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Action Plans Study: Principles of Green Chemistry, Sustainable Development, and Smart Cities

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Abstract: The sustainability of cities is a challenge due to the growth, functioning, and needs of the population. In this context, the concept of the smart city has gained prominence worldwide in the last decades. In Brazil, it has also drawn attention driven by technological advances and the search for innovative solutions to urban challenges. Several different reports were created aiming to assess and categorize the advancement of cities in this regard. Some of them established their own indicators for this evaluation, whereas others are based on standards ISO 37120 and ISO 37122. The focus of this study revolves around the examination of indicators presently utilized, which may be influenced by initiatives grounded in the principles of green chemistry (PGCs). Furthermore, it explores how these principles can aid in the realization of the targets outlined in the Sustainable Development Goals (SDGs) set forth by the United Nations. Two case studies are presented, the first pointing out how PGCs and SDGs can correlate with smart city reporting indicators. The second is a case study centered on the Brazilian city of Curitiba (PR). We aim to exemplify how the city's action plans underscore the significance of synergy among the principles of green chemistry, the objectives of sustainable development, and indicators for smart cities. Assessing how chemically green a city can be is a relevant argument for future industrial installations and stakeholders and the influence of this index on the quality of life of its population. Such an approach not only fosters innovation and efficiency but also fosters environmental stewardship, thus contributing to overall sustainability.

Keywords: environment; innovation; sustainable chemistry; sustainable cities; ISO 37122; sustainability tool

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1. Introduction

The pursuit of sustainable and ecologically responsible practices has increasingly become a focal point across various fields. Chemistry is one of the key areas in advancing sustainable and ecologically responsible practices by offering the tools and knowledge needed to understand, prevent, and mitigate environmental impacts.

This connection is primarily evident through green chemistry, a discipline focused on designing chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Green chemistry (GC) is an approach that uses methods and processes to reduce or eliminate the use of toxic substances and the generation of hazardous waste, becoming a critical element of building a more sustainable future [1,2]. By prioritizing the design of chemical products and processes that cause less environmental impact, GC aims for economic efficiency, preserving natural resources, and protecting human health [1,2].

For instance, we list below some key ways in which chemistry is linked to sustainability:

(a) Pollution Prevention: Green chemistry aims to prevent pollution at its source by creating processes that minimize waste and toxic by-products, reducing the need for

expensive and energy-intensive waste management and cleanup efforts, leading to cleaner air, water, and soil [3].

(b) Renewable Resources: Chemistry facilitates the shift from fossil-based resources to renewable resources, such as biomass, for producing chemicals, fuels, and materials. This transition supports the development of a bioeconomy, reducing reliance on non-renewable resources and lowering carbon footprints [4].

(c) Degradable Materials: Through chemistry, scientists design materials that break down more easily in the environment or can be recycled efficiently, reducing burden of persistent pollutants, such as plastics, and supports the circular economy by promoting the reuse of materials [5].

(d) Biofuels and Bioenergy: Chemistry drives innovation in bioenergy by developing advanced biofuels (such as cellulosic ethanol and biodiesel) and other forms of bioenergy, which are essential for reducing greenhouse gas emissions and transitioning to a low-carbon economy [6].

(e) Energy Solutions: Chemistry is relevant in developing sustainable energy technologies, such as solar cells, batteries, and fuel cells, helping reduce greenhouse gas emissions and provide cleaner energy alternatives to fossil fuels [7].

(f) Health applications: Green chemistry principles guide the creation of products that are safer for human health and the environment. By eliminating harmful chemicals and reducing toxic emissions, chemistry contributes to safer consumer products and a healthier ecosystem [8].

As can be observed, the contributions of chemistry are broad. In this context, the principles of green chemistry have emerged as a fundamental guide to redefining the conventional approach to the chemical industry, prioritizing efficiency, safety, and minimizing environmental impact [1,9,10].

It is essential to consider not only sustainable practices in isolation but also to integrate them into a broader development panorama, aligned with the objectives for sustainable development [11].

Within the scope of sustainable development, it is essential to consider the role of smart cities (SC) as catalysts for positive changes. Smart cities are urban areas that leverage technology, data, and innovative design to enhance the quality of life, improve efficiency, and promote sustainability [12,13]. This category of urban agglomerations focuses on optimizing resources, reducing environmental impacts, and improving infrastructure and services, seen as a practical manifestation of sustainable development principles at the urban level [14]. They aim to create livable, resilient, and environmentally friendly urban spaces by incorporating sustainable practices in energy, transportation, water management, waste management, and other contributions [15,16].

Therefore, taking all these elements into consideration, the success of smart cities can be measured by how well they align with Sustainable Development Goals (SDGs). Thus, by adopting innovative technologies and efficient practices, SC can become real "urban laboratories", transforming them into spaces where environmental sustainability and social well-being intertwine [17–19].

In the 21st century, the Sustainable Development Goals (SDGs) (2015) and ISO 37122 (2019) [20] emerged in a context that already values sustainability and the strengthening of its three pillars (environmental, social, and economic). In this scenario, PGCs can be seen not only from a restorative point of view, but also as principles of a more conscious and more sustainable applications.

The ISO 37122 standard standardizes indicators for evaluating smart cities. This paper proposes the study of how PGCs are integrated within the SDGs and the indicators established by the ISO 37122. Thus, the integration of the principles of green chemistry (PGCs) [21] with the Sustainable Development Goals (SDG) [22] becomes an essential strategy to promote significant sustainable advances. In this context, it is important to identify indicators that can measure the progress of cities through actions based on the

PGCs. These indicators can make possible to assess the environmental and social impact of the practices adopted.

Thus, the purpose of this study is to explore the role of green chemistry as a strategic tool in achieving the Sustainable Development Goals (SDGs). We aim to analyze how implementing its principles can contribute to specific SDG objectives. Additionally, we seek to identify and discuss indicators related to smart cities that may be influenced by adopting sustainable practices based on PGCs. Our goal is to examine how this integration can positively impact urban environmental behavior. Yet, as a complementary objective, this study will evaluate the performance of Curitiba city (PR), recognized as the smartest city in the world in 2023. We will assess its positioning and scores in the Ranking Connected Smart Cities report, particularly focusing on projects that have garnered international recognition for sustainability aligned with PGCs.

2. Methodology

2.1. Systematic Review of the Literature

The systematic search and review of the extant literature was performed using the methodology Methodi Ordinatio [23], which ranks the papers in the portfolio based on three elements: year of publication, number of citations, and journal metrics. This ranking is performed by applying the equation InOrdinatio (1).

$$InOrdinatio = \left\{ (\Delta * IF) - \left[\lambda * \left(\frac{ResearchYear - PubYear}{HalfLife} \right) \right] + \Omega * \frac{\sum Ci}{[(ResearchYear + 1) - PubYear]} \right\} \quad (1)$$

where *IF* represents the mean impact factor and corresponds to the selected journal metrics (JCR, CiteScore, SNIP, or SJR SCImago); Δ is a value ranging from 1 to 10 assigned by the researcher, with higher values indicating a greater importance of the impact factor; λ is a value between 0 and 10 that the researcher assigns to the relevance of the publication year; Ω is a value between 0 and 10 that the researcher assigns to the significance of the publication's annual average of citations; *ResearchYear* denotes the year in which the research is being conducted, while *PubYear* represents the year the paper was published; $\sum Ci$ is the total number of citations found in Google Scholar; and *HalfLife* refers to the median cited half-life of journals with JCR 2020 [23].

The steps of the methodology are detailed in the sequence.

Steps 1–4: The intention of research was to find papers which presented these three themes approached together: "Green Chemistry", "Sustainable Development", and "Smart Cities". The search was performed on Web of Science, and Scopus, collecting articles in English, with no temporal limitation. Table 1 presents the search parameters, and the number of papers found.

Table 1. Results of the search in research bases.

Keywords	Web of Science	Scopus
TS = ("green chemistry") AND TS = ("sustainable development") AND TS = ("smart cities")	3	0
TS = ("green chemistry") AND TS = ("sustainable development") AND TS = (indicators)	13	6
TS = ("smart cities") AND TS = ("sustainable development") AND TS = (indicators)	96	15
TS = (green chemistry) AND TS = (smart cities) AND TS = (indicators)	0	0
Total	112	21

The included papers was determined by the keywords used in the search in scientific bases.

As can be observed, there is a scarcity of scientific works that simultaneously address the three themes. It can be inferred that the extant literature has a gap when simultaneously addressing the three themes together: green chemistry, sustainable development, and smart cities. In this sense, understanding the interactions amongst these topics can help improve smart city indicators.

Step 5: The filtering procedures were applied: the duplicates, and the elimination by reading the TAK. Then, 99 papers remained in the portfolio for the final reading and analysis.

Step 6: The elements year of publication, number of citations, and journal metrics were identified for each paper. These elements are semi-automatically found by the tool RankIn, which can be accessed in [23].

Step 7: Applying the InOrdinatio: The equation InOrdinatio (1) is automatically calculated by the tool RankIn. RankIn is a software (version 1) where the researcher pastes the list of papers of the portfolio, and it calculates automatically the scientific relevance based on the elements (year, citation, and journal metrics). The value for each variable can the defined by the researcher and easily established in the respective field in RankIn, as in Figure 1.

LEGEND:	
Ranking:	after applying the equation, the researcher must rank from highest to lowest to form the ranking
Article:	full article title
IF:	impact factor (last year CiteScore, or the estimation of it from the JCR in case of non-existent CiteScore)
Year:	year the article was published
Ci:	total citations found on Google Scholar
InOrdinatio:	InOrdinatio v2 = {(Δ* IF) – [λ* (ResearchYear – PubYear)/HalfLife] + Ω* ∑ Ci/[(ResearchYear+1) –PubYear]}
Δ:	is the value between 0 and 10 that the researcher assigns to the importance of the publication's IF
λ:	is the value between 0 and 10 that the researcher assigns to the relevance of the year of publication
Ω:	is the value between 0 and 10 that the researcher assigns to the importance of the publication's annual average of citations
ResearchYear:	is the year in which the research is being performed. Eg: 2022
PubYear:	is the year the article was published. Eg: 1998
Half-Life	median Cited Half-Life of journals with JCR 2020 (7.6)
Δ:	8
λ:	5
Ω:	10
ResearchYear:	2023
Note 1:	The impact factor is automatically filled in, based on the journal title or ISSN
Note 2:	Mandatory fields are: Δ, λ, Ω, ResearchYear, Article, Year, Journal e Ci

Figure 1. RankIn table used to calculate the InOrdinatio value of the articles. Source: Adapted from Pagani [23].

