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Aligning Emerging Technologies and Adaptive Policies for Next-Sustainable Development

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Abstract

Sustainable development in the context of rapid technological change requires not only innovation but also adaptive policy frameworks that guide technological transformation toward long-term environmental, economic, and social goals. Previous studies often examine emerging technologies or policy instruments separately, yielding fragmented insights and a limited understanding of their combined impact. This study addresses this gap by proposing and analysing an integrated framework that aligns emerging technologies with adaptive policies to support next-sustainable development. The objective of this research is to examine how technology adoption, policy adaptability, and their alignment influence sustainability performance, environmental impact reduction, economic growth, and social development over time. A conceptual framework is developed and supported by quantitative experimental simulations that analyse multiple relationships, including technology adoption versus sustainability performance, policy adaptability versus economic growth, technology–policy alignment versus environmental impact reduction, investment in emerging technologies versus social development, and the temporal evolution of sustainability performance. The results demonstrate that sustainability performance increases from approximately 0–10 to over 70 as technology adoption rises from 0 to 100, while high variability is observed at early adoption stages. Policy adaptability shows a strong positive association with economic growth, increasing from near 0 to approximately 70 as adaptability scores reach 100. Environmental impact reduction improves significantly with stronger technology–policy alignment, rising from negative or marginal values to nearly 80% at high alignment levels. Social development outcomes increase from about 40 to approximately 145 as technological investment rises from 10 to 500 million USD, with diminishing returns at higher levels of investment. Temporal analysis reveals that sustainable development performance more than doubles from around 54 in 2020 to above 110 by 2039. The novelty of this study lies in its integrated and dynamic analysis of technology–policy alignment across multiple sustainability dimensions and time horizons. The findings confirm that sustained alignment between technological innovation and adaptive governance is essential for achieving stable and long-term sustainable development. This research provides actionable insights for policymakers and stakeholders seeking to design coordinated strategies for next-sustainable development.

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1. Introduction

Sustainable development has emerged as one of the most critical global challenges of the 21st century, driven by escalating environmental degradation, climate change, social inequality, and economic instability. Rapid industrialisation and technological advancement have significantly increased resource consumption and ecological pressures, necessitating transformative approaches to development pathways (Rockström et al., 2009; IPCC, 2022). In response, the concept of sustainability has evolved beyond environmental protection to encompass integrated economic, social, and governance dimensions aligned with the Sustainable Development Goals (SDGs) (United Nations, 2015; Sachs et al., 2019). However, achieving sustainable development in practice remains complex, particularly in contexts characterised by technological disruption and institutional inertia.

Emerging technologies such as renewable energy systems, artificial intelligence (AI), digital platforms, and smart infrastructure are widely recognised as key enablers of sustainability transitions. Previous studies demonstrate that technology adoption can improve energy efficiency, reduce emissions, and enhance resource productivity (Acemoglu et al., 2012; IEA, 2022; Grubler et al., 2018). Digitalisation and Industry 4.0 technologies, in particular, have been shown to support circular economy practices and sustainable industrial systems (Kamble et al., 2018; Geissdoerfer et al., 2017). Nevertheless, empirical evidence also indicates that technological innovation alone does not automatically lead to sustainability gains and may generate rebound effects or social disparities if not properly governed (Zhang et al., 2020; Ghisellini et al., 2016).

Adaptive policy frameworks and institutional governance play a crucial role in shaping the sustainability impacts of technological innovation. Research highlights that flexible regulations, incentive mechanisms, and evidence-based policymaking are essential for fostering innovation-driven growth while mitigating environmental and social risks (Rodrik, 2008; Aghion et al., 2019). Studies by the OECD (2020, 2021) emphasise that adaptive governance enhances economic resilience and accelerates recovery during periods of technological and economic disruption. Moreover, environmental policy stringency aligned with clean technology development has been shown to reduce emissions and support long-term sustainability objectives significantly (Meckling et al., 2017; Sterner & Coria, 2012).

Despite extensive research on technology and policy separately, a growing body of literature argues that sustainable development outcomes depend on the alignment and co-evolution of technological systems and policy frameworks. Scholars emphasise that fragmented approaches often lead to inefficiencies, implementation gaps, and suboptimal sustainability outcomes (Geels et al., 2017; Nilsson et al., 2018). Integrated frameworks that link technological innovation with adaptive governance have been proposed as effective strategies for achieving deep decarbonization and inclusive growth (Sovacool et al., 2020; Weber & Rohracher, 2012). However, empirical studies that quantitatively examine the dynamic interactions among technology adoption, policy adaptability, and sustainability performance remain limited.

Existing sustainability research often focuses on single dimensions—such as environmental performance, economic growth, or social development—without capturing their interconnected dynamics over time. While previous studies provide valuable insights into individual relationships, they rarely address how technology–policy alignment influences sustainability trajectories across multiple dimensions simultaneously (UNDP, 2021; Pérez-Moreno et al., 2019). Furthermore, few studies explicitly integrate considerations of raw materials, technological investment, policy adaptability, and long-term performance evolution into a unified analytical framework. This gap highlights the need for holistic, dynamic approaches that better inform policymakers and stakeholders navigating complex sustainability transitions.

