Teaching the "10 Rs" of circular economy in technological-level undergraduate courses offered in Brazil: an exploratory analysis via fuzzy TOPSIS class

International Journal of Sustainability in Higher Education

1711

Received 25 March 2024
Revised 29 July 2024
21 October 2024
Accepted 4 November 2024

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Abstract

Purpose – This study aims to provide an analysis of teaching the "10 Rs" – Refuse, Rethink, Reduce, Reuse, Repair, Remodel, Remanufacture, Reuse, Recycle and Recover energy, in technological-level undergraduate courses offered in Brazil. Technological undergraduate courses are more dynamic and pragmatic than bachelor's degrees and aim to meet market demand.

Design/methodology/approach – The study collected data from 39 educators who know the reality of technological-level undergraduate courses in Brazil. The data were analyzed using the fuzzy technique for order preference by similarity to ideal solution class technique.

Findings – The main findings of the research show potential for improvement in teaching all the "Rs" analyzed when considering technological-level undergraduate courses. Refuse, Restore and Recover energy are the most critical when considering how they should be taught in undergraduate technology courses in Brazil.

Originality/value – The paper's originality lies in a unique empirical analysis of the circular economy – which is increasingly emerging as an intriguing approach to seeking sustainability in production chains – and the new generation of professionals in technological undergraduate courses who need to be educated and aligned with these concepts. The results can improve the curriculum, syllabus, course objectives and learning outcomes, upgrading the courses' pedagogical projects.

Keywords Circular economy, Technological-level course, Undergraduate degree, Fuzzy TOPSIS, Developing country

Paper type Research paper

The authors are grateful for the support of the National Council for Scientific and Technological Development (CNPq/Brazil) under the grants no. 304145/2021-1 and no. 303924/2021-7.

Erratum: It has come to the attention of the publisher that the article, Favaro, R., Moraes, G.H.S.M.d., Sigahi, T.F.A.C., Pinto, J.d.S., Rampasso, I.S., Moro, S.R. and Anholon, R. (2024), "Teaching the "10 Rs" of circular economy in technological-level undergraduate courses offered in Brazil: an exploratory analysis via fuzzy TOPSIS class", International Journal of Sustainability in Higher Education, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/IJSHE-03-2024-0218 was published with the incorrect city listed in the affiliation details for Suzana Regina Moro. This has now been corrected in the online version of the paper. The publisher sincerely apologises for any inconvenience caused.

International Journal of Sustainability in Higher Education
Vol. 26 No. 7, 2025
pp. 1711-1727

1467-6370
DOI 10.1108/IJSHE-03-2024-0218

1. Introduction

Circular economies aim to transform linear production and consumption into integrated models to preserve and value existing resources through optimum resource use (Kirchherr *et al.*, 2017; Potting *et al.*, 2017). The concept is intrinsically linked to sustainability, balancing economic growth with environmental preservation and social justice. In this way, future generations will have a more balanced and resilient future (Awan *et al.*, 2020), making sustainable development possible (Kirby, 2019).

Products, components and materials are reused as much as possible in the circular economy (CE). As a result, products are designed to be functional and durable, encouraging intensive use, sharing or renting. Furthermore, components are reused, repaired, renewed or recycled (Al-Swidi *et al.*, 2023). In this approach, subcomponents are retained for continuous value creation after the end of the product's service life, to extend the useful life and retain subcomponents for the purpose of prolonging the useful life of the product (Al-Swidi *et al.*, 2023).

Within the CE, Potting *et al.* (2017) highlight circularity strategies in the production chain known as the "10 Rs" (refuse, rethink, reduce, reuse, repair, remodel, remanufacture, reuse, recycle and recover energy). Such strategies have gained wide acceptance in the academic community and industry and are widely used in actions aimed at the CE (Geissdoerfer *et al.*, 2020).

Future professionals must be trained in alignment with sustainable development concepts; in this sense, higher education institutions (HEIs) become remarkable (Rampasso *et al.*, 2021). HEIs have increased their engagement in the development of professionals trained to deal with real-world challenges; however, it is still clear that many HEIs face challenges in enhancing their actions in this sense (Rampasso *et al.*, 2021).

Focusing more specifically on sustainability in the production chain and understanding the strategies associated with each of the "10 Rs" mentioned by Potting *et al.* (2017) will allow students and future professionals to make a difference in their training and contribute to a better society. Technological-level undergraduate courses stand out in some countries, and students must be trained in sustainability concepts.

The technological-level undergraduate courses are professional and closely related to the job market. This translates into continuous collaboration between educational institutions and the productive sector to share knowledge, experiences, interests and needs. Collaboration is crucial to developing curricula and strategies. Brazil's colleges, federal education institutes, science and technology and universities offer technological-level undergraduate courses. They are regulated by the Ministry of Education and Culture (MEC) and offer nationally recognized undergraduate degrees (MEC, 2020). Undergraduate courses at the technological level are important in Brazil because they prepare professionals to work in strategic areas of the country's economy, including information technology, logistics, business management, public security and management of public resources.

