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A converging path: a decade's reflection on net zero emissions and the circular economy

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In the past decade, global sustainability efforts have increasingly focused on two critical paradigms: achieving net zero emissions (NZE) and advancing the circular economy (CE). This article provides a detailed examination of the challenges and breakthroughs in harmonizing these approaches, drawing from a broad range of academic discussions, technological innovations, policy developments, and practical implementations. We identify specific obstacles, such as technological limitations, policy inertia, and economic and social barriers, that hinder progress towards NZE and CE. The paper then outlines targeted solutions, including cutting-edge technologies like carbon capture and storage, policy frameworks that incentivize sustainable practices, and examples of successful circular economy models. Through a critical analysis of both the synergies and tensions between NZE and CE, the article highlights the necessity for cross-sector collaboration, robust policy support, and ongoing innovation to overcome these challenges. Concluding with a forward-looking perspective, we emphasize strategic pathways for integrated sustainability efforts, advocating for a multi-faceted approach that combines technological advancement, policy reform, and stakeholder engagement. By offering a more nuanced understanding of the interplay between theoretical goals and practical realities, this revised abstract aims to inspire action and foster a collective move towards a sustainable global future.

KEYWORDS

net zero emissions, circular economy, sustainability, policy development, socioeconomic impact

1 Introduction

In an epoch marked by accelerating ecological degradation and growing concerns surrounding climate change, the entwined paradigms of net zero emissions (NZE) and the Circular Economy (CE) have emerged as beacon concepts for global sustainable transformation. Both of these frameworks, though distinct in their specifics, share a profound interconnectedness rooted in the need to address our anthropogenic impacts on the environment.

Net zero emissions, a term now echoing in international policy chambers and boardrooms alike, encapsulates the aspiration to strike a balance, wherein anthropogenic greenhouse gas outputs are neutralized by equivalent removals or offsets (Davis et al., 2018; Rahman and Wahid, 2021). The momentum behind this target is not solely driven by environmental urgency. As elucidated by numerous studies over the past decade, this balance embodies multifaceted implications, spanning economic, social, and geopolitical spheres (Rogelj et al., 2021). The daunting reality of sea-level rise, the increasing

volatility of climate patterns, and the subsequent socio-economic ramifications have reinforced the cruciality of this emission equilibrium (Van Soest et al., 2021; Bergero et al., 2023).

Concurrently, the circular economy offers a profound shift from the entrenched linear model that has long dominated our production and consumption habits. Eschewing the traditional "take, make, dispose" approach, the circular paradigm emphasizes a regenerative design, underpinned by reduction, reuse, and recycling. It challenges the very ethos of our consumption-driven economies, urging a transition towards systems that harmoniously coexist with ecological cycles and prioritize resource efficiency (Naqvi et al., 2017; Mies and Gold, 2021; Corvellec et al., 2022; Dzhengiz et al., 2023; Munaro and Tavares, 2023; Tunio et al., 2024).

Over the last 10 years, profound transformations have punctuated the global sustainability landscape, offering a rich tapestry of insights, challenges, and achievements. Examining this decade allows us a deeper understanding of the pivotal shifts in both perception and actions related to NZE and the CE. This examination transcends pure academic analysis; it serves as a platform to assess past milestones, discern challenges, and inform future approaches.

The primary objective of this article is to provide an exhaustive exploration of the interconnected evolution of two paramount sustainability paradigms that have dominated the last decade's discourse: NZE and the CE. By traversing through a diverse landscape of academic literature, technological breakthroughs, policy shifts, and tangible applications, we aim to elucidate the fundamental principles of these paradigms, chronicle their historical trajectory, critically assess the challenges and roadblocks they've encountered, and undertake a comparative analysis of regional adaptations and outcomes. Furthermore, we seek to unearth the intricate dance of synergies and tensions between these two paradigms, leveraging real-world case studies for in-depth insights, and gauge their broader socio-economic reverberations on the global stage.

The novelty of this article lies in its ambitious integrated approach. While many analyses have delved deep into either NZE or the CE, few have ambitiously attempted to meld the two into a singular, coherent narrative. Our article embarks on this interdisciplinary journey, marrying these seemingly distinct paradigms to reveal their overlapping trajectories, mutual reinforcements, and occasional areas of discord. Moreover, by weaving theory with practicality, our narrative also bridges the chasm between academic postulations and the gritty realities of on-the-ground implementation, presenting a fresh and pragmatic perspective on a decade's worth of sustainability endeavors.

2 Literature review and critique

The multifaceted conversation surrounding NZE and the CE over the last decade underscores the growing global emphasis on sustainability. The literature has evolved from rudimentary understandings to intricate discussions on feasibility, mechanisms, challenges, and the interconnectedness of these frameworks. The subsequent detailed exploration endeavors to provide a comprehensive overview of the academic discussions and their critiques.

2.1 Net zero emissions

A considerable part of the literature accentuates the urgency and pathways to achieving net zero. Ürge-Vorsatz et al. (2020) reviewed recent advances in key options and strategies for converting the building sector to be climate neutral. Table 1 provides a comprehensive literature review on the Net Zero Emissions (NZE) concept from 2013 to 2024. It initiates with the fundamental principles of NZE, highlighting the urgency due to increasing carbon levels and foregrounding pivotal international agreements such as the Paris Agreement. The table subsequently delves into the Paris Agreement's central role in advancing NZE, accentuating the crucial merger of global politics with environmental science. The technological routes to achieving NZE are explored, emphasizing the significance of innovations like renewable energy and carbon capture. Additionally, the economic prospects and socio-political dimensions are illuminated, indicating a potential surge in GDP growth and accentuating the necessity for aligned global policies. The table further scrutinizes the challenges and potential hindrances in the NZE trajectory, advocating for a holistic approach. Concluding, the literature review offers a forward-looking perspective, underlining the essentiality of persistent research, novel technologies, and synchronized international efforts.

2.2 Circular economy

Similarly, Table 2 provides a comprehensive literature review on the Circular Economy (CE) from 2013 to 2024. It begins by introducing CE's foundational principles, advocating for a move away from linear models. The table then delves into circular business models, highlighting their benefits and challenges.