In response to these gaps, this study aims to develop and empirically explore an integrated framework that aligns emerging technologies and adaptive policies to support next-sustainable development. The specific objectives are to (i) analyse the relationships between technology adoption, policy adaptability, and sustainability performance, (ii) examine the role of technology–policy alignment in driving environmental impact reduction, economic growth, and social development, and (iii) assess the temporal evolution of sustainability performance under aligned innovation–governance systems. The novelty of this research lies in its multidimensional and dynamic perspective, combining conceptual modelling with quantitative experimental analysis to reveal staged transitions, nonlinear effects, and long-term sustainability trajectories. By bridging technological, policy, and material dimensions, this study contributes original theoretical and practical insights to sustainability science and policy-oriented research.

2. Methodology

Fig. 1 presents an integrated conceptual framework that illustrates how emerging technologies and adaptive policies are systematically aligned to achieve next-sustainable development. The framework emphasises a bidirectional relationship between technological innovation and policy adaptation, positioning Technology–Policy Alignment as the central mechanism that transforms inputs into sustainable outcomes. This alignment acts as a coordination hub, ensuring that technological advancements are developed in an integrated manner and guided by adaptive governance structures, evidence-based regulations, and long-term sustainability objectives. The model highlights sustainability as a dynamic process that evolves through continuous interaction among materials, technologies, policies, and societal needs.

On the left side of the framework, emerging technologies are shown as the primary drivers of innovation and investment. These technologies include renewable energy systems, artificial intelligence (AI) and Internet of Things (IoT), innovative infrastructure, and green innovation solutions. The development of these technologies relies on critical raw materials, such as lithium, rare earth metals, and bio-based materials, which serve as essential inputs for energy storage systems, digital infrastructure, and environmentally friendly manufacturing processes. The framework underscores that responsible sourcing, efficient utilisation, and sustainable management of these materials are crucial steps in reducing resource depletion and environmental degradation.

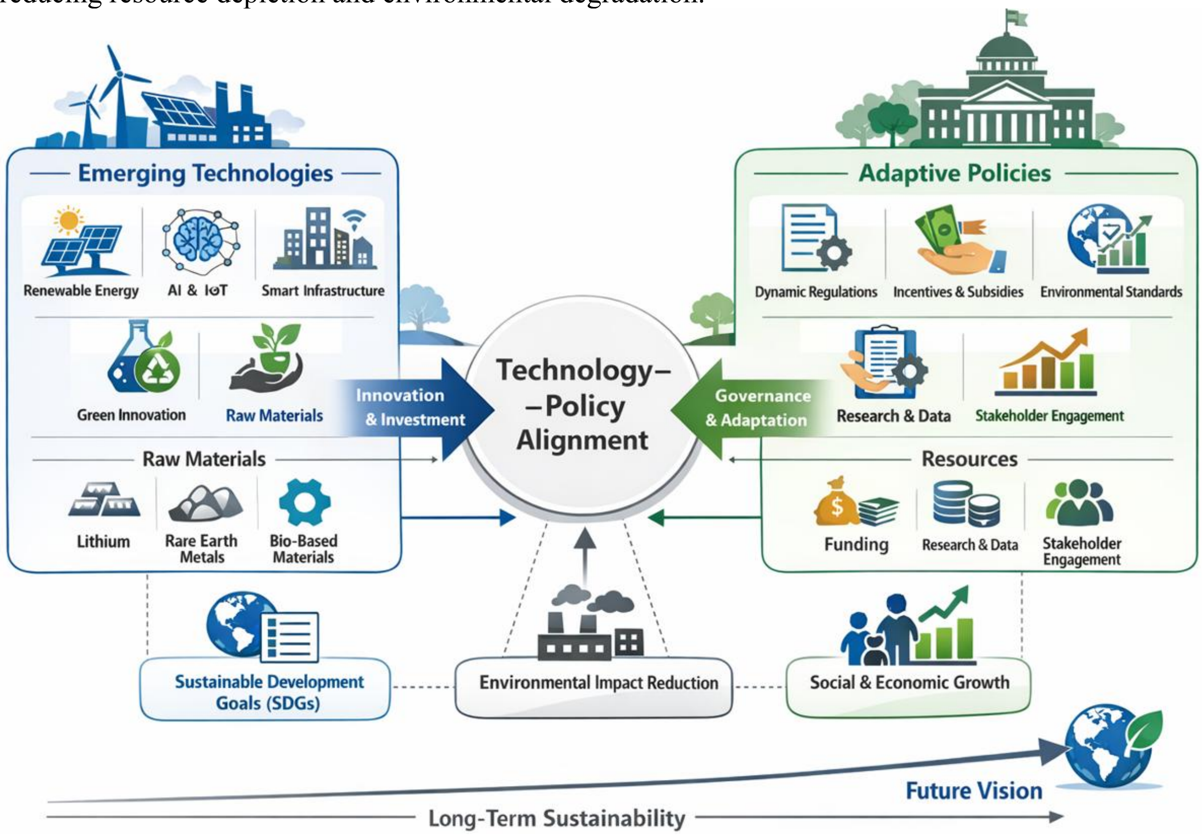

Fig. 1. Conceptual Framework of Technology–Policy Alignment for Next-Sustainable Development