These courses generally have a shorter duration than a bachelor's degree or degree and aim to provide students with more practical training focused on the job market. Professionals trained in such courses have specific technical skills and are prepared to meet the demands of the job market, which has become increasingly competitive and demanding (MEC, 2020).

Studying the academic literature on including sustainability in technological undergraduate education is necessary to deepen the discussion and provide consolidated information to support curricular changes, teacher training and capacity building. Curricular transformation is essential for sustainable education (Wachholz and Merrill, 2012).

In the context presented above, this research aims to understand the perception of education professionals about the teaching of the "10 Rs" in technological undergraduate courses in Brazil. Thus, the research question is "What is the level of insertion of the "10 Rs" of sustainability in higher education in technology in Brazil?"

This article consists of four additional sections beyond this introduction. Section 2 is dedicated to the theoretical foundation, Section 3 presents the methodological procedures developed to achieve the results, Section 4 discusses the results and associated debates and Section 5 presents the conclusions and final considerations.

2. Literature review

2.1 Circular economy

The CE has gained significant global attention due to its ability to enhance and foster sustainable production and consumption (Awan *et al.*, 2020). This occurs through adopting streamlined models based on continuous growth and the efficient use of resources, overcoming the limitations associated with traditional approaches based on unlimited resources (Govindan and Hasanagic, 2018).

There have been many different definitions of the CE offered by different researchers. According to Geng *et al.* (2009), it is an economy based on spiral loops that minimize matter, energy flow and environmental deterioration without limiting economic growth and social progress. Based on Franklin-Johnson *et al.* (2016), the CE is defined by the circular (closed) flow of materials and the efficient use of raw materials and energy. Awan *et al.* (2020) define the CE as an activity, a set of processes for reducing the material used in production and consumption, enhancing material resilience, closing cycles and exchanging supply of sustainability to maximize the ecological system.

The set of practices that aim to keep products in circulation even after their useful life is called the CE. There are two main approaches: the open-loop supply chain and the closed-loop supply chain. Unlike traditional remanufacturing, which focuses on economic value, the recycling process from a circular perspective incorporates both economic and environmental considerations, establishing itself as a distinct approach to the traditional recycling process (Awan *et al.*, 2020).

With the rising middle class, there has been a decline in consumption patterns and increased demand for better-modified and manufactured goods. At the same time, throughout the 21st century, there is a projection of an exponential increase in the consumption of materials globally, with an estimated eight-fold increase by the end of 2050. Projections indicate a three-fold increase in global demand for natural resources, which presupposes a need that benefits greater exploitation of natural resources (Kok *et al.*, 2023; Reh, 2013). For these reasons, in the past decade, there has been no focus on proper waste management, as recent media attention highlights the tragic impacts resulting from human activity on the environment (Vardopoulos *et al.*, 2021).

Resource management must be improved to identify opportunities that promote individual well-being simultaneously with environmentally sustainable practices. The principles of a CE present promising approaches to facing challenges such as resource scarcity, price increases, waste minimization and reducing energy consumption and pollutant emissions associated with conventional production (Geissdoerfer *et al.*, 2020). Local production needs to be strengthened to reduce logistical costs and achieve economic independence. However, there are significant challenges, including quality issues related to material connections, wear and tear and contamination from use, as well as high setup and process costs and complexities in the supply chain (Arnold, 2023; Greer *et al.*, 2021).

Assume that it is possible to overcome the challenges outlined above. If implemented effectively, the CE can lead to a sustainable and profitable industry (Saari *et al.*, 2024). This would allow the dissociation of the negative impacts of resource depletion and environmental degradation (Morseletto, 2020) with a significant reduction in carbon emissions and the consumption of nonrenewable resources (Murray *et al.*, 2017). The CE boosts economic growth while reducing environmental impact. The premise is that preserving the value of products, components and materials by promoting "internal cycles," such as reuse, renewal and remanufacturing, increases resource efficiency (van Loon *et al.*, 2021).

Bakker and den Hollander (2020) and Reike *et al.* (2018) provide strategies for the CE and attractive schemes for applications. Potting *et al.* (2017) presented a very complete study that contains a well-defined and almost full set of ten CE strategies.

To promote the term CE, researchers popularized another term, linear economy, as it fits as an antonym. When referring to an economy as circular, it is suggested that it does not have a net impact on the environment; instead, it seeks to restore any damage caused during resource acquisition while minimizing waste generation throughout the production process and the product's useful life. The word "circular" also carries another meaning related to the cycle (Murray *et al.*, 2017).

This paradigm shift directly impacts the requirements in the design and manufacturing processes, demanding that the entire product life cycle be designed toward a sustainable CE, as proposed by Korhonen *et al.* (2018). This redirection means that product development, from raw material extraction to production, must be strategically planned to avoid or minimize natural resources. According to ecological and resource conservation principles, the final product must be designed for prolonged and intensive use. Therefore, considerations regarding easy repairability and reprocessing must be incorporated from the early design phases. In a closed-loop system context, requirements for a product derive from the time of production and use and involve changes in the handling of the product or its components after the primary life cycle (Korhonen *et al.*, 2018).

