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REVIEW ARTICLE

Towards a green industry through cleaner production development

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Abstract

The growth in global production and consumption rates has resulted in increased pollution generation by industrial companies. To this end, cleaner production is one of the most widely used strategies to reduce the environmental impacts of industry and gain competitive advantage. However, it is still adopted slowly in many places. Therefore, the objective of this study is to propose a framework composed of governmental, scientific, and industrial strategies, policies, initiatives, and research opportunities for the development of cleaner production. The best practices of the top countries in the cleaner production technical-scientific scenario and the main implementation challenges and opportunities for its scientific development were identified and were the reference for the framework proposals. In the government sector, the framework suggests actions to encourage the adoption of cleaner production practices through national policies, legislation, tax incentives, and educational campaigns. In the scientific sector, it suggested the development of studies about the factors that motivate its adoption, studies about clean technologies, and studies about the cleaner production implementation difficulties. In the industrial sector, it highlighted the importance of the engagement of upper management to focus on efforts to increase the efficiency of manufacturing processes with the adoption of clean technologies, management systems, strengthening of the research and development areas, and replacement of hazardous raw materials. Thus, this study contributes with initiatives that will help the implementation of cleaner production practices, reducing the generation of pollution in industry, increasing the efficiency of its processes, and aligning countries and societies to sustainable development.

Keywords Cleaner production · Development framework · Technical-scientific scenario · Triple helix
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Introduction

Environmental issues came to the spotlight in international agenda at the end of the twentieth century (Khalili et al. 2015; Kubota and Cantorski 2013). In this period, important technological, scientific, and industrial advances occurred and countries like the USA, China, and Germany reached high levels of industrial development (Kan et al. 2012; Ashton et al. 2017). However, the depletion of natural resources, high levels of pollution, and global warming were some of the negative impacts resulting from this scenario (UNIDO/UNEP 2015).

Different studies, such as Orhan et al. (2021) and Soylu et al. (2021), have identified a positive correlation between CO_2 emissions, environmental degradation, economic growth, trade openness, and energy use in many countries during the last decades, demonstrating a negative impact on the environment due to the intensive economic advancement. Therefore, the international awareness of the damage caused by companies has also grown (Severo et al. 2017). The

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environmental management importance has gained strength due to increased social and governmental pressures. Countries' environmental policies have become increasingly stringent, requiring corporations to adopt initiatives to minimize their environmental impacts (Zhang et al. 2013; Yilmaz et al. 2015).

The Rio Declaration and Agenda 21 formalized sustainable development (SD) as an objective of the international community in the 1990s. The SD expresses the importance of harmonious development on social, economic, and environmental spheres, emphasizing the dependence relationship between them (Zilahy et al. 2009; Khalili et al. 2015). Thus, economic growth should not result in the natural resource depletion and environmental destruction but should guarantee the next generation survival while reducing poverty at world levels (Henriques and Catarino 2015; Khalili et al. 2015).

Therefore, several international institutions have taken actions to promote SD (Zou et al. 2017), especially in industrial companies. The industry is an important sector for several countries' economies, being one of those responsible for economic growth. However, its manufacturing processes have a significant impact on pollution levels and environmental degradation (Huang et al. 2013; Jia et al. 2014; Silvestre and Neto 2014). Thus, several solutions and technologies were developed to reduce environmental impacts of industrial activities (Faé Gomes et al. 2013; Khalili et al. 2015; Hens et al. 2018).

Among these solutions, cleaner production (CP) is a strategy used by many industrial company managers as a mechanism to promote processes less polluting (Ashton et al. 2017; Kubota and Cantorski 2013; Neto et al. 2016). The United Nations Environment Programme (UNEP) conceptualized CP in 1989 as the continuous application of a preventive and integrated environmental strategy to processes, products, and services, with the objective of increasing companies' overall efficiency and reducing risks to humans and the environment (Yusup et al. 2014; Nemet et al. 2016; Hens et al. 2018).

In the subsequent years to the CP conceptualization, UNEP, in partnership with the United Nations Industrial Development Organization (UNIDO), developed several projects to demonstrate the applicability of this strategy in developing countries. These projects culminated in the creation of the National Cleaner Production Centers (NCPC) program in 1995. These centers were established in developing countries in partnership with local organizations. They have the mission to facilitate international collaboration among companies around the world, share knowledge, experiences, and discoveries on techniques and practices for the use of clean technologies, and provide support to organizations on CP adoption (Severo et al. 2015; UNIDO; UNEP 2015). Those centers offer services to raise awareness of the benefits and advantages on adopting CP; develop CP projects to demonstrate its environmental, financial, and social benefits; help obtain financing; provide policy advice to national and local governments; and disseminate technical information (UNIDO 2021).

From 1995 to 2015, NCPCs were opened in more than 58 countries, where they supported numerous CP implementations and tracked their results. The centers have accumulated great experience since their creation and are currently one of the main institutions fostering the expansion of CP practices in the world (UNIDO; UNEP 2015).

CP allows the waste reduction through more efficient processes because it reduces the use of resources and the pollution generation, improves the company image, increases employee satisfaction levels due to positive impacts on health and safety, and reduces the productive systems' operating costs, increasing economic performance, and leveraging the companies' profits (Aparecido et al. 2013; Ashton et al. 2017; Gonçales Filho et al. 2018).

CP integrates waste management with pollution prevention, seeking the creation of environmentally and socially friendly production processes. It can be developed in two ways: implementing clean technologies to processes that result in lower environmental impacts and improving existing processes efficiency (Huang et al. 2013; Campos et al. 2020).

Therefore, clean technology (CT) development and improvement are important factors in CP implementations. Technological improvements have great potential to reduce environmental impacts on manufacturing processes, favoring more ecologically efficient methods and equipment, reducing the use of energy, water, and raw materials, and improving productivity (González 2005; Hall and Helmers 2013; Pinkse and Dommisse 2009).

The CP practice implementation can be done on three levels, according to Figure 1 (Gonçales Filho et al. 2018).

In Figure 1, it is possible to observe that CP aims to eliminate and minimize industrial waste and emissions with three-level actions. Level 1 is composed of source reduction strategies, and internal recycling actions compose level 2. Waste reduction in its source can be achieved by modifying the product or process. The product can be designed to minimize negative impacts on the environment during its life cycle and process modifications can be done through housekeeping, replacing raw material, or promoting technological changes in the manufacturing process. The third level is based on waste reuse strategies as external recycling and biogenic cycles (Espuny et al. 2021; Gonçales Filho et al. 2018).

However, there are challenges to implement CP. External factors such as instability in the political, economic, and market sectors cause insecurity to companies, which become reluctant to invest in its adoption (Dobes 2013; Gonçales Filho et al. 2018). Internal factors such as lack of leadership and senior managers inexperience with CP, lack of monitoring and reviews of implementations, and use of old and inefficient technologies hinder the success of CP practices. Inefficient communication, insufficient employee training, a lack of

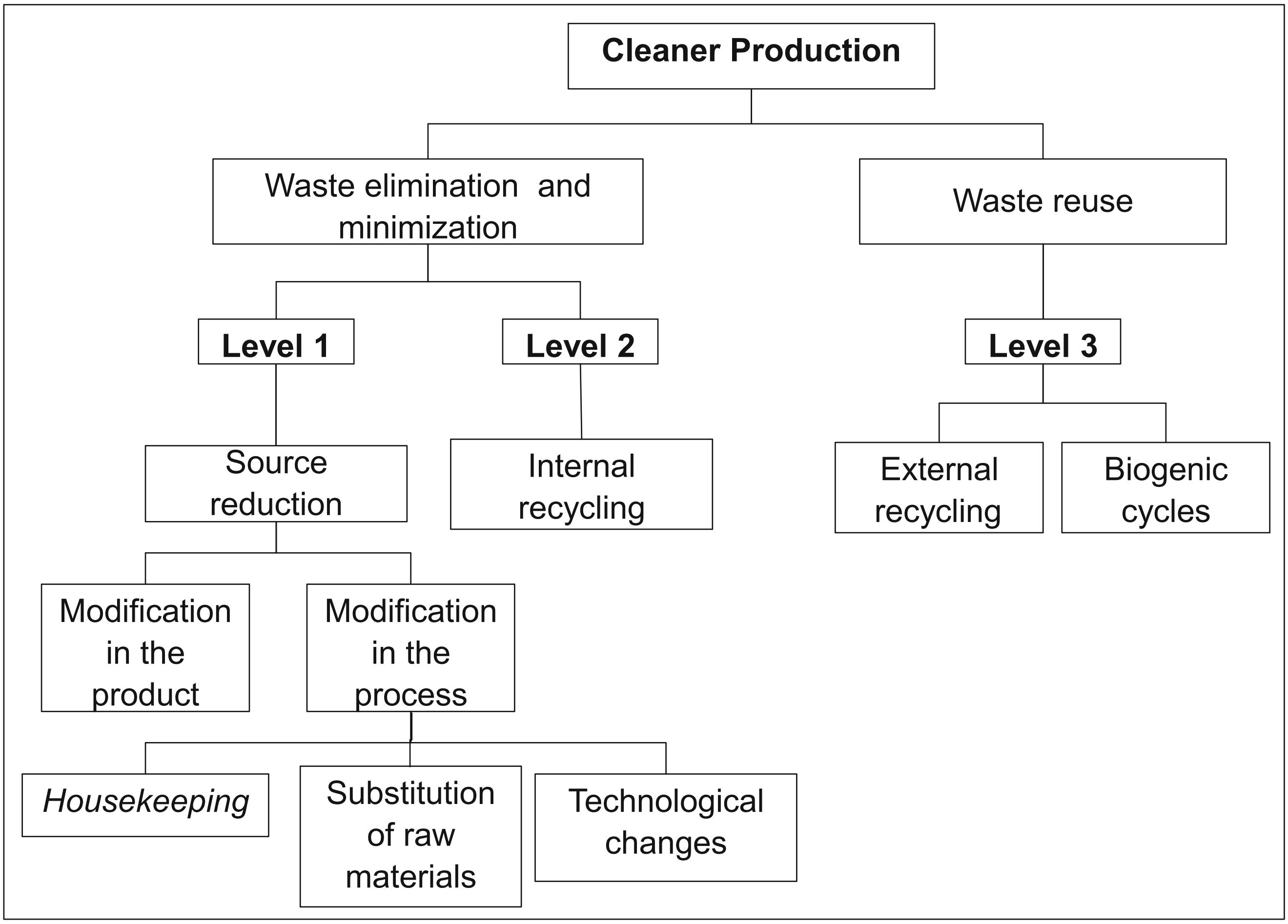

Fig. 1 CP practices focus on waste elimination, minimization, and waste reuse. They can be implemented in three levels: level 1: source reduction; level 2: internal recycling; and level 3: external recycling/biogenic cycles. Source: adapted from Gonçales Filho et al. (2018)

knowledge about clean technologies, lack of employee involvement, and resistance to change are also internal barriers faced by companies during CP adoption (Aparecido et al. 2013; Khalili et al. 2015; Gonçales Filho et al. 2018).

