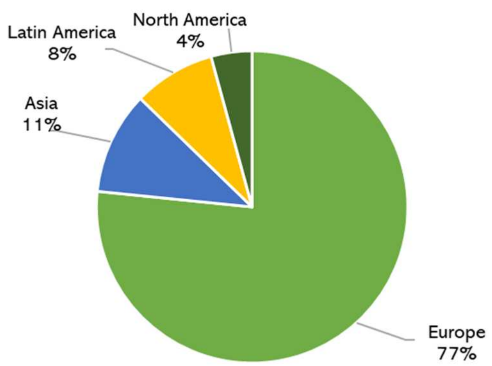

Fig. 3. Distribution of research works per country (Based on author affiliation)

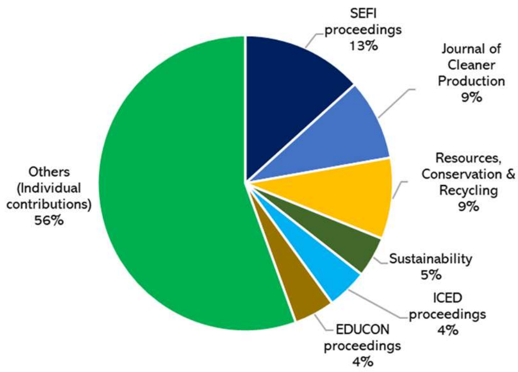

Fig. 4. Most relevant sources (journals and proceedings) in selected works

Table 1. Selected works classified by type of methodological approach and year of publication

Year	Methodological Approach			
	Case study	*Review*	*Framework*	*Survey*
2021	[17]			[15] [18]
2020	[19] [20] [4] [13] [21] [22] [16] [7] [23] [24] [25]	[6] [10] [26]		[9] [14]
2019	[27] [28] [29] [30] [31] [32] [33]	[34] [35]	[36] [37]	
2018	[12] [38] [39] [40]	[41]	[42]	
2017	[43] [44] [45]		[46]	
2015	[47]			
2014			[48]	

B. Content Based-Analysis

This subsection includes the analysis of the type of intervention (learning approach), the CE strategies studied and, the lifecycle stage analyzed in the selected works. Each topic is described in detail as follows.

The methodological approach is classified into four categories in this study. The first one corresponds to case studies, which include novel approaches, methods, and learning strategies to implement CE in the classroom. Commonly, this type of approach is demonstrated through a case study which is performed as an academic project. The second corresponds to reviews that include research works that are focused on consolidating and study the existing literature about CE or sustainability implementation in high education institutions.

The third category encompasses the framework articles that propose a theoretical foundation regarding the implementation of CE and the required conditions to generate adequate results in the learning process. Finally, the surveys include research works based on surveys to experts and students to identify motivations, drivers, and barriers from implementing CE in engineering courses. Table 1 summarizes the evolution of methodological approaches during the last years from the selected works obtained in the literature search.

The type of interventions in this study was classified into three main categories: i) project-based, which consists of applying knowledge and methodological tools in a project that commonly is presented as a challenge and must include the course content; ii) course-based, which implies developing a full content related to CE during the semester; and iii) curriculum-based, which involves a broader integration of CE in several courses during the engineering program. For the selected works, it was found that most CE implementations are based on project-based initiatives (32%), closely followed by course-based approaches (29%), and a few initiatives type curriculum-based (7%). (See Fig. 5).

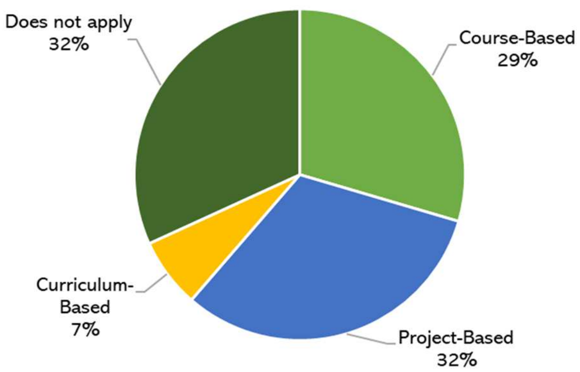

Fig 5. Breakdown of learning approaches found in the literature.

This study covered Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle and Recover in terms of CE strategies. After analyzing the selected works, it was identified that most of the works are focused on reuse and recycling (66% approximately). The rest of the strategies were covered between 18 and 22%. It was also found that several contributions were not oriented to any strategy (15%). Fig. 6 summarizes the breakdown of CE strategies considered in the selected works.