Key technological advancements supporting CE, such as innovative recycling methods and bio-based materials, are discussed. The economic impact of CE, including a potential 1.8% rise in global GDP by 2045, and its socio-cultural implications are emphasized, underscoring the role of education. The table also examines policy frameworks, with a spotlight on the European Union's Action Plan, and outlines global cooperative initiatives. Challenges, including technological gaps and policy fragmentation, are addressed. The review concludes by projecting future trends in CE, emphasizing continuous innovation, collaboration, and adaptive policy-making.

2.3 Intersections

Table 3 explores the intersection of Net Zero Emissions (NZE) and Circular Economy (CE).

They are vital environmental approaches in the 21st century. While CE aids NZE by reducing waste, and lessening the need for energy-intensive processes, challenges arise, like potential emission increases and balancing renewables. Economically, CE benefits support NZE, but transition costs may be problematic. Policies promoting CE can accelerate NZE, though some CE practices may conflict with NZE objectives. Case studies show industries like fashion and cities using CE principles effectively reduce emissions.

TABLE 1 Literature review on net zero emissions (2013–2024).

Section	Summary	References
Introduction to the NZE Concept	Foundational concepts of NZE introduced, with a focus on rising carbon levels and upcoming international agreements like the Paris Agreement	De Jong et al. (2015); Anderson and Peters (2016); Davis et al. (2018)
The Paris Agreement and the Rise of NZE	Analysis of the Paris Agreement's emphasis on NZE, examining the convergence of international politics and environmental science during a pivotal climate moment	Anderson and Peters (2016); Anika et al. (2022); Fankhauser et al. (2022)
Technological Avenues to Achieve NZE	Overview of technological solutions, including renewables, carbon capture, and storage, with a call for swift implementation	Rogelj et al. (2015); Meys et al. (2021); Zhao et al. (2022)
Economic and Socio-Political Dimensions	Investigation into NZE indicates a potential 2.5% GDP growth by 2050, addressing economic concerns and emphasizing socio-political challenges with recommendations for global policy alignment	Geels et al. (2016); Geels (2018); Fankhauser et al. (2022)
Challenges and Potential Setbacks	A critical look at the obstacles in the NZE journey, encompassing technological, economic, and policy challenges. An integrated approach is advocated	Bridge et al. (2013); Geels (2018); Zhao et al. (2022)
Looking Forward	Future-oriented exploration projecting the next 3 decades of NZE, emphasizing innovative technologies, global collaboration, and the need for continual research and dynamic policy adjustments	Mohan and Katakojwala (2021); Hale et al. (2022); van der Spek et al. (2022)

TABLE 2 Literature review on circular economy (2013–2024).

Category	Key findings/Highlights	References
Fundamentals of CE	Introduced basic principles and strategies of CE, advocating for a shift from linear models	Stahel (2016); Shirvanimoghaddam et al. (2020); Diamantis et al. (2021)
Business Models and Implementations	Examined the benefits of circular business models using case studies and assessed corporate adoption, highlighting both challenges and positive outcomes for sustainability and profitability	Lewandowski (2016); Rizos et al. (2016); Urbinati et al. (2017)
Technological Innovations for CE	Evaluated key technological advancements like recycling technologies and bio-based materials that furthered CE.	Smol et al. (2017); Kouhizadeh et al. (2020); Ranta et al. (2021)
Economic and Socio-Cultural Impacts	Highlighted a potential 1.8% rise in global GDP by 2045 from CE models, addressing economic myths, and emphasized societal shifts and the importance of education in CE adoption	Kapsalis et al. (2019); Friant et al. (2020); Corvellec et al. (2022)
Policy Frameworks and Global Initiatives	Examined policies supporting CE, focusing on the European Union's Action Plan, and explored global initiatives highlighting international collaborations and policy alignment	Pomponi and Moncaster (2017); Domenech and Bahn-Walkowiak (2019); Padilla-Rivera et al. (2020)
Challenges and Critiques	Enumerated potential challenges in global CE adoption like technological gaps and policy fragmentation	Millar et al. (2019); Kovacic et al. (2020); Corvellec et al. (2022)
The Road Ahead	Projected future CE trends and emphasized the need for innovation, cooperation, and adaptive policymaking	Patwa et al. (2021); Ding et al. (2023); Todorović and Obradović (2023)

TABLE 3 Intersection of net zero emissions and circular economy (2013–2024).

Section	Key findings	References
Introduction	NZE and CE are major 21st-century paradigms with converging principles for climate mitigation	Arsic et al. (2023); Okorie et al. (2023)
CE's Role in NZE	CE reduces waste and energy-intensive extraction, aiding NZE.	Bonsu (2020); Mulvaney et al. (2021)
Challenges in Merging NZE & CE	CE processes can raise emissions; balancing renewables with reused tech is hard	Bonsu (2020); Meys et al. (2021); Khalifa et al. (2022)
Economic Considerations	CE offers economic benefits supporting NZE. Transition costs might pose challenges	Lee et al. (2017); Okorie et al. (2023)
Policy Synergies & Conflicts	CE-promoting policies can boost NZE, but some CE practices might conflict with NZE goals	Domenech and Bahn-Walkowiak (2019); Bonsu (2020)
Case Studies: NZE & CE	Fashion industries highlight CE's emission reduction capabilities; cities with CE principles show decreased carbon footprints	Meys et al. (2021); Govindan (2023); Okorie et al. (2023)

2.4 Critique

Upon examining the depth and breadth of this literature, certain critical gaps emerge. One such chasm is the occasional lack of context specificity in proposed solutions. While many frameworks appear effective in Western contexts, their applicability in developing or transitional economies remains underexplored. Moreover, while there's an increasing confluence of net zero and CE literature, there remains a siloed approach in many studies, highlighting the need for more interdisciplinary research that explicitly explores their intersections.

To sum up, the past decade has witnessed an expansive growth in literature centered on NZE and the CE. While it has laid a solid foundation, offering invaluable insights, there are pressing areas that need further exploration, especially as the world seeks to operationalize these ambitious yet crucial paradigms. As scholars and practitioners continue to navigate this space, future research must ensure a holistic, inclusive, and context-specific approach.