The need to overcome these barriers highlights the importance of studies that identify and propose initiatives that can be incorporated into CP adoption efforts to stimulate its use. Government, industry, and academia are the sectors with the most important roles in solving the countries' environmental problems. Their efforts and initiatives when focused on CP dissemination are catalysts for its development (Khalili et al. 2015). The triple helix model (Fig. 2) points out these sectors as the innovation main generators and responsible for driving sustainable economic development in modern societies, including CP solution creation (Kimatu 2016).

The triple helix is a concept that incentivizes innovation through closer relations between the "actors" university, organizations, and government. The mentioned actors should strengthen their institutional relations in order to foster a technological pole, discussing the main obstacles and opportunities for economic development, defining their roles to achieve this goal. Usually, this procedure is articulated at a regional level, through the establishment of growth agreements, or even through the formation of municipal technology councils. The results that are usually expected are the construction of new facilities by the public authorities; improvement of students by the universities; and negotiation of new supplier relationships, articulating competitive supply chains. This initial interaction, when well-organized, provides better industry outputs and improves the local economy (Etzkowitz, 2008). As examples of development based on the triple helix, one can cite the partnership between Stanford (university), Silicon Valley (government), and Google, Apple, and Facebook (companies) in San Francisco (USA), developing a strong technology industry. In Brazil, one can cite examples from São José dos Campos, involving the Institute of Aerospace Technology (university), Air Force (government), and Embraer (organization) in São José dos Campos, developing a recognized aviation industry (Baptista et al. 2020; Pique et al. 2020).

The government is responsible for regulating relations between these sectors, creating partnerships, promoting

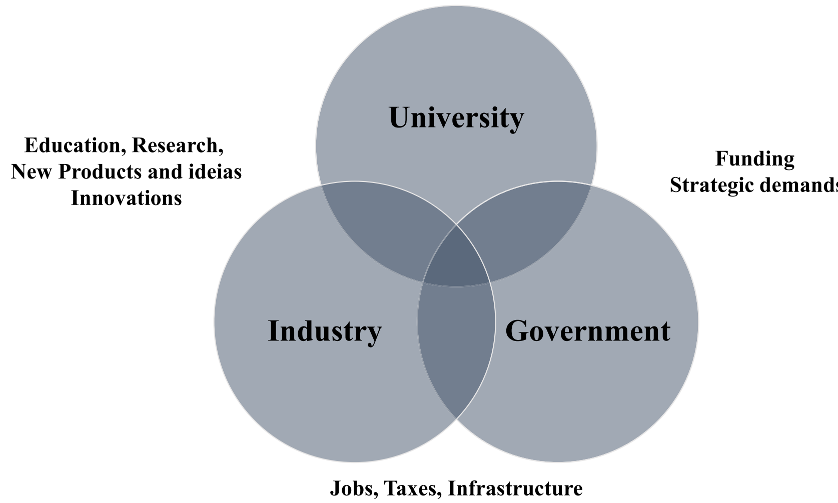

Fig. 2 The triple helix model is composed of industry, government, and university and their interactions aim to accelerate innovation and generate knowledge to solve the contemporary challenges. Source: Kimatu (2016) and Ranga and Etzkowitz (2013)

research, and ensuring the necessary infrastructure for companies. The industry generates employment and income and is responsible for the strategic demands of innovation, which can be developed internally by its research and development (R&D) departments or through partnerships with the other two sectors. Universities, on the other hand, are responsible for the education and training of professionals, and for the new products, ideas, and innovations of R&D (Kimatu 2016; Leydesdorff and Etzkowitz 1996; Leydesdorff and Meyer 2006).

The government, industry, and university are responsible for identifying sustainable initiative opportunities. They should be prepared and motivated to assume their responsibilities in promoting SD by encouraging and developing sustainable policies, adopting environmental objectives and strategies in their economic, environmental, and social spheres, and disseminating their actions and results transparently (Almeida et al. 2015; Ashton et al. 2017; Vieira and Amaral 2016). Thus, these sectors CP's incentive initiatives contribute to countries' SD.

Thus, considering the theme importance, 31 reviews of CP have been published in the last 5 years. Among the most cited works, Dong et al. (2019) present new perspectives on cleaner production in mines, to eliminate waste in dams. Wang et al. (2017) review the reduction of technological impacts on rare earth element extraction in China. Vieira and Amaral (2016) identified the main issues that prevent the wider implementation of cleaner production. Tiwari et al. (2016) analyzed solid waste that could replace concrete in civil construction activities, and Hoyos-Martínez et al. (2019) studied the production of tannins in nature, highlighting the main positive and negative impacts.

However, despite the contributions of these reviews to the CP improvement, they are restricted to specific areas and do not consider the potential of coordinated actions from governments, companies, and universities to CP development. Thus, this study is different from prior studies because it adds contributions from the triple helix's sector perspectives by means of the study of innovations and patents; business initiatives; white papers; university initiatives; and researchers' initiatives. The diversity of data sources and the authors' contributions allowed a review of scientific and technical content simultaneously, resulting in a broader and more detailed understanding of the subject. Thus, this work makes it possible to fill scientific gaps related to the need for identification of the main factors that motivate the various sectors of industry and society to adopt CP (Wesseh Jr and Lin 2015; Severo et al. 2017; Hens et al. 2018), and the identification and proposal of solutions to the main difficulties faced by companies during the CP implementation (Severo et al. 2015; Govindan et al. 2016; De Oliveira et al. 2016).

Therefore, the research question posed in this study is: how it is possible to promote cleaner production initiatives to contribute to sustainable development? Answering this research question, this article has the objective of proposing a CP development framework composed of policies, strategies, initiatives, and research opportunities to be developed by the governmental, industrial, and academic sectors, filling the gap of prior studies by bringing a broader view of CP's technical and scientific potential to contribute to SD. The CP policies, strategies, and initiatives that were prominent in the top countries of the CP technical-scientific scenario and the main CP implementation challenges and opportunities identified in the literature were analyzed and adapted in light of the authors' expertise, serving as a benchmark for the framework proposals. It is expected that the public sector, business organizations decision-makers, and academic institutions can use the framework to guide their scientific, technological, public, and private initiatives and investments aiming the CP development and, consequently, contribute to SD.

The article is organized into 5 sections, considering this introduction. In the second section, the research method and its stages are described, in the third section, the research results are presented and discussed, in the fourth section, the CP development framework is presented and discussed, and in the fifth section, the authors' conclusions are presented, followed by the references.

Research method

The research that originated this article was conducted according to the flow of activities presented in Figure 3.

The research was conducted in five phases: (1) objectives and method definition; (2) research criteria, data collection, and organization; (3) CP technical-scientific scenario mapping; (4) CP framework elaboration; and (5) conclusion. Table 1 describes all the phases and stages of this research.

This research can be classified as having a descriptive and analytical objective, with an applied nature, a qualitative approach, and as experimental research. The descriptive objective consists of describing the state of a theme at the moment of research realization, and the analytical objective consists in using the facts or information available for developing analyses. The nature is applied, because the research seeks a solution to a socioeconomic problem. The approach is qualitative because the research is focused on the investigation of concepts associated with the CP field of study, seeking an in-depth conclusion about good initiatives that can be adopted by industries, governments, and universities to develop CP. Finally, the research can be considered experimental because the authors raised information that would allow them to answer the research question (Kothari and Garg 2019).

Thus, at the end of this study, a framework was proposed for the CP development consisting of suggestions of policies, strategies, initiatives, and research opportunities to be developed by governments, industries, and universities. The initiatives mapped in the CP technical-scientific scenario and the opportunities and challenges identified in the theme's literature were analyzed and adapted in the light of the authors' expertise and served as a benchmark for the framework proposal (Figure 4).

Results and discussion

Technical-scientific scenario

This topic presents the main CP actions, achievements, initiatives, and policies adopted by their governments, industries, and scientific communities of the countries that stand out in the CP technical-scientific scenario. From the ten most cited countries in the CP area, the four with the highest *h* indexes (Brazil, China, the USA, and Malaysia) were analyzed. These countries are references in academic-scientific terms due to the initiatives mapped and, therefore, will serve as a basis for the framework to promote this strategy.

Brazil

Brazil is the country with the highest *h*-index (16) on the theme. It was one of the thirteen countries, with China, Croatia, the Czech Republic, Hungary, India, Mexico, Nicaragua, Slovakia, Tanzania, Tunisia, and Zimbabwe, which received the first NCPCs. The National Center of Clean Technologies was founded in 1995, with the support of the National Industrial Learning Service of Brazil. This center was responsible for creating the Brazilian Cleaner Production Network (BCPN) in partnership with the Brazilian Business Council for Sustainable Development. This network is composed of organizations and professionals dedicated to accelerating the transfer of information and CT among companies in the country, and provides specialized services in CP (Kist et al. 2009; Pereira and Sant'Anna 2012; UNIDO; UNEP 2015).