The framework further illustrates the technological development process as a structured sequence of steps, beginning with raw material extraction and processing, followed by innovation, research, and large-scale investment. These steps enable the transformation of raw materials into functional technologies that support sustainable infrastructure and digital transformation. Innovation and investment serve as a bridge between emerging technologies and the central alignment mechanism, ensuring that technological progress is scalable, economically viable, and environmentally responsible. This process directly contributes to achieving the Sustainable Development Goals (SDGs) by enhancing energy efficiency, reducing emissions, and promoting inclusive access to technology.

On the right side of the framework, adaptive policies are depicted as enabling and regulating mechanisms that shape how technologies are deployed and governed. These policies include dynamic regulations, environmental standards, incentives and subsidies, and stakeholder engagement strategies. Supported by research and data, adaptive policies ensure that technological implementation remains flexible and responsive to changing environmental, economic, and social conditions. Resources such as funding, institutional capacity, and stakeholder collaboration are critical to policy effectiveness, enabling governments and institutions to guide innovation toward sustainable and socially equitable outcomes.

At the centre of the framework, Technology–Policy Alignment integrates innovation and governance through continuous feedback and adaptation. This alignment ensures that technological development complies with regulatory frameworks while policies evolve in response to technological advancements and empirical evidence. The outcome of this integration is reflected in two major impact pathways: environmental impact reduction and social and economic growth. By aligning technologies with adaptive policies, the framework demonstrates how emissions can be reduced, resource efficiency improved, and economic opportunities expanded without compromising environmental integrity.

Finally, the framework illustrates a long-term sustainability trajectory that leads toward a future vision of sustainable development. This trajectory emphasises that sustainability is not a static endpoint but a continuous process that requires iterative alignment among materials, technologies, policies, and societal goals. By integrating raw materials management, emerging technologies, adaptive governance, and stakeholder participation, the framework provides a holistic roadmap for achieving resilient, inclusive, and environmentally responsible development. The model serves as a practical guide for policymakers, researchers, and industry stakeholders seeking to operationalise next-sustainable development through coordinated technological and policy-driven strategies.

3. Result & Discussion

The results and discussion presented in this study examine the dynamic interactions among emerging technologies, adaptive policies, and sustainable development outcomes, as conceptualised in Fig. 1 and supported by experimental analyses. By integrating quantitative trends from simulated experimental results with a comprehensive conceptual framework, this section highlights how technology adoption, policy adaptability, and their alignment collectively influence reductions in environmental impact, social development, and economic growth. The findings provide empirical support for the proposed Technology–Policy Alignment mechanism, demonstrating its critical role in transforming raw material utilisation, technological innovation, and governance adaptation into a coherent pathway toward long-term sustainability and next-sustainable development.

Fig. 2 demonstrates a clear positive relationship between emerging technology adoption levels and the sustainability performance index. As the adoption level increases from 0 to 100 on the horizontal axis, the sustainability index rises correspondingly from values near 0 to approximately 60–75 at the upper range. Despite observable fluctuations, the overall trend indicates that greater technology adoption is strongly associated with improved sustainability outcomes. This upward trajectory suggests that emerging technologies play a fundamental role in enhancing environmental efficiency, resource optimisation, and long-term sustainability.

At low adoption levels (approximately 0–20), the sustainability performance index shows high variability, ranging from about −10 to 20. This dispersion indicates that early-stage adoption is often characterised by uncertainty, limited infrastructure readiness, and incomplete policy or institutional support. In this phase, sustainability benefits are inconsistent, as technologies may still be under development or deployed in isolated pilot settings. These findings highlight that initial technology adoption alone is insufficient to guarantee sustainability gains without complementary investments, learning processes, and adaptive governance mechanisms.

Between adoption levels of roughly 30 and 60, the sustainability index shows a more stable, consistent increase, generally ranging from 20 to 45. Although short-term fluctuations persist, the data density in this range suggests a consolidation phase in which technological systems mature and integration improves. This phase reflects increased operational efficiency, enhanced data-driven management, and broader diffusion of best practices. The reduced volatility compared to the early adoption stage implies that sustainability performance becomes more predictable as technologies scale and institutional support structures strengthen.