Promoting the CE through national legislation and international initiatives has been consolidated over the past few decades. This has marked significant advances in several world regions. In 1996, Germany stood out as a pioneer by establishing the "Closed Cycle of Substances and Waste Management Law," later reorganized in 2012 as the "Circular Economy Law" (Su *et al.*, 2013). In a subsequent normative evolution, Japan, in 2005, established the "Basic Law for the Establishment of a Society Based on Recycling" (Zhang and Chen, 2014), followed by China in 2009, which enacted the "Economic Promotion Law Circular of the People's Republic of China" (Lieder and Rashid, 2016). The European Union's contribution to the global legislative panorama is also highlighted.

Although the CE's theoretical foundations are not novel, and there is growing interest in it, there remains a lack of consensus on its definition and conceptualization. As a result, CE is interpreted in different ways by various stakeholders, varying according to their specific interests and priorities (Kirchherr *et al.*, 2017). Kirchherr *et al.* (2017) highlight this divergence. They identified and reviewed 114 different CE definitions in the literature, highlighting conceptual heterogeneity. Furthermore, more consensus is needed to conceptualize and operationalize CE principles (Reike *et al.*, 2018).

The study by Potting *et al.* (2017) was commissioned by the Dutch Ministry of Infrastructure and Environment to inform the Dutch parliament about progress toward a CE. This was to reduce waste and promote sustainable resource use. The main idea of the study is to provide a conceptual framework for measuring the progress of transitioning to a CE in product chains. It highlights the importance of innovation, especially technological innovation, in enabling sustainable strategies. It assesses the role of innovation at different levels of environmental ambition.

Circularity highlights strategies that reduce natural resource consumption and waste production. Opting for high circularity strategies, such as more brilliant product use and manufacturing, to the detriment of low circularity options, such as incineration, can maintain the valuable life of your products and their parts in the chain for more extended periods, generating more significant environmental benefits (Potting *et al.*, 2017).

According to Potting *et al.* (2017), some strategies can increase effectiveness in achieving circularity (from the highest number to the lowest, that is, from R9 to R0; see "circularity strategies in the production chain" list in the following text). Thus, for example, R0, R1 and R2 require more innovation in product design and innovations in recipes at this point and present this hierarchy as a "rule of thumb," recognizing that the order is not always consistent. This highlights the presence of exceptions and side effects, indicating that order R may not be suitable for specific products or under certain conditions. For these reasons, the hierarchy between strategies must be taken with discretion, but it can still provide helpful guidance when examining CE strategies (Morseletto, 2020). Circularity strategies in the production chain are as follows:

(1) Using and manufacturing smarter products
- *R0* – Refuse: make a product redundant by abandoning its function or offering the same function with a radically different product.
- *R1* – Rethink: make the use of the product more intensive through its sharing or multi functionality. Example: shared scooters.
- *R2* – Reduce: increase the efficiency of a manufactured product or consume less natural products or resources to produce it.

(2) Extend the useful life of products and their parts
- *R3* – Reuse: a product that still has acceptable use conditions and can be used by another consumer.
- *R4* – Repair: repair a product to return to its original functionality.
- *R5* – Restore: recover an old product by updating it.
- *R6* – Remanufacture: using parts of a discarded product in a new product with the same functionality.
- *R7* – Reuse: use discarded products or their parts in a new product with a different function.

(3) Useful application of materials
- *R8* – Recycle: process materials to obtain the same or lower quality grade, usually in raw materials.
- *R9* – Recover energy: incinerate materials for energy recovery.

The aforementioned list is elaborated by the authors based on Potting *et al.* (2017, p. 5).

In addition to technological advances, product design and revenue models, Potting *et al.* (2017) present transitions to a CE, which requires innovation and socio-institutional changes. Based on technology applications in product chains, three types of transitions to a CE can be identified (Lima *et al.*, 2024; Potting *et al.*, 2017):

(1) CE transitions that focus on a specific and radically new technology shaping the transition. This involves radical innovation in the core technology, requiring socio-institutional changes to integrate the new technology into society. An example is the emergence of bioplastics.

(2) CE transitions, where socio-institutional changes are central, with technological innovation playing a secondary role. These transitions often involve incremental innovation in the core technology. An extreme example is packaging-free stores.

(3) CE transitions where socio-institutional changes are central and facilitated by enabling technology, such as the transition to the sharing economy. This type of transition primarily involves socio-institutional changes but relies on information technology to connect service providers and users.

2.2 Technological-level undergraduate courses in Brazil

Higher-level technological undergraduate courses in Brazil have significantly expanded in recent years, and the number of students enrolled in them currently represents a portion of higher-level students (ABRES, 2024). Higher-level technological undergraduate courses are degree programs that typically focus on meeting the specific demands of the job market. They train professionals to perform functions related to applied research, dissemination of technologies, management of production processes and entrepreneurship, among others. These courses are shorter than bachelor’s degrees, usually lasting three to four years. Upon completing the course, the graduate is designated a technologist and receives a higher-level diploma (IFSC, 2024).