BCPN has created a guide for the implementation of CP practices on Brazilian companies. A methodology divided into 5 phases was proposed: planning and organization, pre-

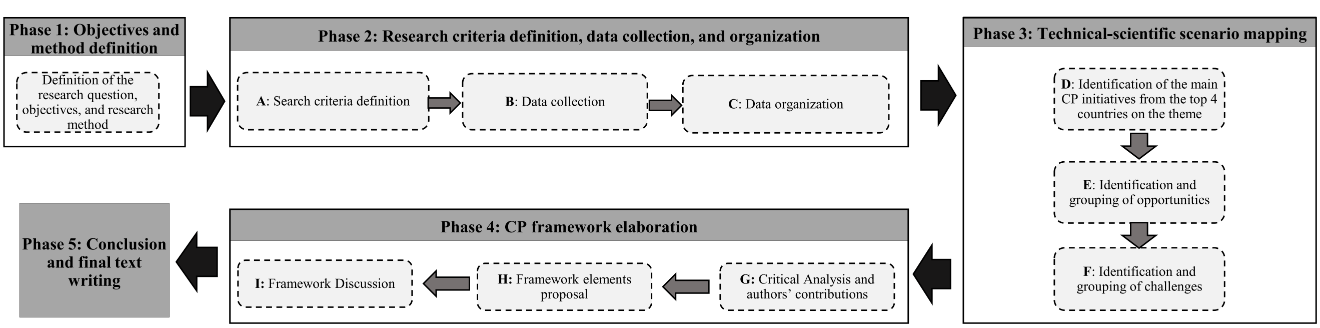

Fig. 3 The research method flow is composed of five phases. Phase1: objectives and method definition; phase 2: research criteria definition, data collection, and organization; phase 3: technical-scientific scenario mapping; phase 4: CP framework elaboration; and phase 5: conclusion and final text writing

Table 1 Description of the research phases and stages

Phases	Stages	Description
Phase 1: objectives and method definition	Definition of the research question, objectives, and research method	The research question to be answered by the study, the objectives, and the study research method were defined.
Phase 2: research criteria definition, data collection, and organization	A: defining search criteria	The search criteria for data collection were established. It was defined that only articles in the English language would be studied because it is the most commonly used language by the academic researchers (Nunhes and Oliveira 2018). The research term chosen was "cleaner production" present only in the articles' titles, so that the studies would be strictly related to the theme. The period studied was from January 1, 2014 to January 31, 2020. This period was chosen because the most recently published articles already consider the scientific advances developed in previous studies and expand their discoveries, representing what exists of current practices in the subject and trends of future research. The platform chosen was Scopus because it is one of the largest academic databases and it provides a broad view of scientific production on the CP area (da Motta Reis et al. 2020). The most studies available in other databases, such as the Web of Science, are also found at Scopus, so it is the complete database on the subject (Mongeon and Paul-Hus2016). At this stage, the patents research criteria were established. It was defined that only priority patents with one of the terms "cleaner production," "clean technology," "clean energy," or "pollution prevention" present in their title or in their objective description would be studied. Priority patents are usually registered in the origin country of their inventor, so it is a good country technology development indicator. Unlike the article research, it was necessary to cover several patent areas for a more detailed understanding of the technologies in this field of knowledge. The period studied was from 2000 to 2020. There were not defined restrictions on the type of patent registration and patent time of usefulness because the study objective is to map all the innovations in CP area created during the study period. The Orbit Intelligence platform was chosen for the patent study because it gathers patents of more than 100 patent offices around the world, allowing a broad analysis of CP-related technology development.
	B: data collection	The information about 97,509 patents that satisfied the search criteria and 275 articles was collected. The 30 most cited articles were used in the third phase of the research to identify and systematize the main CP development opportunities and difficulties.
	C: data organization	The data were organized in table format as appendix, and available in the supplementary material of this article. The ten most cited countries (Appendix 1 in the Supplementary information), research institutions (Appendix 2 in the Supplementary information), funding centers (Appendix 3 in the Supplementary information), scientific journals (Appendix 4 in the Supplementary information), and authors (Appendix 5 in the Supplementary information) in CP area were ranked according to their *h*-index. Only countries, organizations, and authors with more than three publications in the topic were eligible to enter the rankings, so there were only five scientific journals eligible. *H*-index is intended to quantify the productivity, impact, and relevance of scientific research. The index *h* of *N* indicates that the author has at least *N* articles with *N* citations in each and none of his other articles has more than *N* citations (Hirsch 2005). Finally, the 30 most cited articles are available in Appendix 6 in the Supplementary information. The countries with the highest number of CP-related priority patents have also been identified. This information has been systematized in the graph presented in Figure 5. The software used to process the data was Microsoft Excel. Finally, the two most recent patents registered in each country of the technical-scientific scenario were analyzed and discussed.
Phase 3: technical-scientific scenario mapping	D: identification of the main CP initiatives from the top 4 countries on the theme	The technical-scientific scenario consists of the main strategies, policies, and initiatives adopted by institutions in the industrial, governmental, and academic sectors in countries prominent in the development of technological and scientific innovations in the area of study. Thus, the

Table 1 (continued)

Phases	Stages	Description
		initiatives reflect some of the reference practices in the theme under study and that can serve as a benchmark for other countries and institutions (Costa et al. 2021; Nunhes et al. 2021; Reis et al. 2021). During stage D, the main initiatives, innovations, and practices in the governmental, industrial, and academic sectors of the four most cited countries in CP area (identified in stage C) were studied. The content analysis of each country's main publications on this theme, such as articles, official documents, white papers, reports from national and international agencies, and government pages was conducted. There were studied reports about UNEP and UNIDO CP initiatives (UNIDO, UNEP 2015), national CP policy documents from selected countries (BRAZIL; 2006, 2011; DOE; 2007), law texts (Cleaner Production Promotion Law 2002), and reports from national CP foment agencies (CNTL et al. 2003; US EPA 2020a; ISSE 2020). The technical and scientific publications of each country were meticulously analyzed to identify and systematize its objective, method, and main contributions. Content analysis is a method of textual data analysis focusing on the contextual meaning of the text and the subjective analysis of its content through the systematic themes or patterns identification. Such analysis allows building knowledge and understanding the phenomenon studied (Hsieh and Shannon 2005; Elo et al. 2007). Therefore, this method was chosen for mapping the CP technical-scientific scenario.
	E: identification and grouping of opportunities	The CP scientific development opportunities were identified from the content analysis of the 30 most cited articles identified in stage B. All the articles were analyzed by focusing on the identification of its objectives, methods, contributions, and CP scientific development opportunities. Next, these opportunities were grouped in clusters according to their similarities.
	F: identification and grouping of challenges	The previous stage procedures were repeated, but with a focus on CP practice challenges presented by the same 30 articles.
Phase 4: CP framework elaboration	G: critical analysis and authors' contributions	The critical analysis of policies, strategies, and initiatives of the countries studied in the technical-scientific scenario and the CP development opportunities and challenges was conducted. The initiatives and strategies were adapted to the areas of actuation of the different triple helix sectors to overcome the CP development challenges. The policies adopted by the countries studied were adjusted to the industrial and academic sectors as suggestions of practices for the CP development. The scientific and technical advances developed at universities, researchers, and companies and the opportunities for scientific development served as a benchmark to propose actions for reducing companies' environmental impacts.
	H: framework proposal	The CP development framework was developed based on the analysis made in stage G. It suggests policies, strategies, initiatives, and research opportunities to be developed by the three triple helix sectors to promote CP practices.
	I: framework discussion	In stage I, the suggestions proposed in the framework were discussed to ensure their understanding.
Phase 5: conclusion	Conclusion	Finally, in the 5th phase, the conclusion and the final text were written outlining this article's contribution to CP area.

assessment, evaluation, feasibility study, and implementation (CNTL et al. 2003).

Another important initiative was the structuring of CP state forums made by the Brazilian government with the purpose of articulating a national CP policy (Brazil 2006). In 2011, the first Brazilian national policy based on CP aspects was created: The Action Plan for Sustainable Production and Consumption.

The policy's action plans foster sustainable policies, programs, and initiatives with the objective of improving the solutions to Brazil's socio-environmental problems. Actions and targets have been defined segmented into 4-year cycles starting in 2011, in the areas of education, public policies,

