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CIRCULAR CHEMISTRY

Adapting linear chemistry to mitigate the climate crisis

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In this article we explore the imperative shift from a linear economic model to a circular one, with a particular focus on the pivotal role of chemistry in this transition. It elucidates the critical global challenges stemming from unsustainable resource extraction and the linear «take-make-dispose» approach, including climate change, resource depletion, and biodiversity loss. Circular chemistry emerges as a promising solution, guided by principles of green chemistry and circular economy. It advocates for perpetual material cycles, emphasizing sustainable end-of-life strategies and product design that prioritizes reuse and recycling. We underscore the need for chemistry to prioritize efficiency, safety, and circularity, while also addressing challenges associated with complex waste streams and the responsible mineralization of chemicals. Achieving circular chemistry necessitates cooperation among individuals, educational and scientific institutions, industries, and regulatory bodies, and as such it can significantly contribute to mitigating global environmental crises by establishing sustainable material circulation as a cornerstone principle.

Keywords: **circular chemistry**, **sustainability**, **environmental crises**, **planetary boundaries**, **circular economy**.

Over the past decades, awareness of the finite nature of the many resources modern life relies on has grown. While at the same time, the negative environmental and social consequences of extraction have become increasingly obvious. Faced with several global crises, including climate change, energy, and resource scarcity, as well as decreasing biodiversity, it can only be concluded that the currently dominant, linear «take-make-dispose» production routes are not sustainable. For the past 50 years humanity's demand on ecological resources per year has exceeded those generated by the planet in the same year. Furthermore, the margin by which demand exceeds supply has been continually increasing, resulting in earth overshoot day– the date on which the annual demand for resources exceeds the planet's regenerative capacity for the year– occurring earlier each year (Earth Overshoot Day, 2023). Chemical manufacturing processes contribute heavily to this. With the mounting consumption of resources and production of chemical waste, both during and after production, directly contributing to adverse human and environmental health effects (Persson et al., 2022).

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In this reflection article we highlight circular chemistry as a key concept, elaborating on this

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alternative approach to traditional chemistry, and the opportunity it provides to address many of the interconnected global crises. In fact, we strongly believe circular chemistry is essential to mitigating the climate crisis. As chemistry is the enabling technology for the linear economy, circular chemistry and circular technologies are now needed to realize the more sustainable circular economy. This requires an expansion in the scope of sustainability to include considerations beyond process optimization to the entire lifecycle of products and services (Keijer et al., 2019). Additionally, regarding by-products and waste as resources, and focusing chemical design on the anticipation and avoidance of future problems are both prerequisites for circular chemistry. This requires a shift away from the traditional approach and towards systems thinking guided by an understanding of the molecular basis of sustainability (Mahaffy et al., 2019).

INTERCONNECTED PLANETARY CRISES

Since industrialisation, human activities have had an immense impact on the natural environment of the planet. Among other deviations, increasing greenhouse gas emissions, resource extraction and land use change are contributing to climate change. Given its ability to single handedly alter earth systems and their processes, dramatically altering life on earth for all living beings, the climate crisis is perhaps the most urgent of the interconnected crises being faced today. Mostly driven by social and economic systems based on unsustainable resource extraction and consumption, human activities contribute to both the problem and the potential solutions (Rockström et al., 2023).

In an attempt to define a safe operating space for humanity within which the destabilisation of the earth system can be avoided, the concept of *planetary boundaries* was developed (Richardson et al., 2023, Rockström et al., 2009, 2023; Steffen et al., 2015). Nine boundaries, including climate change, biogeochemical flows, freshwater use, ocean acidification and novel entities (chemicals and other types of man-made materials) were defined. Many of the control variables of these boundaries require the measurement or transformation of chemical substances, highlighting the link between chemistry and the overarching earth systems governing the climate (Mahaffy et al., 2019). Examples of control variables include the concentration of carbon dioxide in the atmosphere, which is a control variable for the climate change boundary, and ocean surface carbonate ion concentrations, as a measure for ocean acidification (Mahaffy et al., 2019). Though all nine planetary boundaries are interconnected with each other to varying degrees, climate change has been identified as a priority boundary (Steffen et al. 2015). Furthermore, while exceeding any of the boundaries contributes to the destabilisation of the earth system, exceeding the climate change boundary alone is likely to push the earth out of the Holocene state into the Anthropocene (Rockström et al., 2023; Steffen et al., 2015).