For this study, the value 5 was established for the year of publication (λ = 5), 10 for the number of citations (Ω = 10), and 8 for the impact factor (Δ = 8). These values were chosen because the citations number is more relevant for this research, followed by the impact factor. Also, the year of the publication is not so relevant in this case because most articles were published in the last decade.

Step 8 and 9: The papers were downloaded and then read for the content analysis. In order to better organizing the reading, two analyses were performed: year of publication and publication by country. In this way, it is possible to note the regionalization of these themes and how these themes are current and of greater relevance and publication in the last decade.

The content of the portfolio allowed the development of concepts regarding relevant themes (i.e., green chemistry, sustainability, smart cities) and their relationship with the promotion of sustainability in the context of implementing the SDGs. The relationship between PGCs, SDGs, and smart city indicators emerged from isolated studies of each theme from the perspective of sustainability. This research confirmed the existence of this relationship.

2.1.1. Quantitative Analysis

The main keywords that appear in the articles (Figure 2) were as follows: smart cities (28); smart city (22); sustainability (22); sustainable development (22); Sustainable Development Goals—SDGs (20); indicators (10); fuzzy (6); sustainable cities (6); green chemistry (5); and life cycle assessment (5). The overall analysis on the keywords cloud suggests that the research in this context is related to green solvents, green synthesis, and process optimizations, processes that are more environmentally friendly and have less energy involved.

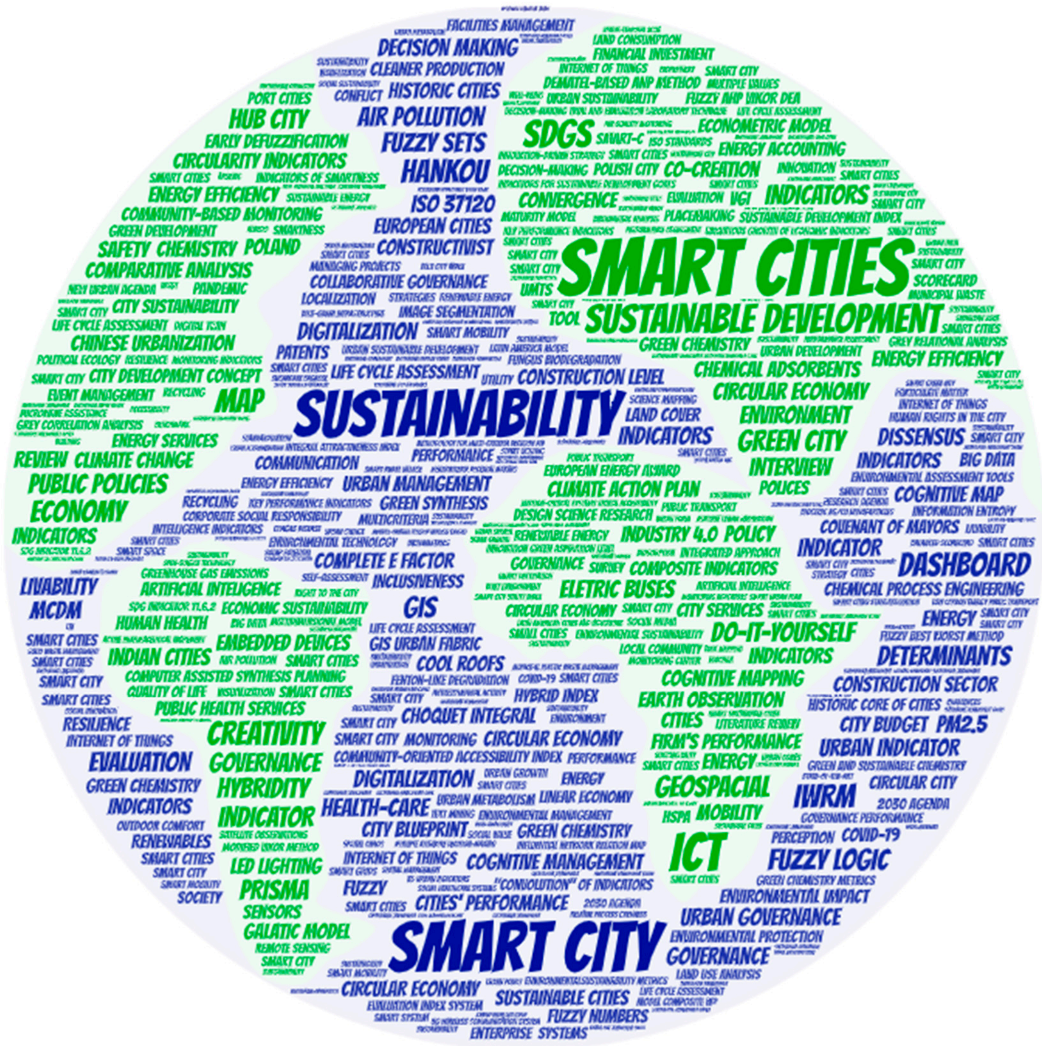


Figure 2. Keywords of the searched articles. Source: Developed by the authors based on data research (2024).

Notably, this topic has gained greater interest over the past decade, as depicted in (Figure 3a). In the last three years alone, there has been more publications in this field compared to the period between 2004 and 2020. However, none of these publications delve into the suggested keywords combinations ("green chemistry", "smart cities", and "indicators") with the same focus as this article, highlighting the necessity of evaluating their interrelationship.

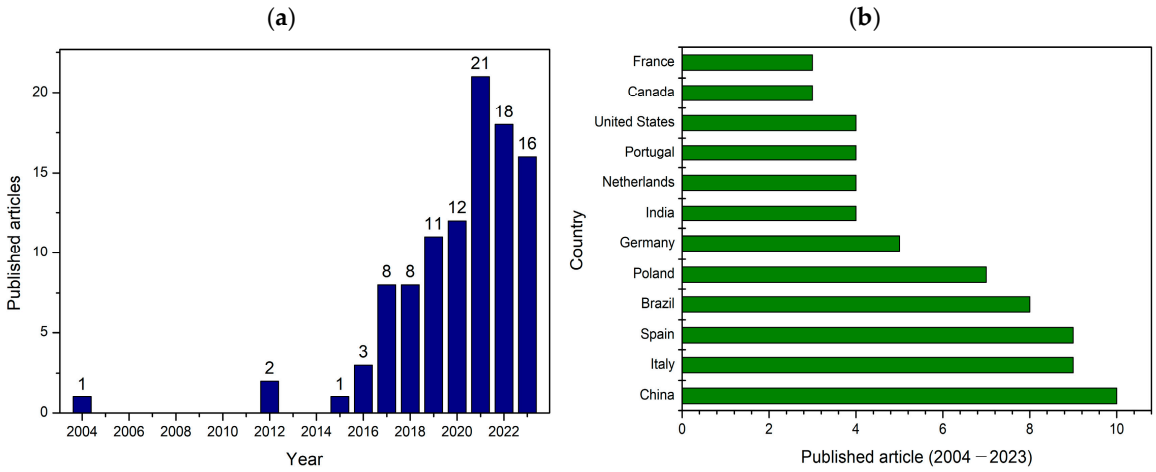


Figure 3. Analysis of the published articles (**a**) per year between 2004 and 2023; (**b**) per country (from first author).

Regarding the analysis of publications per country (Figure 3b), it can be inferred that the countries with the highest number of publications on this subject are: China (ten articles); Italy and Spain (nine articles each); Brazil (eight articles); Poland (seven articles); Germany (five articles); India, Netherlands, Portugal, and United States (four articles each); Canada and France (three articles each). The Top 10 is followed by Belgium, Iran, Korea, Qatar, Romania, Saudi Arabia, and Ukraine (two articles each); finally, the last countries consist of Colombia, Finland, Greece, Japan, Latvia, Lithuania, Mexico, Norway, Peru, Russia, Slovakia, South Africa, Sweden, and United Kingdom (one article each).

2.1.2. Content Analysis

Sustainability has guided the growth strategies of various industries and society. These strategies cover the environment, society, and governance, aiming not to deplete and compromise resources for future generations. This issue, already widely discussed by several authors, was analyzed in this work from the point of view of green chemistry. The data analysis was performed by comparing the 12 Principles Of Green Chemistry [24], the Sustainable Development Goals (SDGs) by the United Nations [22], and the indicators for smart cities according to ISO 37122 [20]. This comparison aimed to show the importance of applying green chemistry and how it can contribute to advancing smart cities. At the same time, it is possible to notice the presence of green chemistry in important indicators that correlate with sustainability.

Understanding how the 12 Principles Of Green Chemistry can be found in the smart cities indicators helps note the importance of collaborating with the development of more sustainable and eco-friendly practice and that not just technologies are essential in smart development, but the best utilization of raw resources and lowering pollution are crucial for growth.

2.2. Case Studies

The first case study in this article was a comparative analysis of indicators used by some reports on smart/sustainable cities with the 12 Principles of Green Chemistry proposed by Paul and Anastas [24]. Emphasizing the meaning and integrating them with the twelve principles, which can be used as tools, can help promote the evidenced indicators.

The second case study is the evolution of the city of Curitiba, which was evaluated based on Descriptive Comparative Analysis using the data released in the nine reports of the Connected Smart Cities Ranking from 2015 to 2023. The positioning of the city in question in each axis proposed by Urban Systems was considered, and the actions that contributed to becoming a smarter and more sustainable city were commented on. These actions were evaluated according to PGCs.

3. Discussion

3.1. Smart Cities and Their Importance in the Search for Sustainable Development

A smart city is an urban area that uses digital solutions (information and communication technologies—ICT) to improve traditional networks and services. This way, the city becomes more efficient and/or more environmentally friendly and more socially inclusive, enhancing its attractiveness to citizens and businesses [25–27]. According to the European Commission, smart cities "mean smarter urban transport networks, upgraded water supply and waste disposal facilities and more efficient ways to light and heat buildings. It also means a more interactive and responsive city administration, safer public spaces and meeting the needs of an ageing population" [25].