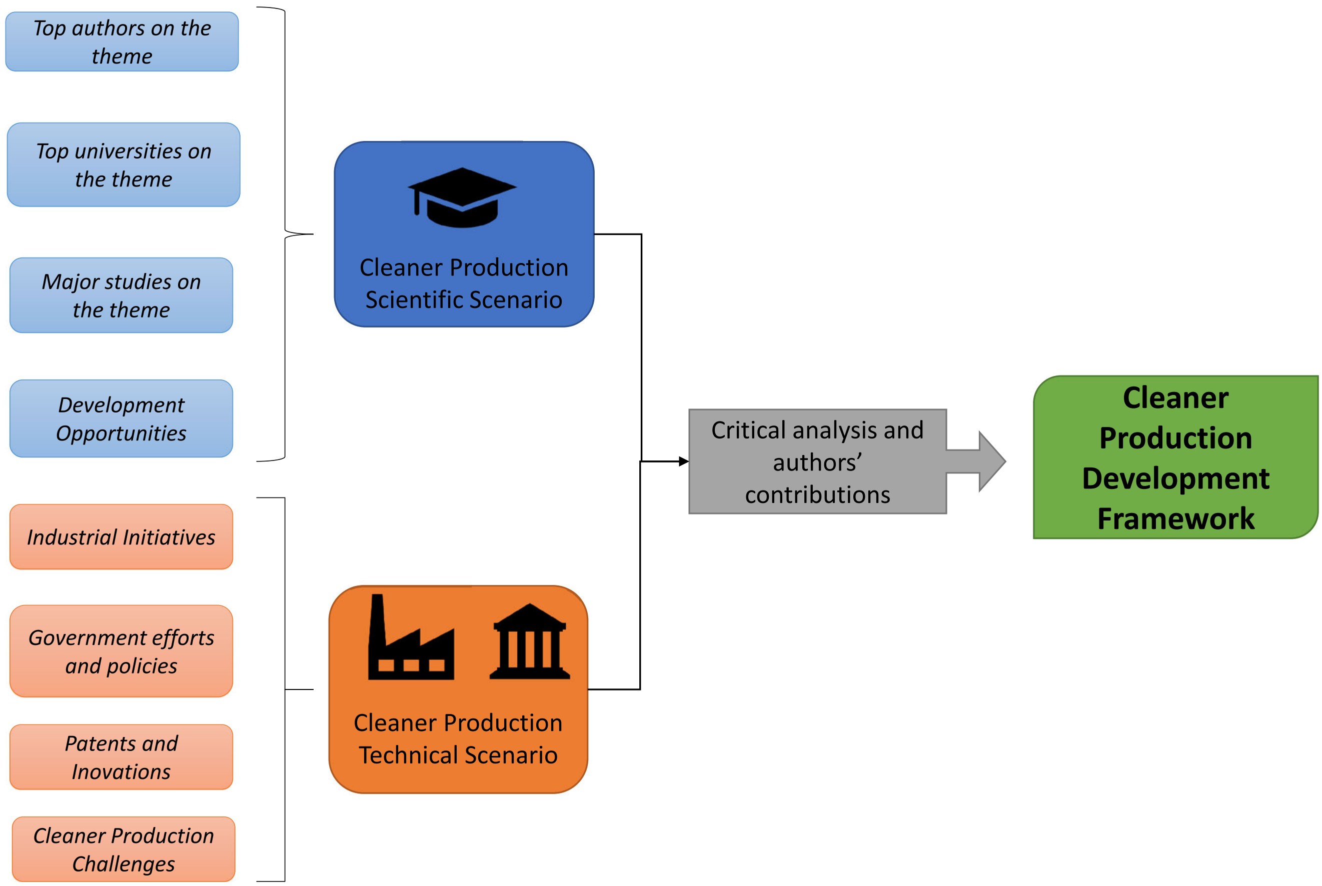

Fig. 4 The CP development framework proposals were elaborated based on critical analysis and benchmarking of the policies, strategies, and initiatives from industries, governments, and universities of the top CP technical-scientific scenario countries.

solid waste recycling, sustainable retailing, sustainable construction, and sustainable industry, to encourage the adoption of pollution prevention practices (Brazil 2011). Implementation strategies are redefined at the end of each cycle according to the evolving needs of the Brazilian economy.

The first cycle (2011 to 2014) actions focused on the dissemination of sustainable consumption and production culture. Different training and qualification processes were conducted on the subject. A Public Administration Environmental Agenda was created, resulting in an investment of USD 3.53 billion in solid waste plans and infrastructure, while several programs and partnerships between the public and private sector were formed (Brazil 2014). The actions of the second cycle of implementation (2016 to 2020) will only be published in 2021.

The Brazilian academic-scientific community stands out for developing internationally influential works on CP. Brazil obtained the highest number of citations (548) between 2014 and January 2020 at Scopus. Articles by Brazilian authors and universities are also among the most cited worldwide in this theme, which will be presented next.

Among the 10 most cited authors about CP, six are Brazilian. Among the 30 most cited articles on CP between 2014 and January 2020, six of them are authored or coauthored by any of these authors. Prof. Dr. Severo, Prof. Dr. Dorion, and Prof. Dr. de Guimarães studied the joint application of CP with environmental management practices in Brazilian companies and their respective impacts on organizational performance in the 5th and 8th most cited articles (Severo et al. 2017, 2015). Prof. Dr. Ometto studied the impact of ISO 14001 on CP practices in the 20th most cited article (De Oliveira et al. 2016) and the implementation of best practices in a paper production process in the 28th most cited article (Silva et al. 2015). Finally, Prof. Dr. Agostinho and Prof. Dr. Giannetti performed the analysis of the articles published in the international workshop on advances in CP in the 9th and 27th most cited articles (Almeida et al. 2015, 2017).

Prof. Dr. Giannetti, B. F has extensive experience in this field of study. He is the co-founder of the Advances in Cleaner Production Network, an international forum for the exchange of information and research results about CP technologies, concepts, and policies (ACPN 2020). Giannetti also composes the editorial board of the *Journal of Cleaner Production*

(*JCP*) and is the associate editor of the *Journal of Environmental Accounting and Management* (FAPESP 2020).

Regarding the 10 most cited teaching and research institutes in the CP area and ordered according to their *H*-index, 4 are Brazilian. Among them, UNIP stands out because it has the Production and Environment Laboratory (LaProMA) dedicated to CP studies (UNIP 2020). LaProMA is one of the founders and organizers of the International Workshop on Advances in Cleaner Production in collaboration with the *JCP* that is one of the largest international events in this area and occurs annually, bringing together some of the leading researchers on the subject.

However, despite the Brazilian government initiatives to promote and develop the CP and the prominence of Brazilian researchers in the global context, there is a lack of integration between the universities and government, and a notorious absence of public policies that encourage the adoption of this strategy. This fact has generated few practical results regarding the CP adoption by Brazilian companies and few partnerships between universities/research centers and companies (Neto et al. 2016; Pereira and Sant'Anna 2012). Therefore, Brazil develops less technologies than the innovation leading countries in CP area, what can be seen in the number of priority patents related to CT registered in the country.

Brazil is not among the 15 countries that most develop patents in this area (Figure 5), showing that, although it stands out in other CP aspects, the country is still far from those at the top of this ranking. Brazil registered 89 patents during the studied period, 500 times fewer patents than China and 200 times fewer than the USA. The two most recent patents registered by inventors in Brazil, with the term cleaner production, were "Thermo Insulating Concrete" and the patent "Production of ceramic proppant from iron ore and/or waste rock from its exploitation and/or tailings from its beneficiation with the agglomeration of fine and ultrafine particles".

The patent "Thermo Insulating Concrete" is an invention that includes glass fiber rejects in concrete intended for construction. The thermal insulating performance is superior to conventional concrete. Thus, it is possible to reduce the use of natural aggregates in the production of concrete, allowing the reuse of waste that would otherwise be sent to landfills. This patent decreases the negative environmental impacts and reduces the cost of waste treatment for municipalities and organizations (Mendes et al. 2018).

The patent "Production of ceramic proppant from iron ore and/or waste rock from its exploitation and/or tailings from its beneficiation with an agglomeration of fine and ultrafine particles" is a process of ceramic proppant that allows the agglomeration of several products and by-products of the ore—including tailings—forming a ceramic product with high

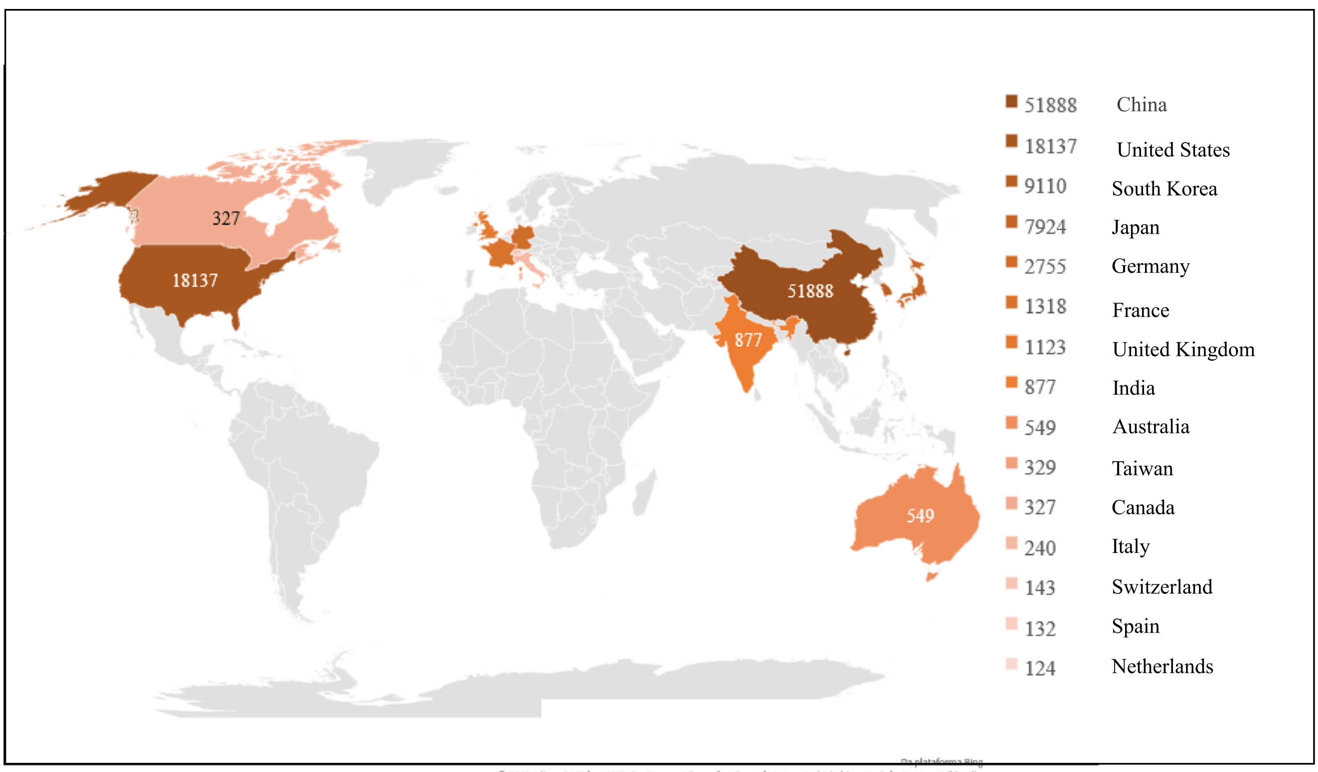

Fig. 5 Top 15 countries on CP patents development (2000-2020). The number of patents developed by the countries is represented by the color intensity, that is, as darker the color, the greater the number of patents. Source: Orbit Intelligence (2020)

added value. This invention allows the reduction of tailings in dams, avoiding damage to the environment and saving financial and natural resources (Da Silva and Januario 2021).

