Área temática: Gestão socioambiental

Título do trabalho: THE INTERSECTION OF TECHNOLOGY AND CIRCULAR ECONOMY PRATICES

Resumo

Este estudo explora a conexão entre o avanço tecnológico e a adoção de práticas sustentáveis sob a perspectiva da Economia Circular. Frente aos desafios ambientais atuais e à crescente demanda por modelos produtivos mais limpos, propõe-se um modelo funcional que auxilia organizações na condução de uma transição eficiente e sustentável. A pesquisa tem como foco identificar as etapas prioritárias antes da implementação tecnológica, analisar como a tecnologia pode fortalecer práticas sustentáveis e avaliar sua viabilidade em diferentes contextos empresariais. A metodologia adotada baseia-se em entrevistas com especialistas das áreas de sustentabilidade e inovação, cujos relatos contribuem para compreender, na prática, o papel das tecnologias da Indústria 4.0 nesse cenário. Os achados indicam que, embora a tecnologia exerça papel estratégico nesse processo, sua efetividade depende de um ambiente organizacional previamente estruturado e alinhado com princípios sustentáveis. Conclui-se que a articulação entre inovação tecnológica e economia circular é essencial para o fortalecimento de modelos de produção mais responsáveis e resilientes.

Keywords: Economia Circular, Sustentabilidade, Tecnologia, Indústria 4.0, Inovação.

Abstract

This study explores the connection between technological advancement and the adoption of sustainable practices from the perspective of the Circular Economy. In view of current environmental challenges and the growing demand for cleaner production models, a functional model is proposed to assist organizations in conducting an efficient and sustainable transition. The research focuses on identifying the priority steps before technological implementation, analyzing how technology can strengthen sustainable practices, and assessing its viability in different business contexts. The methodology adopted is based on interviews with experts in the areas of sustainability and innovation, whose reports contribute to understanding, in practice, the role of Industry 4.0 technologies in this scenario. The findings indicate that, although technology plays a strategic role in this process, its effectiveness depends on a previously structured organizational environment aligned with sustainable principles. It is concluded that the articulation between technological innovation and the circular economy is essential for strengthening more responsible and resilient production models.

Keywords: Circular Economy, Sustainability, Technology, Industry 4.0, Innovation.

1 Introduction

Currently, society faces the consequences of decades of environmental degradation resulting from human activities, particularly since the onset of industrialization. The Industrial Revolution undeniably represented a pivotal moment in history, significantly advancing productive systems through the introduction of machinery. However, as the adage suggests, “there is no free lunch”; the operation of these machines requires energy—whether from fossil fuels or renewable sources—and inevitably leads to the emission of pollutants into the atmosphere. (Ahuti, 2015). The exponential growth of industrial and urban activities has exponentially increased the emission of gases that damage the ozone layer, favor global warming and the greenhouse effect, and thus trigger a series of consequences such as the extinction of biomes; the melting of glaciers; the pollution of water and soil resources and climate change (Pereira & do Vale Pereira, 2012).

In this context, it is essential for companies to adopt sustainable practices to mitigate environmental degradation. The green transition has thus gained prominence among large organizations seeking to reduce the environmental impacts of their operations (Geng, Sarkis & Bleischwitz, 2019). Simultaneously, rapid technological advancement offers new possibilities (Popkova et al., 2022). It is therefore important to examine how such technologies can support sustainability efforts, despite the tendency of firms to prioritize profit and productivity over environmental goals (Fonseca, 2012). This study aims to explore how Industry 4.0 systems can reconcile economic performance with ecologically sustainable development.

Given the current climate crisis, the depletion of natural resources, and the widespread availability of emerging technologies, this study is motivated by the urgent need to examine the potential positive relationship between sustainability and technological innovation. This topic holds increasing relevance in the corporate sphere, where governance must adapt to the complex challenges of the digital era through strategic planning, systemic adjustments, and sustainable practices (Cortese et al., 2019). The circular economy model, centered on waste reduction and responsible production, aligns closely with technological tools that can facilitate these objectives. However, for this alignment to be effective, technological implementation must be guided by a clear understanding of circular principles. Without this foundation, the use of technology risks leading to inefficient automation, resource misallocation, and missed sustainability outcomes (Bradu et al., 2023).

This study is guided by the central research question: Is there a relationship between the adoption of technology and the transition to a Circular Economy? It seeks to analyze the causal link between these variables and how they can be structured within organizations to maximize results. The general objective is to propose a functional model that supports companies in adopting cleaner and more sustainable production through technological innovation. The specific objectives include: (i) identifying key steps prior to technology implementation (SO1); (ii) determining how technology can align with sustainable practices (SO2); and (iii) assessing the feasibility of technology adoption across different organizational contexts, considering goals and available resources (SO3). Accordingly, the study explores the phases necessary for a successful green transition and examines how technology can serve as a facilitator in this process. By proposing essential steps for responsible corporate growth and evaluating the interaction between technology and sustainability across diverse scenarios, the research contributes to the advancement of corporate environmental management.

The article presents an overview of the historical context of environmental impacts, the relationship between technology and sustainable practices, and a comparative analysis of linear and circular economic models. It also addresses relevant regulations, sustainability initiatives, and the technological foundations of Industry 4.0. The methodology involves in-depth interviews with experts, yielding insights and practical recommendations for organizational implementation.