According to CNE Opinion No. 436/2001, the first technology courses in Brazil were introduced in São Paulo at the end of the 1960s and 1970s. At that time, the business context reflected an environment strongly influenced by industrialization, in which qualified labor grew substantially. In 1968, Law No. 5,540 promoted significant changes in higher education, allowing the creation of short-term technological courses that represented a more agile route to the job market.

Technological professional education has its fundamental guidelines established through Resolution CNE/CP n° 1/2021 and is integrated into different levels and teaching modes, covering both undergraduate and postgraduate courses. This resolution is crucial in consolidating essential elements for structuring Higher Technology Courses (HTC) and updating the National Catalog HTC (NCHTC). Furthermore, it determines that HTCs must foster the entrepreneurial capacity of students, promote the understanding and assessment of the social, economic and environmental impacts arising from production and new technologies and adopt an interdisciplinary approach, among other aspects. The resolution also establishes a commitment to meet citizens’ demands, the job market and society, aligning with the country’s policies to promote sustainable development (Brasil, 2021).

The NCHTC, created by the Ministry of Education to establish curricular guidelines for creating, organizing and evaluating technology courses, is an essential tool for organizing and regulating such courses in Brazil (MEC, 2016). The NCHTC established 134 denominations of HTC divided into 13 technological axes. These broad categories group similar areas of knowledge in the courses (MEC, 2016).

Some courses stand out within the technological axes recognized by the MEC: Environment and Health; Control and Industrial Processes; Educational and Social Development; Management and Business; Information and Communication; Infrastructure; Military; Food Production; Cultural Production and Design; Industrial production; Natural resources; Public security; and Tourism, Hospitality and Leisure (Oliveira *et al.*, 2022). In addition to the technological axes and course names, the NCHTC provides relevant information such as the completion professional profile that corresponds to the list of actions that graduates of the higher technology course, in their professional practice, are capable of carrying out, the minimum required infrastructure necessary for the courses to operate, minimum workload, among others (MEC, 2016).

3. Methodological approach

Figure 1 presents the steps taken in the research that enabled the results.

The literature review (Step 1) was conducted on several scientific databases, including Emerald Insight, Science Direct, Scopus, Springer and Wiley. Initially, the terms "sustainability," "circular economy" and "sustainability in higher technology courses" were used to understand the relevance of the topic. Then, to improve the search in context, the terms "higher technology course in Brazil," "higher education and sustainability" and "teaching sustainability in HTC" were used. A variety of articles were scrutinized. After several analyses, due to the relevance of the topic and a high number of citations, the study by Potting *et al.* (2017), called "Circular Economy: Measuring Innovation in the Product Chain," was selected as the basis for structuring the research protocol.

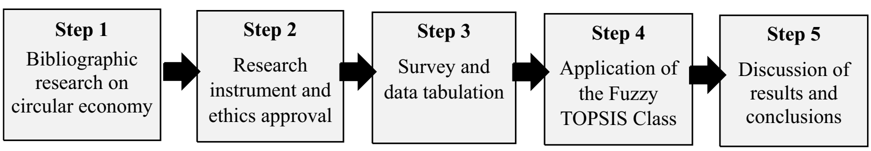
The data collection used in this research was a survey, following the recommendations of Forza (2002). According to the author, research objectives must be clearly defined to conduct a survey, and likely respondents must be invited. The research in question was characterized by an objective study to evaluate the teaching of the "10 Rs" in higher education technology courses offered in Brazil. The respondents were teachers and coordinators with experience in this type of education.

A transparent and objective survey is recommended by Forza (2002). Participants must be able to answer the questionnaire fluidly and the researcher must be able to analyze the data easily. The aforementioned author also recommends ensuring data confidentiality, testing the survey before sending it to participants and defining the data collection method, which must be based on research needs (Forza, 2002). Our study considered all of the above factors.

Based on the findings of Potting *et al.* (2017), the questionnaire contained questions relating to the characteristics of the respondent as well as evaluations of each of the "10 Rs" (Step 2) that had been listed in aforementioned "circularity strategies in the production chain" list. The respondent gave his perception of how much the concept of the aforementioned "R," its potential contributions to achieving the CE and related examples are being taught to future professionals in technologically advanced undergraduate courses offered in Brazil, which are on the technological level.

Using the Fuzzy Triangular Numbers, respondents were asked to assess their perception of each of the "Rs" through a linguistic scale, as shown in Table 1; the corresponding fuzzy triangular numbers are already provided in this table.