Therefore, although the Brazilian academic-scientific community is globally known for its work in the CP area, there is a lack of effective initiatives to promote its adoption in public and private organizations and initiatives to encourage the development of clean solutions and technologies in the country. Therefore, the Brazilian government should encourage the R&D of clean technologies, implement taxes for the most polluting economic sectors of the country, subsidize the development of innovations and patents, and promote public-private partnerships between companies, research centers, and the government (Adebayo et al. 2021a, 2021b).

China

China has the second-largest *h*-index on the subject (14). Its intense industrialization process has generated severe environmental problems (Peng and Liu 2016). Air pollution, biodiversity losses, soil pollution, water pollution, water scarcity, and high waste generation have caused serious economic losses, social damage, and high health costs in China (Soylu et al. 2021; Kan et al. 2012; Li et al. 2014; Liu and Diamond 2005; Lu et al. 2015).

The Chinese government began an intense process to combat pollution due to the seriousness of the environmental crisis in the country (Liu and Diamond 2005). China invested USD 378.5 billion in 16 sustainability programs between 1978 and 2015, most of it in the last 20 years (Jingtao 2019). To make its energy matrix cleaner, China was the country that most invested in renewable energy between 2010 and 2019 in the world (Ajadi et al. 2019).

Therefore, CP was an important solution for the prevention and reduction of environmental impacts generated by Chinese industries (Peng and Liu 2016). To expand and intensify the CP adoption, several government agencies have promoted research on the subject (Changbo et al. 2015).

China received one of the first NCPCs. The Chinese government has been promoting the opening of Regional Cleaner Production Centers and Enterprise Cleaner Production Centers since 1994 spreading these strategy practices throughout the country. At least 22 CP centers were opened in several provinces until 2012, which played an important role in the search for SD in China (Changbo et al. 2015; Peng and Liu 2016; UNIDO; UNEP 2015).

Between 1992 and 2002, the Chinese government enacted laws regulating and encouraging CP adoption among its companies. The 2002 CP Promotion Law stands out as the first CP-specific legislation adopted by a developing country (Changbo et al. 2015; Shi et al. 2008).

In this law, several policies were defined aiming for the inclusion of CP practices in national plans and programs through tax incentives, support to research and clean technology development, and partnerships with international institutions (Cleaner Production Promotion Law 2002). The CP application has proven to be more efficient than conventional end-of-pipe approaches to pollution control in the country (Shi et al. 2008).

The CP Promotion Law established mandatory audits for three categories of companies: companies that exceeded the national and local pollution generation standards, companies where the rate of energy consumption per unit produced exceeded the limits defined by the government, and all companies that used or produced toxic and hazardous materials. Thus, as opposed to the strategies of most other countries where CP had been promoted voluntarily, mandatory audits became the focus of Chinese pollution response policies (Bai et al. 2015; Peng and Liu 2016; Zhang et al. 2013).

Thus, China is a successful case in the adoption of CP practices among developing countries (Peng and Liu 2016). The CP advances in the country warm the attention of the world academic-scientific community, where Chinese works have been the most cited in recent years (565 quotes).

Three of the 30 papers analyzed have Chinese authors' participation. Wesseh Jr and Lin (2015) developed an optimization model to estimate the optimal amount to be invested by the government of Liberia in the research and development of renewable energy technologies in order to drive replacement of fossil fuel use, reduce the environmental costs of the country's economic development, and reduce greenhouse gas emissions. Jia et al. (2014) developed an assessment indicator framework for the industry of vanadium extraction from stone coal for assessing the cleaner production process. Finally, Long et al. (2014) designed and constructed a novel plant in pilot scale for fabric rope dyeing with supercritical carbon dioxide fluid for cleaner production of textiles. The plant and application processes designed are water and effluent free and allow energy conservation, being environmentally friendly in comparison with conventional dying processes.

Among the 10 most cited institutes in the articles published by its researchers in this area, 2 are Chinese: Ministry of Education and Wuhan University of Technology (WUT). WUT is a reference in research in China, with 34 research centers. Engineering, materials development, logistics, mechatronics, information technology, and environmental technology laboratories are among the centers developed by the Chinese government. Simultaneously, the university has about 230 research centers in partnership with local companies (Wuhan University of Technology 2020).

All investment from research institutions and the Chinese government has reflected on the level of CT development in the country. China is the country with the most patents registered (Figure 5), 51,888, 2.8 times more than the USA, which is the second country with most patents in this area (18137). The latest patents filed in China were "Notification method for refrigerator, appliance, and refrigerator" and "Improved label fabric coating and manufacturing method".

The patent "Notification method for refrigerator, appliance, and refrigerator" is an application used in smart appliances, enabling a database that stores the technical information of the food that is packed inside. In this way, the foods are controlled and users are notified of their expiration. This application can be used in foodservice establishments, such as restaurants and bars, and the food industry, improving cost management and reducing waste generation (Fei et al. 2019).

The patent "Improved label fabric coating and manufacturing method" is a method to improve the quality of the labels that are sewn onto clothes, using a comfortable, practical, and consumer-friendly material. A printer is used to produce these labels, saving all the tasks of the fabric industry, such as designing, weaving, coating finishing, and organic solvents. To achieve these results, this invention relies on soft-coated tape that does not irritate the skin, wash protection, clearly printed material, and good readability, among other attributes (Hong et al. 2021).

Therefore, driven by the pressures of their country's serious socio-environmental problems, the Chinese government and society have been adopting initiatives to promote the reduction of pollution generated by their industries, to increase the environmental efficiency of their companies and to adopt a clean energy matrix (Hong and Li 2013). Those many initiatives to promote sustainable practices and partnerships between the Chinese government, industry, and academia have generated important achievements and advances in the area (Changbo et al. 2015; Hou et al. 2019). Thus, CP stands out as an important strategy for China's SD, which should continue to invest in the replacement of fossil fuels, R&D of clean technologies, and encourage public-private cooperation in developing solutions to the country's environmental problems (Soylu et al. 2021).

United States of America

The United States of America (USA) is the country with the third-largest *H*-index in CP theme (*H*-index = 10). The USA's high industrialization has made it one of the most polluting countries in the world (US EPA 2020a). Thus, the importance of addressing environmental impacts and preventing pollution generation was realized even before the CP concept emerged. Between the 1970s and 1990s, the American government enacted several environmental laws regulating the main practices that were causing the pollution of the country's soil, air, and water (Miller et al. 2008). However, many of them still had an end-of-pipe approach, being directed to pollution control, treatment, and disposal only after it was generated (Burnett 1998; Miller et al. 2008).

The US Environmental Protection Agency (EPA) is the primary government agency responsible for protecting the American environment. Since its establishment in 1970, the agency has been developing environmental laws, overseeing its enforcement and encouraging research into sustainable solutions to the country's environmental problems (US EPA 2020b).

American private companies played an important role in developing strategies focused on pollution prevention in the USA, which subsequently became the basis of the country's environmental policies. The large multinational 3M emerged with the Pollution Prevention Pays (3P) strategy in 1975, which was widely adopted by several other companies.

3P works to prevent pollution by reducing waste at source, adopting new technologies, changing processes and raw materials, and establishing an incentive program for employees to suggest and implement solutions to reduce the companies' environmental impacts. At 3P, improvements should ensure financial return by reducing waste and pollution control costs (Miller et al. 2008; Ochsner et al. 1995).

These pollution prevention initiatives have been titled in many ways in the USA, including waste minimization, waste reduction, cleaner production, and pollution prevention (P2), the most widely adopted in the country (Miller et al. 2008). In 1990, the EPA introduced the Pollution Prevention Act, officializing pollution prevention at the source (P2) as the official strategy of the US government as opposed to end-of-pipe approaches. Strategies were defined focusing on industry, government, and public attention on reducing the amount of pollution through cost-effective changes in production, operation, and raw material use (Harrington 2013; US EPA 2020c).

Thus, the USA has achieved several advances in reducing the pollution generated by its companies (Shapiro and Walker 2018). Between 1991 and 2012, the EPA conducted about 370,000 pollution prevention projects through the Toxic Release Inventory (TRI) Program in several American industries. It is estimated that each of these projects reduced the emission of chemicals from 9 to 16% per year, totaling a prevention of generation of 5 to 6.35 billion kilos in chemical waste (Ranson et al. 2015).

In the academic-scientific area, Prof. Dr. Donald Huisingh stands out as the second author with the highest *H*-index among the 10 most cited authors in this area. He has extensive experience with CP. During his life, he has supported the CP practice implementation in more than 300 organizations and founded *JCP*, being currently the journal Editor-in-Chief Emeritus (Elsevier 2020a).

The *JCP* is one of the main periodicals in the CP area. Founded in 1993, it acts as a platform for theoretical and practical discussion on CP practice advances and applications. Among the 30 most cited articles in the period studied and available at Scopus, 29 were published in this periodical, indicating his high relevance (Elsevier 2020b).

Five of the 30 papers analyzed have American authors' participation. Khalili et al. (2015) proposed the application of a methodology to leaders of higher education could assess the necessity of creating training programs to develop the human capital needed to support SD, infusing CP concepts and theories at academic programs. The proposed methodology was formulated to utilize expert judgment to assess the importance of a matrix of CP—SD indicators needed for the design of CP-infused academic programs in teaching and research. Almeida et al. (2015, 2017)) identified CP strategies proposed on the published articles in the 4th and 5th International Workshop Advances in Cleaner Production, respectively, to help companies, government, and society to speed up to SD. The strategies are focused on sustainability strategies, raw material replacement, renewable energy, technological developments, and product and policy changes. Yilmaz et al. (2015) analyzed eleven best available techniques (BATs) of cleaner production for iron casting process, using a life-cycle approach (LCA). The BATs analyzed decreased overall environmental impact of casting by 60–90%. Finally, Ortolano et al. (2014) evaluated the dissemination of cleaner production in Pakistan's industrial sector by assessing the performance of two of Pakistan's CP centers and the survey of 80 leather tannery and textile processing firms.

