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Perspective

Circular Economy and Green Chemistry: The Need for Radical Innovative Approaches in the Design for New Products

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Abstract: The idea of a circular economy (CE) has gained ground over the past ten years as a means of addressing sustainable development and getting around the limitations of the current and linear dominant production and consumption patterns. The primary goal of a CE is to encourage the adoption of closing-the-loop production methods to improve resource use efficiency, modify chemical processes, and increase product and material lifespan. According to the 2030 Agenda for Sustainable Development, which focuses on 17 Sustainable Development Goals, 14 of which call for the appropriate application of green chemistry (GC) concepts and patterns, the role that chemistry may play in the shift toward more sustainable models is critical. By serving as the foundation for novel products made from renewable feedstocks and designed to be reused, recycled, or recovered with the associated minimum energy requirements, green and sustainable chemistry could be the key to unlocking the economic potential of the CE toward new product design and ultimately solving waste management problems. The aim of this perspective paper, while using a variety of literature sources, is to essentially capture the main issues associated with the CE and GC paradigms and how these two approaches can merge toward sustainable business models and the production of new materials. This integration focuses on reducing waste, conserving resources, and minimizing negative environmental impacts, while also considering economic viability. However, the obstacles to achieving implementation of the CE and GC principles are investment, environmental education, and legislation. To advance toward the circular economy and green chemistry, international agreements should be reconsidered to provide an appropriate framework, including the creation of incentives for businesses and individuals to adopt circular practices, the establishment of education programs to promote the benefits of circular practices, and the development of regulations to support the transition to sustainable production and consumption patterns.

Keywords: circular economy; green chemistry; energy efficient chemical production; waste management

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1. Introduction

To address sustainable development and get around the limitations of the current linear production and consumption patterns, the circular economy (CE) concept has gained traction in recent years [1]. The primary goal of the CE, as stated by the Ellen Macarthur foundation [2], is to promote the adoption of closing-the-loop production patterns to improve resource usage efficiency and longevity. Increased circularity is thought to be a key driver of the Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda for Sustainable Development [3] (Mancini and Raggi, 2021) and the broader objectives of sustainability [4]. Transforming the linear economy, which has been the dominant model since the onset of the industrial revolution, into a circular one is by no means an easy task, as most products we use are designed for a make–dispose culture [5]. This inadvertently results in the depletion of resources and the loss of wealth from waste and, nowadays, the widely accepted solution to dispose products is waste recycling [6]. In the context of our current environmental challenges, recycling will not adequately overcome the sheer amount of waste that the world produces today [7]. The CEs point of departure from the recycling economy is through the incorporation of many closed loops and preventive design mechanisms before the waste is generated and disposed [8]. In fact, the CE concept goes beyond recycling, through waste prevention and reduction, but also technological and organizational innovations across and within value chains [4].

As noted by the United Nations in the 2030 Agenda, 14 out of 17 SDGs call for the appropriate application of green chemistry (GC) concepts and patterns that are considered vital for allowing the shift toward more sustainable approaches [9]. GC is an approach that focuses on product designs and procedures that eliminate or minimize the impact of hazardous chemicals on the environment [10]. GC possesses the potential to reduce the hazardous impact of chemicals on the environment and human health, thereby improving quality of life and the state of the environment [11]. Besides the perceived environmental and social benefits of GC, its adaptation also provides economic benefits [9], such as the reduced use of chemicals, reduced capital used in waste storage, and treatments and environmental compensation payments for the damage caused [12]. The choice of safer and more sustainable chemistries has a significant impact on the product lifecycle, including the potential sustainability of these materials' production, usage, reusing, recycling, and ultimately, the end of its life [13]. Overall, the goal of GC is to establish molecular sustainability by going beyond research in laboratories and expanding the focus toward industry and communities, as a way of responding to current environmental, economic, and societal challenges [14].

Generally, the CE and GC are expected to present new and innovative business opportunities, through (1) better planning of resource use, (2) replacing fossil energies and material resources with renewables, (3) reusing and recycling and, finally, (4) circular governance. The present study focuses on the role played by the circular economy and green chemistry in the needed search for radically innovative approaches to design new products from various sources, including from waste fractions. The aim of this perspective paper, while based on a variety of literature sources, is to essentially capture the main issues associated with the CE and GC paradigms and how these two approaches can merge toward sustainable business models and the production of new materials. Integrating the circular economy and green chemistry into research is important because it leads to the development of sustainable and environmentally friendly production methods. This integration focuses on reducing waste, conserving resources, and minimizing negative environmental impacts, while also considering economic viability. It promotes the use of renewable resources, closed-loop systems, and the development of biodegradable products, which in turn helps to address issues related to resource depletion, pollution, and climate change. Ultimately, the integration of the circular economy and green chemistry within research can help to create a more sustainable future for both the environment and the economy.

1.1. The Circular Economy

The rise of the circular economy concept in Europe is credited to Walter Stahel, who sketched an economic model aimed at closing loops in industrial processes with a visionary outlook on creating jobs, improving economic performance, preserving resources, and preventing waste [15]. Stahel was a member of the Club of Rome, an elite group founded by the entrepreneur Aurelio Peccei (1908–1984), comprising intellectuals, politicians, and business people who hold influential and powerful positions in global affairs and environmental protection. The most known output of the Club of Rome was the support to and the publication of the seminal book “The Limits to Growth”. Around the year 2010, Ellen MacArthur was incorporated into the same group and became a member [2], followed by Anders Wijkman, a former member of the European Parliament and the President of the Club of Rome (2012–2018). The latter eventually delivered a report based on models that predicted positive effects on climate, environment, and economy, which resulted in the first EU Circular Economy Package. Since then, the Circular Economy (CE) concept has started receiving increased attention in Europe and has attracted many disciplines, from environmental to economics and social sciences [16,17]. However, much earlier, around the 2000s, China was already playing a central role in theorizing, implementing, and up-scaling, embedding CE principles in its vision of an “ecological civilisation” with a focus on industrial innovation [18]. Albeit in parallel, China and Europe have continued to share common perspectives on the CE discourse relating to waste reduction and resource efficiency coupled with increased material circularity [19]. Many national governments and international economic policy bodies are now attempting to develop strategies for the implementation of CE practices at micro, meso, and macro levels [20]. As a result, the CE is virtually appearing everywhere from the Chinese 5-year plans to the European Green Deals, to the formation of non-governmental circular economy networks and in many corporates such as Ikea, iPhone, and Renault, among others [21]. In Europe, the transition to the circular economy follows a bottom-up approach which includes initiatives of environmental organizations, civil society and non-governmental organizations [22]. In contrast, China promotes a top-down approach based on national policies toward environmental responsibility and development strategies [22]. According to Genovese and Pansera [23], bottom-up initiatives can only become effective if they are complemented and coupled with top-down approaches, such as government support through incentives and rewards for positive externalities by companies and organizations. This complementary approach can be considered of great importance for many developing countries in Asia and Africa, which are yet to develop strong policies toward the transition to a circular economy.