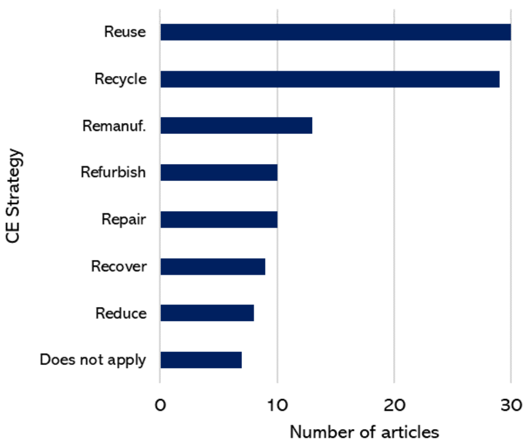

Fig. 6. CE strategies covered in selected works

Lifecycle stages are covered by most of the selected works. The holistic approach involving the lifecycle stages of design, manufacturing, use, and final disposal shows a higher preference (42%). This is followed by contributions solely oriented to design (33%), and some works focused on final disposal or end of life (15%). Other works do not imply a preference for some lifecycle stage and were classified as "Does not apply". (See Fig 7).

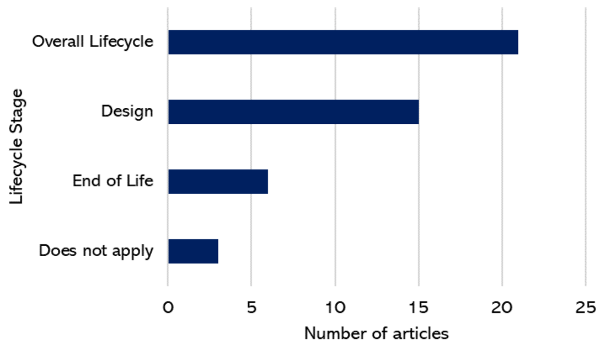

Fig. 7. CE strategies considered or studied in selected works

IV. Findings and Discussion

This section aims to address the first research question proposed at the beginning of this article. Discussions are based on results obtained and shown in the previous section.

The small number of research works compared to CE literature shown in Fig. 2 can be explained from many perspectives. The novelty of the topic (approximately 10 years) [27], which implies that the potentiality and benefits of CE are barely getting to know in the industrial and academic field massively. On the other hand, the topic of CE has not been fully implemented in universities around the world, and therefore (CE integrated into the curriculum), there is not a strong field of research on the topic. Besides, most CE researchers focus on industrial applications rather than train engineering students, which will be responsible for ensuring sustainability in future generations. The 100:1 ratio (CE vs. CE in engineering education) shown in Fig.2 demonstrates that it is necessary to concentrate research efforts in engineering education. Mainly ensure that future generations of engineers have more tools and frameworks to implement CE in production and service companies.

In terms of regional contributions to CE in engineering education, European countries lead the research, which is consistent with the degree of advancement in policies, projects, and public-private initiatives to implement CE not only in industrial scenarios but also in industrial scenarios in typical daily activities. Other regions (Asia, Latin America, and North America) have little participation in the number of selected works, which is expected to increase in the coming years by implementing new sustainability policies and more robust programs to face climate change and natural resource preservation. Africa and Oceania have not registered participation in any of the selected works. This situation is somewhat paradoxical since Europe, with the fewest resources and continental area, is the leader in CE implementation in both industrial and academic scenarios. Meanwhile, the rest of the regions, which have greater resources and continental areas, are lagging.

Regarding the type of intervention, it was found that the most common approach is project-based, which commonly involves the application of rules or strategies to increase the circularity and sustainability performance of products or solutions to specific problems. Moreover, the course-based course covers extended content related to CE, and it is commonly evidenced in elective or optional courses. This situation demonstrated that most universities are not considering the CE as a critical competence or issue to cover in the training of future engineers. However, Project-based approaches like [20, 21, 4, 7], demonstrate that engineering students can generate more sustainable solutions when a new topic (e.g., sustainability or CE) is included in the project.

Reuse and recycling were the most studied CE strategies in the selected works. Remarking recycling as a sustainable path to achieve sustainability, despite it can be not always the best choice since it involves consumption of resources to generate new raw material [49], [50]. However, other alternatives like remanufacture, refurbish, and repair can extend the lifespan of products without involving the energy and resource consumption that implies recycling material. There is an essential gap in other strategies that can be more suitable depending on the nature and functionality of the product. CE is associated with recirculation of material and slowing the loop and maintaining the value of material as long as possible.