3 Methodology

Embarking on this journey to understand the intertwined realms of NZE and the CE over the past decade necessitated a rigorous methodological framework. Our data collection strategy was twofold. First, academic databases such as JSTOR, Scopus, and Google Scholar were scoured to glean peer-reviewed articles, conference proceedings, and white papers. In parallel, gray literature was incorporated into our dataset, drawing from reports of international bodies like the UN and IPCC, publications from various governments, and contributions from notable NGOs. This approach was taken to ensure we were capturing not just theoretical and empirical studies, but also real-world applications and policy directives.

With the vastness of available literature, establishing clear selection criteria became paramount. We initiated our screening process by filtering studies published between 2013 and 2023 using specific keywords related to our focal themes. This was followed by setting inclusion and exclusion benchmarks. Pertinent to our analysis were studies that directly engaged with our themes, showcased clear research methodologies, and bore relevance to either global or regional policy implications. Conversely, we sidestepped studies with tangential relevance or those without rigorous methodological outlines, making exceptions for recognized gray literature. Through this meticulous process, we curated a diverse dataset that encapsulated various geographies, sectors, and academic disciplines.

The analytical lens we adopted was tripartite. We embarked on a temporal analysis, meticulously charting the ebbs and flows in the research frequency, technological innovations, and policy shifts over the years. This allowed us to identify discernible trends and pivotal moments that shaped the decade. Next, our evaluation of successes was rooted in both quantitative metrics, such as actual reductions in emissions and adoption rates of circular practices, and qualitative insights gleaned from transformative case studies. Lastly, we delved into a gap analysis, merging content analysis with a meta-review to spotlight overlooked areas, persistent challenges, or emergent domains warranting attention.

In essence, our methodology, by synthesizing diverse sources and adopting a multifaceted analytical approach, sought to provide an encompassing, objective, and nuanced exploration of the past decade's developments in NZE and the CE.

4 Conceptual framework

As we navigate the complex web of research, practices, and policies encompassing NZE and the CE, it becomes paramount to first anchor our understanding in a robust conceptual framework. This not only offers clarity but also ensures consistency in the interpretations and implications drawn throughout this study.

4.1 Net zero emissions

At its core, the concept of net zero emissions revolves around achieving a balance between the greenhouse gases put into the atmosphere and those taken out. It does not insinuate a complete cessation of emissions but emphasizes offsetting any emissions produced through practices like carbon capture, reforestation, and the use of sustainable energy sources. The guiding principle here is equilibrium; the goal is to ensure that anthropogenic activities don't increase the net amount of greenhouse gas concentrations in the atmosphere, thus mitigating the impacts of climate change (Delafield et al., 2021; Stern and Valero, 2021; Okorie et al., 2023).

Figure 1 delineates the strategic roadmap towards achieving global net-zero carbon emissions by 2050. It charts the decline in CO_2 emissions in gigatons (Gt CO_2) over 3 decades, segmented by sectors: Buildings, Transport, Industry, Electricity and Heat, and Others (Naqvi et al., 2016; Rehan et al., 2017). Key milestones are pinpointed throughout this timeline, highlighting vital shifts such as the cessation of new coal plant approvals in 2021, the target for 60% of global car sales to be electric by 2030, and the aim for 50% of heating demand to be met by heat pumps by 2045. Cumulatively, these actions guide a global trajectory towards sustainable energy consumption and carbon neutrality by mid-century (Bouckaert et al., 2021).

4.2 Circular economy

Traditionally, our economic systems have largely followed a linear model: extract, produce, consume, and discard (Naqvi M. et al., 2017; Naqvi et al., 2021). In stark contrast, the CE champions a regenerative approach. It's grounded in three foundational principles: design out waste and pollution, keep products and materials in use, and regenerate natural systems. This model posits that economic growth can be decoupled from resource consumption. By emphasizing sustainable production, prolonging product lifespans, promoting reuse and recycling, and driving innovations that harness waste as a resource, the CE strives for a system where nothing goes to waste. Figure 2 delineates the transformative journey from a linear to a CE, spotlighting the strategic progression to boost product circularity. Initiating with "Refuse" (R0), the model advocates for the discontinuation or innovative substitution of certain products. As we ascend, strategies like "Rethink" (R1) promote more intensive product