2 Literature review

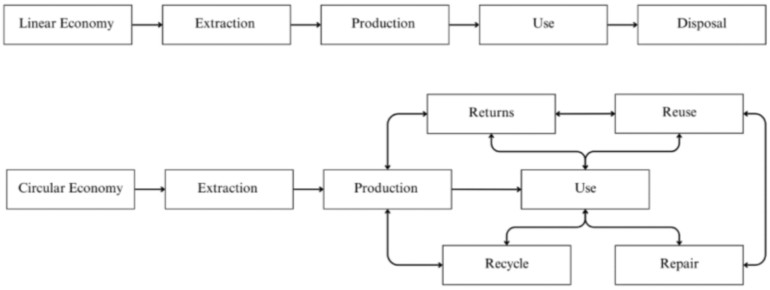
Over the past three decades, the linear economic model—based on the cycle of production, consumption, and disposal—has significantly impacted ecosystems, prompting regulatory interventions by global authorities concerning corporate use of natural capital and waste management (CN1, 2021). In response, sustainability has increasingly become a strategic priority for organizations, driven not only by internal awareness but also by growing pressure from investors and stakeholders focused on environmental, social, and governance (ESG) practices (Rau & Yu, 2024). In this context, long-term strategic thinking is essential for aligning profitability with purpose and transparency. The integration of social and environmentally responsible practices, without compromising organizational performance, is vital for long-term viability—positioning both technology and the circular economy as key enablers of this transformation. Since the Industrial Revolution, the linear economic model—based on extraction, production, consumption, and disposal—has dominated global production systems. Although effective in generating economic growth due to low production costs, this model has proven environmentally unsustainable (Sariatli, 2017). Considering current ecological challenges, transitioning to a circular economy has become a necessity rather than a choice.

2.1 Linear and circular model

The linear economy emerged with industrialization, supporting rapid economic expansion and improving living standards through mass production and intensive resource use (MacArthur, 2013). However, it relies heavily on non-renewable resources, emphasizes short product lifespans, lacks integration across value chains, and generates significant environmental externalities (Gubeladze & Pavliashvili, 2020). Its long-term impacts include global warming, pollution, and excessive waste accumulation, threatening both ecosystems and public health (Sariatli, 2017). While once successful, the “cradle-to-grave” logic of the linear model is now viewed as unsustainable and incompatible with the demands of the 21st century (MacArthur, 2013).

On the other hand, the circular economy (CE) complements Lean principles by aiming to balance economic development with environmental and social sustainability. It promotes the reintegration of materials into the production cycle through reduction, reuse, and recycling (Gonçalves & Barroso, 2019). Unlike the linear model, which moves from extraction to disposal, the CE model recognizes the finite nature of material and energy resources and seeks to close the loop of production. As illustrated in Figure 1, while the linear model reflects unplanned and inefficient resource use, the circular economy is based on redesigning products from the outset to enable post-use employability. In contrast to the linear model’s unsustainability due to resource scarcity and environmental degradation, CE offers economic, environmental, and social benefits, including reduced pollution, climate change mitigation, cost savings, and innovation—while enhancing quality of life and conserving public resources (MacArthur, 2013).

Figure 1 - Linear Economy x Circular Economy.



Source: The Authors (2024).

A major challenge to circularity is the widespread practice of planned obsolescence, particularly in sectors like electronics. Companies often design products with limited lifespans or promote constant upgrades through: (1) style obsolescence (consumer pressure to follow trends), (2) functional obsolescence (new features replacing older models), and (3) systemic obsolescence (e.g., battery failures or costly repairs) (Wilhelm, 2012; Rivera & Lallmahomed, 2016). However, some corporations are shifting toward circular strategies. Firms like Coca-Cola and General Motors have incorporated reverse logistics, recyclable inputs, and extended product lifecycles, demonstrating practical applications of CE principles (Romero-Hernández & Romero, 2018). Beyond environmental goals, the circular model also serves a strategic purpose—enhancing corporate reputation and market visibility (Geng, Sarkis, & Bleischwitz, 2019).

2.2. Inevitable transition to a circular economy

According to Sørensen (2018), the transition to a circular economy is inevitable for all organizations—even within laissez-faire economies. As natural resources become increasingly scarce and environmental degradation worsens, firms that do not voluntarily adopt circular practices will eventually be compelled to do so through regulatory mechanisms such as Pigouvian taxes. These taxes, designed to internalize negative externalities by reflecting environmental costs in production, encourage profit-maximizing firms to adopt cleaner and more efficient models.

Globally, the first steps toward a circular economy have been largely driven by legislation and public policy. In Brazil, the *Política Nacional de Resíduos Sólidos* (- Solid Waste National Policy - PNRS), established by Law No. 12.305/2010, set a legal framework for integrated waste management (Teixeira & Teixeira, 2022). In the European Union, the European Green Deal (2019) outlines a roadmap to achieve climate neutrality by 2050. The Netherlands, a global leader in circular initiatives, adopted a national strategy in 2016 that aims to make Amsterdam fully circular by 2050 (Ellen MacArthur Foundation, 2024). Similarly, China—despite its vast population and resource constraints—enacted the Law for the Promotion of Circular Economy in 2008, requiring provincial governments to incorporate CE in their investment plans (Cardoso, 2015). Thus, whether through voluntary corporate initiatives or regulatory enforcement, the shift toward a circular economy is both urgent and unavoidable in the face of global environmental challenges.

2.3. Sustainable practices

As there is always the opportunity to start with small actions and given that there is no magic recipe that points to sustainable practices that are viable in all organizations, in view of the available resources/capital added to the variety of sectors and markets (Gonçalves & Barroso, 2019), we have separated in this article some sustainable proposals so that each company can adapt and implement the items below considering its core and its organizational strategy.