As recommended by Brazilian legislation, the research ethics committee evaluated and approved the research project and the instrument as part of the ethical approval process. The data collection process began once the questionnaire was prepared and the necessary authorizations had been obtained. The website of the Brazilian Ministry of Education (MEC)



Source: Authors' own creation

Figure 1. Research steps

Table 1. Linguistic scale and respective representation of fuzzy triangular number

Scale	Fuzzy triangular no. *l*	*m*	*u*
The concept of the "R" under consideration, its potential contributions to achieving the circular economy, and its examples ARE PRACTICALLY NOT included in the teaching of future professionals in higher technology courses offered in most Brazilian institutions	0	0	2.5
The concept of the "R" under consideration, its potential contributions to achieving the circular economy, and related examples are covered in a SUPERFICIAL way in teaching future professionals in higher technology courses offered in most Brazilian institutions	0	2.5	5
The concept of the "R" under consideration, its potential contributions to achieving the circular economy, and related examples are REGULARLY addressed in the teaching of future professionals in higher technology courses offered in most Brazilian institutions	2.5	5	7.5
The concept of the "R" under consideration, its potential contributions to achieving the circular economy, and related examples are ADEQUATELY addressed in the teaching of future professionals in higher technology courses offered in most Brazilian institutions	5	7.5	10
The concept of the "R" under consideration, its potential contributions to achieving the circular economy, and related examples are covered in a STRUCTURED WAY in the teaching of future professionals in higher technology courses offered in most Brazilian institutions	7.5	10	10

Source: Authors' own creation

was used to search for technological undergraduate courses to identify potential participants. Initially, all websites of public institutions (approximately 1,386 on-site technological courses in operation) were searched. Only a few websites listed the professors of technological undergraduate courses. After analyzing the resumes of all professors listed on the websites, 240 potential participants who met the established criteria were identified. All of them were invited to participate in the survey. Forty professionals were contacted, which represents a response rate of 16.67%. After excluding one questionnaire due to incomplete data, 39 valid questionnaires were selected for further processing.

Of the 39 respondents, all have more than seven years of experience, 92% (36) have more than 10 years and 41% (16) have more than 20 years of experience in technological higher education courses. Regarding the respondents' degrees, 74% have Doctorates and 26% have Master's degrees (in different areas).

The data collected from the respondents were analyzed using the fuzzy technique for order preference by similarity to ideal solution (TOPSIS) class technique in a design adapted from Ferreira *et al.* (2018) (Step 4). Fuzzy set theory is valid for data with uncertainties (Zadeh, 1965), applying it to survey results in more reliable answers. The TOPSIS method, initially proposed by Yoon and Hwang (1995), is widely used to organize alternatives in order of preference and this aspect of the fuzzy TOPSIS class allows the allocation of objects or elements into classes (Ferreira *et al.*, 2018).

Notably, the sample of 39 respondents is suitable for the fuzzy TOPSIS class. In this method, the most crucial aspect is the selection of a qualified and capable sample. In the fuzzy TOPSIS class, statistical tests are not of interest; instead, it is the deep understanding of the participants and the ability to model uncertainty, ensuring mathematical robustness. As an example, Tietz Cazeri *et al.* (2024) investigated CE practices and applied the fuzzy TOPSIS class to 12 experts.

The steps for operationalizing the fuzzy TOPSIS class recommended by Ferreira *et al.* (2018) are as follows:

- Step 1

Define the linguistic variables to evaluate the weight of the criteria and the alternatives for the criteria in question. From this, construct the decision matrix $\widetilde{D}$ and the weight vector $\widetilde{W}$:

- Step 2

Normalize the matrix $\widetilde{D}$ using equation (1). The matrix $\widetilde{R} = \left(\widetilde{r}_{ij}\right)_{m \times n}$ will be obtained:

$$r_{ij} = \begin{cases} \left(\dfrac{l_{ij}}{u_j^+}, \dfrac{m_{ij}}{u_j^+}, \dfrac{u_{ij}}{u_j^+}\right), \left(u_j^+ = max_i\, u_{ij}\, for\, benefit\, criteria\right) \\ \left(\dfrac{l_j^-}{u_{ij}}, \dfrac{l_j^-}{m_{ij}}, \dfrac{l_j^-}{l_{ij}}\right), \left(l_j^- = min_i\, l_{ij}, for\, cost\, criteria\right) \end{cases} \quad (1)$$

Calculate the matrix $\widetilde{V} = \left(\widetilde{v}_{ij}\right)_{m \times n}$ weighting the matrix $\widetilde{R}$ by the weight vector $\widetilde{W}$:

- Step 3

For each class, define the ideal positive solution (A_p^+) and the ideal negative solution (A_p^-), as shown in equations (2) and (3):

$$A_p^+ = \left\{\widetilde{v}_{p1}^+, \widetilde{v}_{pj}^+, \ldots, \widetilde{v}_{pm}^+\right\}, \left(\widetilde{v}_j^+ = \widetilde{q}_{pj}\right) \quad (2)$$

$$A_p^- = \left\{\widetilde{v}_{p1}^-, \widetilde{v}_{pj}^-, \ldots, \widetilde{v}_{pm}^-\right\}, \left(\widetilde{v}_j^- = \widetilde{q}_{pj}'\right) \quad (3)$$

$\widetilde{q}_{pj}$ = profile closest to the class, weighted and normalized.