1.2. Green Chemistry

The emergence of green chemistry dates to the 1980s, when the negative effects of industrial development became apparent. Concerns grew over environmental damage and occupational hazards that were heavily tied to industrial activities [24]. Especially in the chemical sector, the rise in harmful chemical products at the time demanded a more structural approach to implementing policies targeted at their reduction. This led to the convening of multiple global meetings that resulted in policies and initiatives such as the “Brundtland Report 1985”, the “Alternative Synthetic Routes for Pollution Prevention” Initiative in 1991, and the “Agenda 21” of the 1990s. These, together with the reports that followed, had the collective consensus of prioritizing environmental, social awareness, and sustainable development [25]. At its core, green chemistry focuses on using chemical expertise and knowledge to reduce or eliminate the formation and use of hazardous substances throughout the planning, manufacturing, and application of chemicals [26]. For example, traditionally, chemical industry residues are pre-treated to reduce toxicity before disposal. However, such measures are extremely cost extensive. Applying a green chemistry approach when dealing with industrial residues requires the utilization of multi-dimensional aspects, such as greener process design and techniques to limit waste generation during production, being also mindful of the cost and energy involved in the entire process and, lastly, considering the processing and disposal of any left-over residues [27]. In 1998, Paul Anastas and John C. Warner provided an excellent breakdown of the “12 principles of green chemistry” [28], which included elements such as atom efficiency, energy efficiency, degradation, and waste reduction, providing an essential toolbox for sustainable chemical design and synthesis, which halts pollution at a molecular level [29].

Over the years, scientists have been reporting on key trends that align with GC principles. Such areas of research include the following: (i) studying catalytic and biocatalytic processes to produce highly selective, pure chemicals without producing hazardous by-products [30,31], (ii) selection for new, safe, and sustainable source materials, such as biomass [32,33], (iii) creating chemicals that are eco-friendly and less hazardous, (iv) innovative alternatives, toward non-toxic and renewable solvents, such as supercritical fluids, water, and ionic liquids [34], (v) innovative reaction conditions, such as light reacting, ultrasound, and microwave [35] and (vi) novel alternatives for the decontamination of polluted water and air for quality improvement, such as photocatalytic reactions. While it is not possible to use all 12 principles simultaneously in constructing a green chemistry sustainable process, it is possible to apply as many as is feasible at various points of a product's lifecycle [36,37].

2. The Nexus between Green Chemistry and the Circular Economy

It is increasingly clear that green chemistry plays a crucial role in shifting from linear to circular product and material use by allowing the continuing sustainable cycle of resources up to the disposal [38]. Green chemistry can be considered as a strategy to move toward the circular economy, by modifying and making the manufacturing processes of products efficient in preventing and reducing waste. Much research has been dedicated toward the development of synthetic procedures that can align with the 12 guiding principles of GC with a further step to also include concepts of circularity [39,40]. Some of the examples include keeping resources in use for as long as possible [41] as well as the usage of chemicals made from resources that are usually considered as waste to reduce the dependence on depleting non-renewable resources [42]. For the successful implementation of circularity, durable raw materials are an important component; therefore, advances in chemistry are required to increase a product's lifespan for use, reuse, and recycling [43]. Lastly, an important element that helps provide consistency, maintain quality, and offer safety to prevent potentially harmful impacts on the environment and human health is an appropriate level of purity of all materials and products [2]. In this regard, there is a need to create product chemicals and materials that are green and sustainable [44]. Most chemicals are made without keeping toxicity levels in mind and the impact they will have on humans and the environment [45], whereas GC emphasizes that environmental integration and safety measures in chemical systems are insufficient to address societal challenges and promote a transition toward sustainability. Rather, economic, social, political, and technological factors must also be considered [46].

Green chemistry ultimately forms the foundation of a safe and sustainable circular economy [47]. Both GC and the CE adhere to the notion of rethinking the design of chemicals, materials, and products [48], and can be applied together to build a value chain and business model that describes the full range of activities needed to create a product or service [49]. Since GC focuses on molecular synthesis for the design of new products and materials, it can play an essential role in securing circularity in two essential sustainability aspects: (i) designing safer, less toxic chemicals and chemical processes and (ii) using renewable feedstocks. More importantly, sustainable GC could be the key to unlocking the economic potential of the CE in waste management and new product design, by providing the foundation for cutting-edge products that employ renewable feedstocks, are made to be reused, recycled, or recovered, and have minimal energy requirements connected with them. For this reason, the above-mentioned aspects will be explored in deeper detail to showcase the nexus between GC and the CE, whilst demonstrating that GC can be regarded as a necessary tool toward the transition to a CE and a bioeconomy. Figure 1 shows a schematic representation of a system that can integrate the CE and GE in a strategic sustainability framework. The main goal of the CE and GC is, firstly, to correct the linear system that leads to the production of the main product (blue flows) and by-products (residues that need further inputs to be upgraded and become usable, yellow flows) and secondly, to design new and innovative products (green flows feeding back) based on the application of CE and GC approaches to produce value-added products back into the market.