2.3.1. 3Rs to 10Rs

As much as the definition of circular economy is vast, all definitions gravitate around a fundamental principle known as the "R framework". Initially, the EC principles emerged from the framework of the 3Rs – reduce, reuse, recycle (Junior & Nagai, 2024). Later, "Recover" was added as the fourth "R" through the European Union's Waste Framework Directive (Backes, 2020). Other frameworks have been proposed by academics and practitioners, such as the 5Rs - refuse, rethink, reduce, recycle (Ghosh, 2020) which evolved into the 6Rs - reduce, reuse, recycle, recover, remanufacture, and redesign (Joshi, Venkatachalam & Jawahir, 2006) to the 9Rs - refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (Potting, et al., 2017) and finally to the 10Rs - refuse, rethink, reduce, reuse, repair, refurbish remanufacture, repurpose, recycle, and recover (Rabaia, et al., 2024). Regardless of the amount of "Rs", all structures aim to transform the linear economy into a circular economy to sustainably use resources and minimize environmental impact.

2.3.2. Asset Management

Asset management is characterized as a set of practices to maximize the value of a company's assets by monitoring the life cycle, from their acquisition to their final disposal. It involves practices and techniques to intelligently manage an organization's tangible and intangible resources, in addition to having a direct connection with sustainability due to the fundamental role it plays in the use, maintenance, and preservation of natural and material resources (Acerbi, et al., 2020). In practice, asset management can manifest itself, for example, through energetic sustainability by reducing energy consumption; extending the useful life of equipment to prevent early replacements and the careful selection of suppliers to evaluate the composition and life cycle of the products supplied. These measures not only save companies the operation but also unequivocally improve the image and reputation since it is able to reduce their ecological footprint on the environment.

2.3.3. Reverse Logistics

It is a process that involves all logistical activities (collection, transport, storage, sorting, treatment or final disposal) of products or materials after consumption or sale with the aim of giving a purpose to this waste. As the name suggests, reverse logistics is classified as a version contrary to conventional logistics since both benefit from the same processes. Thus, the retrograde flow aims to send (discarded) products to the stages of remanufacturing, refurbishment, reuse or recycling (Mueller, 2005).

Currently, a great example of reverse logistics is in the technological field with the collection of used electronic products, which if disposed of incorrectly can contaminate water and soil due to their high composition of heavy metals and toxic substances. Case studies prove that even with limitations and deficiencies present in the reverse flow of this sector, e-commerce retailers experience through reverse logistics, an economy with less environmental impacts and more sustainability (Kokkinaki, et al., 2000).

2.3.4. Performance Economy

It is characterized by companies that practice the circular economy by changing the traditional business model, through the shift from the paradigm of ownership to the access economy. In short, in this type of economy the customer becomes a user of the products and not the owner of the products, this means that customers do not buy the products but rather have access to their use as needed (Ficci, 2018). Practical examples of this approach can be observed in companies such as Michelin Solutions, a company based in the United States that instead of following the standard model of selling tires chooses to rent them (Stahel & Stahel, 2010, p. 122). Similarly, YCloset, a Chinese clothing company where clothes are made available for rent (Colao, 2012). These companies are focused on modern solutions that are based on reuse and sustainability in consumption.

2.3.5. Sharing Economy

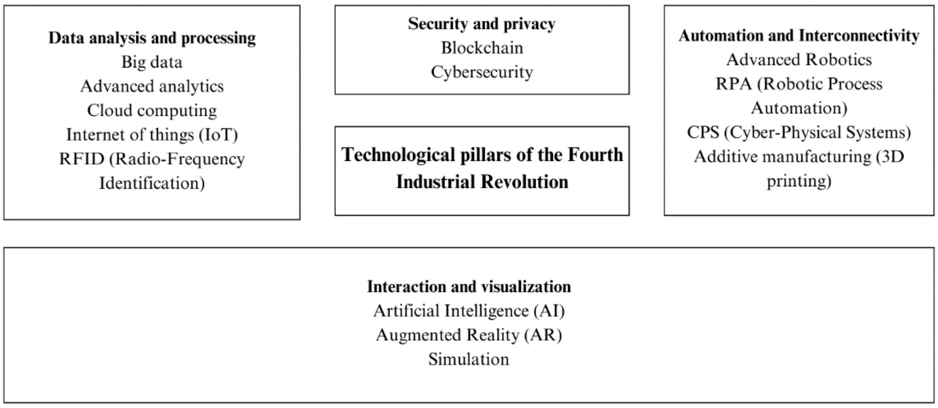
The sharing economy or also known as the collaborative economy is an economic model based on the philosophy of sharing surplus resources between individuals, businesses, or communities. In short, it offers a cost-effective and practical alternative to the consumption of goods and services, encouraging shared access in place of permanent ownership of assets and ultimately representing a step towards more sustainable practices (Stemler, 2017). Common examples include platforms like Uber and Airbnb, as well as bike-sharing systems, coworking, and even tools. Data from the World Economic Forum estimates that the sharing economy generated around US$ 229 million in 2015 with growth projections for the coming years (World Economic Forum, 2016). Therefore, the sharing economy is considered an enabler for the circular economy since customers are served through existing surplus products and services and not by the production of new ones (Egerton, 2016).