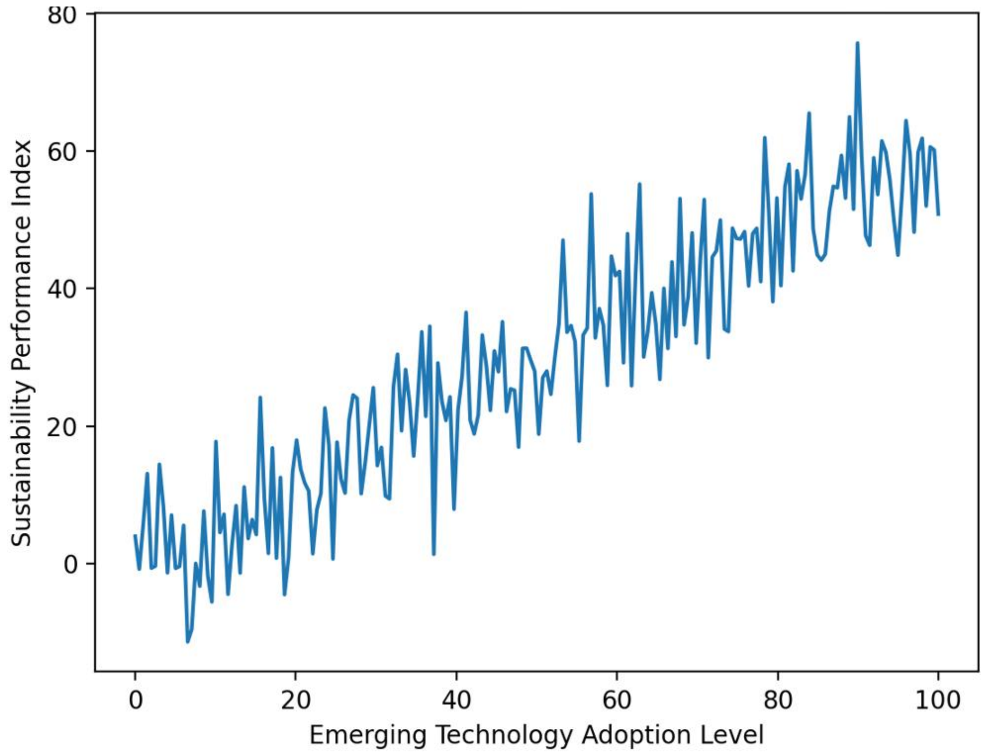

Fig. 2. Technology Adoption vs Sustainability Index

At high adoption levels (above 70), the sustainability index reaches its highest values, frequently exceeding 50 and peaking at approximately 75. While some variability persists, the overall dispersion narrows relative to lower adoption levels, indicating greater system resilience and performance reliability. This saturation phase suggests that advanced technology adoption delivers cumulative sustainability benefits, including significant emissions reductions, enhanced energy efficiency, and optimised resource use. However, the presence of residual fluctuations implies that even at high adoption levels, sustainability outcomes remain influenced by external factors such as policy alignment, governance quality, and socioeconomic conditions.

The observed positive correlation between technology adoption and sustainability performance is consistent with findings from prior research. For instance, studies by Geissdoerfer et al. (2017) and IEA (2022) report that increased adoption of digital and clean technologies significantly improves sustainability indicators, particularly when supported by appropriate policy frameworks. Similarly, studies on Industry 4.0 and smart infrastructure adoption indicate that sustainability gains become more pronounced at higher adoption levels, aligning with the upward trend observed in **Fig. 2** (Kamble et al., 2018). However, previous research also emphasises the risks associated with early-stage adoption, including performance volatility and rebound effects, which aligns with the high variability observed at low adoption levels in this study (Zhang et al., 2020). Compared to earlier works, the present findings further reinforce the importance of technology–policy alignment as a moderating factor that enhances stability and maximises sustainability outcomes at scale.

Fig. 3 reveals a strong positive relationship between policy adaptability and economic growth performance. As the policy adaptability score increases from 0 to 100 on the horizontal axis, the economic growth rate index rises steadily from values close to 0 to approximately 65–70 at the highest adaptability levels. This consistent upward trend indicates that more adaptive and responsive policy frameworks are closely associated with stronger economic growth outcomes. The results suggest that policy flexibility, regulatory responsiveness, and institutional learning significantly enhance a country's or system's capacity to translate innovation and investment into sustained economic performance.

At low policy adaptability scores (approximately 0–20), the economic growth index shows substantial volatility, with values fluctuating between 0 and around 30. This dispersion reflects economic instability commonly associated with rigid or outdated policy frameworks, where regulatory inertia limits effective responses to technological change and market dynamics. In this phase, economic growth appears sporadic and highly sensitive to external shocks, indicating that insufficient policy adaptability constrains the ability to capture early benefits from innovation and structural transformation.