$\widetilde{q}_{pj}'$ = furthest in class, weighted and normalized profile.

- Step 4

Calculate the total distance of each alternative *i* about the ideal solutions, using equations (4) and (5):

$$d_v\left(\widetilde{v}_{ij}, \widetilde{v}_{pj}^+\right) = \sqrt{\frac{1}{3}\left[\left(l_{ij} - l_{v_{pj}^+}\right)^2 + \left(m_{ij} - m_{v_{pj}^+}\right)^2 + \left(u_{ij} - u_{v_{pj}^+}\right)^2\right]} \quad (4)$$

$$d_v\left(\widetilde{v}_{ij}, \widetilde{v}_{pj}^-\right) = \sqrt{\frac{1}{3}\left[\left(l_{ij} - l_{v_{pj}^-}\right)^2 + \left(m_{ij} - m_{v_{pj}^-}\right)^2 + \left(u_{ij} - u_{v_{pj}^-}\right)^2\right]} \quad (5)$$

$$D_i^+ = \sum_{j=1}^{n} d_v \ \tilde{v}_{ij}, \tilde{v}_{pj}^+ \tag{6}$$

$$D_i^- = \sum_{j=1}^{n} d_v \ \tilde{v}_{ij}, \tilde{v}_{pj}^- \tag{7}$$

- Step 5

Calculate the coefficient of each alternative I using the equation (8):

$$CC_i^p = \frac{D_i^-}{\left(D_i^+ + D_i^-\right)} \tag{8}$$

- Step 6

For each class *i*, determine its class; the class will be the one that presents the highest value of CC_i^p for alternative *i* among all classes.

The aforementioned list is elaborated by the authors based on Ferreira *et al.* (2018).

In the adapted conception of the fuzzy TOPSIS class that was used in this study, each respondent assumed the "role" of a criterion, with their response weighted by their ability to assess the topic; this ability was evaluated by the time they indicated to have experience, by their academic degree (Master or PhD) and their publications; it is understood that the more correlated the field of education is to sustainability and/or CE, the greater the ability to infer about the topic. As there are uncertainties in allocating these respondents according to their ability to infer about the topic, a fuzzy vector was adopted, expressed by Table 2.

The authors of this article carefully analyzed each participant's curriculum and classified them according to their ability to assess the issues. Given the respondents' good qualifications, in the original scenario, the classifications ranged from intermediate capacity to very high capacity to assess the item.

For a more precise analysis to verify the robustness of the results, it is recommended to carry out a sensitivity analysis (Wallace, 2000). For Wallace (2000), sensitivity analysis is crucial to understanding the effects of changes to the parameters of a model or system in relation to its outputs or results. In Step 5, the results are discussed and conclusions established.

Table 2. Fuzzy weights assigned for specialists

Ability to assess the item in question	Fuzzy representation *l*	*m*	*u*
Very low	0.2	0.2	0.4
Low	0.2	0.4	0.6
Intermediate	0.4	0.6	0.8
High	0.6	0.8	1
Very high	0.8	1	1

Source: Authors' own creation

4. Results and discussion

4.1 Results of the fuzzy TOPSIS class method

The survey involved 39 participants, and for each of them, a triangular fuzzy number (l, m, n) was assigned; the matrices generated for the fuzzy TOPSIS class calculations in MS Excel were of large dimensions, and thus, they were not fully presented in the text. First, with the collected data, the decision matrix $\widetilde{D}$ was prepared, bearing in mind that each respondent assumed the role of a criterion. Since the respondents were considered experts in the subject matter, the letter E was used for abbreviation, followed by their respective numbers. Then, the weight vector $\widetilde{W} = \left(\widetilde{w}_j\right)$ was calculated, based on the respondents' expertise (in this analysis, these weights defined the so-called Base Scenario). The data from matrix $\widetilde{D}$ were normalized considering the "benefits criterion" and weighted by the weight vectors presented in Table 2, making it possible to obtain the matrix $\left(\widetilde{v}_{ij}\right)_{m \times n}$.

The highest level of the scale was considered as the "Expected" class (the description provided is related to the implementation of the "10 Rs" teaching in higher technology courses in Brazil), the intermediate level of the scale was considered as the "Regular" class (the description provided is moderately related to the implementation of the "10 Rs" teaching in higher technology courses in Brazil) and the lowest level of the scale was considered as the "Unacceptable" class (the description provided is not related to the implementation of the "10 Rs" teaching in higher technology courses in Brazil). Table 3 presents the classes and profiles adopted for this classification in this analysis.

From the classes and profiles mentioned earlier, the Positive Ideal Solution for the "Expected" class became the highest level of the scale and the Negative Ideal Solution for the same class became the lowest level of the scale; the Positive Ideal Solution for the "Regular" class became the intermediate level of the scale and the Negative Ideal Solution for the same class became the lowest level of the scale; finally, the Positive Ideal Solution for the "Unacceptable" class became the lowest level of the scale and the Negative Ideal Solution for the highest level of the scale.