Different indicators can be used to evaluate smart cities. To try to standardize the indicators used by smart city rankings, the ISO 37122 can be utilized [20]. The list of smart cities indicators according to ISO 37122 is based on six criteria: completeness, technology neutral, simplicity, validity, verifiability, and availability. The ISO 37122 includes 19 different themes: economy; education; energy; environment and climate change; finance; governance; health; housing; population and social conditions; recreation; safety; solid waste; sport and culture; telecommunication; transportation; urban/local agriculture and food security; urban planning; wastewater; and water [20].

Smart cities are sustainable urban models, mainly related to the operational functions of a city in an intelligent, technological, competitive, and innovative way [6,17].

Currently, smart cities are closely related to sustainability/sustainable development [18,28–31]. It is not surprising to refer to these cities as "smart sustainable cities" [18,31] or "smartainability cities" [30]. Another important point that demonstrates a close relationship between smart cities and sustainable development is international standard annex B—"Mapping of ISO 37122 indicators to United Nations Sustainable Development Goals (SDGs)" (2015) [20]. In this way, a smart city that invests in certain areas and indicators can collaborate in promoting sustainability on a small or large scale.

Smart cities relate to objective 11 of the SDGs, but they meet other objectives of the 2030 agenda, as they encompass several other sustainable actions in their construction. Thus, urban sustainability is achieved through the advances of these spatial systems that seek to develop economically and socially with a high quality of life and environmental preservation [22,23].

3.2. Concepts and Principles of Green Chemistry

In 1998, Paul Anastas and John Warner wrote about the 12 Principles Of Green Chemistry (12 PGCs) [24], as shown in Figure 4. These principles guide green chemistry promotion with conscious attitudes. The 12 PGCs are according to international standards (ISO 14001) [32] that relate to the environmental management system. Organizations that wish to demonstrate care by promoting sustainability, the production of eco-friendly products, and safety in production must be agreement to ISO 14001 [32].

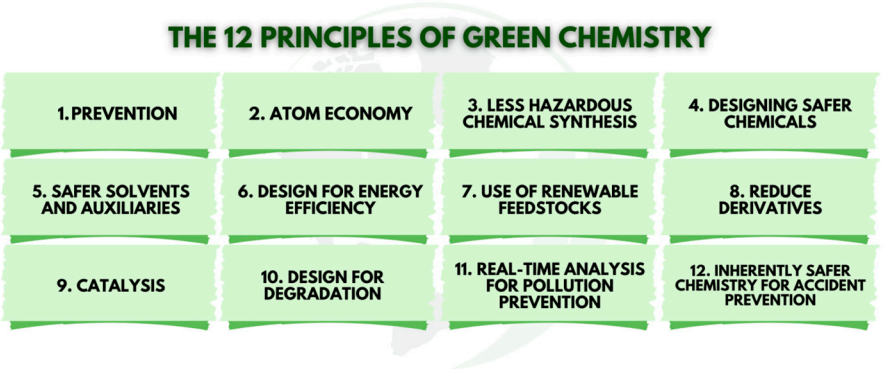


Figure 4. The twelve principles of green chemistry. Source: Adapted from Anastas e Warner [21].

The adjective "green" is frequently used by researchers currently with the aims of funding requirements, promoting your research, creating new sustainable alternatives, or creating new opportunities, among other finalities [33]. For a process or research to be green on the fact, it is necessary to have more than the word "green" written in a paper. To be considered "green", the research needs to relate to one or more of the 12 PGCs, at minimum.

The purpose of employing the 12 PGCs include minimizing waste and toxic emissions, utilizing green solvents and alternatives to conventional organic solvents, enhancing energy efficiency and employing renewable energy, and utilizing renewable and sustainable raw materials. Below, a concise explanation of each of the twelve PGCs can be found. [24,34]:

1. Prevention: This principle focuses on minimizing waste generation as much as possible, as addressing future waste issues can be more challenging and costly.
2. Atom economy: Rather than solely focusing on reaction yield, this principle emphasizes incorporating reagent atoms efficiently into the final product to reduce waste at the molecular level.
3. Less hazardous chemical synthesis: Methods must be meticulously chosen to ensure they do not pose risks to human or environmental health. Substances used and generated should be minimally toxic for handling and disposal.
4. Designing safer chemicals: This principle integrates aspects of chemistry, toxicology, and environmental science to reduce toxicity while maintaining functionality and effectiveness.
5. Safer solvents and auxiliaries: The aim is to replace conventional organic solvents or auxiliary substances with less harmful or contaminating alternatives.
6. Design for energy efficiency: Emphasis is placed on minimizing environmental and financial impacts through energy economy. This involves considering energy sources and forms used, as well as operational conditions such as temperature and pressure.
7. Use of renewable feedstocks: Natural-based materials can serve as renewable raw materials or feedstocks, offering technically and economically viable alternatives to chemicals or petrochemicals.
8. Reduce derivatives: Minimizing the generation of derivatives or co-products, especially in multi-step processes, requires careful review of reactions and processes to avoid unnecessary by-products.
9. Catalysis: Catalyzing reactions can enhance energy efficiency and reduce derivatives, but careful selection of environmentally friendly catalysts is essential. Ideally, catalysts should be recoverable post-reaction to minimize waste.
10. Design for degradation: Products must not be toxic, bio-accumulative, or environmentally persistent at the end of their life/function to ensure safe disposal without harm to the environment.
11. Real-time analysis for pollution prevention: Monitoring and controlling reactions to prevent hazardous by-products are crucial. Understanding reaction mechanisms allows for proactive pollution prevention during the process.
12. Inherently safer chemistry for accident prevention: Safety is paramount in green chemistry, aiming to reduce risks and prevent accidents to ensure the well-being of workers, communities, and the environment.

3.3. The Role of Green Chemistry in Sustainable Development

The Sustainable Development Goals (SDGs) were adopted in 2015 by the United Nations. There are 17 integrated goals to be practiced by all countries to ensure that in 2030, poverty will be eliminated and the planet will be more protected. The 17 SDGs can be applied in every context and must use all collaborative resources: technology, know-how, creativity, and finance [22].

Relating the PCGs with the SDGs creates a true web with strong connections, in which PCGs connect strongly with more than one SDGs and demonstrates reciprocity, as shown in Figure 5. This is because PGCs think about promoting sustainability and environmen-

tally friendly processes while SDGs are about protecting the planet and promoting social, economic, and environmental sustainability in different contexts.

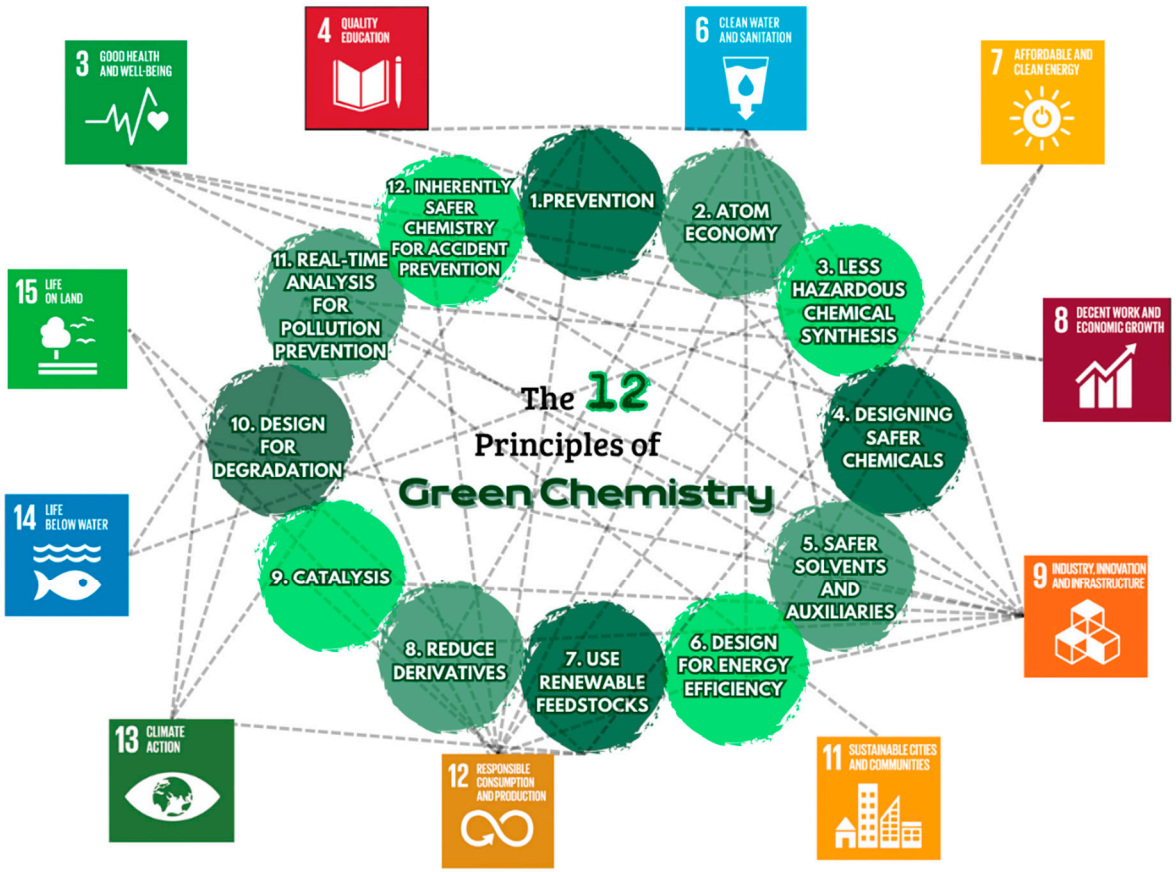


Figure 5. PGCs-SDGs web represents the strong relationship between them. Source: Elaborated by the authors from research data (2024).

Out of the 17 Sustainable Development Goals (SDGs), 11 can be influenced by the implementation of the 12 Principles of Green Chemistry (PGCs). Detailed explanations regarding how these principles can impact each of the eleven SDGs are provided below, emphasizing the utilization of green chemistry practices.

3. Good health and well-being: Promoting health and well-being using green chemistry can be achieved by reducing the number of deaths and illnesses caused by dangerous chemicals and contaminants and also by supporting research and development of vaccines, medicines, and treatments using less aggressive materials [35].