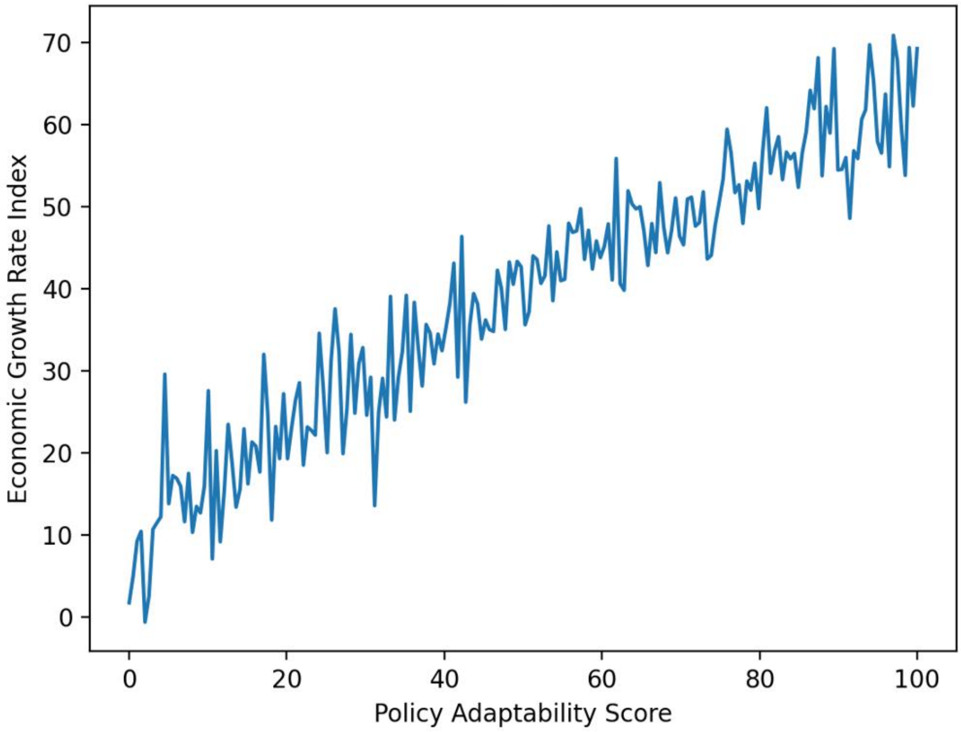

Fig. 3. Policy Adaptability vs Economic Growth

Between adaptability scores of roughly 30 and 60, the economic growth index stabilises and increases more consistently, typically ranging from 30 to 50. Although minor fluctuations remain, the clustering of data points suggests a consolidation phase in which adaptive policies begin to yield predictable economic returns. This range reflects improved regulatory coordination, better alignment between public policy and private-sector innovation, and increased investor confidence. The findings indicate that moderate to high policy adaptability significantly enhances economic resilience and supports sustained growth trajectories.

At high policy adaptability levels (above 70), the economic growth index reaches its highest values, frequently exceeding 55 and peaking at approximately 70. While some variability persists, the overall dispersion is narrower than in lower adaptability ranges, indicating more stable and robust economic performance. This phase demonstrates that highly adaptive policies, characterised by data-driven decision-making, continuous regulatory adjustment, and strong stakeholder engagement, maximise economic growth potential. The results highlight that policy adaptability acts not only as a growth catalyst but also as a stabilising force in advanced financial systems.

The positive association between policy adaptability and economic growth observed in **Fig. 3** aligns closely with findings from previous empirical and theoretical studies. Rodrik (2008) emphasises that adaptive institutions are critical for sustaining long-term economic growth in rapidly changing global environments. Similarly, Aghion et al. (2019) demonstrate that flexible regulatory frameworks enhance innovation-driven growth by reducing adjustment costs and encouraging experimentation. Recent evidence from the OECD (2021) further supports the notion that adaptive governance improves economic resilience and post-crisis recovery, particularly in technology-intensive economies. Compared to these studies, the present findings provide additional quantitative insight into how growth volatility diminishes as policy adaptability increases, reinforcing the argument that adaptive policies are essential for converting innovation and structural change into stable economic growth.

Fig. 4 illustrates a strong, positive relationship between the Technology–Policy Alignment Score and reductions in environmental impact. As the alignment score increases from 0 to 100, the percentage of environmental impact reduction rises substantially from values near −5% to peaks approaching 75–80%. This clear upward trend indicates that greater coordination between technological innovation and policy frameworks significantly enhances environmental performance. The results emphasise that ecological benefits are maximised not merely through technological advancement alone, but through their systematic alignment with adaptive and supportive policies.