With the values of D_i^+ and D_i^- for each class, it was possible to calculate the indicator CC_i^p and, by selecting the highest of them, determine to which class each alternative belongs, as indicated in Figure 2.

After completing all the steps of the fuzzy TOPSIS class, a sensitivity analysis was conducted to verify the data's robustness. Two alternative scenarios were tested, as illustrated in Figure 3. All calculations were performed for the alternative scenarios, and the comparison of the allocation into classes is shown in Figure 4.

The sensitivity analysis results highlight the robustness of the findings, as there were no changes in the allocation classes for the items in question.

Table 3. Classes and profiles adopted for analysis in the base scenario

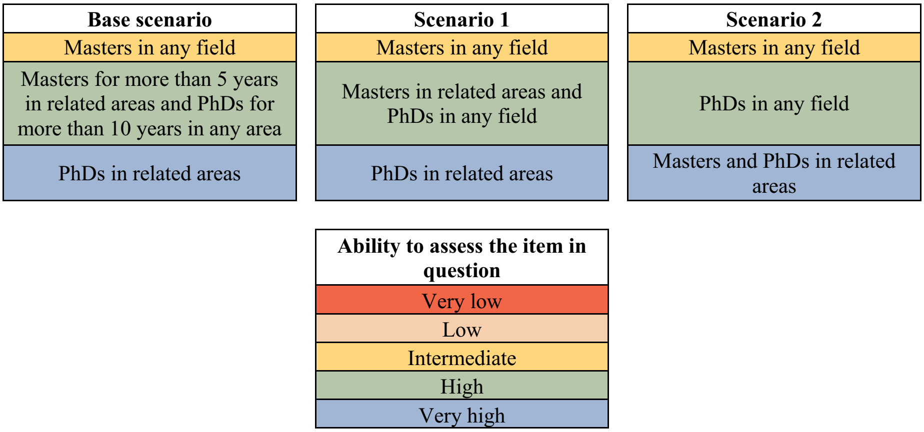
Class	Profiles
Expected	5 = the concept of the referred "R," its potential contributions to achieving the circular economy, and related examples are SYSTEMATICALLY included in teaching
Regular	3 = the concept of the referred "R," its potential contributions to achieving the circular economy, and related examples are included in teaching on a REGULAR basis
Unacceptable	1 = the concept of the referred "R," its potential contributions to achieving the circular economy, and related examples are PRACTICALLY NOT included in teaching

Source: Authors' own creation

Item	Expected	Regular	Unacceptable	Class to which the item belongs
R0	0.392	0.572	0.608	Unacceptable
R1	0.385	0.624	0.615	Regular
R2	0.487	0.650	0.513	Regular
R3	0.520	0.667	0.480	Regular
R4	0.465	0.616	0.535	Regular
R5	0.381	0.564	0.619	Unacceptable
R6	0.440	0.618	0.560	Regular
R7	0.405	0.603	0.595	Regular
R8	0.531	0.659	0.469	Regular
R9	0.298	0.446	0.702	Unacceptable

Notes: Red color = unacceptable; orange color = regular; yellow color = regular
Source: Authors' own creation

Figure 2. Values of CC_i^p for each class and identification of allocation of the "Rs"



Source: Authors' own creation

Figure 3. Scenarios considered in the sensitivity analysis

4.2 Discussion

With the results obtained, it is possible to highlight the most critical items and discuss them in light of the literature. The findings show that none of the analyzed items are classified as "Expected," demonstrating the need to intensify actions in undergraduate technology courses to enhance CE concepts. As the United Nations (2012) mentioned, continuous improvement in teacher training and capacity building is extremely important so that concepts can be conveyed to students most effectively. In Brazil, difficulties exist in integrating sustainability,

Item	Base scenario			Scenario 1			Scenario 2		
	Expected	Regular	Unacceptable	Expected	Regular	Unacceptable	Expected	Regular	Unacceptable
R0	0.392	0.572	0.608	0.390	0.572	0.610	0.386	0.569	0.614
R1	0.385	0.624	0.615	0.384	0.621	0.616	0.381	0.623	0.619
R2	0.487	0.650	0.513	0.484	0.646	0.516	0.482	0.648	0.518
R3	0.520	0.667	0.480	0.515	0.669	0.485	0.516	0.666	0.484
R4	0.465	0.616	0.535	0.463	0.614	0.537	0.462	0.614	0.538
R5	0.381	0.564	0.619	0.378	0.558	0.622	0.376	0.561	0.624
R6	0.440	0.618	0.560	0.430	0.612	0.570	0.435	0.614	0.565
R7	0.405	0.603	0.595	0.406	0.610		0.404	0.605	0.596
R8	0.531	0.659	0.469	0.527	0.657	0.473	0.528	0.656	0.472
R9	0.298	0.446	0.702	0.292	0.441	0.708	0.293	0.442	0.707

Notes: Red color = unacceptable; orange color = regular; yellow color = regular
Source: Authors' own creation

Figure 4. Results of sensitivity analysis

as Rampasso *et al.* (2021) pointed out. Still, with creativity and consistent debates, efforts can be made toward better curriculum structures.