4. Quality education: The quality of basic education can affect the awareness and knowledge of professionals, which can encourage them to seek the use of green chemistry in their projects and processes [36]. Quality education will ensure that citizens have relevant technical and professional skills. These skills are necessary to promote sustainable development in different areas [36,37]. With a solid knowledge base and a willingness to seek alternatives to usual processes, education is capable of preventing anything.

6. Clean water and sanitation: Many chemical processes can be used to treat water before and after consumption and to recycle and reuse it. In this way, green chemistry can be used by chemists and chemical engineers to improve water quality and increase the collection efficiency and expand supply, promoting the sustainable use of water [1,37].

7. Affordable and clean energy: Energy efficiency can be optimized by diversifying the energy matrix used, using renewable energy, technological investment in clean energy, and modernizing services [38,39]. These improvements can positively impact the environment and be an economic advantage in the long term. Although the initial costs may be high, the

medium- and long-term disadvantages may be even more significant: scarcity/exhaustion of natural resources, climate change, and energy crisis, among others.

8. Decent work and economic growth: Investment in research alone contributes to decent work and economic growth because it can promote productive activities, create decent jobs, entrepreneurship, creativity and innovation, and reduce the proportion of young people who do not work or study or have no training. Scientific activities can support technological diversification and innovation in a variety of ways [10]. Green chemistry can influence the preservation of natural resources, increasing the efficiency of their use [1,2]. Furthermore, using chemicals appropriately and safely to conduct chemical reactions and processes improves workers' safety [1]. Economic growth becomes a natural attraction for smart cities when linked to social and environmental development [40].

9. Industry, innovation, and infrastructure: Research, actions, and processes involving green chemistry directly or indirectly support advancing research, innovation, and technology. It makes it possible to update and modernize attitudes that impact sustainability through more ecological infrastructures and industrial processes [10].

11. Sustainable cities and communities: According to the twelve PGCs, green chemistry seeks not to pollute before, during, or after processes. This can improve sustainable urbanization and environmental impact at different scales. It is collaborating with the advancement of smart cities [31,41,42].

12. Responsible consumption and production: Using ecological raw materials is a way to use natural resources and reduce waste efficiently. This reduction can be achieved through prevention, reduction, recycling, and reuse [9]. Efficient and intelligent resource management promotes more sustainable consumption and production and reduces adverse impacts on human health and the environment [28,43]. It can encourage a culture of control for pollution prevention throughout all production/product life cycles [44].

13. Climate action: Green chemistry affects climate health indirectly when it favors the environment's health. Promoting research based on the 12 PGCs can reduce the climate impact by adapting processes to be less environmentally harmful [45]. Based on prevention, less hazardous chemical syntheses, safer solvents and auxiliaries, reducing derivatives, and designing for degradation, among others, can have positive effects on the environment [46].

14. Life below water: It is possible to preserve aquatic life by generating compounds that are biodegradable in the short term or through reactions that degrade contaminants before discarding them, thus preventing them from affecting marine life in any proportion. The life below water can be preserved by good municipal wastewater management. Another way to use green chemistry is to correct acidity and remove ocean contaminants [47,48].

15. Life on land: All PGCs can influence the quality of life on Earth. Above all, the selection of raw materials for the processes, the disposal of waste and derivatives that may be generated, and degradation throughout the entire life cycle of the products are important [49,50]. Everything can affect the environment, biodiversity, and even human life. When effectively employed, the 12 PGCs can aid in eliminating or, at the very least, mitigating this effect.

Table 2 contains the association with the target goals of the SDGs, which can be achieved when the respective PGCs are applied.

Table 2. Relationship of how PGCs can collaborate directly or indirectly with the target goals of the SDGs.

Principle of Green Chemistry	SDGs (United Nations)	Target Goals (SDGs—United Nations)
1. Prevention	4. Quality Education	4.4. By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship
		4.7. By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development
		4.10. By 2030, substantially increase the supply of qualified teachers, including through international cooperation for teacher training in developing countries, especially least developed countries and small island developing states
	6. Clean Water and Sanitation	6.3. By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
	12. Responsible Consumption and Production	12.5. By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse.
		12.9. Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production
	13. Climate Action	13.3. Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning.
2. Atom Economy	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
	12. Responsible Consumption and Production	12.4. By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil in order to minimize their adverse impacts on human health and the environment.
3. Less Hazardous Chemical Syntheses	3. Good Health and Well-Being	3.9. By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.
	6. Clean Water and Sanitation	6.3. By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.

Table 2. *Cont.*

Principle of Green Chemistry	SDGs (United Nations)	Target Goals (SDGs—United Nations)
4. Designing Safer Chemicals	3. Good Health and Well-Being	3.9. By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.
		3.11. Support the research and development of vaccines and medicines for the communicable and noncommunicable diseases that primarily affect developing countries and provide access to affordable essential medicines and vaccines, in accordance with the Doha Declaration on the TRIPS Agreement and Public Health, which affirms the right of developing countries to use to the full the provisions in the Agreement on Trade Related Aspects of Intellectual Property Rights regarding flexibilities to protect public health, and, in particular, provide access to medicines for all.
	6. Clean Water and Sanitation	6.3. By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.
	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
5. Safer Solvents and Auxiliaries	3. Good Health and Well-Being	3.9. By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.
	6. Clean Water and Sanitation	6.3. By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.
	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
6. Design for Energy Efficiency	6. Clean Water and Sanitation	6.4. By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
	7. Affordable and Clean Energy	7.3. By 2030, double the global rate of improvement in energy efficiency.
	9. Industry, Innovation and Infrastructure	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
	12. Responsible Consumption and Production	12.2. By 2030, achieve the sustainable management and efficient use of natural resources.

Table 2. *Cont.*

Principle of Green Chemistry	SDGs (United Nations)	Target Goals (SDGs—United Nations)
7. Use of Renewable Feedstocks	7. Affordable and Clean Energy	7.2. By 2030, increase substantially the share of renewable energy in the global energy mix.
		7.4. By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
		7.5. By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing states, and land-locked developing countries
	12. Responsible Consumption and Production	12.2. By 2030, achieve the sustainable management and efficient use of natural resources.
	13. Climate Action	13.2. Integrate climate change measures into national policies, strategies and planning.
	15. Life on Land	15.1. By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements.
8. Reduce Derivatives	6. Clean Water and Sanitation	6.3. By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
	12. Responsible Consumption and Production	12.2. By 2030, achieve the sustainable management and efficient use of natural resources.
9. Catalysis	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
		9.5. Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending
	12. Responsible Consumption and Production	12.2. By 2030, achieve the sustainable management and efficient use of natural resources.

Table 2. *Cont.*

Principle of Green Chemistry	SDGs (United Nations)	Target Goals (SDGs—United Nations)
10. Design for Degradation	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
	12. Responsible Consumption and Production	12.4. By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil in order to minimize their adverse impacts on human health and the environment.
	13. Climate Action	13.3. Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning.
	14. Life Below Water	14.3. Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels
	15. Life on Land	15.5. Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species
11. Real-Time Analysis for Pollution Prevention	8. Decent Work and Economic Growth	8.2. Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labor-intensive sectors.
		8.4. Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programs on sustainable consumption and production, with developed countries taking the lead.
	9. Industry, Innovation and Infrastructure	9.5. Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.
	11. Sustainable Cities and Communities	11.3. By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.
		11.6. By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
	12. Responsible Consumption and Production	12.2. By 2030, achieve the sustainable management and efficient use of natural resources.
		12.10. Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products.
	13. Climate Action	13.3. Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning.

Table 2. *Cont.*

Principle of Green Chemistry	SDGs (United Nations)	Target Goals (SDGs—United Nations)
12. Inherently Safer Chemistry for Accident Prevention	3. Good Health and Well-Being	3.9. By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.
	8. Decent work and Economic Growth	8.8. Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment.
	9. Industry, Innovation and Infrastructure	9.4. By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
	12. Responsible Consumption and Production	12.4. By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.

Source: Elaborated by the authors from research data (2024).

3.4. Sustainability Indicators in Smart Cities

ISO 37122 is an international reference to smart cities indicators that consider different themes, and together with the ISO 37120 [51] and ISO 37101 [52] documents, they guide indicators and assist public management in programs and projects to maintain or improve cities and promote greater sustainability [20]. According to ISO 37122, cities/third parties using this document must report at least 50% of its indicators. Other indicators can be complemented for a more comprehensive approach to analyzing smart and sustainable cities. Cities must work on collected data that is verifiable, auditable, reliable and justified. Therefore, no rule determines whether these data should be collected by the community itself or outsourced companies, with the second option being more common. The interpretation of results must be between themes, considering the context of the city [20].

Annex B of ISO 37122 compares how each indicator of each proposed theme can collaborate with the United Nations SDGs. Table 2 of this work contains how each SDG can be affected by actions involving the principles of green chemistry. Briefly, the diagram of Figure 6, contains which indicators can be directly/indirectly impacted by attitudes that are consistent with the principles of green chemistry. At least 13 themes involving more than 30 indicators can be improved by applying the 12 PGCs by researchers in public/private institutions, companies, industries, and even the community.