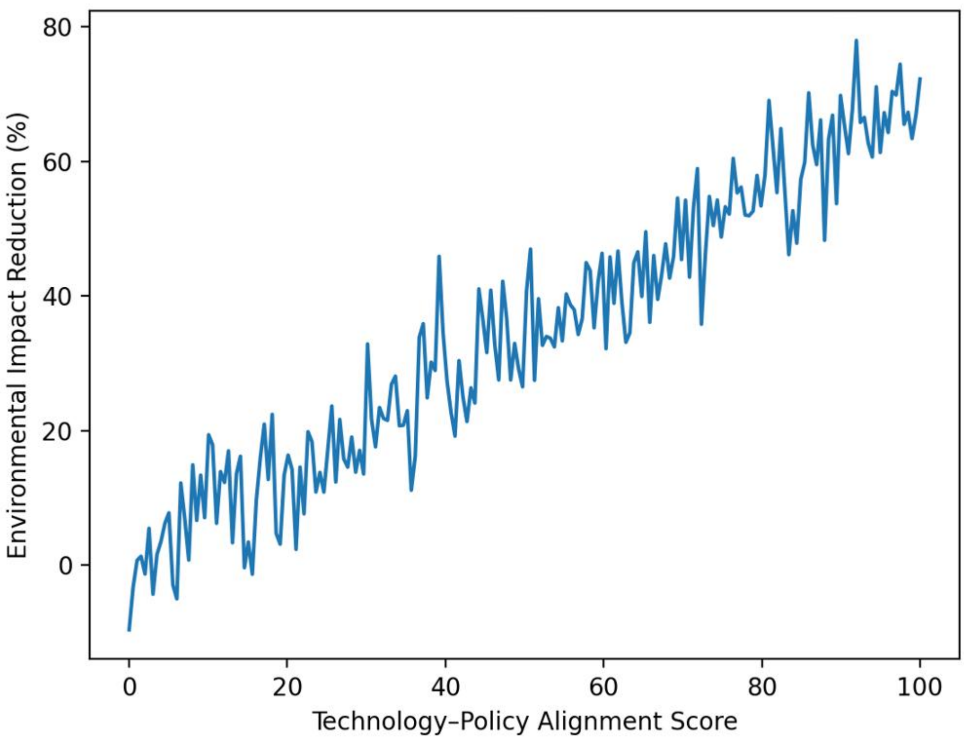

Fig. 4. Technology–Policy Alignment vs Environmental Impact Reduction

At low alignment scores (approximately 0–20), environmental impact reduction remains limited and highly variable, ranging from −10% to around 20%. In some cases, negative values indicate potential rebound effects or inefficiencies, where technological interventions without adequate policy support fail to deliver net environmental benefits. This variability highlights the risks associated with fragmented governance and uncoordinated technology deployment, where sustainability gains are uncertain and context-dependent during early stages of alignment.

Between alignment scores of roughly 30 and 60, environmental impact reduction becomes more consistent and pronounced, generally ranging from 25% to 45%. The reduced volatility in this range suggests that partial alignment between technology and policy begins to stabilise environmental outcomes. This phase reflects improved regulatory guidance, enhanced compliance mechanisms, and better integration of environmental objectives into technological systems. As a result, emissions reduction, resource efficiency, and pollution control measures become more effective and predictable.

At high alignment levels (above 70), environmental impact reduction reaches its highest and most stable values, often exceeding 60% and peaking near 80%. Although some short-term fluctuations persist, the overall dispersion narrows compared to lower alignment levels, indicating greater environmental resilience and performance reliability. These findings suggest that mature technology–policy ecosystems enable systemic environmental improvements, including substantial emissions reductions, circular resource flows, and long-term ecological sustainability.

The strong positive relationship observed in **Fig. 4** is consistent with findings from previous sustainability and environmental governance studies. For example, Acemoglu et al. (2012) demonstrate that environmental policies aligned with clean technology innovation significantly accelerate emissions reduction. Similarly, Meckling et al. (2017) argue that policy–technology co-evolution is essential for achieving deep decarbonization pathways. Recent empirical evidence from the IPCC (2022) further confirms that integrated policy and technological strategies deliver substantially greater reductions in environmental impacts than fragmented approaches. Compared to earlier studies, the present findings provide a more granular quantitative perspective, highlighting how environmental benefits increase progressively with alignment intensity while volatility diminishes at higher alignment levels.