Seven of the analyzed items were allocated to the "Regular" category: R1 (Rethink), R2 (Reduce), R3 (Reuse), R4 (Repair), R7 (Remanufacture), R7 (Recover) and R8 (Recycle). However, items R2 and R8 vary slightly in the third decimal place, causing uncertainty in their allocation to either the "Regular" or "Unacceptable" classes. Items R0 (Refuse), R5 (Restore) and R9 (Recover Energy) are allocated to the "Unacceptable" class in this study, meaning they are the most critical when considering how they should be taught in undergraduate technology courses in Brazil.

Regarding R0 (Refuse = making a product redundant by abandoning its function or offering the same function with a radically different product), there is a significant opportunity for debates related to changes in consumer habits and new business models of sustainable companies to be discussed in the curricular activities of undergraduate technology courses. Such debates do not require significant investments but rather engagement and participation from the faculty. As Potting *et al.* (2017) point out, such an "R" requires socio-institutional changes, which should be discussed in the classroom.

Considering the specificities of each professional's training, item R5 (Restore = restoring an old product by updating it) should also be discussed in the classroom. For example, technologists in industrial process courses should increasingly consider how old machines can be updated to meet companies' needs. Not all companies have the capital to acquire more modern equipment, and the retrofitting process can be interesting from an economical and sustainable standpoint.

Regarding item R9 (Recover energy), this is a less promise alternative than others but needs to be discussed in the classroom so that students discern more interesting alternatives before adopting them. Understanding the challenges of implementing energy recovery at the end of a product's life is essential because other sustainability topics are valued with this concept. In addition to being a highly critical item, since it has low circularity, the most promise approach is to keep the life cycle of products and their parts in the chain for more extended periods, generating more significant environmental benefits (Potting *et al.*, 2017).

The main findings of the research indicate that there is potential for improvement in teaching all the "Rs" analyzed when considering technological undergraduate courses when examining the teaching of those "Rs." Refuse, Restore and Recover Energy are the most critical topics when considering how technology undergraduate courses should be taught in Brazil.

This article's originality lies in a unique empirical analysis of the CE – which has increasingly emerged as a powerful method of achieving sustainable production chains – and the need to educate and align new generations of professionals enrolled in technological undergraduate programs with these concepts to succeed. To improve the curriculum, the program, the course objectives and the learning outcomes, it is critical to update the course pedagogical projects based on the study results.

Therefore, the article formalizes a procedure arguing in favor of a multicriteria decision technique known as the fuzzy TOPSIS class as an essential instrument for data analysis and correlation and for extracting meaningful results from data analysis.

5. Conclusions and final considerations

The CE increasingly emerges as an intriguing approach to pursuing sustainability in production chains, and the new generation of professionals needs to be educated and aligned with these concepts. Technological undergraduate courses in Brazil are more dynamic and pragmatic, aiming at meeting market demands. This study aimed to provide an overview of the teaching of the "10 Rs" in these courses, and based on the results obtained, it can be affirmed that the objective was achieved.

The "3Rs" that require greater attention due to their "Unacceptable" classification are: R1 = Refuse = make a product redundant by abandoning its function or offering the same function with a radically different product, R6 = Renew = recover an old product by updating it and R10 = Recover energy = incinerate materials to recover energy. The same attention should be paid to the "2Rs" that presented uncertainty between the "Regular" and "Unacceptable" classes due to the proximity of the values obtained, namely: R2 = Rethink = make the use of the product more intensive through its sharing or multifunctionality and R8 = Adapt = use discarded products or their parts in a new product with a different function. The other "Rs" were classified as "Regular," but a more intense and direct application in teaching these subjects is also necessary.

It is, therefore, concluded that there are significant possibilities for improvements in the aforementioned teaching. With the information contained in this research, a proposal for solving and minimizing this problem would be to review each Course Pedagogical Project, in which teachers, coordinators and education specialists could debate and have arguments regarding this need to add knowledge relevant to the CE and sustainability in each of the 13 technological axes available in the CNCST (National Catalog of Higher Education Technology Courses) (Brasil, 1996).

The authors of this article also advocate for using the multicriteria decision-making technique in studies to measure sustainability integration in higher education, given its ability to address uncertainties and allow for weighting perceptions according to each respondent's experience.

The research has limitations, such as the sample size, which could be better despite being qualified and representative of technological undergraduate courses. In addition, the focus on only technological undergraduate courses in one country is a limitation. Future research can replicate the method individually in each of the 13 technological axes available in the NCHTC and even explore it more regionally in the country studied. Qualitative studies are also suggested, which will deepen the results in specific contexts.

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