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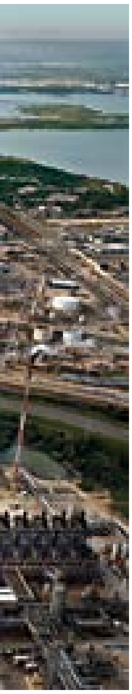
Figure 1. Environmental pollution is often the result of the lack of adequate end-of-life solutions for products used in modern life. Image of the petrochemical plant in Baytown, Texas, USA, taken by photographer Edward Burtynsky in 2019.

«Plastics often consist of one or more polymers and several additives to achieve the desired characteristics of the product, making them very difficult and potentially hazardous to recycle»

Through planetary cycles, materials connect many of the earths systems to each other. An example illustrating this is the planetary carbon cycle which connects ocean acidification, changes in biosphere integrity, climate changes and the chemistry of the carbon cycle. Which further, through climate change interacts with land-system change, change in biogeochemical flows and freshwater use (Mahaffy et al., 2019). The novel entities boundary, which includes chemical pollution,



plastics, novel biological materials and naturally occurring elements that have been mobilised through anthropogenic activities, further emphasises that the manipulation of matter contributes to the cycles of earth systems. Although measurement of chemical substances is central to the quantification of other planetary boundaries, the sheer volume of chemical substances makes this almost impossible for the novel entities boundary. This has led to the conclusion that this boundary is already far exceeded (Persson et al., 2022; Steffen et al., 2015). Additionally, there is a growing body of research directly linking chemical pollution to human illness related to environmental toxicants and decreasing wildlife populations (Persson et al., 2022). Environmental pollution is often the result of a lack of suitable end of life solutions for products used in modern life (Figure 1). This highlights a need to move away from production routes resulting in waste and towards product cycles that include end of use solutions in which resources never become waste or pollution.

WHY IS CHEMISTRY IMPORTANT?

Chemistry's leading role as the enabling technology in our current, linear economy highlights the role that it can also have in enabling the circular economy. As advocates of the circular economy, The Ellen MacArthur Foundation emphasise that avoiding a climate catastrophe and completing the already occurring energy transition is only possible through a circular economy. Neither the energy nor the materials transition is possible without taking dramatic steps away from linear «take-make-dispose» modes of production that rely on resource extraction. Continued and increasing demand on resources requires additional extraction with the attached negative environmental and social consequences. Furthermore, the additional greenhouse gas emissions released as a result, have the potential to threaten the entire purpose of the transitions. The circular economy and circular chemistry, address climate change by reducing emissions from industry, land-use and agriculture through the redesign of products and services (Ellen MacArthur Foundation, 2019).

OPTIMISATION OF THE LINEAR ECONOMY IS NOT ENOUGH

Over time chemists have become more aware of the potentially detrimental effects that the indispensable materials they design, and produce can have on both humans and the environment. This led to the introduction of Green Chemistry in the 1990s (Anastas and Warner, 1998). An approach to chemistry summarised by twelve guiding principles, that has since provided a framework for more sustainable practices as well as momentum for developing cleaner products and processes. The twelve principles of Green Chemistry (Figure 2) focus on a direct sustainability assessment of chemical reactions that is well suited to the optimisation of linear production routes (Keijer et al., 2019). However, alone these strategies do not go far enough to achieve circular economies and mitigate the many environmental crises.

Similarly, the recent focus in chemical synthesis on the use of renewable resources and reduction of waste in production often omits consideration of the full lifecycle environmental footprint (Galán-Martin et al., 2021). For example, the replacement of fossil-based starting materials in plastic production with biomass-based alternatives, as in the case of bioPE (biopolyethylene). In the production of bioPE, ethylene sourced from dehydrated bioethanol is used, which does not improve the recyclability or degradability of the product. Furthermore, a recent study showed that shifting from petroleum-based plastics to biobased plastics, without additional recycling, results in worsening biosphere integrity and biogeochemical nitrogen flows (Bachmann et al., 2023).