2.4. The Fourth Industrial Revolution – Requirements and Pillars of Industry 4.0

The rapid advancement of technology has reshaped consumption, production, and supply chain management, compelling firms to adopt innovation to stay competitive (Gubeladze & Pavliashvili, 2020). Industry 4.0 plays a critical role in this transformation by promoting virtualization, system connectivity, and integrated logistics to reduce waste and enhance operational efficiency (CNI, 2021). Its key principles include real-time monitoring, interoperability between humans and machines, and decentralized decision-making (Teixeira & Teixeira, 2021), supported by four main technological pillars: data analysis, security, automation, and interaction (Teixeira & Teixeira, 2022).

Data Analysis and Processing involves technologies such as Big Data, Advanced Analytics, Cloud Computing, IoT, and RFID. These tools enable rapid data management, real-time tracking, and strategic insights through AI and machine learning (Albertin et al., 2017; Inoue et al., 2019; Teixeira & Teixeira, 2022). *Security and Privacy* rely on Blockchain and Cybersecurity to ensure data integrity, confidentiality, and protection against cyber threats (Albertin et al., 2017; Teixeira & Teixeira, 2022). *Automation and Interconnectivity* include Advanced Robotics, RPA, CPS, and 3D Printing, which automate repetitive tasks, integrate digital and physical systems, and enable on-demand, flexible production (Albertin et al., 2017; Inoue et al., 2019). *Interaction and Visualization* technologies such as AI, AR, and Simulation support user interaction and strategic modeling, blending real and virtual elements for operational optimization (Albertin et al., 2017; Teixeira & Teixeira, 2022).

Figure 2 - Technological pillars of the Fourth Industrial Revolution.

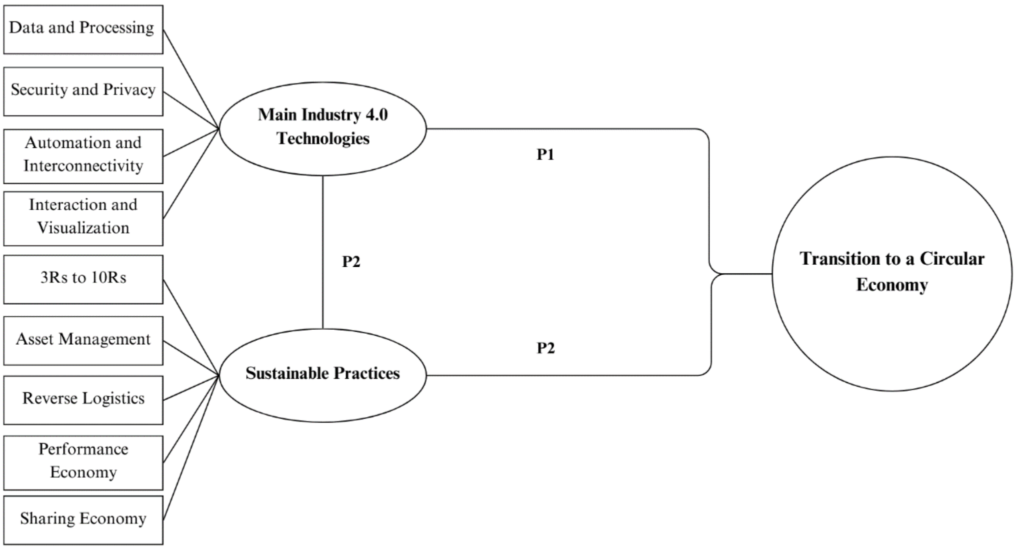


Source: The Authors (2024).

2.6. Theoretical framework proposal

The conceptual structure of this article can be represented by the relationship of some variables that represent the concepts of technology and sustainable practices. The variables that involve sustainable practices can be represented by 3Rs to 10Rs; Asset Management; Reverse Logistics; Performance Economy and Sharing Economy. The variables of Industry 4.0 technologies were grouped into groups according to their functionality, representing tools that help for data analysis and processing; security and privacy; automation and interconnectivity and interaction and visualization. Through these variables we can explain the propositions that represent anticipated answers to research questions. According to Yin (2009), this procedure helps the researcher to direct the work of collecting information.

Figure 3 - Proposed theoretical framework.



Source: The Authors (2024)

Proposition (P1) suggests that technology facilitates the transition to a circular economy by providing innovative tools for process optimization and resource management. Proposition (P2) posits that technology enhances productivity and operational efficiency, thereby influencing sustainable practices and enabling this transition. These propositions seek to clarify the relationships between technology and circular economy adoption, identifying key factors that impact successful implementation, which will be examined through the study’s methodological framework.

3 Methodology

This study utilized in-depth interviews with experts in technology and corporate sustainability to obtain detailed, contextual insights. This qualitative approach captures subjective experiences essential for comprehending complex phenomena, enabling researchers to interpret participants’ perceptions and beliefs (Boyce & Neale, 2006). The methodology was selected to provide a comprehensive understanding of the interaction between technology, sustainability, and modern business practices, addressing the research objectives. Participants were selected for their expertise aligned with the research focus (Rutakumwa et al., 2020). The first interviewee is a Sustainability Sales leader at a leading technology firm, specializing in applying innovations such as Artificial Intelligence to ESG, Enterprise Asset Management (EAM), and supply chain management. The second is a sales representative managing sustainability software portfolios in Brazil, with extensive experience in operational meteorology, business development, and ESG. An interview guide of 11 questions, developed from the literature review, addressed challenges, opportunities, and benefits of integrating technology with sustainability. It also examined how technological innovations support the alignment of sustainability with organizational goals, especially regarding the transition to a circular economy (Table 1).