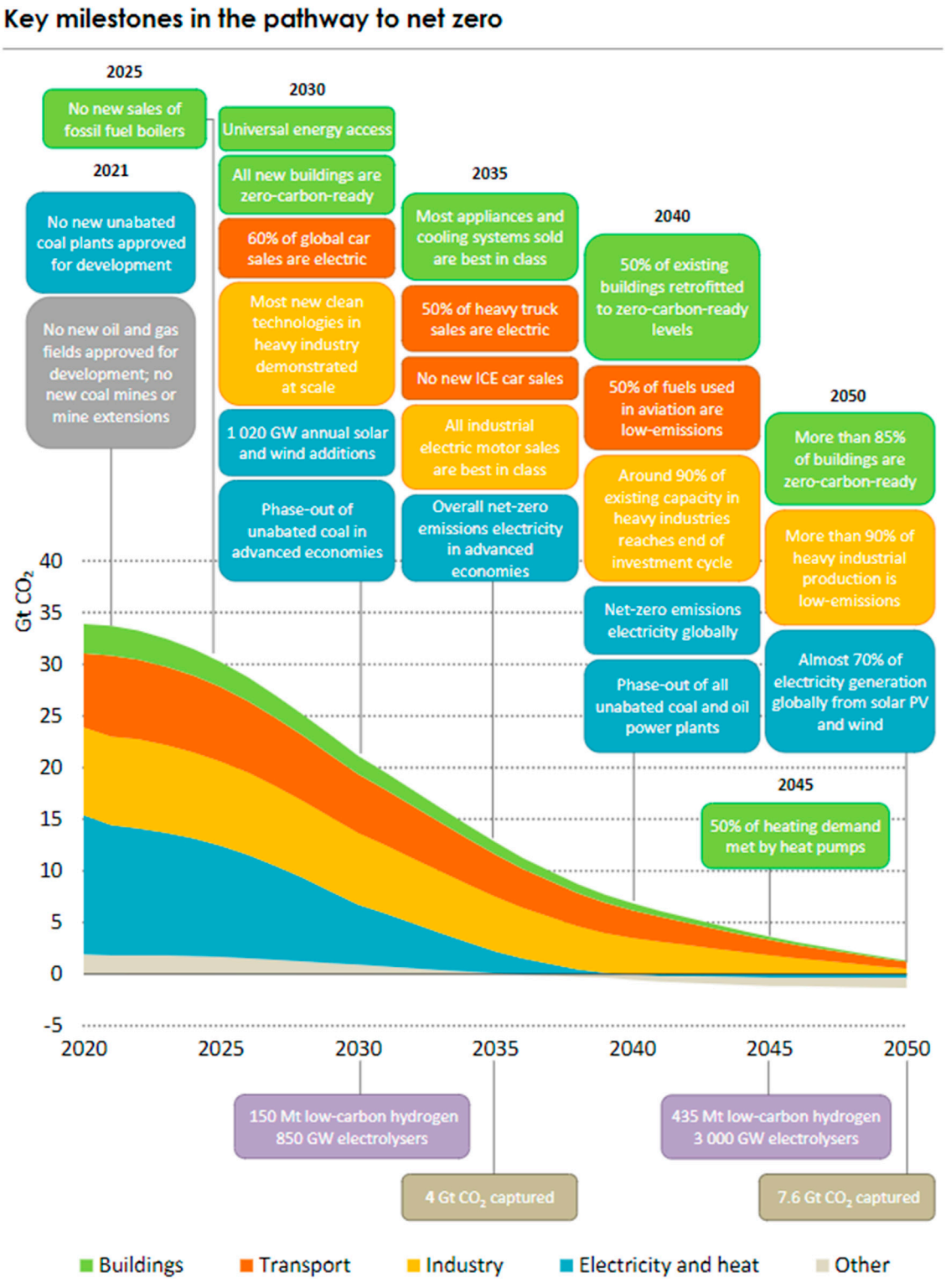

FIGURE 1
Roadmap to 2050: Key milestones and interventions for global carbon dioxide emission reduction across sectors (Bouckaert et al., 2021).

utilization, such as shared use, and "Reduce" (R2) emphasizes conservation in resource utilization. The continuum further underscores the significance of product longevity through "Reuse" (R3), "Repair" (R4), and "Refurbish" (R5). Transitioning towards repurposing, "Remanufacture" (R6) and "Repurpose" (R7) champion the ingenious reincarnation of discarded products or components. Lastly, the framework accentuates the sustainable reprocessing and energy retrieval through "Recycle" (R8) and "Recover" (R9). Collectively, the represented strategies serve as a blueprint for embedding sustainability at the core of consumption

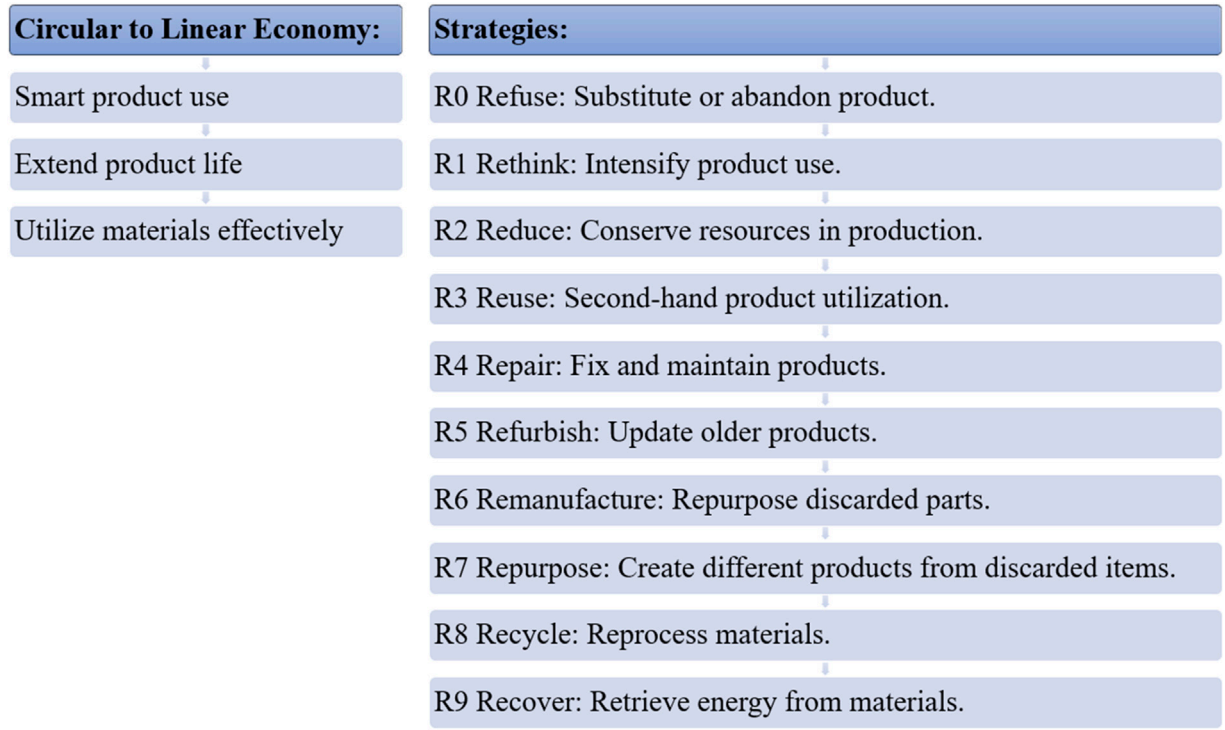

FIGURE 2
Strategies for transitioning from linear to CE: From smart product usage to material recovery (Kirchherr et al., 2017; Potting et al., 2017; Kristoffersen et al., 2020).

and production (Kirchherr et al., 2017; Potting et al., 2017; Kristoffersen et al., 2020).