Circular chemistry through both its guiding principles (Figure 3), particularly principle 8, and the ladder of circularity or resource hierarchy, advocates for increasing prevalence of life cycle assessments and deeper consideration on the necessity of material use (Keijer et al., 2019). Highlighting that while approaches based on the principles of green chemistry may improve the sustainability of the linear «take-make-dispose» production routes, they do little towards closing product cycles and contributing towards a circular economy. In order to mitigate the climate crisis and combat earth overshoot day, chemistry needs to go beyond the optimisation of linear production routes. As long as production routes remain linear, the same issues at the product stage will persist, producing waste for which there is no adequate handling method.

CIRCULAR CHEMISTRY

With its foundations in green chemistry and the circular economy, circular chemistry seeks to be an alternative to the current «take-make-dispose» approach, contributing to the achievement of broader sustainability and aiding in the mitigation of the environmental crises. A circular economy is based on the reuse and regeneration of products, components and materials, keeping them at their highest utility

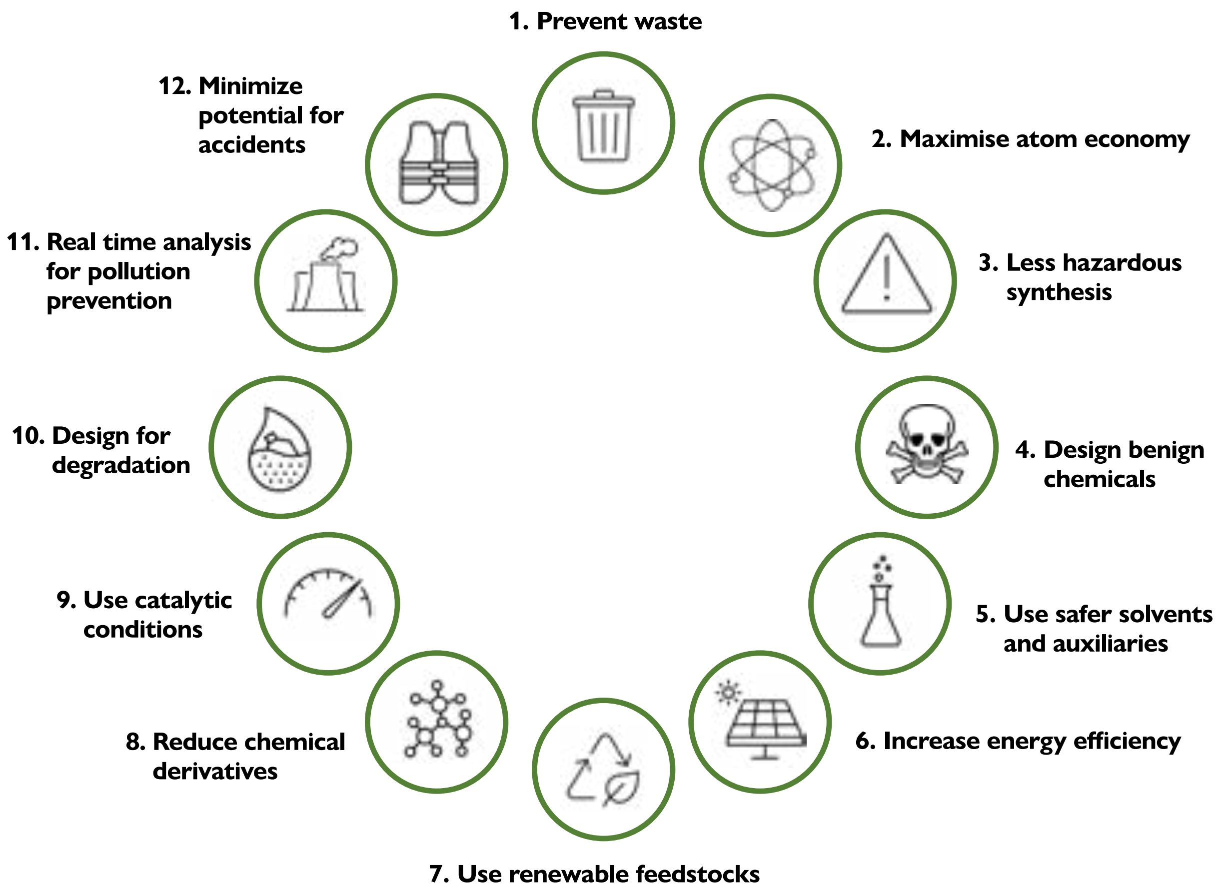


Figure 2. The 12 principles of green chemistry as elaborated by Anastas and Warner (1998), focusing on a direct assessment of chemical reaction sustainability.

and value for as long as possible. With their role in manipulating matter, chemists and chemistry are essential in achieving this.