Table 1 - Interview Script

Questions	**Theoretical Reference**
Q1: In your view, what is the role of technology in promoting sustainability?	(Popkova et al. 2022)
Q2: What are the main technologies that help for greater sustainability within companies?	(Teixeira & Teixeira, 2022)
Q3: What are the main barriers or the most significant challenges when associating technology and sustainability?	(Neves & Marques, 2022)
Q4: In your view, are companies currently looking for a more sustainable environment with less waste? Or is it a response to stakeholder expectations and pressures?	(Fonseca, 2012)
Q5: Can you share any examples of a sustainability project or initiative that has had a significant impact?	(Cortese, et al., 2019)
Q6: What are the sustainable practices in the operations in which you operate?	(MacArthur Foundation, 2013)
Q7: What are the key sustainability policies and guidelines you follow?	(Rau & Yu, 2024)
Q8: How do you handle sustainability-related regulatory compliance in different markets?	(Sariatli, 2017)
Q9: What are your recommendations/steps for a company that wants to start the transition to a cleaner economy?	(Sørensen, 2018)
Q10: What are the steps that you deem crucial for more sustainable practices before implementing the technology?	(Albertin, et al., 2017)
Q11: Do you believe that the use of technology for the implementation of more sustainable practices is feasible in all cases and types of companies?	(Bradu, et al., 2023)

Source: The Authors (2024)

4 Analysis and discussion of results

In-depth interviews revealed that both participants view technology as playing a significant and multifaceted role in promoting sustainability. Over the past decade, technological advancements have enhanced productivity and communication, increasing public awareness of environmental responsibility, such as proper waste disposal. One notable achievement is the substantial reduction in paper consumption through digitization of organizational processes, facilitating a transition to a circular economy. Companies leverage Industry 4.0 tools not only to minimize resource waste but also to achieve financial gains aligned with sustainable practices. Thus, technology integrated with green principles advances both environmental preservation and operational efficiency.

Participants shared success stories illustrating this synergy. Natura, a pioneer in sustainability since the 1970s, transformed the cosmetics market by introducing refillable products, reducing packaging costs and environmental impact while adding business value (Silva et al., 2021). Similarly, IBM has advanced sustainability since the 1990s, coupling social and governance initiatives with technological innovation. IBM's Envizi ESG Suite centralizes ESG data management, optimizing operations and generating approximately $80 million in annual savings. External clients such as Growthpoint and Melbourne Water have also benefited, improving emissions reporting and meeting UN Sustainable Development Goals through enhanced data transparency and management (IBM Case Studies, 2023). This Software as a Service (SaaS) consolidates dispersed data from various systems, simplifying sustainability management and enabling real-time identification and correction of energy inefficiencies across organizational units (Lucas, 2023).

4.1. Main barriers when associating technology and sustainability

The integration of sustainability and technology faces key challenges, primarily financial and human resource constraints. Technological investments often demand significant capital, and balancing these costs against environmental benefits remains difficult, especially due to the complexity and uncertainty in calculating Return on Investment (ROI) from sustainable innovations (Sobreira, 2022). Moreover, constantly evolving environmental regulations require ongoing staff training, adding to organizational workload and resource demands.

Technical risks also pose obstacles. Dependence on automated systems increases vulnerability to power outages and connectivity failures, potentially halting operations. Additionally, the risk of cyber-attacks and data breaches has grown, with serious legal and financial implications for organizations (Pandey, Singh & Gunasekaran, 2023). Interoperability remains another barrier: despite initiatives like the Matter Protocol, which aims to standardize communication across devices from major tech firms (Amazon, Google, Apple), incompatibility between platforms still hampers seamless data exchange (Zegeye, Jemal & Kornegay, 2023).

4.2. The search for sustainability: a voluntary movement or a response to the expectations and pressures of stakeholders?

Currently, companies pursue sustainability not only due to stakeholder pressure but also for economic efficiency. Reducing operational costs—such as paper, water, energy, and packaging—can enhance profitability while contributing to environmental goals, even when the primary motive is financial. This supports Sørensen's (2018) view that efforts to improve efficiency can lead to reduced environmental impacts, even if unintentionally. Stakeholder influence—exerted by investors, consumers, employees, NGOs, governments, and society—is increasingly significant. As resource scarcity and environmental degradation intensify, regulatory bodies impose stricter controls, and consumers and investors prioritize companies with strong ESG and CSR commitments.

Thus, the drive for sustainability often results from both internal values (e.g., ethics, corporate responsibility, brand reputation) and external pressures (e.g., regulation, market expectations). In many cases, legal mandates are the primary catalyst for corporate environmental engagement (Rau & Yu, 2024).

4.3. Sustainability guidelines and regulatory compliance in different markets

The jurisdiction, location, and sector in which a company operates determine the laws, regulations, and sustainability guidelines it must follow, guiding managerial decisions on essential and mandatory sustainable practices (Sariatli, 2017). For instance, the European Union enforces regulations such as REACH, which governs chemical safety, and the Industrial Emissions Directive (IED), which sets emission limits for industries. In the United States, laws like the Clean Air Act, Clean Water Act, and Resource Conservation and Recovery Act (RCRA) regulate air pollutants, water pollution, and waste management respectively.

In Brazil, legislation including the National Solid Waste Policy (PNRS), the Forest Code, and CONAMA directives govern waste disposal, forest conservation, and pollution control. China, despite resource constraints and population size, has implemented stringent environmental standards and promotes circular economy initiatives focused on recycling and reuse across households and businesses. Globally, sustainability policies reflect the principles of eco-efficiency introduced by the World Business Council for Sustainable Development (WBCSD) in 1992, emphasizing efficient resource management without increasing organizational marginal costs. Key eco-efficiency factors include reducing material and energy intensity, minimizing toxic substance dispersion, promoting recycling, maximizing renewable resource use, extending product lifespans, and increasing service intensity (Assunção, 2019).