4.3 Inherent connection

While on the surface, NZE and the CE might appear as distinct paradigms, a deeper exploration reveals a symbiotic relationship. The CE, with its emphasis on reducing waste, inherently reduces emissions tied to waste management, product production, and resource extraction. Meanwhile, the push for net zero directs industries towards sustainable energy sources, which further aligns with the circular philosophy of sustainable resource use. For instance, an industry adopting circular practices might prioritize recycled materials, which often have a lower carbon footprint than new materials. Similarly, in striving for net zero, industries could adopt technologies that have circular benefits, like biogas production from organic waste. This interwoven relationship suggests that the pathways to achieving NZE can be both complemented and accelerated by embracing the principles of the CE (Mohan and Katakojwala, 2021; Di Vaio et al., 2023; Mallick et al., 2023).

4.4 Progress and pathways: evaluating our journey towards 2050

In our critical assessment of the current position towards achieving the 2050 sustainability goals, we meticulously analyze the latest data on key indicators such as greenhouse gas emissions, recycling rates, and renewable energy adoption. This analysis aims to objectively evaluate our progress relative to the milestones delineated for 2025, 2030, and further, utilizing Figure 1 as a benchmark to identify both advancements and shortcomings. We also acknowledge various hurdles since the roadmap's initiation, including technological constraints, financial barriers, policy stagnation, and significant global disruptions, critically examining how these factors shape our path towards 2050. This leads to an informed evaluation of the feasibility of meeting our 2050 goals, incorporating scenarios and models that consider different levels of intervention, policy reforms, and technological developments. To navigate these challenges, we propose strategic recommendations focused on closing the identified gaps and propelling forward momentum. These include urging greater investment in green technologies, advocating for more robust policy support, fostering international collaborations for climate action, and encouraging stronger partnerships between public and private sectors. The culmination of this analysis in the manuscript's conclusion underscores the critical need for immediate and collective efforts to realign our trajectory with the ambitious targets for 2050, highlighting the urgency of adopting these strategic recommendations to ensure a sustainable future (Naqvi et al., 2013; Mont et al., 2014; Gielen et al., 2019; Moustakas et al., 2020; Moyer and Hedden, 2020; van Vuuren et al., 2022).

5 Milestones and achievements

Over the last decade, the convergence of NZE and CE principles has led to a plethora of notable milestones and achievements. This

section delves into some of the key advancements across technological, policy, and practical domains, which have not only showcased the potential of these paradigms but have also set the stage for further evolution.

5.1 Technological innovations

The nexus of net zero and circularity has been a crucible for numerous technological innovations. Carbon capture and storage (CCS) technologies, for instance, have matured significantly, offering a viable avenue for industries to mitigate their emissions (Meys et al., 2021; Sankaran, 2023). Furthermore, the rise of Industry 4.0 technologies, such as the Internet of Things (IoT) and artificial intelligence, has facilitated the tracking, management, and optimization of resources within circular supply chains, ensuring minimal waste and efficient recycling or repurposing (Fraga-Lamas et al., 2021; Bag and Pretorius, 2022).

Another breakthrough has been in the realm of renewable energy storage. The advent of advanced battery technologies and green hydrogen solutions has not only accelerated the shift towards renewable energy sources but also embedded circular principles by emphasizing the recyclability and longevity of storage mediums (Naqvi et al., 2012; Cusenza et al., 2019; Bonsu, 2020; Raza Naqvi et al., 2023).

Lastly, innovations in bio-based materials have provided sustainable alternatives to traditional plastics and other non-degradable products. These materials, often derived from agricultural waste or algae, align with both the net zero objective (by sequestering carbon) and the circular notion of leveraging waste as a resource (Leipold and Petit-Boix, 2018; Thakker and Bakshi, 2023).

A recent pilot project in the UK, involving the use of hydrogen-powered domestic condensing boilers, has showcased significant potential for reducing residential carbon emissions. This project, involved retrofitting existing gas networks to accommodate hydrogen fuel, demonstrating a scalable solution for urban and suburban households aiming for net-zero emissions (Al-Mufachi and Shah, 2022; Roy et al., 2024).

5.2 Policy developments

Policies form the backbone of systemic change, and the past decade has witnessed several landmark policy developments. Numerous countries have announced their net zero targets, bolstered by comprehensive roadmaps that factor in circular principles. For instance, the European Union's Green Deal envisions a climate-neutral continent by 2050 and has embedded circularity as a core strategy, fostering a regulatory environment that promotes sustainable production and consumption (Bonciu, 2020; Jesic et al., 2021).

Many nations have also introduced incentives for industries adopting circular practices, such as tax breaks for companies engaging in sustainable sourcing or extended producer responsibility (EPR) schemes that mandate manufacturers to manage the end-of-life phase of their products (Ghisellini et al., 2016; Ramasubramanian et al., 2023). Furthermore, the rise of cross-border coalitions and partnerships, like the Circular Economy 100 (CE100) initiative, has facilitated knowledge exchange, setting international best practices and promoting collaborative policy-making (Howard et al., 2019; Velenturf and Purnell, 2021).

A prime example of policy-driven innovation is the European Environmental Agency's "ammonia Adoption Act," a pioneering policy designed to expedite the transition of power plants to ammonia fuel in gas turbines. By offering financial incentives and regulatory support, this Act aims to reduce carbon emissions significantly, with a target of converting 30% of the EU's gas-powered plants to ammonia by 2030, thereby potentially cutting annual CO_2 emissions in the power sector by up to 20 million tons. This initiative highlights the EU's proactive approach in leveraging ammonia, a carbon-free fuel, to achieve substantial strides towards its net-zero emissions goals, setting a precedent for global energy policy (Sciences et al., 2016; Rahman and Wahid, 2021).

5.3 Case studies

The synthesis of net zero and circular principles has yielded tangible results across various sectors:

Automotive: Companies like Tesla have championed not only electric vehicles but also the circular use of materials. Their battery recycling program aims to recover critical metals and reintroduce them into the production cycle, embodying circularity while pushing for net zero transportation (Bonsu, 2021; Song and Zhou, 2023).

Fashion: Brands such as Patagonia have integrated circularity by promoting repair, reuse, and recycling of their products. Their commitment to reducing carbon footprint goes hand-in-hand with initiatives like sourcing organic materials and encouraging consumers to buy used products (Bocken et al., 2016; Dezi et al., 2022).

Urban Development: Cities like Amsterdam have embarked on a mission to become fully circular by 2050. This entails waste-to-resource initiatives, sustainable infrastructure development using recycled materials, and promoting green energy sources, all converging towards a net zero, circular urban landscape (Kurniawan et al., 2021; Mutezo and Mulopo, 2021).