Circular chemistry requires the adoption of processes that continuously cycle materials through value chains, creating endless loops of reuse mimicking natural cycles. This optimises resource efficiency while also preserving finite resources and eliminating waste. While this allows room for diversifying the resource base used in production, e.g. bio-based materials, unlike the current linear processes circular chemistry includes built in sustainable end of usage options for each product. These are essential to living within the earth's means. In addition, the circular chemistry approach includes the anticipation and avoidance of future problems through the inclusion of systems thinking and a broader definition of sustainability in which the molecular basis of sustainability plays a leading role (Mahaffy et al., 2019), highlighting the position of circular chemistry at the forefront of what is necessary to live within the earth's means for present and future generations.

DESIGN FOR REUSE AND RECYCLING IS ESSENTIAL

The twelve guiding principles of circular chemistry (Figure 3) were formulated to provide a framework analogous to that of green chemistry and to support the transition to the circular economy via circular chemistry. One of the central propositions and requirements of circular chemistry is to avoid waste completely by keeping products at high value. However, given the present linear modes of production a steppingstone to achieving complete recirculation of materials, products and resources, is the redirection of waste streams and their application as feedstocks. Ideally this results in the elimination of waste altogether. The replacement of single-use plastic bottles and packaging for beauty, personal care and home cleaning products with refillable designs and models could facilitate an 80–85 % reduction in greenhouse gas emissions from this sector alone (Ellen MacArthur Foundation, 2019).

The current waste problem should be addressed with circular strategies. One of the greatest limitations