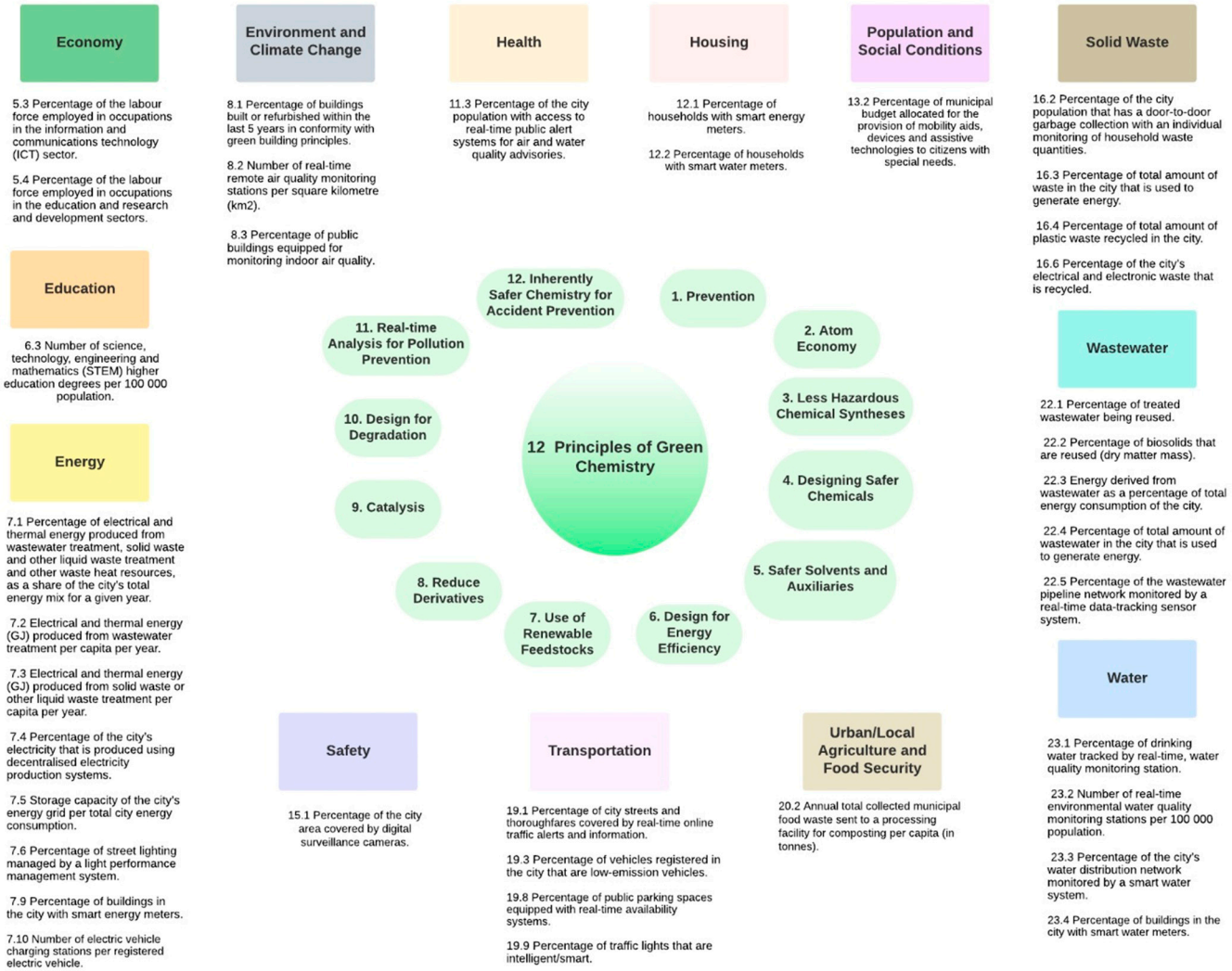


Figure 6. Indicators according to ISO 37122 that are directly or indirectly related to practices based on green chemistry. Source: Elaborated by the authors from research data (2024).

Economic growth can be promoted through "green research" and practical results that drive development and technology [53–55]. In education, the numbers of professionals with high degrees of study in STEM (Science, Technology, Engineering, and Mathematics) have the techno-scientific knowledge capable of bringing about sustainable advancement [56–58]. Climate changes can be mitigated if production is cleaner and air quality is improved/maintained. Air quality also affects health and quality of life problems [59,60]. Moreover, green chemistry is behind developing more efficient drugs and medical processes while being environmentally friendly [11,61–63].

Green chemistry is concerned with minimizing, reusing, and/or treating solid and liquid waste. Solid waste is often a raw material source for new research [50,64–67], while liquid waste can be treated by various catalytic processes [68–71]. Reducing liquid and solid waste improves the quality of water, air, and soil, which are essential indicators for the population's life quality. Housing, transport, and energy indicators are related to the efficiency of diversified, clean (green), and safe energy matrices, which do not compromise the population's health or deplete natural resources, affecting the environment and future generations [30,38,39,72–74].

Thus, it can be inferred that the role of green chemistry is indispensable for the progress of a smart city. Planning activities based on PGCs is imperative to prevent, control, reduce, reuse, and transform waste, mitigating potential public health hazards and environmental contamination. Efficient implementation of these practices, particularly in projects and processes transitioning from theoretical concepts to real-world applications, whether in industrial operations or through citizen engagement, will propel smart cities toward sustainable development.

4. Case Studies

Section 4.1 deals with multiple cases of smart city reports and their respective indicators. The tables in each report relate the indicator to the SDGs and PGCs, which it correlates with, either as a collaborative or unfavorable action for the promotion of each item in the last two columns. The conclusion of the study exemplifies how the three (indicators, SDGs, and PGCs) can be correlated.

Section 4.2 is a case study on a smart city, Curitiba, based on data from the RCSC Ranking, discussing some actions applied to the town and relating these to ISO 37122 (which guides smart city indicators), SDGs, and PGCs.

4.1. Case 1: Rankings of Smart Cities

Currently, different private companies rank smart/sustainable cities. The ranking can be at national or international level, using their own indicators based on the ISO 37122 standard or not. The non-standardization of these indicators makes it difficult to compare rankings. What happens is that the same cities can occupy different positions when evaluated by different means. The existence of ISO 37122 is an attempt to standardize rankings. However, as its use is still optional and/or partial, it is difficult to establish direct comparisons between these ranks. Regarding some indices or ranks, we have the IESE Cities in Motion Index, IMD Smart City Index, Arcadis Sustainable Cities Index, and Ranking Connected Smart Cities, among others.

IESE Cities in Motion Index (CIMI) is a research platform jointly launched by the Center for Globalization and Strategy and the Department of Strategy at IESE Business School. Its goal is to promote change at a local level and develop ideas and tools to make cities more sustainable and smarter. This platform works around four factors: sustainable ecosystem, innovative activities, equity between citizens, and connected territory [75]. CIMI evaluated, in 2022, 183 cities in 92 countries. Their methodology includes nine dimensions: human capital (ten indicators); social cohesion (seventeen indicators); economy (eleven indicators); governance (sixteen indicators); environment (eleven indicators); mobility and transportation (thirteen indicators); urban planning (eighth indicators); international profile (five indicators); and technology (twelve indicators) [75]. Of the more than 100 CIMI

indicators, Table 2 contains some most strongly related to the principles of green chemistry, whether these principles are opportunities to pollute less or to mitigate existing pollution. Moreover, the outcomes of these indicators may have positive or negative repercussions on the respective Sustainable Development Goals (SDGs) mentioned, as evidenced by one or more target goals cited in Table 3.

The IMD Smart City Index (SCI) is a report that has a partner, the World Smart Sustainable Cities Organization (WeGO). In this evaluation, the residents' opinions were considered, specifically 120 residents in each city, in a total of 114 cities, in 2023. In the 2023 version, the final score for each city is computed considering the last three years of the survey (with the weight of 3:2:1 for 2023:2021:2020, respectively) [76]. The methodology evaluates the residents' perceptions of issues related to structures and technology applications available to them in their city. There are two pillars: the structures pillar refers to the existing infrastructure of the cities, and the technology pillar describes the technological provisions and services available to the inhabitants. Each pillar is evaluated over five key areas: health and safety, mobility, activities, opportunities, and governance [76]. The SCI indicators are more specific and punctual, which is understandable as it is a "citizen's survey". But, in the same way, there are points that can be impacted by PGCs actions, Table 4. The indicators chosen and enumerated in Table 4 have the potential to contribute to as many as nine SDGs.

The Arcadis Sustainable Cities Index 2022 report examines 100 cities from 47 countries provide a holistic measure of urban sustainability. Each city is ranked across three sub-indices: planet (nine indicators), people (seven indicators), and profit (eight indicators) [77]. The methodology of the evaluation corresponds to three dimensions of sustainability —social, environmental, and economic and can be described as the triple bottom line. The measure of these three pillars aims to capture environmental factors like energy usage and emissions, measure social performance including quality of life, and assess business environment and economic performance [77]. The all report is about sustainability, but the indicators that converge to PGCs are contained in Table 5. The three pillars outlined by Arcadis, while primarily centered on environmental health (planet), citizen education, and economic growth, synergize with numerous Sustainable Development Goals (SDGs), particularly through indicators that can directly or indirectly impact climate actions.

The ranking developed by Urban System in partnership with the company Sator, called Ranking Connected Smart Cities (RCSC), aims to map Brazilian cities with the greatest development potential [78]. The RCSC has so far nine editions since 2015. In 2023, the RCSC collects data and information from all Brazilian municipalities with more than 50 thousand inhabitants, totaling 656 cities. The methodology used to carry out the study is based on specific criteria, which are grouped into eleven sectors: mobility (eleven indicators), urbanism (ten indicators), environment (fourteen indicators), energy (four indicators), technology and innovation (fifteen indicators), economy (fourteen indicators), education (twelve indicators), health (nine indicators), security (six indicators), entrepreneurship (five indicators), and governance (twelve indicators). The indicators comply with ISO 37122, ISO 37120, and NBR 37122 [78,79], and they are capable of optimization through the execution of PGCs, as shown in Table 6.

Table 3. Indicators of the IESE Cities in Motion Index that can be affected by PCGs applications and impact the SDGs.