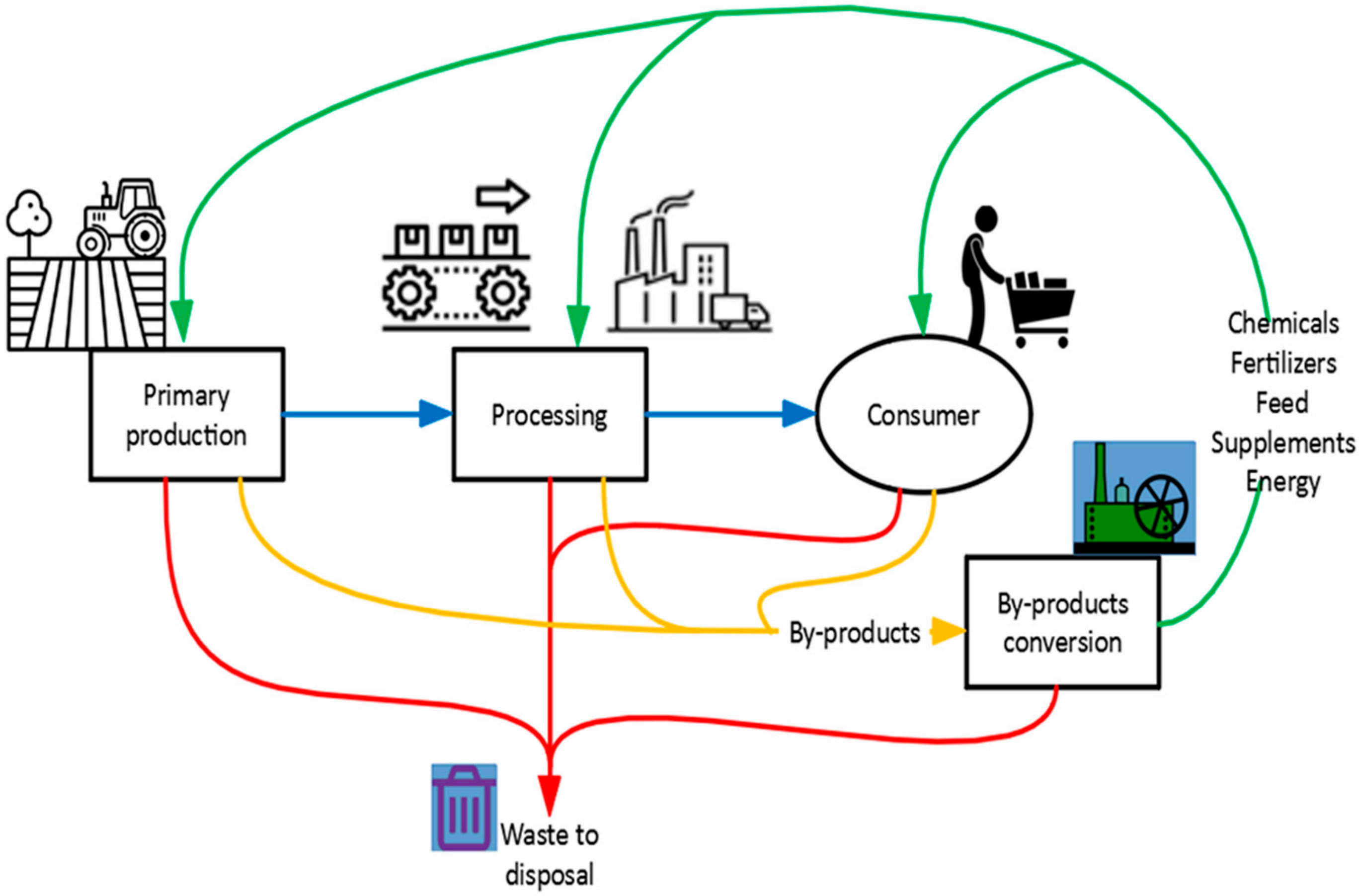

Figure 1. Schematic representation of a system that can integrate the circular economy and green chemistry in a strategic sustainability framework.

2.1. Green Chemistry in Practice

2.1.1. Waste Management Using a GC Approach

Over the next 30 years, the global annual waste is anticipated to increase from 2.01 billion tons in 2016 to 3.4 billion tons [50]. Carelessly discarding materials or products that were of no further use was not a cause of concern in past decades, as natural resources were seemingly unlimited [51]. Such a practice is commonly referred to as a linear process, where entities change or progress straight from one stage to another, i.e., used to discard [52]. He et al. [53] conducted a review of municipal solid waste (MSW) management across 219 countries and concluded that the dominant MSW management practice remains to be landfill disposal in both developed and underdeveloped countries. The decomposition of solid waste in landfilling, if not properly managed, is known to have a significant negative influence on the soil, air, water quality, and human health [54]. In particular, hazardous waste streams have resulted in undesirable bioactivity and ecotoxicity in cases like that of the thalidomide-inducing birth defects in the city of Bhopal (India) or the sinking shallow tube wells being drilled into groundwater, which contaminated the drinking water supplies with arsenic in Bangladesh [55]. Furthermore, MSW is the fourth largest contributor to global greenhouse gas (GHG) emissions, being responsible for 5.5–6.4% of global methane (CH_4) emissions annually [56]. The CE uses the waste hierarchy system to deal with waste management (EU Directive 2008/98/EC). The hierarchy prioritizes handling waste by (1) prevention, (2) preparation for reuse, (3) recycling, (4) energy recovery, and (5) disposal. This strategy helps promote environmental preservation and returns valuable materials to the economy [57]. On the other hand, the first principle of GC is waste minimization, with consideration to each of the three main stages of a material's life, namely production, use, and disposal. While GC emphasizes how waste needs to be prevented at the production stage, there are effective interventions that can be performed at the usage and disposal stages. In this framework, a useful tool is the product life cycle analysis (LCA), which can be used to assess the environmental impacts of a new product from its raw material sourcing (residual feedstock) up to its end-of-life disposal. The application of the LCA can help monitor the progress of the circular economy and green chemistry intervention by providing a comprehensive view of the lifecycle of innovative products, identifying a product's hotspots and by providing strategies for closing the loop and reducing waste. For example, the LCA of new products may reveal that the packaging is the most significant contributor to its environmental impact and this information can further inform the development of more sustainable packaging solutions, such as biodegradable or compostable packaging. Overall, a LCA provides a comprehensive view of a product's environmental impact and provides information for the development of more sustainable solutions within a circular economy and green chemistry context.