By charting these milestones and achievements, it becomes evident that the marriage of NZE and CE principles has not only been conceptually enriching but has also led to tangible, impactful advancements across the global sustainability landscape.

6 Challenges and limitations

While the previous section celebrated the milestones, it's equally vital to critically engage with the challenges and setbacks that have surfaced over the decade. Integrating NZE and CE principles, despite its potential, has been a journey marred with multifaceted obstacles, ranging from technological bottlenecks to socio-political constraints.

6.1 Technological challenges

The realm of technology, although bustling with innovation, has had its share of hurdles. For instance, while Carbon Capture and

Storage (CCS) emerged as a promising avenue, its scalability and economic viability remain concerns. High operational costs and concerns about the long-term storage integrity have made widespread adoption slow. Similarly, while bioplastics hold promise, their decomposition rate, under certain conditions, is not as rapid as anticipated, posing waste management challenges.

6.2 Economic limitations

Transitioning to a CE often requires significant upfront investments. Small and medium enterprises (SMEs), in particular, find it challenging to invest in sustainable and circular innovations due to limited capital and perceived economic risks. Moreover, the global market still predominantly rewards linear economic practices, creating a competitive disadvantage for early circular adopters.

6.3 Policy and regulatory setbacks

Although many policies support circular and net zero initiatives, they sometimes exist in silos, lacking an integrated approach. Furthermore, the enforcement of these policies is inconsistent across regions. For instance, Extended Producer Responsibility (EPR) regulations vary widely, leading to discrepancies in their effectiveness. International trade policies, at times, inadvertently promote linear practices, creating barriers for circular products and services.

6.4 Socio-cultural barriers

The shift towards circularity and net zero requires a significant behavioral change. Consumerism, fueled by a culture of disposability, often clashes with the principles of the CE. The allure of "newness," whether in gadgets, fashion, or even vehicles, often supersedes the appeal of sustainable, long-lasting, or recycled products.

6.5 Supply chain complexities

As businesses aim to embed circularity into their operations, they grapple with the complexity of ensuring sustainability throughout the supply chain. Tracking the origin, lifecycle, and end-of-life of products and materials is an intricate task, often exacerbated by a lack of transparency and standardization in global supply chains.

6.6 Geopolitical challenges

Climate change, NZE, and circularity are global issues. However, geopolitical tensions can sometimes stall collaborative efforts. Differences in economic development, priorities, and capabilities mean that nations approach these paradigms at varied paces, leading to coordination challenges at international forums.

In assessing these challenges and setbacks, it's evident that the journey towards integrating NZE and CE principles is not linear. The myriad obstacles encountered underscore the need for continued innovation, robust policies, global collaboration, and a shared vision to navigate this transformative path.

7 Synergies and tensions

The interplay between NZE and the CE has undeniably forged powerful synergies, yet it has also unveiled certain tensions. This dynamic relationship, oscillating between collaboration and friction, has been instrumental in shaping the trajectory of sustainable development over the decade.

7.1 Synergies

Resource Efficiency and Emissions Reduction: CE practices emphasize the efficient use of resources, which directly translates to reduced energy consumption and consequently, lesser emissions. For example, recycling aluminum saves up to 95% of the energy required to produce it from raw materials, thus drastically reducing associated emissions.

7.2 Waste-to-energy

The principles of the CE advocate for harnessing waste as a resource. This aligns seamlessly with net zero ambitions when organic waste is transformed into bioenergy, providing renewable energy while diverting waste from landfills.

7.3 Sustainable product design

Products designed with circular principles in mind tend to have extended lifespans, are easier to repair, and are built for recycling or composting. This approach directly reduces the carbon footprint associated with frequent manufacturing of disposable products.

7.4 Case study—the ellen MacArthur foundation's jeans redesign initiative

This project brought together major fashion brands to produce jeans that last longer, can be easily recycled, and are made in ways that are better for the environment and the health of garment workers. The reduced need for constant production, owing to the durability of these jeans, complements net zero targets.

7.5 Tensions

Bio-based Materials vs. Carbon Sequestration: While bio-based materials, like those used in some bioplastics, are hailed in the CE for their potential to decompose, their production might involve the use of plants that could otherwise sequester carbon. There's a balance to

strike between using plants for materials and allowing them to act as carbon sinks.

7.6 Recycling energy intensity

Some recycling processes, though circular, are energy-intensive. For instance, certain e-waste recycling procedures, while recovering valuable materials, consume significant amounts of energy, thus posing challenges for net zero objectives.

7.7 Carbon offsetting and natural land use

Net zero often involves carbon offsetting practices like afforestation. However, if not managed with a circular mindset, these can conflict with natural land uses, potentially displacing agriculture or natural ecosystems.

7.8 Case study—palm oil biofuels

Once celebrated as a renewable alternative to fossil fuels, palm oil biofuels have come under scrutiny. While they align with the circular idea of using organic matter for energy, their production has led to deforestation, biodiversity loss, and ironically, increased greenhouse gas emissions due to the clearing of carbon-absorbing forests.

By examining these synergies and tensions, it becomes evident that while the pathways of NZE and the CE frequently converge, they sometimes also diverge. It's this intricate dance between alignment and divergence that necessitates an integrated, nuanced approach to sustainability, ensuring that in our pursuit of one objective, we don't inadvertently compromise the other.

8 Socio-economic impact

The intertwined journey towards NZE and the CE has far-reaching socio-economic implications. From the creation of new industries and the obliteration of some traditional sectors to redefining economic hierarchies globally, the transformation has been profound. A thoughtful assessment reveals both commendable strides and formidable challenges on this socio-economic frontier.

8.1 Job creation

The transition to net zero and circular models has been a catalyst for new employment opportunities. Renewable energy sectors, such as wind, solar, and bioenergy, have witnessed significant job growth. Additionally, as companies increasingly adopt circular practices, roles centered around sustainable product design, resource management, and waste-to-resource technologies have burgeoned. According to the International Renewable Energy Agency (IRENA), the renewable energy sector alone could employ up to 42 million people globally by 2050, a vast leap from around 12 million in 2020.