Regulatory compliance varies by market and sector, highly regulated industries like mining and oil face strict environmental requirements. Publicly traded companies often disclose ESG practices through sustainability reports and international certifications. In contrast, smaller firms face fewer obligations, highlighting the importance of tailoring compliance to company size, sector, and market-specific regulations (Rau & Yu, 2024).

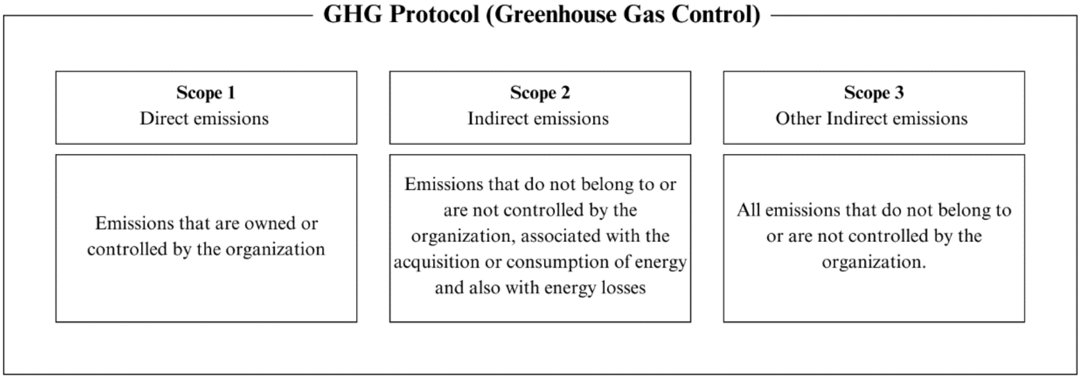
4.4. Recommendations regarding the circular journey

To initiate the transition toward a cleaner and more circular economy, the primary recommendation is to conduct a comprehensive assessment of resource usage and the environmental footprint generated by the organization. For small and medium-sized enterprises (SMEs), this can be achieved through asset management tools and operations management systems. Platforms such as Monday.com™ and Trello™ have been shown to support this transition by facilitating digital workflows, reducing paper use, and enhancing resource efficiency—ultimately lowering CO_2 emissions (Acerbi et al., 2020; Teixeira & Teixeira, 2022).

Everyday sustainable practices—such as minimizing printing and encouraging reusable materials—also contribute meaningfully to circular goals. Promoting such behavioral shifts often depends on education and awareness. Increased exposure to innovative procedures fosters understanding and encourages sustainable habits (Lucas et al., 2019). Thus, embedding sustainability values into training across all organizational levels is critical to cultural transformation.

For large and multinational organizations—particularly in sectors like energy, industry, finance, and public administration—monitoring greenhouse gas (GHG) emissions is essential. The GHG Protocol (2001) provides a global framework for this, categorizing emissions into three scopes. Scopes 1 and 2 are mandatory for participating organizations, while Scope 3 remains voluntary due to measurement challenges.

Figure 4 - Scopes of the GHG Protocol.



Source: The Authors (2024)

As the image above (Figure 4) explains, scope 1 deals with direct emissions from the company's own operation, scope 2 indicates indirect emissions associated with the consumption of electricity and other forms of energy necessary for operations, while scope 3 reports indirect emissions related to the entire supply chain. Practically exemplifying these scopes in the operation of a cake factory: the emissions from the oven (scope 1), the use of electricity (scope 2) and the transport and packaging of the product (scope 3). Therefore, the first step, regardless of the size of the organization, is to understand in detail the impact of organizations on the social and environmental environment in order to identify and implement strategies to optimize these ills, aiming at an economy towards sustainability and efficiency.

4.5. Crucial steps before implementing technology

Through an in-depth literature review and validation through rigorous methodology, the crucial steps before implementing technology in pursuit of a sustainable environment are as follows:

a) Initial Assessment: Perform a comprehensive evaluation of the company’s operations to identify primary emissions and environmental and social impacts. This diagnosis is fundamental for effectively guiding sustainability efforts and technology implementation.
b) Alignment with Goals and Values: Ensure sustainable practices align with the company’s mission and strategic objectives. A clear vision of sustainability goals integrated within the business model is essential.
c) Employee Education and Engagement: Educate and engage employees to foster shared understanding and commitment to sustainability goals, enhancing the effectiveness of initiatives.
d) Value-Based Hiring: Recruit employees whose values align with the company’s sustainability mission, as misalignment can hinder the adoption of sustainable practices.
e) Process Optimization and Waste Reduction: Prioritize optimizing existing processes and minimizing resource and time waste before introducing new technologies, enhancing operational efficiency and sustainability.

The literature emphasizes and the methodological means used proves that, in addition to the implementation of technology, these preliminary steps are essential to create a solid foundation for sustainable practices within the company.

4.6. Feasibility of using technology to adopt sustainable practices in companies of different sizes.

Given the planet's finite resources and escalating environmental impacts, fostering a sustainability mindset is crucial for all companies, regardless of size. However, the feasibility of adopting sustainable technologies varies. Small businesses, such as hair salons, can implement effective sustainability practices through simple measures like reducing water and energy waste without advanced technology. Conversely, larger firms, especially multinationals with complex, multi-site operations, require sophisticated sustainability technologies, such as resource management software, to effectively monitor and report their environmental performance (Acerbi et al., 2020). It is important to differentiate between technology types: basic, affordable technologies—like energy-efficient equipment—are accessible and beneficial for all business sizes, while advanced sustainability management systems are better suited for larger organizations. Therefore, the adoption of sustainability technologies should be tailored to each company's size, scope, and specific needs.