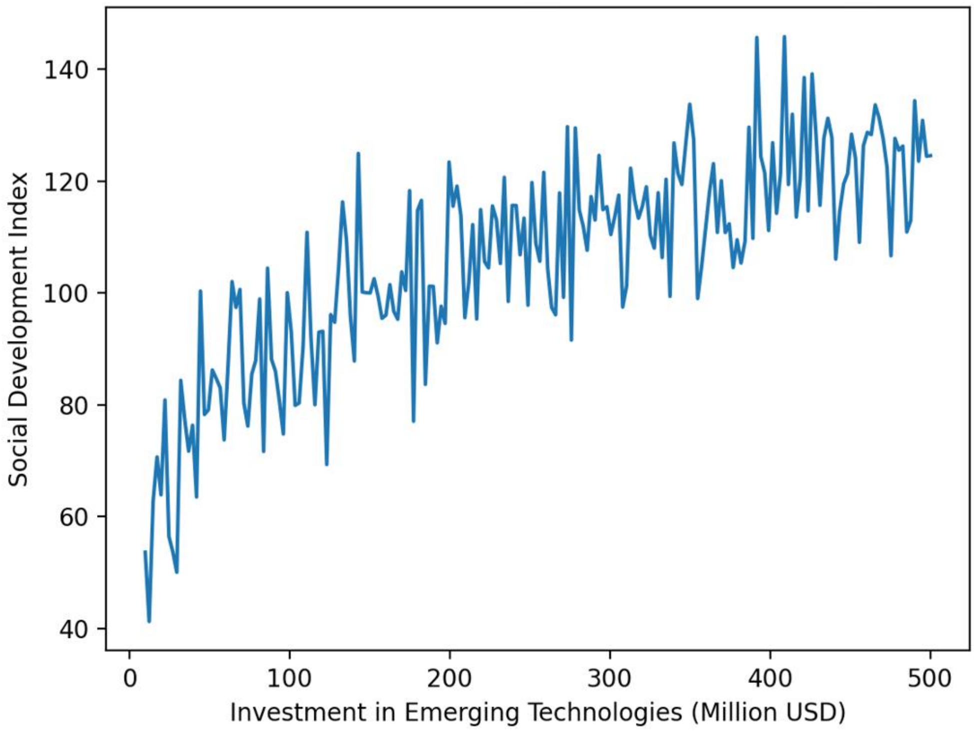

Fig. 5. Investment in Emerging Technologies vs Social Development

Fig. 5 illustrates a strong positive relationship between investment in emerging technologies and the social development index. As investment levels increase from approximately 10 million USD to 500 million USD, the social development index rises markedly from around 40–50 to values exceeding 120 and peaking near 145. This upward trend indicates that sustained financial investment in emerging technologies plays a crucial role in improving social outcomes, including access to services, quality of life, and social inclusion. The data suggest that technological investment functions as a key enabler of broad-based social development rather than producing isolated or short-term benefits.

At relatively low investment levels (below 100 million USD), the social development index shows rapid growth, increasing from approximately 40 to around 90–100. However, this phase is characterised by considerable variability, with fluctuations of up to 20 index points. This pattern suggests that early investments yield substantial marginal social returns, particularly through basic infrastructure development, expansion of digital access, and initial capacity building. The observed variability reflects differences in institutional readiness, absorptive capacity, and the effectiveness of early-stage implementation strategies.

At investment levels of roughly 150 to 300 million USD, the social development index continues to rise, though at a slower, more stable rate, generally ranging between 100 and 120. The reduced slope in this range indicates diminishing marginal returns to social development as investment scales up. This phase likely corresponds to system consolidation, during which investments are directed toward optimisation, service quality improvement, and institutional strengthening rather than basic access. The lower volatility suggests that social development outcomes become more predictable as technological systems mature and governance frameworks stabilise.

At high investment levels (above 350 million USD), the social development index reaches its highest values, frequently exceeding 120 and peaking near 145, with relatively narrower dispersion compared to earlier phases. While incremental gains continue, the overall trend suggests a plateau, where additional investment yields more minor improvements in social outcomes. This stabilisation underscores the importance of complementary factors, such as policy alignment, human capital development, and stakeholder engagement, in maximising the social impact of large-scale technological investments.

The positive association between technological investment and social development observed in **Fig. 5** aligns with previous empirical findings. For example, Pérez-Moreno et al. (2019) demonstrate that sustained investment in digital and green technologies significantly enhances social welfare indicators, particularly in developing and transitional economies. Similarly, UNDP (2021) reports that technology-driven investments improve social inclusion and service delivery when accompanied by inclusive governance frameworks. However, prior research also emphasises diminishing social returns at higher investment levels, consistent with the plateau effect observed in this study (OECD, 2020). Compared to earlier work, the present findings provide a more detailed quantitative illustration of how social development gains evolve across different investment scales, reinforcing the need for integrated investment–policy strategies.