Index/Ranking	Dimension	Indicators	SDGs (United Nations)	PGCs
IESE Cities in Motion Index	Human Capital Indicators	1. Secondary and higher education	4. Quality education	1. Prevention/4. Designing safer chemicals
		9. Number of universities		1. Prevention/4. Designing safer chemicals
	Social Cohesion Indicators	18. Health Care Index	3. Good health and well-being	1. Prevention/3. Less hazardous chemical synthesis
	Economy Indicators	36. Productivity	8. Decent work and economic growth	9. Catalysis
	Governance Indicators	40. ISO 37120 certification	11. Sustainable cities and communities	1. Prevention/4. Designing safer chemicals/6. Energy efficiency/ 8. Reduce derivatives/9. Catalysis/11. Real-time analysis for pollution prevention
		50. Research offices	8. Decent work and economic growth	1. Prevention/2. Atom economy/4. Designing safer chemicals/ 6. Energy efficiency/7. Use of renewable feedstocks/8. Reduce derivatives/9. Catalysis/11. Real-time analysis for pollution prevention
	Environment Indicators	55. CO_2 Emission	3. Good health and well-being/ 13. Climate action	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/12. Inherently safer chemistry for accident prevention
		56. Methane Emission	13. Climate action	
		57. Environmental Performance Index	12. Responsible consumption and production	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/11. Real-time analysis for pollution prevention/ 12. Inherently safer chemistry for accident prevention
		58. CO_2 Emission Index	13. Climate action/15. Life on land	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/12. Inherently safer chemistry for accident prevention
		59. Pollution Index	3. Good health and well-being/ 15. Life on land	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/11. Real-time analysis for pollution prevention/ 12. Inherently safer chemistry for accident prevention
		60. PM_{10}		1. Prevention/4. Designing safer chemicals/8. Reduce derivatives/ 9. Catalysis/10. Design for degradation
		61. $PM_{2.5}$		
		62. Percentage of population with access to water supply	6. Clean water and sanitation	
		64. Solid waste	12. Responsible consumption and production/14. Life below water	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation
		65. Climate vulnerability	13. Climate action	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/11. Real-time analysis for pollution prevention

Table 3. *Cont.*

Index/Ranking	Dimension	Indicators	SDGs (United Nations)	PGCs
IESE Cities in Motion Index	Mobility and Transportation Indicators	69. Bicycles per household	3. Good health and well-being	1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/ 10. Design for degradation
		70. Bike sharing		
		72. Traffic Inefficiency Index	13. Climate action	
		77. Vehicles in the city	3. Good health and well-being/ 13. Climate action	
	Urban Planning Indicators	79. Bike Advance		
		81. Bicycle stations		
		82. Electric charging stations	7. Affordable and clean energy	6. Design for energy efficiency/7. Use of renewable feedstocks
		84. Percentage of the urban population with adequate sanitation services	6. Clean water and sanitation/14. Life below water	3. Less hazardous chemical synthesis/4. Designing safer chemicals/ 5. Safer solvents and auxiliaries/8. Reduce derivatives
		85. Artificial intelligence (AI) projects	9. Industry, innovation and infrastructure	1. Prevention/9. Catalysis/11. Real-time analysis for pollution prevention/12. Inherently safer chemistry for accident prevention
	Technology Indicators	93. Innovation Cities Index	11. Sustainable cities and communities	

Source: Developed by the authors based on data research (2024).

Table 4. Indicators of the IMD Smart City Index can be affected by PCGs applications and impact the SDGs.

Index/Ranking	Pillar	Areas	Indicators	SDGs (United Nations)	PGCs
IMD Smart City Index	Structures	Health and Safety	Basic sanitation meets the needs of the poorest areas	3. Good health and well-being/ 6. Clean water and sanitation	3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives
			Recycling services are satisfactory	12. Responsible consumption and production	1. Prevention/2. Atom aconomy/3. Less hazardous chemical synthesis/4 .Designing safer chemicals/7. Use of renewable feedstocks/8. Reduce derivatives/9. Catalysis/10. Design for degradation
			Public safety is not a problem	3. Good health and well-being	1. Prevention/11. Real-time analysis for pollution prevention
			Air pollution is not a problem	3. Good health and well-being/13. Climate action/15. Life on land	2. Atom economy/3. Less hazardous chemical synthesis/ 4 .Designing safer chemicals/8. Reduce derivatives/9. Catalysis/ 10. Design for degradation/11. Real-time analysis for pollution prevention/12. Inherently safer chemistry for accident prevention
		Activities	Green spaces are satisfactory	11. Sustainable cities and communities/13. Climate action/15. Life on land	1. Prevention/3. Less hazardous chemical synthesis/5. Safer solvents and auxiliaries/7. Use of renewable feedstocks/8. Reduce derivatives/11. Real-time analysis for pollution prevention
		Opportunities (Work &School)	Lifelong learning opportunities are provided by local institutions	4. Quality education/8. Decent work and economic growth	1. Prevention/11. Real-time analysis for pollution prevention
	Technologies	Health and Safety	A website or App allows residents to effectively monitor air pollution	3. Good health and well-being/13. Climate action	1. Prevention/9. Catalysis/11. Real-time analysis for pollution prevention/12. Inherently safer chemistry for accident prevention
		Mobility	Bicycle hiring has reduced congestion	3. Good health and well-being	1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/ 10. Design for degradation
		Opportunities (Work and School)	IT skills are taught well in schools	4. Quality education/8. Decent work and economic growth/ 9. Industry, innovation and infrastructure	1. Prevention/9. Catalysis/11. Real-time analysis for pollution prevention/12. Inherently safer chemistry for accident prevention

Source: Developed by the authors based on data research (2024).

Table 5. Arcadis Sustainable Cities Index indicators that converge to PGCs and impact the SDGs.

Index/Ranking	Pillar	Indicators	SDGs (United Nations)	PGCs
Arcadis Sustainable Cities Index	Planet pillar	Air pollution	3. Good health and well-being/ 13. Climate action/15. Life on land	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/ 11. Real-time analysis for pollution prevention/12. Inherently safer chemistry for accident prevention
		Bicycle infrastructure	3. Good health and well-being/ 13. Climate action	1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/ 4. Designing safer chemicals/8. Reduce derivatives/10. Design for degradation
		Energy consumption and renewable energy share	7. Affordable and clean energy	6. Design for energy efficiency/7. Use of renewable feedstocks
		Environmental exposure	13. Climate action/15. Life on land	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/ 11. Real-time analysis for pollution prevention/12. Inherently safer chemistry for accident prevention
		Green spaces	11. Sustainable cities and communities/ 13. Climate action/ 15. Life on land	1. Prevention/3. Less hazardous chemical synthesis/5. Safer solvents and auxiliaries/7. Use of renewable feedstocks/8. Reduce derivatives/11. Real-time analysis for pollution prevention
		Greenhouse gas emissions	11. Sustainable cities and communities/ 13. Climate action	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/ 12. Inherently safer chemistry for accident prevention
		Sustainable transport incentives	3. Good health and well-being/ 13. Climate action	1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/ 4. Designing safer chemicals/8. Reduce derivatives/10. Design for degradation
		Waste management	12. Responsible consumption and production/14. Life below water/ 15. Life on land	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation
	People pillar	Education	4. Quality education/8. Decent work and economic growth	1. Prevention/4. Designing safer chemicals
	Profit pillar	Access to reliable electricity	7. Affordable and clean energy	6. Design for energy efficiency/7. Use of renewable feedstocks
		Economic development	8. Decent work and economic growth/ 9. Industry, innovation and infrastructure	1. Prevention/9. Catalysis
		Green finance	8. Decent work and economic growth/ 9. Industry, innovation and infrastructure	

Source: Developed by the authors based on data research (2024).

Table 6. Indicators of the ranking connected smart cities report, which can be changed by executing PGCs and respective SDGs that can be improved.

Index/Ranking	Pillar	Indicators	SDGs (United Nations)	PGCs
Ranking Connected Smart Cities	Mobility	Cars/inhabitants	3. Good health and well-being/ 13. Climate action	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/10. Design for degradation
		Cycle paths		1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/ 4. Designing safer chemicals/8. Reduce derivatives/10. Design for degradation
		Percentage of low emission vehicles	3. Good health and well-being/ 13. Climate action/15. Life on land	
		Smart Traffic Lights	3. Good health and well-being/ 13. Climate action	1. Prevention/6. Design for energy efficiency
	Urbanism	Land Use and Occupation Law	9. Industry, innovation and infrastructure/11. Sustainable cities and communities	1. Prevention
		Percentage urban water service	6. Clean water and sanitation	1. Prevention/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives
		Percentage urban sewage service		
	Environment	Percentage of low emission vehicles	13. Climate action	2. Atom economy/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives/9. Catalysis/10. Design for degradation/ 12. Inherently safer chemistry for accident prevention
		Percentage losses in water distribution	6. Clean water and sanitation	1. Prevention/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives
		Percentage urban water service		
		Percentage urban sewage service		
		Percentage of sewage treatment	6. Clean water and sanitation/14. Life below water	
		Recovery of recyclable materials	12. Responsible consumption and production	1. Prevention/2. Atom aconomy/3. Less hazardous chemical synthesis/ 4. Designing safer chemicals/7. Use of renewable feedstocks/8. Reduce derivatives/9. Catalysis/10. Design for degradation
		Percentage solid waste collection coverage	12. Responsible consumption and production/14. Life below water	
		Risk area monitoring	9. Industry, innovation and infrastructure	11. Real-time analysis for pollution prevention
		Percentage of plastic waste recovered	12. Responsible consumption and production/14. Life below water	1. Prevention/3. Less hazardous chemical synthesis/4. Designing safer chemicals/7. Use of renewable feedstocks/8. Reduce derivatives/ 9. Catalysis/10. Design for degradation
		Power Granted UFV Energy	7. Affordable and clean energy	6. Design for energy efficiency
		Power Granted Wind Energy		
		Power Granted Biomass		

Table 6. *Cont.*

Index/Ranking	Pillar	Indicators	SDGs (United Nations)	PGCs
Ranking Connected Smart Cities	Technology and Innovation	Percentage of formal higher education jobs	4. Quality education/8. Decent work and economic growth	1. Prevention/4. Designing safer chemicals
		Smart Traffic Lights	3. Good health and well-being/ 13. Climate action	1. Prevention/6. Design for energy efficiency
		Growth of Technology Companies	8. Decent work and economic growth/ 9. Industry, innovation and infrastructure	9. Catalysis
		Technology Parks	9. Industry, innovation and infrastructure	1. Prevention/9. Catalysis/11. Real-time analysis for pollution prevention/ 12. Inherently safer chemistry for accident prevention
		Incubators		
	Health	Cycle paths	3. Good health and well-being/ 13. Climate action	1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/ 4. Designing safer chemicals/8. Reduce derivatives/10. Design for degradation
		Percentage solid waste collection coverage	12. Responsible consumption and production/14. Life below water	1. Prevention/2. Atom economy/3. Less hazardous chemical synthesis/ 4. Designing safer chemicals/7. Use of renewable feedstocks/8. Reduce derivatives/9. Catalysis/10. Design for degradation
		Percentage urban sewage service	6. Clean water and sanitation	1. Prevention/3. Less hazardous chemical synthesis/4. Designing safer chemicals/8. Reduce derivatives
	Security	Control and operations center	9. Industry, innovation and infrastructure	11. Real-time analysis for pollution prevention
		Risk area monitoring	9. Industry, innovation and infrastructure	
	Education	Teachers with Higher Education	4. Quality education	1. Prevention/4. Designing safer chemicals/9. Catalysis
		Education Expenses		
		Vacancies at Public University	4. Quality education/8. Decent work and economic growth	
		Employed workforce in the education sector		
		Percentage of formal higher education jobs		
	Entrepreneurship	Growth of Technology Companies	9. Industry, innovation and infrastructure	9. Catalysis
		Technology Parks		1. Prevention/9. Catalysis/11. Real-time analysis for pollution prevention/ 12. Inherently safer chemistry for accident prevention
		Growth of Creative Economy Companies	8. Decent work and economic growth/9. Industry, innovation and infrastructure	9. Catalysis
		Incubators	9. Industry, innovation and infrastructure	1. Prevention/9. Catalysis/11. Real-time analysis for pollution prevention/ 12. Inherently safer chemistry for accident prevention