2.1.2. Waste Management–Production Stage (Chemical Synthesis Techniques)

From being a major contributor to waste production, solvents and auxiliaries frequently pose health and environmental risks. Using safer chemicals still stands as a core pillar of GC [58]. Principle five of GC considers two main options: the search for synthesis techniques that minimize the use of solvents or do not require them (mechanochemistry), and the replacement of dangerous solvents with safe solvents, such as water, supercritical carbon dioxide, or benign solvents, which are specially created for a particular procedure [59,60]. In 1992, Roger Sheldon first proposed the idea of the E-Factor, or environmental impact factor. This measure aids in calculating the waste produced per kilogram of a product. A prominent and early example of this is the synthesis of ethylene oxide, which was made via a chlorohydrin intermediate. The E-Factor for the entire synthesis was calculated as five, meaning that for every kilogram of the product, 5 kg of waste was to be disposed. This value ignores wastewater that has been contaminated with chlorine by-products, hence the E-Factor is likely to be higher. By swapping chlorine with molecular oxygen in the synthetic procedure, the E-Factor decreased to 0.3 (0.3 kg of waste per 1 kg of product). The formation of wastewater was also eliminated as the non-chlorinated alternative method produced ~16 times less waste than the traditional method. Since then, numerous publications by green chemists' have reported instances where novel procedures or products have allowed many synthetic methods to be compliant with the aspects of sustainability. Of wide interest is the use of water, a benign solvent, which is risk-free and safe from hazards. It can be an effective solvent for large-scale chemical processing. Due to the hydrophobic effect and the fact that many organic compounds do not dissolve in water, the characteristics of water have even improved reaction speeds [61]. However, water is not a universal solvent, and other alternatives need to be considered [62]. Supercritical fluids (SCFs) are an option for conventional (mostly toxic) organic solvents. SCFs are substances that can co-exist as both a gas and liquid above a certain temperature and due to this, they exhibit properties that are desirable for solvents [63]. The toxic organic solvents, which are traditionally used for the decaffeination of green coffee beans, and the perchloroethylene used in dry cleaning have now been replaced by supercritical CO_2. This strategy has resulted in reduced waste generation and cost-effectiveness, since large amounts of solvents were required for the conventional processes [64].

Beyond laboratory research, eliminating waste at the production stage using GC is a widely utilized technique in the industry. The GC approach has brought positive results, as demonstrated by several examples. The varnish and paint industry is already producing solvent-free paints and lacquers. The detractor industry has eliminated all phosphorus-containing detergents [65]. Recently, a non-toxic, vegetable-based hair dye called "Hairprint" from the Warner Babcock Institute for Green Chemistry has been created as an alternative to the poisonous, skin-irritating, and carcinogenic colors [66]. Companies, such as Merck, BMS, and Solutia, among others, have demonstrated how safer chemicals or procedures have aided them in more sustainable manufacturing, which lessens the amount of waste generated, but more so can have the impact of improving the yields of synthetic products. This, in turn, leads to greater economic viability of operations. Elevance CleanTM 1200 is a volatile organic compound (VOC)-free bio-based solvent that is another powerful, environmentally friendly degreasing solvent created by Elevance Renewable Sciences. For its exceptional cleaning capabilities, Elevance CleanTM 1200 won the bio-based product innovation of the year award at the 2015 WBM bio business awards. This non-flammable solvent complies with the numerous stringent environmental laws as it is made from natural oils. The company has since then ventured into personal care products, coatings, and surfactants, which are formulated from non-toxic sources with a smaller environmental footprint [67]. The above practical examples allude that GC aims to lessen, and possibly eliminate, the risk of waste rather than restricting it by regulating exposure to dangerous substances.

2.1.3. Waste Management–Usage Stage (Recycling)

A popular strategy of waste handling at the usage stage is recycling. Several materials successfully undergo recycling, but recycling is particularly important for plastics, since they are a major component of solid waste, being not biodegradable and taking more than a thousand years to degrade into the soil. Moreover, if burned, some plastics are toxic. Therefore, it is essential to recycle them as much as possible. The four ways of recycling plastics are primary, secondary, tertiary, and quaternary. Primary and secondary recycling typically follow a closed-loop system, where mechanical means are used to shred existing material and the pelletized form is remolded to produce the same material again. Quaternary recycling involves the incineration of "hard to recycle" materials, which are usually contaminated and not adequate for primary and secondary recycling. Recovery of energy from incineration is recommended [68]. Although primary and secondary recycling are the current conventional forms of preserving plastic material in circulation, their closed-loop nature limits their potential for creating a sustainable economic value of the process. Additionally, the continued mechanical processing of plastic reduces its robustness with time, hence a material cannot be recycled forever [69]. At the moment, tertiary recycling, namely the process by which a waste plastic material is converted into chemicals and fuels, is on the rise. This aspect of recycling is gaining increased attention worldwide and is often referred to as "chemical recycling" [70].

Chemical recycling is a universal term that describes the breakdown of plastic into its original monomers, sub-polymer fragments, or other small species using heat or chemicals. As the products formed are precursor materials, these can be useful in a myriad of applications, either to re-form the plastic again or to make other polymers for different products [71]. In chemical degradation, the breakdown process can be assisted by GC-derived techniques, such as glycolysis, hydrolysis, methanolysis, and aminolysis, where certain solvents are employed to "cleave" bonds between monomers, thereby fragmenting them. This can be regarded as the reverse of condensation-type reactions. Unfortunately, due to the nature of the chemical recycling process, not all polymers can be recycled in such a way. Only materials that are initially formed through condensation reactions (such as polyesters, polyamides, or polyurethanes) can be chemically depolymerized [72]. However, since most thermosetting plastics, which make up ~87% of the plastics in circulation, are formed from addition polymerization (the opposite of condensation), the technique of using solvents is currently limited in its application [73]. However, it should be noted that polymers from addition polymerization can be broken down using gasification, pyrolysis, and thermal cracking, where heat and/or mechanical force are used.

Despite these limits, there is huge potential for chemical recycling as a tool for sustainability. The most easy-to-handle plastics are polyethylene terephthalate (PET) and high-density polyethylene (HDPE). PET is regarded as one of the most recycled plastics by volume, globally. Although PET can be recycled through primary or secondary means, there are some drawbacks. Firstly, the PET needs to be clean enough or considered as pure waste for suitability in the extrusion and melt-recovery process. This is considered a hurdle, due to inconsistencies in consumer-led waste separation and cleaning before discarding or sorting at the municipal waste management level [74]. Another significant problem with the recycling of PET by the re-extrusion method is that the mechanical properties of the recycled material are greatly reduced with each reuse [75]. For these reasons, chemical recycling emerges as a more attractive route to manage PET waste and the extension of such technologies should be amplified in industry.