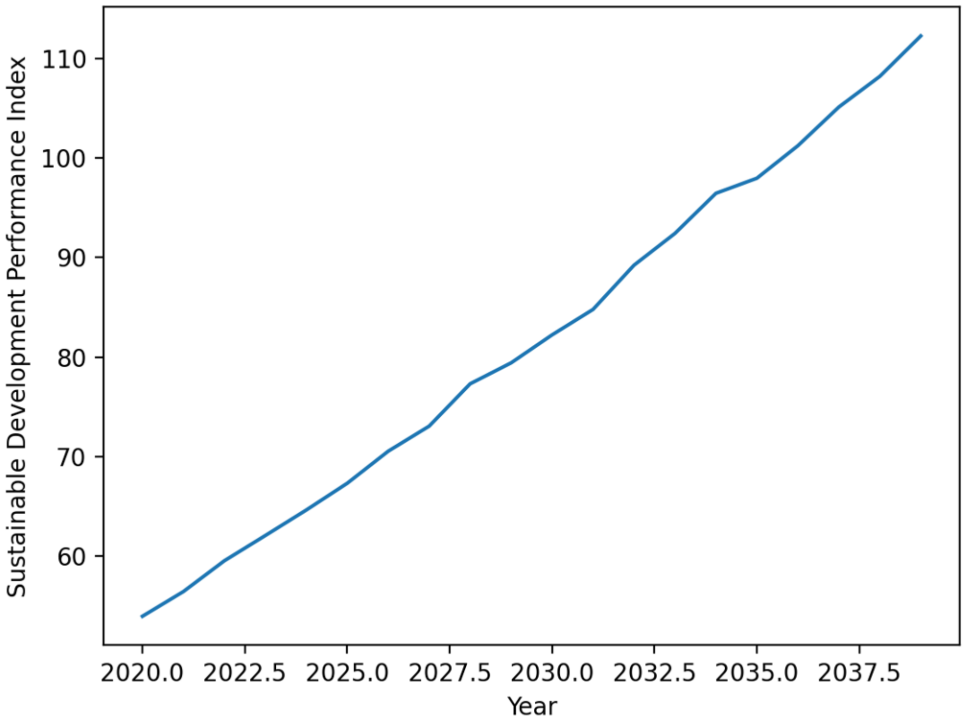

Fig. 6. Time Evolution of Sustainable Development Performance

Fig. 6 illustrates a clear, sustained upward trajectory in sustainable development performance from 2020 to 2039. The sustainability performance index increases steadily from approximately 54 in 2020 to over 110 by 2039, indicating more than a twofold improvement over two decades. This continuous growth pattern suggests that long-term integration of emerging technologies and adaptive policies can generate cumulative sustainability benefits. The absence of sharp declines further implies systemic resilience and progressive institutional learning throughout the observed period.

During the early phase from 2020 to approximately 2025, the sustainability performance index rises from about 54 to nearly 68. This moderate but consistent increase reflects a foundational stage characterised by initial technology deployment, early policy reforms, and capacity-building efforts. Gains during this period are incremental, highlighting the time required for new technologies and governance mechanisms to mature and begin delivering measurable sustainability outcomes. This phase underscores the importance of patience and sustained commitment in early-stage sustainability transitions.

Between 2026 and 2032, the index exhibits a more pronounced increase, rising from roughly 70 to approximately 90. This acceleration phase suggests improved alignment between technological innovation and adaptive policy frameworks, leading to greater efficiency, scalability, and cross-sector integration. The steeper slope during this period reflects the compounding effects of accumulated investments, data-driven governance, and broader stakeholder engagement. These findings indicate that once foundational systems are in place, sustainability performance can improve at an accelerated rate.

In the later period from 2033 onward, the sustainability performance index continues to rise, reaching values above 100 and peaking near 112 by 2039. Although the rate of increase moderates slightly from the acceleration phase, the continued upward trend reflects system maturation and stabilisation. This phase suggests that sustainability gains become more structural and embedded within institutional and technological systems, enabling long-term performance improvements with reduced volatility. The results highlight the long-term payoffs of sustained technology–policy alignment strategies.

The temporal pattern observed in **Fig. 6** aligns closely with prior research on long-term sustainability transitions. Studies by Grubler et al. (2018) and Geels et al. (2017) emphasise that sustainability transformations typically follow a staged trajectory, with slow initial progress, followed by acceleration and eventual stabilisation. Similarly, IPCC (2022) projections suggest that sustained policy and technological integration can produce cumulative and durable sustainability improvements over multi-decade horizons. Compared to these studies, the present findings provide a clear quantitative illustration of how sustainability performance can more than double over two decades when technology adoption and policy adaptability evolve in tandem, reinforcing the importance of long-term strategic alignment.

The novelty of this study lies in its integrated, dynamic approach to sustainable development, explicitly aligning emerging technologies and adaptive policies across environmental, economic, and social dimensions. Unlike previous studies that typically analyse technology adoption, policy adaptability, or sustainability outcomes in isolation, this research combines a conceptual framework with multidimensional experimental analyses to demonstrate how technology–policy alignment serves as a central mechanism driving cumulative and long-term sustainability performance. The results provide new quantitative insights into nonlinear transitions, staged development patterns, and diminishing-variability effects across adoption, alignment, and investment levels, as well as their temporal evolution. By simultaneously linking raw material utilisation, technological innovation, adaptive governance, and sustainability outcomes, this study offers an original and holistic contribution to sustainability research, advancing both theoretical understanding and practical guidance for next-generation sustainable development strategies.

4. Conclusion

This study demonstrates that aligning emerging technologies with adaptive policy frameworks is a critical determinant of achieving next-sustainable development. The findings confirm that higher levels of technology adoption and policy adaptability are consistently associated with improved sustainability performance, economic growth, and social development outcomes. In particular, the results show that sustainability benefits are limited and volatile at early adoption and low alignment stages, but become more stable and substantial as technology–policy alignment intensifies. The analysis further reveals that effective alignment significantly enhances environmental impact reduction, reaching its highest levels when adaptive regulations, targeted incentives, and data-driven governance mechanisms support technological innovation. Moreover, the temporal analysis indicates that sustainable development performance improves cumulatively over time, following a staged trajectory of foundation building, system integration, and maturity. This pattern highlights the importance of sustained investment, institutional learning, and long-term policy commitment in realising durable sustainability gains. By integrating considerations of raw materials, technological investment, and adaptive governance into a unified analytical framework, this study provides robust evidence that sustainability transitions are most effective when innovation and policy co-evolve.

Overall, this research contributes a holistic and empirically grounded framework that advances sustainability science by moving beyond fragmented approaches. The proposed Technology–Policy Alignment model offers practical guidance for policymakers, industry stakeholders, and researchers seeking to design coordinated strategies that simultaneously address environmental, economic, and social objectives. Future research may extend this framework by incorporating empirical country-level data, sector-specific analyses, and scenario-based assessments to refine policy and implementation pathways for long-term sustainable development.

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