Table 6. *Cont.*

Index/Ranking	Pillar	Indicators	SDGs (United Nations)	PGCs
Ranking Connected Smart Cities	Governance	Land Use and Occupation Law	9. Industry, innovation and infrastructure/11. Sustainable cities and communities	
		Risk area monitoring	9. Industry, innovation and infrastructure	11. Real-time analysis for pollution prevention
		Education Expenses	4. Quality education	1. Prevention
	Economy	Employed workforce in the education sector	4. Quality education/8. Decent work and economic growth	9. Catalysis
		Growth of Technology Companies	9. Industry, innovation and infrastructure	
		Growth of Creative Economy Companies	8. Decent work and economic growth/ 9. Industry, innovation and infrastructure	
	Energy	Power Granted UFV Energy	7. Affordable and clean energy	6. Design for energy efficiency
		Power Granted Wind Energy		
		Power Granted Biomass		

Source: Developed by the authors based on data research (2024).

The indicators highlighted in Tables 3–6 converge with the PGCs converge with the PGCs about air quality and preservation of the environment, through prevention, reduction, degradation, and control to provide a better quality of life for the population, life on land, and below water, simultaneously promoting sustainability (objective of the SDGs).

Understanding each indicator can be approached in countless ways. One approach is to interpret them through the lens of green chemistry principles (as outlined in Section 3.2), utilizing them as a mechanism to advance each of the mentioned indicators. It is evident that relying solely on this approach will not suffice to foster sustainability, as it necessitates a broader spectrum of actions. Nevertheless, these principles can be deemed essential tools. Thus, it becomes apparent that PGCs should not be confined solely to research laboratories, industries, or professionals in chemistry, engineering, and processes. Rather, these principles can be applied across diverse activities with the aim of minimizing pollution, conserving resources, preempting future challenges, and ultimately contributing to sustainability efforts.

There is still no assessment or seal for a chemically green city, but some indicators based on ISO 37122 could be applied for this purpose. For example, indicators related to education at different levels promote prevention (PGC 1) and simultaneously SDGs 4 and 8, as it involves a scenario where professionals with decent work promote knowledge, awareness and prevention that can result in economic growth for the city. The use of technologies can simultaneously contribute to prevention (PGC 1), energy efficiency (PGC 6), real-time analysis of pollution prevention (PGC 11), among other PGCs, promoting sustainability through SDGs 3, 13, 14, and 15. Another example is related to energy generation or expenditure, which contribute to SDG 7 and PGC 6.

Furthermore, this analysis is also an invitation to think about chemistry outside the laboratory; urban mobility based on the atomic economy is possible (PGC 2) when the car is replaced by a bicycle (ISO 37122) and the reaction that would generate atmospheric emissions is extinguished (ISO 37122), reducing their impact on climate actions (SDG 13). The reduction in by-products (PGC 8) can be assessed by the percentage of solid waste discarded (ISO 37122), which can be improved through conscious consumption (SDG 12). The use of a local raw material (PGC 7) for an industry installed in the same city is a catalyst (PGC 9) that optimizes time and expenditure for industrial activity (SDG 9) while also contributing to decent work and local economic development (SDG 8). Access to treated water and sewage systems for citizens (ISO 37122) promotes a plan for degradation (PGC 10), preventing safer chemicals (PGC 4) and less harmful syntheses (PGC 3) from contaminating people and terrestrial and aquatic animals (SDG 6, 14 and 15).

In addition to the examples cited, other indicators suggested by ISO 37122 can be applied to assess how chemically green a city is through the PGCs, contributing to sustainable development through the application of the SDGs. This opens up the possibility of a new article just to address indicators for a chemically green city report.

4.2. Case Study: The Performance of Curitiba (PR)

In 2023, Brazil was ranked fourth in sustainability and green chemistry publications. Smart cities in Brazil are increasingly gaining recognition on the international stage. This is exemplified by the city of Curitiba [67], the capital of Paraná state, situated in the southern region of Brazil. Curitiba spans approximately 435 km^2 and is home to around 1.95 million inhabitants [80].

In 2023, Curitiba received important awards as a smart, innovative, and sustainable city: one of the 7 Most Intelligent Communities in the World in 2023 (Intelligent Community Forum—ICF); one of the 6 smartest cities in the world (World Smart City Awards 2023); second most promising emerging ecosystem for startups in Latin America (Global Startup Ecosystem Report 2023 ranking); second best city in Brazil for startups for the third consecutive year (Startup Ecosystem Index Report 2023); Top 3 at the Latam Smart City Awards; second most intelligent, technological, and innovative city in Brazil (Ranking Connected Smart Cities 2023); second place in the "Technology and Innovation" category

of the Ranking Connected Smart Cities 2023; Smart Cities 2023 Gold Seal; Champion city in the Ranking of Cities with Smart Services, (Conexis Brasil Digital and Teleco); Top 3 in the National Innovation Award (PNI), in the Large Innovation Ecosystem category (Sebrae Nacional, by the National Confederation of Industry (CNI), and Business Mobilization for Innovation (MEI); Diamond Seal for excellence in service at the Pinheirinho Entrepreneurial Space, granted by Sebrae Nacional [81].

The RCSC was selected due to its comprehensive analysis of Brazilian cities, particularly because Curitiba has been consistently examined in all editions. This continuity enables comparisons across the years. Notably, Curitiba is not featured in the other international reports referenced in this article. Table 7 contains RCSC results based on which we will interpret the evolution of the Curitiba city, maintaining the focus on PGCs as a tool for this evolution. RCSC report data over nine years reveals that Curitiba has been well evaluated, among the top five in the general ranking in all years assessed. Furthermore, the city obtained first place in the general ranking in two years (2018 and 2022) and second place in two others (2017 and 2023). The strengths of this city are technology and innovation, entrepreneurship, governance, health, and environment, which are the sectors in which it was best evaluated, ranking in the Top 10.

Table 7. Results of the RCSC report for Curitiba from 2015 to 2023 [78,82–89].

RCSC Sectors		RCSC Years								
		2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
General	ranking	5º	3º	2º	1º	3º	3º	3º	1º	2º
	score	28.100	34.884	32.472	31.782	38.016	36.545	37.375	38.571	35.789
Mobility	ranking	4º	4º	4º	7º	13º	46º	22º	13º	25º
	score	3.260	3.797	2.285	3.590	2.318	3.129	3.849	4.026	3.784
Urbanism	ranking	4º	1º	3º	2º	1º	1º	1º	3º	38º
	score	7.270	8.404	7.530	6.554	5.933	7.077	8.455	7.654	7.033
Environment	ranking	2º	4º	2º	20º	88º	72º	3º	8º	9º
	score	5.660	5.154	4.783	6.389	5.407	5.347	5.305	5.461	5.441
Technology and Innovation	ranking	16º	8º	4º	3º	6º	2º	5º	2º	2º
	score	-	4.293	5.084	5.199	3.968	5.281	6.062	6.324	5.847
Health	ranking	-	13º	34º	33º	64º	63º	17º	11º	8º
	score	-	3.401	3.317	4.164	3.304	3.817	3.884	5.471	5.233
Safety	ranking	-	-	-	-	29º	48º	30º	40º	41º
	score	-	-	-	-	2.724	2.866	3.798	3.823	3.636
Education	ranking	6º	14º	1º	5º	91º	39º	-	21º	37º
	score	4.250	4.200	5.801	5.422	4.160	5.125	-	5.455	5.857
Entrepreneurship	ranking	12º	11º	3º	2º	7º	5º	1º	1º	5º
	score	-	2.763	3.842	4.431	2.124	2.105	4.065	2.838	2.639
Economy	ranking	11º	28º	11º	1º	11º	6º	29º	33º	-
	score	-	4.700	5.578	7.570	5.269	6.097	6.555	5.082	-
Governance	ranking	1º	1º	3º	9º	7º	4º	17º	9º	8º
	score	10.770	9.765	7.506	5.944	6.812	7.222	7.407	8.000	7.760

To promote technology, innovation, and entrepreneurship, this city counts on Vale do Pinhão, a movement that integrated Curitiba's innovation ecosystem. Together with the city council, it contributes to developing its 604 startups, promotes constant and free training, provides 991 daily services to formalized Individual Microentrepreneurs, and maintains training programs for the job market in Information Technology (IT). Currently, Curitiba is recognized as one of the best cities in Brazil to undertake and the fastest capital in the

country to open a new company [81]. According to United Nations, the "SDGs promote sustained economic growth, higher levels of productivity and technological innovation". "Technological progress is also key to finding lasting solutions to both economic and environmental challenges, such as providing new jobs and promoting energy efficiency. Promoting sustainable industries, and investing in scientific research and innovation, are all important ways to facilitate sustainable development". The organization also stated that "More than 4 billion people still do not have access to the Internet, and 90 percent are from the developing world. Bridging this digital divide is crucial to ensure equal access to information and knowledge, as well as foster innovation and entrepreneurship" [22]. Based on PGCs, these initiatives that encourage technology, innovation, and entrepreneurship help prevent future pollution/damage (PGC 1), have the technical knowledge to produce sustainably, evaluate and treat the pollution generated in real-time (PGC 11), and undertake more excellent safety for employees and the population (PGC 12). This example of action is associated with education and economy indicators (ISO 37122).