Among the 10 research institutes that have published the most cited articles in the CP area, 2 are American: University of Tennessee (UT) and Illinois Institute of Technology (IIT). UT has important research centers, with emphasis on CP as the Institute of Secure and Sustainable Environment (ISSE). This institute was established to promote the development of policies, technologies, and educational programs in response to environmental issues faced by the world (ISSE 2020).

The second institute is IIT. Its studies on CP were conducted by the Stuart School of Business between 2014 and January 2020. IIT developed the pathways to CP in the Americas project, where partnerships were made among research institutes and companies from 8 countries of the American continent (the USA, Costa Rica, the Dominican Republic, El Salvador, Guatemala, Honduras, Nicaragua, Peru). The objective of the project was to promote and facilitate the adoption of sustainable practices in these countries (Ashton et al. 2017; McPherson et al. 2016).

The most important actions were the strengthening of CP practice teaching in higher education institutions, the sensitization of micro, small, and medium enterprises regarding the CP benefits, the conduction of CP implementation in the project's partner companies, and the creation of a collaboration forum for the exchange of knowledge among these countries (Ashton et al. 2017; McPherson et al. 2016).

Figure 5 shows that the USA is the second country with most CT priority patents registered between 2000 and 2020. Thus, the public and private initiatives on pollution prevention practices combined with the initiatives from American research centers have made the USA a powerhouse in the development of CT. The latest patents filed under cleaner production were "Stimulation of geothermal wells and removal of silica-based deposit" and "Virtual landfill terminal".

The patent "Stimulation of geothermal wells and removal of silica-based deposit" is intended for geothermal plants, i.e., power plants that produce energy using heat from the Earth's interior. Despite being considered a clean energy source, this energy matrix often suffers in maintaining its reservoirs active over time. The most recurrent solutions to avoid interruptions in the operation of these plants are the use of explosives in the wells of the geothermal plant and mechanisms that produce water at high pressure. However, these procedures are dangerous, waste resources—such as water—and require the shutdown of the plants while these interventions are being carried out. To solve this problem, the inventors aim to include a silica-based deposit in the good casing, allowing the alternate injection of an acidic and a caustic composition, artificially producing steam in the water at times of need. In this way, the continuity of energy production is stimulated, using a safer, less polluting mechanism, and without the need for a temporary shutdown of the plant while the necessary repairs are made (Bluemle et al. 2020).

The "Virtual Landfill Terminal" patent is a method that allows the treatment and disposal of solid waste in a single facility. Solid waste is separated into biomass and plastic recyclables. The biomass is transformed into syngas by means of a gasifier. The plastics are processed in this facility, and turned into naphtha, diesel, and/or lubricants. The heat from the biomass and plastics is also captured and used to generate electricity. This structure allows for energy production with less environmental impact, and a significant decrease in oil as a feedstock (Kirkendoll and Tuck 2021).

Therefore, pollution prevention in the country is promoted by national, state, and local programs, private initiatives such as 3P, and scientific research from research institutes, which also have important roles on the development of CP practices in the USA (Miller et al. 2008).

Malaysia

Malaysia is the fourth country with the largest *H*-index on the subject (*H*-index = 8). Its economy was based on the export of commodities until the 1980s when the country began its industrialization (Auyong and Chin 2019; Rahim and Raman 2015; The World Bank 2019). Malaysia's average GDP growth was 9% per year between 1998 and 1996 due to policies to encourage domestic industry, infrastructure, and urban expansion (Muyibi et al. 2008; Rahim and Raman 2015; The World Bank 2020).

The growth of Malaysia's manufacturing sector has exposed the country to several environmental problems. Some studies show the depletion of fishing reserves, air pollution, water pollution, soil pollution, and industrial waste generation as the main challenges faced in the country (Abdullah 1995; Afroz et al. 2003; Muyibi et al. 2008; Poon et al. 2016; Rani et al. 2018).

Since the identification of these environmental problems, the government took initiatives to combat them. Early in the industrialization of Malaysia, its government enacted the Environmental Quality Act (Malaysia, 1974), marking the beginning of the country's efforts in their enterprises' environmental management. This act regulates measures to prevent, reduce, and control pollution in the industry (Abdullah 1995).

A few years later, in 1976, the Department of the Environment (DOE) was created under the Ministry of Natural Resources and the Environment. DOE is responsible for ensuring SD and maintaining a safe, clean, and healthy environment. It supports and oversees sectors of society in adopting sustainable measures (Abdullah 1995; DOE 2020; Yusup et al. 2014).

The DOE adopted CP in 2002 as a pollution prevention practice to be employed in Malaysian industries. The first CP measures and projects were directed to small and medium enterprises since they are most of the country's industrial sector (Rahim and Raman 2015; Yusup et al. 2014).

Researchers from the University of Technology of Malaysia were selected to develop a national program for the CP practice promotion in the country. The studies resulted in the "Cleaner Production Blueprint for Malaysia," which was published in 2007. This document outlines the national plan for the CP promotion in Malaysia, defining strategies for the CP concept and practice development and the dissemination of CTs among the country's companies (DOE 2007; Yusup et al. 2014).

The main actions proposed in this plan include the dissemination of information and training of professionals to support the CP practice adoption, guidelines for training, conducting audits, tax incentives to companies, and incentive to clean technology research centers. Also, in 2007, the DOE published the "Cleaner Production Audit Guidelines" standardizing and promoting CP audits in the country (Yusup et al. 2014).

A few years later, in 2009, the Ministry of Energy, Green Technology, and Water enacted a new national policy, the National Green Technology Policy. It defines initiatives to encourage the use of CTs focused on four aspects: energy, environmental, economic, and social. In continuity with this policy, the Green Technology Master Plan Malaysia was launched in 2017, defining objectives to be achieved by 2030 in the dimensions of energy, manufacturing, transportation, civil construction, waste, and water, aiming at the sustainable use of natural resources (Ministry of Energy Green Technology and Water 2017; Yusup et al. 2014).

Therefore, the universities of Malaysia have been conducting outstanding international research in the CP area. The articles generated by these studies were cited 264 times. Two Malaysian researchers are among the ten most cited authors in CP theme: Prof. Dr. Lai Fatt Chuah and Prof. Dr. Suzana Yusup.

Prof. Lai Fatt Chuah is affiliated with Petronas University of Technology (UTP), and his studies aim at the development and application of new raw materials and production processes for biodiesel manufacturing. Prof. Dr. Suzana Yusup is a chemical engineer also affiliated to UTP. She founded the Biomass Processing Laboratory and studies about green technologies at the university, developing new biomass use processes and clean materials.

Three of the 30 papers analyzed have Malaysian authors' participation. Hayyan et al. (2014) developed a methodology to convert acidic crude palm oil (ACPO) to fatty acid methyl esters (FAME), raw materials used to produce biodiesel. This technology can reduce the total cost of biodiesel production, helping this industry and catalyzing the achievement of green energy goals in Malaysia. Bokhari et al. (2016) developed a cleaner production process of rubber seed oil methyl ester using hydrodynamic cavitation. This technology is a viable way to offset fossil diesel usage, reducing energy consumption during biodiesel production. Finally, Chuah et al. (2016) developed a cleaner production process of methyl ester using waste cooking oil. Methyl ester is biodegradable, renewable, and nontoxic, produces less sulfur oxides emissions and greenhouse gases, and can be used as an alternative fuel to replace petroleum diesel, reducing the environmental impacts.

Regarding patents, the last two registered in cleaner production were "Brush cleaning elements and method of manufacturing the same" and "Systems to remove non-aromatic compounds for the production of para-xylene". The patent "Brush cleaning elements and method of its manufacture" is a method of including adhesive tapes inside industrial vacuum cleaners. With these tapes, the vacuum cleaner provides better conditions of humidity and resistance to debris, preserving the internal structure of the equipment and consequently increasing its useful life. This method reduces material waste and improves vacuum cleaner efficiency (Lee 2021). The patent "Systems to remove non-aromatic compounds for the production of para-xylene" is a system that removes non-aromatic compounds from xylene by isomerization. A clay container is used in this system, separating the non-aromatic compounds from the xylenes into different compartments. In this way, the separation between the elements is cleaner, eliminating the need to include toxic substances to separate the elements (Abichandani et al. 2021).

Therefore, despite being a country with recent industrialization, Malaysia has achieved strong economic growth based on the use of its natural resources to leverage its manufacturing. Thus, to ensure lasting success, the country's government realized that SD should be one of its goals. The policies adopted to promote CP have made Malaysia an example that public policies focused on SD are essential to promote the country's green growth (Yusup et al. 2014).

CP scientific development opportunities and challenges

In this topic are the analyses of scientific opportunities and challenges for CP development. The scientific opportunities were identified in the 30 most cited articles and grouped according to the similarities between them, originating the clusters presented in Table 2.

CT and CP practices have been disseminated diffusely and slowly in many countries, despite their many proven benefits (Bonilla et al. 2010). Therefore, it is necessary to encourage the development of sustainable actions and to study the factors that motivate companies to adopt them (cluster 1).

The industrial companies' environmental performance should be measured to facilitate the identification of improvement opportunities. To this end, the formation of partnerships between them and universities is encouraged. According to Almeida et al. (2017), this facilitates the design and practical application of tools and technologies developed by researchers.

The use of technologies to control and minimize pollution in manufacturing processes enables the reduction of their environmental impacts and generates a competitive advantage for companies (Khorasanizadeh et al. 2016). However, Yong et al. (2016) state that some pollution control equipment is expensive, complex, and does not have an adequate design for implementation, making its use difficult. Thus, the importance of developing new technologies, processes, and clean products suitable for the real needs of companies is highlighted.

Severo et al. (2017) say there is a correlation between the size of companies and the ease of CP implementation. Usually, medium and large companies are more able to invest financial resources in R&D of clean processes, sustainable products, and new CP methodologies and tools. However, the small companies present greater difficulties for this type of initiative.