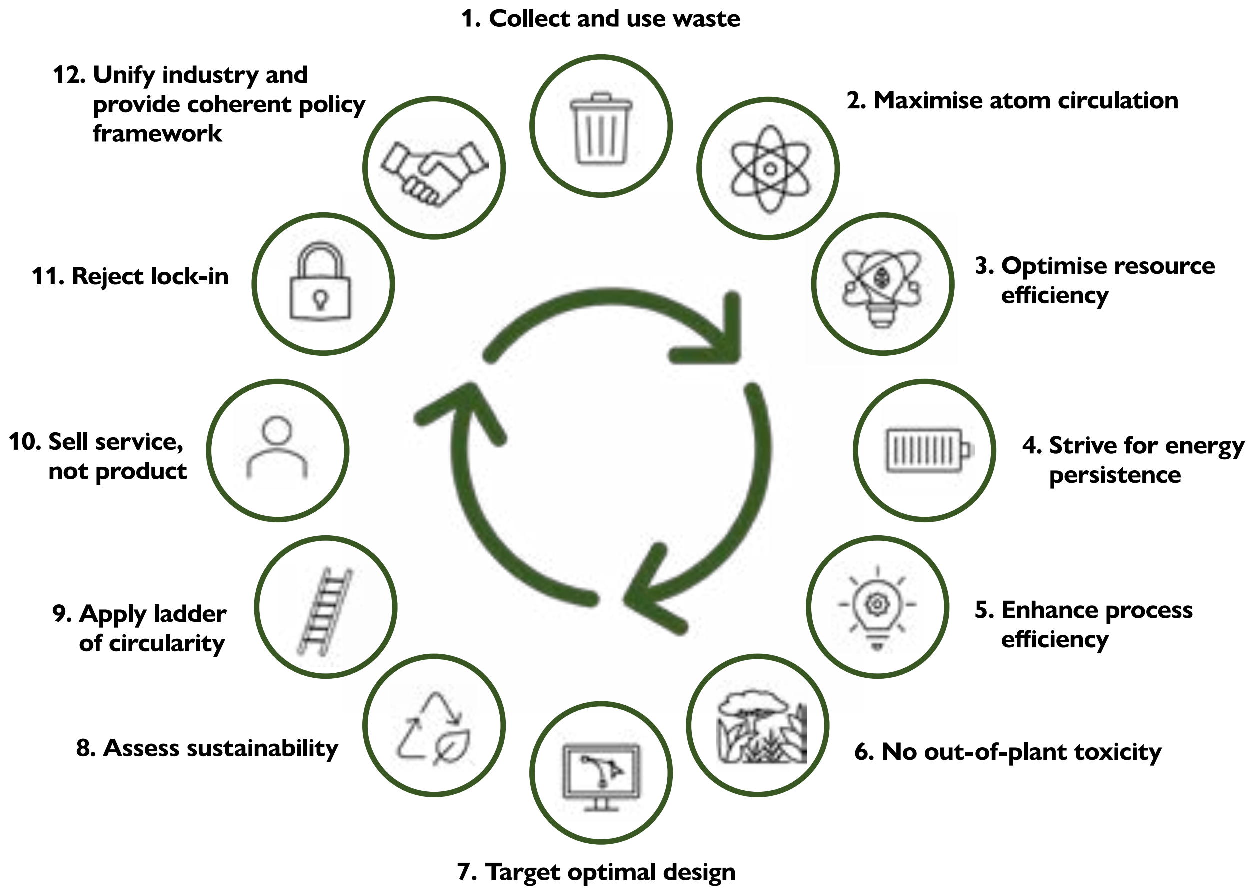


Figure 3. The 12 principles of circular chemistry as elaborated by Keijer et al. (2019), formulated to support the transition to a circular economy.

of the immediate implementation of circularity is the complexity and high costs of recycling or reusing waste that has already been produced. This emphasises that changes are needed in the design phase of product development, designing with circularity in mind. For example, the demand for transition metals is expected to increase substantially going forward, as digitalisation continues to increase and many of the products that reduce greenhouse gas emissions rely on the availability of high-grade metals. Indispensable for its applications in wiring, electric motors, generators and other electronic devices, copper is an example of this.

> **«One of the greatest limitations of the immediate implementation of circularity is the complexity and high costs of recycling or reusing waste that has already been produced»**

Copper production has grown by more than 3000 % since the beginning of the 20th century and is expected to continue to grow (Kümmerer et al., 2020). However, new virgin ore of the right quality is becoming increasingly difficult to find. Rather than continuing to extract virgin resources from the earth, the focus should be directed towards reuse, recovery and recycling what has already been extracted.

The same goes for organic compounds, whose recycling is no less complex, despite not being directly extracted from the earth. For example, plastics often consist of one or more polymers and several additives to achieve the desired characteristics of the product, making them very difficult and potentially hazardous to recycle.

For a circular economy to function, products need to be designed with their end of use solution in mind. Meanwhile materials that are impossible to recycle should be avoided as much as possible. To make this a reality, future products should limit the level of complexity of their constituent parts as much as possible. This highlights a need for targeted innovation. Both the design stage and the end of use stage need to be considered in parallel, as they will be part of the same stage in the circular product cycle. Innovation focused on recycling and reuse anticipates future problems before they can occur, preventing them and contributing to the reduction of pollution.

There are select situations and applications that are not well suited to becoming circular, for which circular solutions are more complex. These often involve the direct application of chemicals to the environment, as in the case of pesticides, or through complex waste streams, such as is often the case with pharmaceuticals. There is a growing body of evidence showing that persistent, mobile and toxic chemicals released into the environment pose a risk to both humans and nature in even the most remote places on earth (Persson et al., 2022).

In cases where recovery at central points before recycling is not possible, products should be designed to mineralise. In other words they should be designed to degrade completely in the environment, thereby feeding into the larger planetary scale biogeochemical cycles. Additional reasoning for the complete mineralisation of chemicals that cannot easily be recovered from environment, is that monitoring, and assessment cannot keep up with their release. Furthermore, the capacity to investigate their actual and potential effects in the environment is not available. A fact emphasised by the exceedance of the novel entities planetary boundary (Persson et al., 2022).