Curitiba has the first photovoltaic plant installed on a deactivated landfill in Latin America (Pirâmide Solar), which, in six months of operation, generated 2 048 985 MWh (megawatts/hour), resulting in savings of BRL 1.17 million to public coffers municipalities [81]. While the PGCs have the sixth principle defined as "Design for energy efficiency", the United Nations described the seventh objective as "Affordable and clean energy", both intending to diversify the energy matrix by renewable sources and increasing energy efficiency. According to United Nations data "Energy is by far the main contributor to climate change. It accounts for 73% of human-caused greenhouse gases", this way "Expanding infrastructure and upgrading technology to provide clean and more efficient energy in all countries will encourage growth and help the environment" [22]. To achieve SDG 7 by 2030, it is necessary to "Invest in solar, wind and thermal power, improving energy productivity, and ensuring energy for all" [22], like what Curitiba has accomplished. Energy, economy, and environment indicators can be associated in this initiative (ISO 37122).

This city has a program that integrates the population into decisions regarding what is a priority for municipal investments. Citizens participate via the Internet, in neighborhood meetings, or at mobile points [81]. Allowing citizens to participate in public decisions and being aware of the city's projects and investments, in addition to registering the improvements they believe to be most necessary and urgent, are in line with SDG 11 "sustainable cities and communities" and PGC 11 "real-time analysis for pollution prevention". According to the United Nations, "Making cities sustainable means creating career and business opportunities, safe and affordable housing, and building resilient societies and economies. It involves investment in public transport, creating green public spaces, and improving urban planning and management in participatory and inclusive ways" [22]. They are the citizens who see and live every day with the problems and solutions of the city. Allowing your participation will help the governance realize the most urgent investments more quickly. After all, a smart city must be created by and for citizens. This integrative program is associated with population and governance indicators (ISO 37122).

Another highlighted project which contributes to the same alignment is "Bairro Novo da Caximba", exchanging irregular stilt houses for a smart neighborhood for 1 693 families in an Environmental Preservation Area, aiming to recover the urban environment, reduce gas emissions and mitigate the effects of climate change [81]. "Supporting vulnerable regions will directly contribute not only to Goal 13 but also to the other SDGs. These actions must also go hand in hand with efforts to integrate disaster risk measures, sustainable natural resource management, and human security into national development strategies" (United Nations, 2015) [22]. Urban region transformation, as accomplished in Curitiba, has the same aims as PGCs 10 and 11: safe disposal without harm to the environment and proactive pollution prevention, with the primary objective of minimizing climate actions. Sustainable neighborhoods are assessed using environment and housing indicators (ISO 37122).

Although mobility is not this city's strongest point, public transport is in the testing phase of electric buses, which will operate from 2024. The city already has electromobility in the Municipal Guard's fleet and taxis. There is also investment in expanding 400 km of the cycle path structure spread across the neighborhoods by the end of 2025. Curitiba already has a 280.2 km cycle path network, including cycle paths, cycle lanes, cycle routes, and shared roads. In addition, the city already has 50 stations for the shared use of 500 shared bicycles, mechanical and electric, which are activated via an app [81]. Using alternative transport, such as electric cars and bicycles, directly contributes to reducing greenhouse gas emissions, which impacts climate change. In the case of using bicycles, human health and well-being still have to be considered. United Nations data reveal that "to limit warming to 1.5 °C global net CO_2 emissions must drop by 45% between 2010 and 2030" and " bold climate action could trigger at least US$26 trillion in economic benefits by 2030" [22]. The contribution to reducing emissions, from the point of view of PGCs, can occur through the following: prevention (environmental education—PGC 1), the use of renewable feedstocks (saving both the generation of more gases and the natural resources that contribute to the capture of harmful gases—PGC 7); design for degradation (adaptation, impact reduction—PGC 10); and real-time analysis for pollution prevention (early warning and real-time problems solution—PGC 11). The issue of urban mobility is assessed using transportation indicators and directly impacts the environment (ISO 37122) through emissions that can be saved by using less polluting alternatives to transport.

To promote environmental sustainability, Curitiba also counts on two Urban Farms: one of them (Cajuru) was the pioneer and it is an example of the cultivation and integral use of food, from seeding to composting. The other one, (CIC) has already had its agroforestry inaugurated, a space to promote agricultural and reforestation techniques, with fruit trees, honey gardens, medicinal plants, and the planting of native seedlings such as yerba mate and araucaria [81]. The Urban Farm projects respond directly to SDG 12, "Responsible consumption and production" (and 2 "zero hunger", not cited by this article), which can be supported by several of the PGCs, such as prevention (waste reduction, through the use total planting—PGC 1); use of renewable feedstocks (using waste for composting and composting for new planting—PGC 7); reducing derivatives (minimizing solid waste during the process—PGC 8); among others. This is another action by a sustainable neighborhood that highlights the city in the economy and urban/local agriculture and food security indicators (ISO 37122).

In addition, other actions such as popularizing the use of renewable energy and carrying out tree planting and river cleaning programs contribute to making the capital an emissions neutral city by 2050 ("100 Mil Árvores" and the "Amigo dos Rios"). The project aims to preserve native stingless bees, which are responsible for 90% of pollination, and support environmental education projects for the population, such as the exchange of recyclable material for fruit and vegetables (103 exchange points benefit 5 thousand people with 55 tons/month) [81]. These projects respond to SDGs 4, 11, and 13, which are, respectively, "quality education", "sustainable cities and communities", and "climate actions". By reducing derivatives, recycling, and preserving natural resources, it is possible to align these projects with PGCs 1, 7, and 8, which are prevention, use of renewable feedstock, and reduce derivatives, respectively. The neutralization of emissions is related to environmental and climate indicators (ISO 37122).

The results reflect Curitiba's tradition of investing in the population's quality of life and promoting the city's sustainable and smart development. It is essential to highlight variations in RCSC rankings over time, indicating challenges and opportunities to improve performance on specific indicators. However, Curitiba continues to be recognized as an intelligent, sustainable city, with a high quality of life, and chemically green, which serves as an example for other cities in Brazil and the world.

This case study helps to understand how it is possible to recognize in the programs and actions implemented in smart cities: which ISO 37122 indicators may be affected, which PGCs may be behind that action, and which SDG it collaborates with. Thus, the objective

of exemplifying that it is possible to recognize a "green city" in a smart city is achieved since it is possible to identify through actions the principles of green chemistry intrinsic to sustainability intentions. In this way, two new paths are possible: admitting green chemistry as an area/dimension/pillar in the already existing indicators or recognizing a "green city" report/seal for which some indicators standardized by ISO 37122 can be used, but from the perspective of green chemistry (PGCs).

The case studies reaffirm the correlation between smart city indicators (according to international reports), SDGs, and PGCs. While the first demonstrates the direct relationship item by item in the tables, the second occurs by analyzing concrete actions in a smart city, identifying the three parameters (indicator according to ISO 37122, SDGs, and PGCs). The relevance of both studies is to support the proposal that it is possible to evaluate sustainability in a smart city from the perspective of green chemistry.

The relevance of both studies is to support the proposal that it is possible to assess sustainability in a smart city from the perspective of green chemistry. This assessment can be performed using currently applied indicators but changing the focus of the area/dimension/pillar to the bias of green chemistry (based on PGCs)—case 1. Another way is through actions and projects executed by the city, identifying the applicable PGCs in it—case 2. Both extrapolate PGCs beyond the laboratories of educational institutions, research institutions, and industries. After all, chemistry is not limited to processes in these controlled environments. It is part of the daily life of any citizen, impacting the quality of life, which, in this case, is assessed by the geographic limitation of the city.

5. Conclusions

The word chemistry has always carried the opposite weight to the word sustainable. What happens is that simple and complex chemical processes are constantly present in our routine and can indeed be sustainable and environmentally friendly. PGCs were initially designed to be applied on an industrial scale. However, their scope can and should include routine processes to prevent pollution, reduce environmental impact, and, above all, promote a better quality of life (on land or below water). This work aligned for the first time the principles of green chemistry (PGCs) as a strategic tool to boost the achievement of the Sustainable Development Goals (SDGs) and efficiency in indicators related to smart cities.

The analysis showed that the adoption of green chemistry principles contributes more than the application of more sustainable practices in the chemical industry, but also positively influences the quality of urban life, because it is not limited to laboratories and industry. The integration of these principles allows advances in the efficiency of chemical processes, reducing environmental impacts, and offering opportunities for innovation in cities, promoting smarter and more sustainable urban management.

In the context of the SDGs, the PGCs are allies that are essential in facing contemporary challenges such as land consumption and environment overloading, energy gradually depleting, scarred and overcrowded landscapes, and congested urban settings and infrastructures, among others. As listed in Table 2, PGCs can be used as tools to achieve several target goals of the SDGs.

In multiple cases (Section 4.1), some indicators used in smart city reports were listed, which can be associated with the SDGs and PGCs. The indicators standardized by ISO 37122 are also associated with the SDGs by Annex B of the standard itself, as referenced in Section 3.1. Thus, it is possible to conclude that there are parameters to assess how sustainable the city is and how much it can contribute to meeting the SDGs. However, the limitation of this study is the need for more standardization of smart city reports since the report can create its indicators using those established by ISO 37122 or not. Thus, the relationship linkage between the Sustainable Development Goals (SDGs) and smart cities or smart city indicators can occur in different ways, collaborating with distinct SDGs depending on the point of view of the smart city report chosen.

In this study, a new model for evaluating smart cities was proposed, grounded in the principles of green chemistry, as exemplified by the case study of the Brazilian city, Curitiba. Its development extends beyond the numerical data presented in the report, which ranked it as the most sustainable city globally. Projects implemented in the city can be evaluated as actions aligned with the United Nations' Sustainable Development Goals (SDGs) and can also be assessed based on green chemistry principles. These initiatives aim to preserve and prolong the lifespan of natural resources for future generations, enhance air and water quality, improve overall quality of life, and contribute to achieving SDG targets for a healthier planet. The limitations of this study include variations in indicators across reports and a lack of standardization like ISO 37122, thus complicating comparisons. Another challenge lies in the breadth of scope; it would be feasible to dedicate an article to each principle of green chemistry (PGC) and its relation to the Sustainable Development Goals (SDGs). Additionally, accessing projects undertaken by cities and qualitatively evaluating them from the perspective of PGCs poses a significant challenge.

For future research, there is potential to assess other smart cities using the PGC model. Moreover, consideration can be given to developing PGC indicators capable of measuring the degree of green chemistry integration within a smart city.

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