There are few companies implementing chemical recycling technologies at a commercial scale. A prominent example is a patented technology by the start-up "Worn Again Technologies", which recycles PET into pellets. During the process, benzaldehyde, benzyl acetate, benzyl benzoate, or other suitable solvents are used to dissolve the polyesters in a solvent system, followed by the chilling of the solvent system and precipitation before filtration to separate the materials. After separation, the plastic is washed, dried, and molded into pellets and/or converted into fibers. Cotton textiles, post-consumer PET bottles, and PET-containing plastic containers can all be processed using this method. Worn Again has also partnered with companies such as Himes and Kering to promote the reduction of textile waste [76]. In Germany, to create polyamides and polyesters from multilayer plastic post-industrial waste, APK AG is demonstrating its new cycling method on a plant that can produce 8000 tons of recycled materials annually. The technology dissolves plastic using a mixture of solvents from a group of cycloalkanes, alkanes, or isooctane [77]. Additionally, CreaSolv, a solvent-based procedure developed by The Fraunhofer Institute, creates plastics with qualities similar to those of virgin materials, while successfully eliminating the impurities and additives [78].

Solvent selection for plastic mixes, which are common in actual plastic waste, remains a challenge in chemical recycling. Two or more plastics are often combined to form multicomponent polymeric materials, with each plastic chosen based on its useful properties. For example, the multilayer plastic films used to make food packaging boxes are extremely difficult to recycle due to their intricate compositions and the incompatibility of their various polymer layers. Additionally, the inherent contaminant nature of colored PET deters its suitability to undergo chemical recycling [79]. To address this challenge, innovations such as STRAP have been developed to generate solvent systems for recycling multilayer polymers through selective dissolution. STRAP includes experimentation, computer modelling, and process design tools to achieve its desired targets. Selective dissolution ultimately enables the separation of different plastics and is tolerant to the additives and impurities present in waste (https://polyloop.fr/strap-recycling/?lang=en, accessed on 11 January 2023). Techno-economic analysis shows that selective dissolution can produce plastics at costs similar to virgin resins, making the process economically viable [80].

Although chemical recycling is currently controversial and is a widely debated topic in the CE community, there is increased awareness of its benefits, as acknowledged by evidence-based research [81].

2.1.4. Waste Management–Disposal Stage (Waste to Energy and Value-Added Products)

The combined GC and CE approach to handling waste and avoiding landfilling or incineration mainly involves the prevention of waste by using it as a resource. As far as biowaste is concerned, the concept of waste to energy is simpler to apply than reusing or recycling, thus biowaste is a commonly used feedstock for recovering bioenergy. Biowaste is biodegradable and transformable waste, which is primarily produced from industrial and agricultural processes, or from residential activities that become municipal waste [82]. Bioconversion is a critical step in dealing with the rising demand for raw materials, manufacturing costs, environmental pollution, and waste management [83]. Over time, the focus on waste management has shifted to the circular economy notion, in which resources, energy, and materials are continuously recycled [84]. The development of biorefineries, which turn biowaste into bioenergy and high-value chemicals, has been encouraged in response to the pressures of environmental depletion and resource scarcity [85], and is considered an important step toward implementing a successful circular bioeconomy [86].

Research has shown that biowaste produces high-value materials, such as biohydrogen, biogas, and biohythane, which could help with the current energy crisis, and, consequently, with emissions reduction [87]. Given that the only by-product of hydrogen combustion is water, it is one of the cleanest and pollution-free fuels available today [88]. As a result, hydrogen is essential for the advancement of low-carbon economies and technology, as it is projected to play a dominant role within the global energy landscape [89]. A range of biotechnologies are used to create biohydrogen, including light-dependent processes, such as photo-fermentation and bio-photolysis, as well as light-independent ones, such as dark fermentation and microbial electrolysis cells [90]. Equally clean as renewable sources of energy, biogas can be produced from food waste, manure, straw, or sewage, through the Anaerobic Digestion (AD) process [91]. AD is regarded as one of the most cost-effective biological treatments for biowaste treatment. It lessens the environmental effects of waste disposal, while enabling energy recovery and the production of nutrient-rich digestate materials [92]. AD converts organic waste into biogas that is used in combined heat and power (CHP) units for the production of heat and electricity, while the digestate by-product is used as a biofertilizer on agricultural lands [93]. The EU has seen a rise in the number of AD plants, from 244 plants in 2010 to 688 in 2016 [94]. Recently, there has been a shift toward small-scale AD plants because they have several advantages over the traditional centralized management system, including fewer transportation needs, a higher community involvement, and the chance to build regional nutrient and energy loops. Anaerobic digestion can also result in the production of biohythane, which is composed of gases similar to those found in biogas, but in different ratios, consisting of 5–10% H_2, 50–60% CH_4, and 35–45% CO_2 [95]. Biohythane considerably increases the efficiency of traditional compression ignition engines and noticeably reduces the emissions of hydrocarbons and nitrogen oxides [96].

Together with waste to energy technologies, the minimization of waste can be achieved by employing biowaste conversion into value added products [97]. Examples reported in the literature include fermentation processes, where solid biowaste can be converted into bio-based products, such as biobutanol, biodiesel, citric acid, ethanol, hydrogen, and lactic acid. Lactic acid (LA) can act as the source of numerous different molecules, which makes it a versatile organic acid. LA is one of the US Department of Energy's "Top Value-Added chemicals from Biomass", due to its importance in the bio-based industry [98]. The manufacture of polylactic acid (PLA), a biopolymer with characteristics similar to those of polyester, has sparked attention, and, in 2018, the PLA segment accounted for 28.3% of the revenue generated by the LA market as a whole. According to recent projections, the market value of LA is expected to increase from USD 2.64 billion in 2018 to over USD 9 billion by 2025 [98]. Recent developments in nanotechnology have allowed researchers to transform liquid, solid, and even gaseous biomass waste into either value-added materials or products with minimum adverse effects [99]. Biomass-derived carbon nanomaterials are widely used for the manufacture of batteries, fuel cells, electro-catalysis, water purification, etc. [100]. For example, nanomaterials can be utilized as electrode modification materials in electrochemical sensors. The synthesis of these materials using plant-based methods has been evidenced using green chemistry technology and is much regarded as a less hazardous route to their manufacture [101]. Moreover, the synthesis of novel biowaste-derived carbon nanomaterials (e.g., graphene quantum dots, carbon nanotubes, and graphene) is widely explored due to their sustainable and cost-effective production on a large-scale [102].

Overall, the various biorefinery techniques that have emerged so far have demonstrated to be sustainable methods for integrated bioproducts, such as biochemicals, biopolymers, bioplastics, biofuels, and biofertilizers that are further used for commercial, agricultural, and industrial applications [103]. The global market value of biowaste-to-energy technology is approximately USD 25.32 billion and is expected to increase to USD 40 billion in 2023 [104].