Therefore, it is possible to observe research opportunities in the area of new technology development (cluster 2) encouraging the implementation of CP actions in companies of several sizes (cluster 1). It is necessary to adapt these new technologies to the various sectors' production processes to eliminate, minimize, or reuse the waste generated (Bokhari et al. 2016).

Still aiming at more efficient processes and more recyclable, reusable, and degradable products, research opportunities for developing sustainable products were identified (cluster 3). The substitution of raw materials and improvement of production processes (Chuah et al. 2016; Deutz et al. 2018; Hayyan et al. 2014), the change of material's chemical properties (Dahunsi et al. 2017; Mia et al. 2018), and use of more efficient production methods (Bokhari et al. 2016) are important initiatives that can be employed in the CP development in industries and can be developed from scientific research.

Another opportunity is to develop new tools and methods that would enable CP development approaches adapted to different countries and business sector realities (cluster 4) (Henriques and Catarino 2015; Jia et al. 2014). Obtaining ISO 14001 certification is one way to foster CP development actions (De Oliveira et al. 2016). ISO 14001, for example, promotes an environmentally friendly culture in companies by incorporating concern with environmental impacts into the day-to-day lives of employees and assisting in the allocation of resources for environmental management decision-making, facilitating the CP action's adoption.

The development of studies on the promotion of clean energy matrices and the use of renewable energy in companies as a scientific opportunity (cluster 5) was also identified. Sáez-Martínez et al. (2016) state that the development of more promising techniques to extract the maximum from the available energy in organic matter, the substitution of fossil fuel by renewable, and the optimization of clean energy matrices are important improvements that allow minimizing the costs of energy use and facilitate the adoption of renewable energy. Therefore, it is essential to develop new strategies to encourage the use of alternative energy sources that have fewer negative impacts on the environment (Scarazzato et al. 2017).

There is also a need to identify the difficulties faced by companies during CP implementation and propose solutions for them (cluster 6) (Severo et al. 2015). This identification is possible through the analysis of the barriers faced by the various industrial sectors (Govindan et al. 2016; Ortolano et al. 2014; Silvestre and Neto 2014), analysis of environmental, economic, and social impacts from the implementation of CP actions (Severo et al. 2015), and analysis of the results of new technologies and tools used to reduce environmental impacts (Henriques and Catarino 2015).

Thus, the identification and systematization of the challenges conducted in this research aim to provide an overview of the issues that most impede the CP development. The challenges were identified in the 30 most cited articles and grouped according to their similarities and the clusters are available in Table 3.

The first challenge identified is the lack of legislation and policies to encourage CP practices in some countries. The development of a macroeconomic policy focused on the formulation of an agenda for CP adoption is essential for the SD of countries due to the important roles of governments and industries in combating social and environmental problems. However, state regulations directed to the protection of society's social and environmental interests are still being slowly adopted; and there is a lack of articulation between

Table 2 Clusters of CP scientific development opportunities

Clusters	Scientific development opportunities	Articles
1. Encouraging the adoption of CP	Study of the factors that motivate the various sectors of industry and society to adopt CP	Long et al. (2014); Van Hoof (2014); Almeida et al. (2015); Henriques and Catarino (2015); Khalili et al. (2015); Wesseh Jr and Lin (2015); Severo et al. (2017); Hens et al. (2018)
2. Clean technologies	Development of technologies to eliminate, reduce, or reuse waste generated by companies	Bokhari et al. (2016); Jakrawatana et al. (2016); Yong et al. (2016); Severo et al. (2017); Hens et al. (2018)
3. New processes and products	Development of green products that are more easily recyclable, reusable, or degradable; and design of more efficient processes that reduce pollution and waste generation	Hayyan et al. (2014); Silva et al. (2015); Yilmaz et al. (2015); Chuah et al. (2016); Bokhari et al. (2016); Dahunsi et al. (2017); Mia et al. (2018); Deutz et al. (2018)
4. New tools and methodologies	Development of CP implementation methodologies adapted to the realities of different countries and business sectors	Jia et al. (2014); Long et al. (2014); De Oliveira et al. (2016); Ozturk et al. (2016); Almeida et al. (2017); Fréon et al. (2017)
5. Renewable energy	National promotion of clean energy matrices and incentives for renewable energy use in enterprises	Sáez-Martínez et al. (2016); Scarazzato et al. (2017)
6. CP barriers	Identification of the difficulties faced by companies during the CP implementation and proposal of solutions for them	Silvestre and Neto (2014); Ortolano et al. (2014); Almeida et al. (2015); Severo et al. (2015); Govindan et al. (2016); De Oliveira et al. (2016)

the public and private sectors to adopt rules effectively appropriate to the reality of the industry. The laws of many developing countries are still guided by end-of-pipe practices, despite the positive results of pollution prevention strategies (Almeida et al. 2015; Khalili et al. 2015).

Thus, governments should strive to develop strategies focused on managing the environmental and ecological risks associated with the industrial activities of their countries (Khalili et al. 2015). Governments should organize themselves so that CP practices can be stimulated and not inhibited by bureaucracies that make their implementation difficult (Hens et al. 2018; Wesseh Jr and Lin 2015).

The second challenge identified is related to supply chain management. Efforts to disseminate sustainable and CP practices through companies' supply chains have gained momentum (Khalili et al. 2015).

However, the complexity of supply chain management in different realities has required a high level of innovation in the search for joint reduction of material and energy waste along the chain, especially in emerging countries (Almeida et al. 2015, 2017).

Thus, initiatives such as reverse logistics and closed-loop supply chains are strategies that can be associated with CP to overcome these barriers. They encourage the planning, implementation, and control of raw material flow management practices focusing on reducing the environmental impacts of the company's products and processes throughout their life cycles (Govindan et al. 2016; Govindan and Soleimani 2017).

The third challenge is related to organizational culture and innovation. The CP implementation requires innovations in technological, operational, managerial, and strategic aspects. However, companies have difficulties in developing an organizational culture focused on environmental innovations due to lack of support from managers, the resistance of employees to change, and lack of government regulation (Henriques and Catarino 2015; Vickers and Cordey-Hayes1999). The transition to an environmentally innovative culture requires efforts from top

Table 3 Clusters of CP development challenges

Clusters	Development challenges	Articles
1. Legislation and policies	Lack of efficient legislation and policies to encourage CP	Almeida et al. (2015); Khalili et al. (2015); Dahunsi et al. (2017); Almeida et al. (2017); Severo et al. (2017)
2. Supply chain management	Complexity of sustainable practice integration along the supply chain and its management	Van Hoof (2014); Almeida et al. (2015); Khalili et al. (2015)
3. Innovation and organizational culture	Lack of top management engagement in implementing an environmentally innovative organizational culture	Henriques and Catarino (2015), Silvestre and Neto (2014)

management, as they are responsible for identifying opportunities to implement CP practices and motivating their employees, and they should be engaged in the search for innovation (Silvestre and Neto 2014).

Framework for CP development

The framework (Table 4) proposes policies, strategies, initiatives, and research opportunities to be adopted by the triple helix entities for the CP promotion. The framework proposals were based on the critical analysis of the actions adopted by the leading countries presented in the technical-scientific scenario (the "Technical-scientific scenario" section), the scientific opportunities for CP development, and the challenges faced by companies during its implementation (the "CP scientific development opportunities and challenges" section). Those elements served as a benchmarking for the framework elaboration and were analyzed and adapted on the light of the authors' expertise.

The actions proposed in the framework are divided into domains within each triple helix sector (government, industry,

Table 4 CP development framework

Sector	Domain	Proposals	Triple Helix Interactions	Technical and Scientific References
Government	Politics and Legislation	Develop national policies and legislation to promote CP practices	Industry and University	Almeida et al. (2017); Auyong and Chin (2019); DOE (2007); Hong and Li (2013); NPC (2002); Vieira and Amaral (2016)
		Regulating highly polluting companies and defining mandatory audits	Industry	Ashton et al. (2017); Bai et al. (2015); NPC (2002); UNIDO and UNEP,(2015)
		Creation of agencies at national, state, and municipal levels to promote CP	Industry and University	Changbo et al. (2015); Peng and Liu (2016); UNIDO and UNEP (2015)
		Foster clean energy in the country	Industry and University	Bokhari et al. (2016); Jakrawatana et al. (2016); Yong et al. (2016); Severo et al. (2017); Hens et al. (2018).
	Education	Develop awareness campaigns about CP's importance and benefits	Industry and University	Khalili et al. (2015); Khorasanizadeh et al. (2016)
		Promotion of CP research with the establishment of research funding centers	University	Neto et al. (2016); Pereira and Sant'Anna (2012); Khalili et al. (2015); UNIP (2020); Wesseh Jr and Lin (2015)
	Economy	Tax industrial-generated pollution and create tax incentives for CP practices and subsidize CP projects	Industry	DOE (2007); Shi et al. (2008); UNIDO and UNEP (2015); Vickers and Cordey-Hayes (1999)
Industry	Planning and Management	Engagement of upper management in defining environmental management as a company priority	Government	Gonçales Filho et al. (2018); Govindan et al. (2016); Shi et al. (2008)
		Inserting the sustainable development into the organizational culture	Government	Henriques and Catarino (2015), Silvestre and Silva Neto (2014)
		Initiatives for academy-business integration, fostering the collaboration with CP expertise institutions	University	Neto et al. (2016); Pereira and Sant'Anna (2012); Khalili et al. (2015)
		Adoption of Green Supply Chain Initiatives	Government	Van Hoof (2014); Almeida et al. (2015); Khalili et al. (2015)
		Voluntary adoption of Integrated Management Systems (ISO 9001, ISO 14001, ISO 45001, ISO 50001)	Government and University	De Oliveira et al. (2016); Ortolano et al. (2014)
	Production	R&D areas strengthening for clean technologies development	University	Pinkse and Dommisse (2009); Scarazzato et al. (2017); UNIDO and UNEP (2015)
		Replacement of hazardous raw materials for cleaner ones	Government and University	Auyong and Chin (2019); Bokhari et al. (2016); Chuah et al. (2016); Mia et al. (2018)
		Adoption of green product design and clean energy	Government and University	Bokhari et al. (2016); Jakrawatana et al. (2016); Yong et al. (2016)
University	Education	Development of CP courses and training in higher education institutions	Government and Industry	Ashton et al. (2017); Khalili et al. (2015); McPherson et al. (2016)
		Create networks to disseminate information on advances in CP practices (congresses, round tables, workshops)	Government and Industry	UNIDO and UNEP (2015); UNIP (2020)
	Research	Creation of specialized clean technology research centers (R&D)	Industry	Bokhari et al. (2016); Jakrawatana et al. (2016); Yong et al. (2016); Severo et al. (2017); Hens et al. (2018).
		Systematization of CP implementation process	Government and Industry	Long et al. (2014); Van Hoof (2014); Almeida et al. (2015);
				Wesseh Jr and Lin (2015); Severo et al. (2017); Hens et al. (2018).
		Study of benefits and motivations of CP practices implementation	Government and Industry	Almeida et al. (2015); Henriques and Catarino (2015); Khalili et al. (2015);
		Development of materials and processes that generates less environmental impact	Government and Industry	Hayyan et al. (2014); Silva et al. (2015); Yilmaz et al. (2015); Chuah et al. (2016); Bokhari et al. (2016); Dahunsi et al. (2017); Mia et al. (2018); Deutz (2018).
		Study and proposal of solutions for the CP challenges	Government and Industry	Silvestre and Silva Neto (2014); Ortolano et al. (2014); Almeida et al. (2015); Severo et al. (2015); Govindan, et al. (2016); De Oliveira et al. (2016).
		Development of new CP approaches adapted to different companies and countries necessities	Government and Industry	Jia et al. (2014); Long et al. (2014); De Oliveira et al. (2016); Ozturk et al. (2016); Almeida et al. (2017); Fréon et al. (2017).