«Circular chemistry provides the chemicals sector with the opportunity to take a leading role in efforts to mitigate the climate crisis»

MODERN CHEMISTRY MUST BE EFFICIENT, SAFE, AND CIRCULAR

Taking advantage of the potential chemistry has to be at the forefront of environmental crises mitigation requires a triple focus on efficiency, safety, and circularity (Flerlage & Slootweg, 2023). The way that chemistry is approached and taught requires a shift from isolated and fragmented knowledge to a holistic, systems approach putting equal weight on considerations of functionality, safety and sustainability (Mahaffy et al., 2019). Developments towards a circular economy must by definition take the planet and people into account, but they must also be scalable and cost effective. There are several cases where innovations designed with sustainability in mind, were not adopted due to cost barriers. An example of this being the reported green synthesis of adipic acid, which requires the use of hydrogen peroxide, a more expensive compound than the final product, thus violating the value chain (Keijer et al., 2019). Rather than seeing this as a roadblock in the widespread adoption of green and circular chemistry, this should be seen as part of the innovation process bringing us closer to the end goal of people and planet focused chemistry.

Despite their positive impact on accelerating the shift towards clean energy, there is a pressing need to recycle batteries. In a recent example of how innovation in chemistry can contribute to the circular economy, Liu and contributors (2020) have developed what they call a «quick-release binder» which will allow for quicker and more affordable recycling of the scarce elements used in batteries, including lithium, nickel and cobalt. To recycle the components of a battery made with this binder, only the addition of alkaline water and gentle shaking is needed. Furthermore, this binder is compatible with how lithium-ion batteries are being produced today.

Another example of how chemistry can contribute to the circular economy is the chemical recycling of plastics. Though not applicable to all plastics, polyethylene terephthalate (PET) and polyamides are good candidates for depolymerisation back to their monomers. Following depolymerisation, the monomers can then be re-used in new applications, keeping the same resources in use for multiple product cycles and avoiding the production of additional waste. All large system changes require pioneers who invest in technologies before the point of commercial viability, for example the first solar panels, to support the innovation process and showcase what the future could look like. Each new technology provides learning experiences and opportunities for optimisation. Given the scale of the environmental crises faced, this cycle needs to accelerate, driving the circular economy and circular chemistry into the mainstream as quickly as possible.

THE ROLE OF REGULATION AND RESPONSIBILITY

The large-scale adoption of circular chemistry and the circular economy requires combined action from individuals, industry, and regulatory bodies. Key drivers in this transition include strong university–industry–government relationships, sustainable chemical logistics and supply chains, as well as rewarding chemical and environmental regulations

(Keijer et al., 2019). Realisation of the circular economy is promoted by directing the ownership of goods and waste from the user back to the producer. One way of achieving this is to shift from payment models based on ownership to service-based systems (Keijer et al., 2019). Examples of this include shared cars, bikes and e-scooters.

In circular chemistry the adoption of service-based business models, which promote efficiency and longevity of the materials rather than production rate and quantity are recommended for producers. Unlike the end user, companies have the assets and knowledge of how to retrieve and repurpose chemical products. This makes them best equipped to target the management of loops of circulating molecules and materials. Shifting the burden of responsibility for repurposing, remanufacturing and recycling to producers also incentivises innovation at the design and reuse stage of the product lifecycle. This encourages the adoption of circular principles and circular chemistry in industry, which in turn makes a significant impact in mitigating global waste problems.

Alongside this, chemistry educators have a vital role to play in altering the culture and practices of chemistry to meet the circular and systems thinking approaches needed to mitigate the climate crisis (Mahaffy et al., 2019). By changing the approach taken in the classroom, chemists and other professionals working in related fields are better prepared to find solutions for the challenges faced in mitigating the climate crisis.

Thus, circular chemistry provides the chemicals sector with the opportunity to take a leading role in efforts to mitigate the climate crisis. Green chemistry has created an environment open to the implementation of less environmentally demanding and damaging processes. Through this, it has laid the groundwork for the inclusion of environmental considerations in the way that chemistry is performed. This must now be further expanded into education, industry and policy spheres. Rather than continuing to draw on new virgin resources, perpetuating the cycle of environmental and social harm associated with resource extraction, waste and the end stage of product use must become the resource. To combat the main problems in the current system, the most sensible cycles must be developed per product class to eliminate waste. Circular chemistry addresses the fundamental challenge of sustainability, namely the circulation of materials.

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