2.1.5. Utilizing Minimum Energy Requirements

Energy that is not used in a synthetic or manufacturing process can likewise be viewed as waste. It is highly desirable to develop chemical processes or systems that consume minimal energy. An example of what green chemists have accomplished to reduce energetic requirements is to lower the energy barrier of a chemical reaction or select suitable reactants, so that the transformation can happen at room temperature, with all the direct and indirect benefits associated with it [30]. The reduction of energy requirements is achieved by employing catalysts, so that a process can be carried out at lower temperatures and pressures. With new catalytic reactions and catalyst types, catalysis offers a range of advantages in terms of process utilization, selectivity, the use of alternative reaction media, and, most importantly, energy savings [105]. An alternative to catalysis is microwave-assisted organic synthesis, which has developed rapidly since the 1980s. The use of microwave energy allows for the reduced energy requirement from conventional fossil fuel-based sources. To increase reproducibility, researchers increasingly employ specialized commercial equipment that measures and regulates the power input, temperature, and pressure [106]. Energy savings, when compared to conventional heating, rely on how well electric energy is converted to microwave energy, as well as on the reactor's properties, the volume of the reaction mixture, and the reaction component's capability to absorb microwave energy. However, the use of microwave heating remains rather unexplored on an industrial scale [107].

Increasing a chemical system's energy efficiency is just one aspect of the solution. Alternative forms of energy are also required. A myriad of sustainable fuels is suitable for powering industrial plants, which target the reduction of carbon-based energy sources [108]. Biofuels, solar energy, wind, hydropower, geothermal energy, and hydrogen fuel cells are a few of these examples. Although the status quo has not currently made use of most of these alternative energies, due to their low capacity and economic non-viability, they are expected to have huge potential in the next decade to power industries [109]. As such, green chemists will play a crucial role in addressing this challenge. One way of doing this is by understanding and developing chemical systems that can transform solar radiation into voltaic energy [110]. Although interest has been shown in organic, inorganic, and hybrid solar cells, organic solar cells have attracted the most attention due to their higher efficiency. The development of materials and polymers that can effectively convert light into current is still a difficult task, but it is essential for the success of this strategy. Another option for addressing the impending rise in energy demands would be proton-exchange membrane (PEM) fuel cells that use hydrogen and oxygen gases. By splitting water, hydrogen is formed and can be used as an energy carrier. A key point is to ensure the that hydrogen utilized is green hydrogen, produced from non-carbon-emitting renewable resources [111].

Another example of GC supporting the reduction of energy requirements comes from the textile industry, which is a key contributor to both water contamination and usage. According to a shocking document published in 2017 titled the Ellen MacArthur Foundation New Textiles Economy report, ca. 50 L of water is required to dye a kilogram of material when using conventional dyeing methods. Drying the dyed material also uses up a lot of energy. To circumvent this energy-intensive practice, supercritical carbon dioxide was discovered by a Dutch start-up (DyeCoo) as an alternative solvent, introducing water-free dyeing. By eliminating the water in this process, less energy is needed for drying, rendering the new process energy economical [112].

2.1.6. Use of Renewable Feedstocks

The use of renewable feedstock is regarded as sustainable as the industrial overuse of finite natural mineral resources is leading to their depletion. Nature generates 180 billion metric tons of renewable biomass each year, but only approximately 4% is currently used by humans. It consists of about 75% carbohydrates, 20% lignin, and the remaining portion is made up of lipids, proteins, and terpenes [113]. The chemical transformations of mono and disaccharides, the reactions of oils, fatty acids, and terpenes, as well as the chemistry of glucose fermentation products, are all methods for turning biomass into usable commodities. The production of ethanol, lactic acid, surfactants, furfural, d-sorbitol sweetener, and medicines, such as penicillin, are the main non-food uses of carbohydrates. It is possible to crosslink defatted soy flour, a cheap commercial product that is mostly made of soy protein and carbs, and use it in biodegradable composite materials with plant fibers, such as flax, hemp, or bamboo. The eco-friendly composites hold promise as a substitute for non-biodegradable composites, such as polypropylene or glass in the construction industry [114,115]. To duplicate the adhesive proteins found in mussels, soy flour has been chemically modified; the resulting product has been commercialized as a wood glue, taking the place of hazardous urea-formaldehyde resins that are often used in plywood and particleboard [116,117].

As most renewable raw materials or feedstock are plant-based, adapting to them is challenging. To avoid burdening the food production sector with the production of feedstock for industrial uses, numerous studies in green chemistry suggest the use of agricultural and food wastes as raw materials for a range of industrial processes. This option is economically advantageous and reduces competition with food production. In addition, using waste helps to prevent pollution and waste management problems [11,118]. Cellulose, lignin, suberin, and other wood components, as well as lactic acid, chitin, starch, glycerol, and oil, are examples of renewable materials. For instance, lignin is a significant waste product of the pulp and paper sector. It has long been burnt as a fuel at industrial sites. Recently, it has been discovered to have use in producing items such as dispersants, additives, and raw materials, for the manufacturing of other compounds, such as vanillin or humic acid [119,120]. Another prevalent natural polymer, which makes up the exoskeleton of arthropods, is chitin (e.g., crustaceans). It is a significant by-product of the seafood industry and can undergo a chemical process, known as deacetylation, to form chitosan. Chitosan has been used for a wide range of industrial purposes, including water filtration and biomedical applications. It should be possible to replace the current petroleum feedstock with a significant number of raw materials by recycling this bioindustrial waste [121].

Research today is mostly focused on creating biodegradable plastics from renewable resources. The production of bioplastics is seen as a more sustainable alternative to traditional petroleum-based plastics, which have a significant impact on the environment. Bioplastics have been designed, in particular, to be biodegradable and compostable, reducing the amount of waste that goes into landfills and the ocean. In addition, the utilization of renewable raw materials in the production of bioplastics has a positive impact on energy use and CO_2 emissions [122].