Skill Transition and Job Displacement: While new opportunities emerge, there's an undeniable displacement in traditional sectors, particularly fossil fuels. This transition, if not managed inclusively, poses the risk of socio-economic disparities. It necessitates reskilling programs and policy frameworks that ensure workers from declining industries find avenues in the burgeoning green sectors.

8.2 Inequality

The shift towards net zero and circularity, if not executed equitably, can exacerbate existing inequalities. On a global scale, while developed nations have the capital and technology to transition swiftly, developing nations might grapple with the costs and complexities of overhauling their systems. Within nations, there's a risk of a "green divide" where only the affluent sections of society can access and afford sustainable, circular products and services, leaving the marginalized further behind.

8.3 Economic paradigm shift

The move towards net zero and circularity is gradually redefining economic success parameters. Gross Domestic Product (GDP), traditionally a measure of success, might not encapsulate the full story anymore. New metrics that account for sustainable practices, resource efficiency, and carbon neutrality are gaining traction. Countries and companies are increasingly being evaluated based on their sustainability credentials, potentially leading to shifts in global economic power dynamics.

8.4 Local economies and decentralization

CE principles advocate for localized production and consumption cycles, reducing the dependency on global supply chains. This approach can rejuvenate local economies, fostering innovation and entrepreneurship at the grassroots level. Similarly, decentralized renewable energy systems, like microgrids, empower local communities, ensuring energy sovereignty and resilience.

8.5 Consumer behavior and costs

As companies transition to sustainable practices, there's often an associated cost—at least initially. This transition can lead to premium pricing for green products and services, influencing consumer buying behavior. Over time, however, as sustainable technologies scale and become mainstream, costs are likely to decrease.

In essence, the March towards NZE and a CE is reconfiguring the socio-economic tapestry globally. While the trajectory promises a sustainable and equitable future, it's laden with complexities that demand meticulous planning, global collaboration, and an unwavering commitment to inclusivity and equity.

9 Global and regional perspectives

The global ethos surrounding NZE and the CE is as diverse as the countries and cultures that embody it. Different regions, based

on their socio-economic contexts, historical legacies, and geopolitical considerations, have adopted varied trajectories. A comparative lens reveals both a rich tapestry of localized approaches and a foundational bedrock of global cooperation.

9.1 Europe

Regarded as a front-runner in sustainability initiatives, Europe's transition is characterized by robust policy frameworks, aggressive carbon neutrality targets, and a commitment to circularity. The European Green Deal and the Circular Economy Action Plan are testament to the region's proactive approach. The embrace of these paradigms is also seen as a strategy to bolster European economic competitiveness in the global arena (Smol et al., 2020; Friant et al., 2021; Johansson, 2021).

9.2 Asia

Asia presents a mosaic of approaches. Countries like China and Japan have made significant strides in integrating CE principles, with China's "eco-civilization" vision and Japan's "Society 5.0" strategy. However, rapid urbanization, population density, and developmental pressures pose challenges. In contrast, countries like India juggle developmental imperatives with ambitious renewable energy targets and grassroots circular innovations (Fukuyama, 2018; Hansen et al., 2018).

9.3 Africa

While Africa has a lower carbon footprint historically, its vulnerability to climate change effects is profound. The continent's approach to net zero and circularity is intertwined with developmental, energy access, and resilience objectives. Innovations like decentralized solar projects and community-based circular initiatives are gaining ground. Yet, the need for infrastructural development often competes with these sustainability goals (Filipović et al., 2022; Kalantzakos et al., 2023).

9.4 The Americas

North America, particularly the U.S., has witnessed a pendulum swing in climate policies, with the recent years indicating a renewed commitment to net zero. Advanced industries in the region are also pioneering circular innovations. Latin America, rich in biodiversity, faces the dual task of conservation and development. Countries like Chile and Costa Rica have set commendable renewable energy and conservation benchmarks (Anika et al., 2022; Da Zhu, 2022).

9.5 Oceania

Regions like Australia and New Zealand, blessed with vast renewable resources, are gravitating towards net zero targets. However, challenges like reliance on coal exports and agricultural pressures create tensions. Indigenous knowledge systems, particularly in New Zealand, are also influencing a unique flavor of circularity (Ranson and Stavins, 2016; Hall, 2021).

Global Cooperation and Knowledge Exchange: Despite diverse regional approaches, global cooperation remains the linchpin. Platforms like the United Nations Framework Convention on Climate Change (UNFCCC) and the World Circular Economy Forum facilitate knowledge exchange, technology transfer, and financial collaboration. Such global synergies are vital, ensuring that the move towards net zero and circularity is not just swift but also equitable (Joss et al., 2013; Bataille, 2020).

In conclusion, the journey towards NZE and the CE, when viewed through a global-local prism, underscores the richness of regional innovations and the indispensability of global solidarity. As the world navigates this transformative phase, it's this delicate dance between localized strategies and global cooperation that will shape the sustainability narrative for generations to come.

10 Theoretical and practical implications

The last decade's discourse surrounding NZE and the CE has been underpinned by a rich tapestry of theoretical models and practical implementations. Rooted in interdisciplinary foundations, the theoretical paradigms around these subjects aspire for a holistic transformation where economic systems operate in harmony with our planet's ecological boundaries. They propose a world that thrives on sustainable resource loops, minimizes waste, and champions inter-generational equity. But how seamlessly does this theoretical vision translate into on-the-ground realities?

In the labyrinth of real-world implementations, myriad challenges arise. Economic imperatives, for instance, often pull businesses in two directions: the pursuit of short-term profits and the longer-term sustainability vision. While CE frameworks advocate a decoupling of growth from resource exploitation, many enterprises grapple with the immediate financial implications of such a transition. Similarly, technological constraints can pose significant hurdles. Although academic models sometimes presuppose the ubiquitous presence of cutting-edge technologies, many regions, especially in the developing world, find themselves navigating a technological chasm.

Equally significant are the socio-cultural dimensions. The sustainability path isn't just carved by economic and technological considerations; it's deeply influenced by societal norms, traditions, and behavioral inclinations. A practice that gains rapid acceptance in one cultural milieu might encounter resistance in another, emphasizing the need for context-specific solutions. The policy landscape further adds to this complexity. Theoretical constructs often rest on the bedrock of strong policy and regulatory support, but the oscillating realities of political will, regulatory frameworks, and bureaucratic dynamics can either propel or hinder progress.