and university). The actions in the governmental sector are segmented into politics and legislation; economic; and education domains. Politics and legislation actions proposed in Table 4 are focused on regulating and driving the other spheres of triple helix to adopt CP practices. The development of laws that encourage companies to engage in solutions to their environmental impacts is a major catalyst for changes in corporate and social attitudes (Bonilla et al. 2010). Thus, the creation of a national policy based on CP and the creation of a network of support agencies for organizations at regional levels are important initiatives for the dissemination of their practices in national territories (Khalili et al. 2015; Zhang et al. 2013). Specific legislation focused on highly polluting industrial sectors is also an important incentive for companies to adopt pollution prevention strategies (Bonilla et al. 2010; Yusup et al. 2014). In this sense, the regulation of voluntary and mandatory audits allows for efficient monitoring of CP implementation (Bai et al. 2015; Hong and Li 2013).

The financial aspect is marked by the subsidy and tax incentive for CP projects with the provision of special advantages in loans for CP implementation in industrial companies (UNIDO; UNEP 2015). Pollution taxing of industries is a practice that internalizes in companies the cost of pollution generated by it, encouraging them to adopt a position of pollution prevention.

The educational aspect reinforces the responsibility of governments to invest in awareness-raising, professional training, and the development of new techniques and tools that stimulate the CP implementation. The government should invest in funding practical and theoretical research for developing CP in the country, catalyzing the creation of solutions to increase the efficiency of its industrial sector and reduce negative environmental impacts. Initiatives to structure curricula for courses on corporate sustainability and partnerships between the universities and companies for developing innovations in the CP area are also encouraged. These actions are proposed to promote and support research institutions in the development of studies and training on CP practices and the dissemination of awareness campaigns about this strategy.

The relevant actions of the academy are divided into education and research. The educational actions focus on the formation of technically trained professionals in CP practices. Like governments, institutions of higher education have an important role in this aspect by being responsible for creating the human capital necessary for developing the countries' economy (Khalili et al. 2015). Thus, they should undertake efforts to develop the necessary training in CP domains for the successful practical applications of this strategy and to disseminate knowledge through congresses, roundtables, workshops, videos, books, and etc. (Bonilla et al. 2010).

In the research item, research fields are suggested to be explored by academic institutions and companies for developing CP knowledge. They were based on the scientific opportunities identified in this study. Efforts are suggested in the development of clean technologies, more efficient production processes, and green materials and products. The study of the difficulties faced by companies during the CP implementation and the development of strategies to overcome them are important initiatives to support the adoption of its practices. The partnerships between government, academia, and industry are fundamental because they allow the knowledge obtained to be transferred between the three spheres, making them applicable (Kimatu 2016).

Finally, the actions regarding industries are segmented into planning and management; and production. The topic of planning and management highlights the importance of the commitment of top management in adopting and encouraging CP practices. Top managers should be aware of the importance of making the necessary investments to implement CP and develop an innovative organizational culture based on SD values (Vieira and Amaral 2016; Gonçales Filho et al. 2018). Thus, the adoption of practices that facilitate the integration of CP into the company's strategy is suggested, such as the structuring CP audits, the development of a green supply chain, and partnerships with research institutions (Ortolano et al. 2014; De Oliveira et al. 2016; de Oliveira et al. 2017).

The implementation of integrated management systems is also encouraged. Among the various standards developed by ISO, the most widely used by organizations are ISO 9001 (quality management), ISO 14001 (environmental management), ISO 45001 (occupational health and safety management), and ISO 50001 (energy management system) (Majerník et al. 2017). These standards contribute to the development of sustainability in all TBL pillars (economic, social, and environmental). In the economic pillar, ISO 9001 is a reference standard for the quality management system assisting managers in standardizing and improving products, services, and processes, reducing variability, and meeting customer needs (Ismyrlis and Moschidis 2015). In the social pillar, ISO 45001 assists managers in seeking efficiency and safety of workers. This standard assists manager in meeting the company's legal requirements and providing salubrious occupational health and safety protection conditions for their employees (Kafel 2016).

In the environmental pillar, ISO 14001 is a benchmark standard for the environmental management system establishing environmental policies, actions, and plans. This standard helps organizations seek a balance between economic growth and reducing negative environmental impacts on society (Kafel 2016). ISO 50001 also presents requirements for companies' efficient energy management, defining guidelines for the use of renewable energy (Nunhes et al. 2019).

Production initiatives make production processes more efficient and less polluting. Thus, practices such as replacing hazardous or polluting materials with cleaner materials, investing in more efficient processes and machines, and adopting renewable energy are suggested. Strengthening the R&D area of companies is essential to make these transformations feasible and to foster the development of clean technologies that meet the needs of their processes.

The framework also highlights the synergistic potential of joint actions and partnerships among governments, industries, and universities, which, if integrated, can leverage the CP development. The government can direct its policies to regulate and promote the use of CP practices in the industry, especially in the most polluting sectors. Government, universities, and industries can also work together to promote the development of solutions to the challenges of implementing this strategy and foster the creation of clean technology development centers; universities can build partnerships with industries to train professionals to work in environmental management and CP; industries can help funding research centers and universities to the development of clean technologies; and industries can encourage the development of research and development (R&D) sectors aimed at technology partnerships, internal organizational changes, and improvements in existing processes and products (Miotti and Sachwald 2003; Trencher et al. 2014). Thus, integrated actions between triple helix sectors can open paths to industries to move towards cleaner production processes.

Conclusion

CP is an important pollution prevention strategy used mainly in industries. Despite its benefits, several countries and commercial sectors face several challenges for its adoption. Therefore, this article proposed a development framework for CP to serve as a guide for actions to promote the strategy in the three spheres of the triple helix, reaching the objective of this research (Ranga and Etzkowitz 2013).

The main scientific contribution of this work was to articulate CP theory with the CP technical-scientific scenario identifying the benefits and challenges of its applications. Thus, this work contributes to the CP study area and encourages studies and research in this line of research minimizing its current challenges.

The main applied contribution of this work was to develop a framework for governments, industries, and scientific academia, based on the analysis of the CP technical-scientific scenario, CP implementation opportunities, and difficulties. It is expected that with the initiatives proposed in the framework, CP's practices will be easier to implement, reducing pollution generation in the industry, increasing the efficiency of its processes, and aligning countries and societies to sustainable development.

Thus, the main novelty of this work is the proposal of an innovative and unprecedented framework with initiatives based on CP good practices and development opportunities identified from the analysis of the technical-scientific scenario and literature. The framework serves as a guide for the main institutions responsible for solving global environmental problems to reduce barriers to the expansion of this strategy.

However, CP practices and their difficulties may vary according to the country and the industrial sector studied (Ortolano et al. 2014). Thus, the limitation of this study is related to the criteria chosen for the country selection and initiatives of prominence in the CP area, which if changed, could present results that complement the framework proposed.

The selection criteria adopted for the countries prioritized their academic performance; therefore, Brazil, China, the USA, and Malaysia stand out in the development of scientific knowledge on the subject. However, while the USA (3rd position) and China (14th position) are on the top of the Global Innovation Index (GII) of 2020, Brazil (64th position) and Malaysia (33rd position) still need to improve innovation creation, fostering CP practical applications and investing in the development of technologies by their universities, research centers, and companies (Cornell University, INSEAD, and WIPO 2020). Furthermore, important countries in industrial technical development such as India, Pakistan, South Korea, Colombia, the UK, and Hungary have not been considered in the studies.

Thus, the achievement of studies in other contexts is suggested, using new combinations of criteria and metrics to identify good practices and needs of different countries and sectors. Additional studies are also suggested in each sphere of the triple helix, to encourage closer relations between them (industry-academia-government), creating national/regional cells for promoting innovations in this area. Future studies that consider cleaner production applications in industrial sectors, such as textiles, metallurgy, food, and technology, among others, are encouraged. Therefore, it is possible to mobilize a set of tools that enhance the sustainable development of various economic segments, attending to their specificity.

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Declarations

Competing interests The authors declare no competing interests.

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