The American business NatureWorks was founded in the late 1980s on the premise of making bottles made from lactic acid polymers, the lactic acid derived from the fermentation of dextrose generated from starch, most typically corn. The company has expanded to include the manufacturing of raw materials for 3D printing, clothing, cleaning wipes, trash bags, and toys [123]. The popular brand Coca-Cola created the first recyclable bottle made of 30% polyethylene blends, where the ethylene is derived from plant sources and not petroleum products. In 2021, a decade later, the company debuted a 100% plant-based bottle, made of corn-derived b-terephthalic acid [124]. To replace polyols made from petroleum, BioBased Technologies (previously Cargill) created a commercial technology for turning vegetable oils into polyols. The moderate process conditions also reduce the reliance on non-renewable feedstocks and save energy [125]. These are some examples showing how bioplastics are increasingly becoming part of our everyday life, but many improvements are still needed. Despite the benefits of bioplastics, they still have to face some environmental challenges, such as high production costs, limited availability of raw materials, and the management of bioplastics waste [126]. To overcome these issues, researchers and scientists have been exploring new sources of raw materials that can be used to produce bioplastics such as algae, cellulose, microbes, and food waste, through bioconversion processes to create a more sustainable future for the plastic industry. Additionally, in the food business, biodegradable packaging has a bright future, though its evolution is influenced by a wide range of variables, including politics, legal changes, and the increased worldwide need for food and energy resources.

A step further from utilizing renewable feedstocks for product formation, biocatalysis has shown to be a significant green chemistry-related technology that aids sustainable manufacturing. Biocatalysis makes use of enzymes, the natural catalysts, which are not only simple to manufacture but also biodegradable and renewable [127]. More and more businesses are focusing on creating and utilizing enzymes as biocatalysts to meet sustainability goals. The 2003-founded California start-up "Newlight Technologies" received USD 9.2 million in funding to develop a carbon-negative technology that creates AircarbonTM (a thermoplastic), by mixing air and methane emissions. About 40% of AircarbonTM is oxygen from the air, and 60% of it is carbon and hydrogen from methane emissions. The technology itself was nothing new, but Newlight Technologies' use of a unique biocatalyst increased the yield by nine times and cut the cost by a factor of three, making AircarbonTM more affordable than plastics generated from oil. Following its commercial scale-up in 2013, AircarbonTM was used for product manufacturing by several well-known companies, including Dell, IKEA, Sprint, and Vinmar [128].

2.2. How Do We Move from Theory to Practice?

While the principles of GC have aided the process of optimization for linear processes since the 1980s, the framework of GC alone no longer fits the status quo of the need for ensuring *true* sustainability. The work by Keijer et al. [129] provided an excellent commentary on the differences between GC and what they term circular chemistry (CC), the latter being a direct interlinking of the GC approach and the CE framework. The authors postulated a new set of guiding principles that hopefully can allow a more holistic consideration when designing processes or products. According to the 12 principles of GC, the key takeaway points are that waste should be prevented, products should be manufactured in a way that allows them to be degraded, safer synthesis materials and chemicals should be produced, and renewability, from an energy source and feedstock point of view, should be incorporated. Going beyond that, CC proposes that waste should not only be prevented at the production stage, but it must be used as a resource and ultimately a "renewable feedstock". This subject has been highlighted earlier and fits well with the CE agenda. In addition, the new framework of CC requires due diligence when evaluating the nature of certain bio-based catalysts, which are purported as "green" in their action, yet the catalysts themselves may be manufactured using linear processes. Lastly, one of GCs principles is manufacturing products that are designed for degradability. The CE, on the other hand, values ensuring the longevity of a material by keeping it in circulation for a long time whilst maintaining its stability. CC considers the raw materials (chemicals) and energy stored in a material as long-term investment. Therefore, by promoting the reusability of a product, CC conserves the stored energy rather than requiring additional input. Ultimately, the principles of CC, as influenced by the circular economy, lie in considering not only the environmental viability, but economic gains too. At best, green chemistry serves as a transition to fulfilling a circular economy and the concept of "circular chemistry" should be emphasized when moving forward.

3. Policy and Structural Issues Related to CE and GC Integration and Adoption

The concept of the circular economy is receiving an increase in visibility and awareness through its incorporation in discussion forums at workshops, international events, and initiatives on trade opportunities that are linked to recycling and waste management. Unfortunately, the concept is still misrepresented, as its ideas are often reduced to mere recycling and waste management, which is not representative of its innovative new product design with the incorporation of green chemistry. From an international trade context, the circular economy is much more than the trade-in of recycled goods and waste management, rather it is tackling the fundamentals that create and maintain value in the economic system through innovation aided by green chemistry. The opportunity to debunk these misconceptions is seldom allowed in public discourse or otherwise not deemed a priority. The role of governments in promoting a circular economy should be adopted toward supporting the rethinking and shifting away from market failure fixers toward being market shapers who set the tone and direction of economic growth and social equity. The scale and complexity of our societal problems require global coordination and collaboration and a global platform for reflection. At their core, the circular economy, green chemistry, and any other innovation should be models where growth is achieved through reduced consumption and sustainability is appropriately achieved through material substitution, cleaner production, or offsets.

Product Service Systems (PSSs) and waste management (WM) value chains may be appealing business models for stakeholders within the circular economy [130]. The PSS is an integrated combination of products and services, and feasibility is the normal stakeholder requirement for business. Waste plans are governed by laws, policies, rules, local conditions, agreements, and stakeholders, which have specific prerequisites and regional bounds [131]. Subsequently, viable regional PSSs are unique. Importantly, WMs practical actions have been founded on the rising knowledge and the steady formation of public opinion in favor of measures that encourage reuse and recycling [132]. It has also been required to restructure society, which includes changing national norms and laws as well as providing incentives and motivation through financial support for investments and other obligations, for a successful circular economy promotion and implementation [133]. Palmer and Truong [134] report that GC initiatives can be profitable in the long term. According to the available data, between 2012 and 2017, US facilities reported 2226 GC activities for 147 Toxics Release Inventory (TRI) chemicals and chemical categories. Most GC activities were reported by the chemical production, fabricated metals, computer, and electronics industries [135]. As per the projections, the US market for chemical end-use products would grow from USD 149.9 billion in 2016 to USD 884.1 billion in 2026 [136]. According to a recent study, GC has gone global, and when bio-based and renewable products replace conventional products and offer new revenue sources to businesses and local economies, the global chemical industry will increase to more than USD 1.5 trillion annually [137].

Due to cost savings, regulations, and consumer demands, GC has experienced substantial expansion. However, this growth remains slow and uneven as large companies in developed markets have implemented GC strategies, but smaller companies in developing countries still have a long way to GC implications [136]. There is a two-way link between businesses and consumers, and businesses' attitudes toward sustainability may have an impact on how their clients and investors behave [138]. Consumer product companies have benefited greatly from the increased consumer awareness and demand for green products. For some industries, including the pharmaceutical sector, cost reductions from GC have taken the number one spot as a motivator [139].