Yet, amid these challenges, the gap between theory and practice also spawns innovation. There have been myriad instances where constraints have catalyzed out-of-the-box solutions, adaptive strategies, and grassroots innovations. However, a critical reflection suggests caution in overly romanticizing these success

stories. Scalability remains a pertinent concern. Models that flourish in a controlled, small-scale environment might not necessarily replicate their success on a larger canvas, owing to amplified complexities.

In essence, the journey towards NZE and a CE, as viewed through the lens of the past decade, underscores the intricate dance between theoretical aspirations and practical challenges. To forge a path that's both visionary and pragmatic, a collaborative, adaptive, and context-sensitive approach is paramount. Only by bridging the chasm between what we envision in theory and what we execute in practice can we hope to steer our global systems towards a more sustainable, resilient, and equitable trajectory.

11 Future pathways

Reflecting on a decade of grappling with the intertwining paradigms of NZE and the CE reveals as much about our past as it does about the possibilities ahead. If history has shown us the challenges, it has equally illuminated pathways of promise. By understanding where we have been, we can better chart where we need to go, ensuring that the next decade is not just a continuation but an elevation.

As we stand on the cusp of this new era, several potential pathways emerge. First, the integration of digital technologies with circular principles is ripe with promise. Technologies such as Artificial Intelligence, Blockchain, and the Internet of Things could redefine how we track, manage, and optimize resource loops, creating a transparent and efficient circular system. There's a vast potential in smart grids, digital twins, and AI-driven supply chains to usher in a new age of circularity that's both effective and scalable.

Secondly, transitioning to a truly CE requires rethinking our design philosophies. The future will demand products designed not just for use, but also for reuse, refurbishment, and recycling. This concept, often termed as "Design for Circularity," will be a linchpin. Encouragingly, educational institutions are already beginning to incorporate these principles into their curricula, suggesting a new generation of designers and engineers equipped to meet these challenges.

However, while technology and design provide tools, it's the policy landscape that often paves the way. The next decade will require more robust, comprehensive, and globally harmonized policies that incentivize circular practices. Financial instruments, such as green bonds and sustainability-linked loans, can also play a pivotal role in funneling capital towards sustainable ventures.

Yet, even as we tread these pathways, areas requiring further exploration become evident. There's a pressing need to delve deeper into the socio-cultural dimensions of circularity, understanding how different communities perceive and adapt to circular principles. Behavioral economics, thus, might offer invaluable insights. Similarly, the intersection of biodiversity and circularity remains an under-explored terrain. As we harness resources, how do we ensure that we're not inadvertently compromising on the planet's biodiversity?

Furthermore, the decade ahead must focus on forging stronger global collaborations. The challenges posed by climate change and resource constraints are borderless, and our solutions must mirror that universality. Platforms for knowledge exchange, technology transfer, and capacity building, especially in regions lagging in the sustainability transition, will be paramount.

As we set our sights on the next decade, pinpointing and implementing specific, impactful strategies, projects, partnerships, and policy frameworks is essential for advancing toward our sustainability ambitions. Envisioning green technology parks that amalgamate renewable energy, sustainable water management, and waste recycling presents a blueprint for industrial evolution, while urban reforestation stands out as a key strategy for carbon sequestration and enhancing urban habitats. Crucial to this journey are strategic alliances that bridge governments, the private sector, and NGOs, enabling large-scale sustainability initiatives, such as the deployment of smart grid technologies for improved energy efficiency and renewable energy integration. Furthermore, adopting comprehensive policy frameworks, including a global carbon pricing mechanism and national mandates for sustainable materials, alongside policies that champion circular economy principles like extended producer responsibility (EPR) and zero-waste regulations, will drive businesses towards minimizing their environmental impact. This integrated approach, focusing on innovation, collaboration, and policy support, is pivotal for transforming the next decade into a period of significant progress towards our comprehensive sustainability goals.

In summary, the future pathways for NZE and the CE are as much about evolution as they are about revolution. While the last decade has laid the foundation, the next must build upon it, ensuring that the interplay between technology, policy, design, and collaboration crafts a world where sustainability is not an afterthought but the very ethos of our existence. The journey ahead is challenging but brimming with the potential of possibility.

12 Conclusion

Over the last decade, the journey towards net zero emissions (NZE) and the circular economy (CE) has revealed a rich blend of ambition, achievement, and innovation, highlighting a growing symbiosis between NZE and CE that enhances our approach to sustainability. This period has underscored the importance of adaptable, context-aware strategies that respect local nuances, and the critical role of technological advancements in fostering inclusive progress without widening social disparities. The collaborative efforts of policymakers, industry, academia, and civil society have proven essential in navigating the complexities of global sustainability efforts. Looking forward, we face a landscape filled with both challenges and opportunities, requiring us to refine our strategies, foster new partnerships, and expand our innovations. As we propose actionable steps for individuals, organizations, and policymakers, our collective endeavor towards a sustainable future is clear. Emphasizing collaboration and innovation, we aim to continue our progress towards our sustainability goals, showcasing the resilience and adaptability of humanity. The lessons learned offer guidance for future efforts, underscoring that achieving a sustainable, harmonious future is a collective journey that demands ongoing commitment and cooperation.

For effective action towards net zero emissions and a circular economy, a collective effort from all societal sectors is essential. We propose actionable steps to transform theoretical insights into meaningful outcomes. Individuals are encouraged to lower their carbon footprint via mindful decisions and recycling efforts, and organizations are called to implement circular economy strategies,

prioritizing resource efficiency and achieving carbon neutrality. Policymakers should facilitate this shift through enabling policies and fostering global cooperation. United in these endeavors, we can expedite our journey towards a sustainable future, anchored by a shared commitment to innovation and ecological responsibility, aiming to fulfill our significant sustainability goals.

Author contributions

MM: Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–original draft. MN: Writing–original draft, Writing–review and editing, Conceptualization. BL: Supervision, Writing–review and editing, Project administration.

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Conflict of interest

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