5 Conclusions

Technological evolution enhances process efficiency and productivity, and its integration with circular economy (CE) principles can significantly transform business performance. Holistically incorporating technology into operations and strategies offers a competitive advantage by fostering innovation, sustainability, and organizational resilience (Popkova et al., 2022). Current technological trends also favor companies adopting more conscious business models (Teixeira & Teixeira, 2022). However, technology should not be viewed as the primary step in the CE transition. Organizational culture, leadership training, and workflow redesign must precede technological implementation, as introducing innovation in disorganized environments hampers success. Prioritizing actions and defining clear objectives are essential to ensuring an effective circular model.

While technology aligned with CE concepts can yield remarkable benefits, its adoption must be evaluated within each organization's context. Factors such as organizational maturity, available investment, and specific challenges determine feasibility, as some technologies may be prohibitively costly and impede transition (Neves & Marques, 2022). Sustainable production aims to reduce waste and costs, necessitating a tailored assessment of whether technology is the most suitable and viable facilitator for each company's clean economy transition.

This study underscores technology's critical role in advancing circular economy practices in modern industries. By elucidating the relationship between technology and sustainability and assessing its viability across contexts, we propose a comprehensive framework for companies pursuing cleaner, more efficient production. Properly aligned technological adoption enhances resource efficiency, minimizes environmental impact, and fosters economic growth, thereby supporting sustainable business models that ensure ecological balance and long-term resilience amid global environmental challenges.

References

Acerbi, F., Polenghi, A., Roda, I., Macchi, M., & Taisch, M. (2020). Exploring synergies between circular economy and asset management. In *Advances in Production Management Systems. Towards Smart and Digital Manufacturing: IFIP WG 5.7 International Conference, APMS 2020, Novi Sad, Serbia, August 30–September 3, 2020, Proceedings, Part II* (pp. 695-702). Springer International Publishing.

Ahuti, S. (2015). Industrial growth and environmental degradation. *International Education and Research Journal*, *1*(5), 5-7.

Albertin, M. R., Elienesio, M. L. B., Aires, A. D. S., Pontes, H. L. J., & Aragão Junior, D. P. (2017). Principais inovações tecnológicas da indústria 4.0 e suas aplicações e implicações na manufatura.

Assunção, G. M. (2019). A gestão ambiental rumo à economia circular: como o Brasil se apresenta nessa discussão. *Sistemas & Gestão*, *14*(2), 223-231.

Backes, C. (2020). The waste framework directive and the circular economy. In *Research handbook on EU environmental law* (pp. 328-343). Edward Elgar Publishing.

Boyce, C., & Neale, P. (2006). *Conducting in-depth interviews: A guide for designing and conducting in-depth interviews for evaluation input* (Vol. 2). Watertown, MA: Pathfinder international.

Bradu, P., Biswas, A., Nair, C., Sreevalsakumar, S., Patil, M., Kannampuzha, S., ... & Gopalakrishnan, A. V. (2023). Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future. Environmental Science and Pollution Research, 30(60), 124488-124519.

Cardoso, N. R. (2015). A china e o seu novo modelo de desenvolvimento sustentável.

CNI. Circular, C. E. (2021). Caminho Estratégico para a Indústria Brasileira.

Colao, J. (2012). Welcome to the new millennial economy: Goodbye ownership, hello access. *Forbes.* Available in:<https://www. forbes. com/sites/jjcolao/2012/10/11/welcome-to-the-new-millennial-economy-goodbye-ownership-hello-access>. Accessed on: June 26th, 2024.

Cortese, T. T. P., Coutinho, S. V., Vasconcellos, M. D. P., & Buckeridge, M. S. (2019). Tecnologias e sustentabilidade nas cidades. Estudos Avançados, 33(97), 137-150.

Ellen Macarthur Foundation. Visando a 100% de circularidade: Amsterdã, 2024. Available in: <https://www.ellenmacarthurfoundation.org/pt/exemplos-circulares/moldando-uma-economia-compartilhada-amsterda>. Accessed on: June 22nd, 2024.

Egerton, S. (2016, August 4). What does the sharing economy mean for a circular economy? Available in:<http://circulatenews.org/2016/08/what-does-the-sharing-economy-mean-for-acircular-economy/>. Accessed on: July 13th, 2024.

Ficci, A. S. (2018). Accelerating India's Circular Economy Shift: A Half-Trillion USD Opportunity: Future-Proofing Growth in a Resource-Scarce World. *FICCI: New Delhi, India*.

Fonseca, R. R. (2012). A sustentabilidade e a economia verde como desafios tecnológicos. Revista USP, (93), 127-136.

Geng, Y., Sarkis, J., & Bleischwitz, R. (2019). How to globalize the circular economy. Nature, 565(7738), 153-155.

Ghosh, S. K. (2020). Circular economy in India. *Circular economy: Global perspective*, 157-185.

Gonçalves, T. M., & Barroso, A. F. D. F. (2019). A economia circular como alternativa à economia linear. Anais do XI SIMPROD.

Gubeladze, D., & Pavliashvili, S. (2020). Linear economy and circular economy-current state assessment and future vision. International Journal of Innovative Technologies in Economy, (5 (32)).