Even though GC has experienced a rapid expansion in recent years, implementation nuances remain between various worldwide marketplaces and even amongst businesses that are operating within the same industry. Despite its potential for cost savings, GC still necessitates initial expenditures and a transition away from extremely capital-intensive infrastructures [140]. According to US rules, manufacturers are required to re-certify with the Food and Drug Administration (FDA) whenever they alter their production methods. Since this procedure is both expensive and time-consuming, it serves to deter businesses from making the necessary investments to create waste-reducing, atom-efficient chemistry [107]. Since most industries are driven by financial gains, the voluntary adoption of sustainable practices seems less likely. To impose greener behaviors, a powerful, appealing, and balanced regulation is needed. The REACH (Registration, Evaluation, Authorization, and Restriction of Chemical Substances), developed and introduced by the European Union in 2007, is the most promising and significant regulation. On the one hand, REACH requires chemical companies to disclose more information about the risks that their products pose to the environment and human health; on the other hand, it offers the possibility of registration exemptions for a process that supports new, sustainable innovation for five years. To establish a sustainable chemical industry, other nations have been inspired by the European Union to develop rules along similar lines [141].

Green chemistry education is also another factor that may dampen the progress of wider GC and CE adoption in industry. Despite initiatives such as "beyondbenign" to enhance GC teaching (https://www.beyondbenign.org/, accessed on 11 January 2023), the majority of chemistry departments worldwide do not include GC in their curricula, which results in a lack of knowledge about the methods and approaches that are now available [29]. It takes an understanding of green engineering, biotechnology, economics, and, most importantly, toxicity to create a successful green process. The lack of training in these fields among chemists generally makes it more difficult to use green chemistry on an industrial scale [142].

The lack of green solutions remains a point of concern for some processes. The complexity of supply chains, resistance to change, perception of green products being more expensive and less effective, and the technical difficulties in identifying greener technologies and materials are some of the major obstacles reported by researchers [143]. If a green technique is not economically appealing, it may still be rejected on a large scale even if all other criteria are in its favor. An example is the work of Martyn Poliakoff from Nottingham University, who developed an innovative approach to employ supercritical CO_2 as a solvent in what at that time was the first continuous flow reactor of this nature [144]. The process was implemented by Thomas Swan and Company, UK. Without any by-product production, the system resulted in the removal of an expensive and energy-intensive separation that the traditional technique required. The factory, however, was unable to offer chemicals at a lower cost than those produced using conventional non-green processes because of the lack of government subsidies. So, after operating commercially from 2002 to 2009, this plant's production was stopped [145]. Focusing on the supply chain dynamics, it is advised that the extensive and international supply chain must undergo several modifications because of the commercialization of green processes. However, such alterations come at a price. For instance, a BPA-free (bisphenol-A-free) covering for food packaging created by Eden Organic Foods was found to be compatible with some foods, such as beans, but not with extremely acidic tomato sauce. To ensure the compatibility of all product types, there is a need to change the coating types for various food types. This unfortunately suggests a smaller market and a change in manufacturing equipment, both of which would raise the cost of production, eventually affecting market price [107].

The above alludes to the fact that an environmentally friendly technique does not guarantee financial success. The industrial use of green processes is frequently hampered by regulatory, economic, political, and technical issues.

4. Conclusions

The circularity of products plays a vital role in the sustainability of the environment. The circular economy focuses on using the product for as long as possible. The use of chemicals is a key driving force toward product development or manufacturing processes. Hence, advancements in chemistry, where the enhancement of chemical designs to achieve an increase in lifespan along with reduced toxicity in a product, should be prioritized. In consideration of the relationship between chemicals and circularity, green chemistry provides a foundation for secure and lasting circular economy practices. With the implementation of green chemistry and circular economy practices, countries can use their resources to their maximum potential with less input in raw material procurements and waste management costs, as well as limiting the rate of depletion of non-renewable resources. GC–CE implementations are not only important for developed countries, but are even more important for developing countries. Developing countries are facing waste management issues and most of their industries are still using linear waste management techniques, which puts pressure on already failing economies. As per the international monetary fund (IMF) world economic output report of 2022, the global economy will likely shrink by one-third by 2023 and will worsen by 2024. Economic growth in the USA is estimated to drop from 5.7 in 2021 to 1.0 in 2023, and in the European area from 5.2 in 2021 to 0.5 in 2023 [146]. During this phase of extreme global economic recession, there is an opportunity presented for adopting GC–CE principles to help sustain vibrant economies. This could be in the form of saving costs for raw material procurement, transportation cost, waste management, and storage costs, along with providing job opportunities for workers in GC–CE-related industries. With the successful adaptation of green chemistry, which is tightly linked with a circular economy approach, the rising issue of waste management is likely to be resolved. In addition, the resource, labor, and energy burden of the disposal of waste will lessen, resulting in a decrease in carbon footprint and health issues caused by waste emissions in the environment.

The main obstacles to achieving a circular economy are investment, environmental education, and legislation. Investing in new technologies and processes for the circular economy is necessary, but it can be difficult to justify the initial costs without clear benefits. Environmental education is important in promoting the circular economy and green chemistry, but it is not widespread enough to reach everyone who needs it. Legislation is needed to support the circular economy, but it can be slow to change, and not all countries have the same level of commitment to the cause. To advance toward the circular economy and green chemistry, international agreements should be reconsidered to provide a framework for investment, education, and legislation. This could include the creation of incentives for businesses and individuals to adopt circular practices, the establishment of education programs to promote the benefits of circular practices, and the development of regulations to support the transition to a circular economy.

In developed countries, there is much awareness of the current environmental crisis, which is likely to increase exponentially over the next few years. However, in developing countries, awareness is comparably very low, especially of the fact that natural resources are depleting and that they should not be over-exploited. Populace ignorance then leads to the over-exploitation of already vulnerable resources. Governments and policy-makers should not only introduce policies for firms and industries, but should also largely invest in education and information dissemination means regarding the best environmental practices. Additionally, countries in the developing world should prioritize local innovations that promote GC–CE whilst providing financial support for such projects, as for many change agents finances remain a major impediment even in developed countries. There should be funding extended to academia, allowing researchers in tertiary institutions to research solutions that are based on GC–CE principles. To ensure a sustainable future and mitigate the effects of climate change, the integration of a circular economy and green chemistry approaches can potentially make sustainable ambitions, such as GHG emissions reductions, possible.

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