In terms of lifecycle stages, most of the selected works are based on a concurrent or overall perspective of CE, which is suitable if a general knowledge of the subject is desired. Nonetheless, the whole lifecycle of products can also be analyzed from the design phase, where the most important decisions are taken and impact the rest of the phases like manufacturing, use, and final disposal. End of life is also relevant, but its success largely depends on the recyclability or recoverability of the product, which is also fixed during the design phase. Thus, more research efforts are required in engineering education related to design for the circularity of products.

V. CHALLENGES FOR IMPLEMENTING CE IN ENGINEERING EDUCATION

A. Challenges

According to the literature review performed in this study and the analysis of selected works, the following issues were identified as critical to introducing and implementing CE in engineering education:

- Before introducing and implementing CE concepts in engineering courses, it is necessary to create awareness about the long-term consequences of human and industrial activities in linear models [9].
- Implementation of unconventional learning methodologies such as Flipped Classroom and Challenge-Based Learning promotes faster and successful implementation of sustainability and circular economy concepts.
- Syllabuses need to be addressed to include the perspective of both the consumer and the producer. Furthermore, should be oriented to generate solutions to industrial-level problems. It is necessary for constant interaction between professors and experts outside the university.
- Students need to take the courses related to environmental issues and sustainability seriously and not as complementary knowledge. From the perspective of institutions, [24] established that in some cases sustainability is included in educational, research outreach, and operational models of universities more as a requirement than a desirable feature.
- There is a predominant weakness in the teaching of circularity topics in high education levels and a lack of contact with professional practice [23]
- University lifelong educational departments should include content related to CE and Sustainable Development for professionals.
- The use of information and communication technologies, digital twin, CAD/CAE tools, augmented reality will facilitate initiatives to include CE in engineering courses.
- Integration of teaching strategies (online offline) to adopt a flexible and globalized offer to reach more population and massively promote the concept of CE.

As a necessary field, engineering education plays a key role in educating future professionals. Thus, CE must be implemented in engineering and related programs like management, business, architecture, and industrial design.

B. Limitations of the study

- The scope and aim of different studies limited the analysis of the literature, especially due to the small number of relevant works found until now. It is necessary to perform a more global review in several years to continue analyzing the evolution of CE in engineering education.
- For this review article, the SCOPUS database was employed since it provides the most comprehensive set of literature compared to other databases (for example, Web of Science). Commonly, all Web of Science articles are included in SCOPUS but not otherwise. On the other hand, other more comprehensive alternatives like Google Scholar included too many records that were not peer-reviewed. This explanation was included in the Limitations Section. Nevertheless, it is possible some research works could be excluded from this study.
- It is possible that several research works that have implemented CE to some degree under a different name or approach were out of this review. Recycling or remanufacturing, among others, are common terms that have been previously covered in engineering education. Therefore, this review is solely focused on works that include the CE term or concept deliberately.
- Potential bias during the reviewing of articles implied the analysis of only indexed works, therefore it excluded books and other type of literature that could be oriented to CE in engineering education. Reports and information

from companies or governments were also excluded from this study. The size of the sample of selected works (45) is still small to generate major analysis and conclusions, more research and implementation is necessary to consolidate a broader analysis.

VI. Conclusions

This article reviewed the implementation of CE in engineering education from research literature around the world during the last decade. A systematic literature approach was applied to identify trends, research gaps, and new research opportunities from existing literature.

The main findings lie in the lack of research efforts in education compared to the technical literature of CE. There is a lack in implementing more holistic approaches to generate awareness, knowledge, and competencies for future engineers in CE and sustainability. Despite some efforts to include these topics in the curriculum, commonly through elective courses, it is necessary to offer mandatory courses and learning activities to strengthen CE from introductory to capstone project or final design courses. On the other hand, CE is partially covered, addressing few research efforts in very impact strategies like manufacturing, repair, and upgrading products. Nowadays, circularity is focused on recycling and reuse, which reduces environmental burdens, but it is also necessary to include product life-extension (durability) as an important alternative to face resource depletion.

The challenges for CE in engineering education are complex and require the participation of industrial partners, consumers, and universities to consolidate industrial ecology systems oriented to zero-waste. It is expected that in future years with the approval of new legislation around the world (especially outside Europe), more countries accelerate in the transition towards CE not only in the industrial field but also in the academic training of future professionals.

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