IBM Case Studies. (2023). Available in:< https://www.ibm.com/products/envizi/case-studies>. Accessed on: June 17th, 2024.

Inoue, J. S. P., Bittencourt, M. V. A. R., Pinto, S. B., Geribello, R. S., & Amarante, M. S. (2019). Indústria 4.0 –Impactos da tecnologia da informação na nova indústria. Pesquisa e Ação (ISSN 2447-0627), V5, N1.

Junior, A. S. T., & Nagai, R. A. (2024). Lean and Green: 3Ms Meets 5Rs Creating Environmental Value for the Planet. In *Entrepreneurship, Technological Change and Circular Economy for a Green Transition: Research Contributions for a More Productive Environment* (pp. 99-119). Cham: Springer Nature Switzerland.

Joshi, K., Venkatachalam, A., & Jawahir, I. S. (2006, October). A new methodology for transforming 3R concept into 6R concept for improved product sustainability. In *IV global conference on sustainable product development and life cycle engineering* (pp. 3-6).

Kokkinaki, A. I., Dekker, R., Van Nunen, J. A. E. E., & Pappis, C. (2000, January). An exploratory study on electronic commerce for reverse logistics. In *Supply chain forum: An international Journal* (Vol. 1, No. 1, pp. 10-17). Taylor & Francis.

Lucas, M. (2023). Futurology. *ITNOW*, *65*(3), 19-19.

Lucas, M. R., Sousa, K. A., Joaquina Ramos, I., & Rego, C. (2019). Sustainable Development, Circular Economy and Entrepreneurship Education. *Innovation research: multiple looks towards a formative convergence (electronic resource)*, 13-30.

MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2(1), 23-44.

Mueller, C. F. (2005). Logística reversa meio-ambiente e produtividade. *Grupo de Estudos Logísticos-UFSC, Florianópolis*.

Neves, S. A., & Marques, A. C. (2022). Drivers and barriers in the transition from a linear economy to a circular economy. *Journal of Cleaner Production*, *341*, 130865.

Pandey, S., Singh, R. K., & Gunasekaran, A. (2023). Supply chain risks in Industry 4.0 environment: review and analysis framework. *Production Planning & Control*, *34*(13), 1275-1302.

Pereira, F., Manfio, V. F., & do Vale Pereira, L. T. (2012). Revolução Industrial e suas consequências.

Popkova, E. G., De Bernardi, P., Tyurina, Y. G., & Sergi, B. S. (2022). A theory of digital technology advancement to address the grand challenges of sustainable development. Technology in Society, 68, 101831.

Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). Circular economy: measuring innovation in the product chain. *Planbureau voor de Leefomgeving*, (2544).

Rabaia, M. K. H., Shehata, N., Olabi, V., Abdelkareem, M. A., Semeraro, C., Chae, K. J., & Sayed, E. T. (2024). Enabling the circular economy of solar PV through the 10Rs of sustainability: Critical review, conceptualization, barriers, and role in achieving SDGs. *Sustainable Horizons*, *11*, 100106.

Rau, P. R., & Yu, T. (2024). A survey on ESG: investors, institutions and firms. China Finance Review International, 14(1), 3-33.

Rivera, J. L., & Lallmahomed, A. (2016). Environmental implications of planned obsolescence and product lifetime: a literature review. International Journal of Sustainable Engineering, 9(2), 119-129.

Romero-Hernández, O., & Romero, S. (2018). Maximizing the value of waste: From waste management to the circular economy. Thunderbird International Business Review, 60(5), 757-764.

Rutakumwa, R., Mugisha, J. O., Bernays, S., Kabunga, E., Tumwekwase, G., Mbonye, M., & Seeley, J. (2020). Conducting in-depth interviews with and without voice recorders: a comparative analysis. *Qualitative Research*, *20*(5), 565-581.

Sariatli, F. (2017). Linear economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability. Visegrad Journal on Bioeconomy and Sustainable Development, 6(1), 31-34.

Silva, T. G. E., Emerenciano, A. C. D. S. J., Musetti, M. A., & Ometto, A. R. (2021). Economia circular: um panorama do estado da arte das políticas públicas no Brasil. *Revista produção online*, *21*(3), 951-972.

Stahel, W. R., & Stahel, W. R. (2010). Selling Performance. *The Performance Economy*, 86-178.

Stemler, A. (2017). The myth of the sharing economy and its implications for regulating innovation. *Emory LJ*, *67*, 197.

Sobreira, D. P. (2022). Desempenho econômico-financeiro das empresas listadas na B3 pertencentes ao segmento energia elétrica.

Sørensen, P. B. (2018). From the linear economy to the circular economy: A basic model. *FinanzArchiv/Public Finance Analysis*, 71-87.

Teixeira, C. H. S. B., & Teixeira, R. L. P. (2021). Cenário da indústria 4.0 e a gestão da qualidade (p. 175-183).

Teixeira, C. H. S. B., & Teixeira, R. L. P. (2022). Convergences between circular economy and Industry 4.0 practices. *Revista de Gestão Social e Ambiental*, *16*(2), 1-18.

Wilhelm, W. B. (2012). Encouraging sustainable consumption through product lifetime extension: The case of mobile phones. International Journal of Business and Social Science, 3(3).

Yin, R. K. (2009). *Case study research: Design and methods* (Vol. 5). sage.

Zegeye, W., Jemal, A., & Kornegay, K. (2023, January). Connected smart home over matter protocol. In *2023 IEEE International Conference on Consumer Electronics (ICCE)* (pp. 1-7). IEEE.

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