POLITECNICO DI TORINO
Repository ISTITUZIONALE

Beyond linearity: Quantifying SDG saturation in complex national innovation ecosystems

Original
Beyond linearity: Quantifying SDG saturation in complex national innovation ecosystems / Masali, G., Morea, D., Giglio, C., Iazzolino, G., Perboli, G., Bruni, M.E.. - In: JOURNAL OF INNOVATION & KNOWLEDGE. - ISSN 2444-569X. - ELETTRONICO. - 12:(2026). [10.1016/j.jik.2025.100907]

Availability:
This version is available at: 11583/3005771 since: 2025-12-11T09:57:34Z

Publisher:
Elsevier B.V.

Published
DOI:10.1016/j.jik.2025.100907

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

27 November 2026

Journal of Innovation & Knowledge 12 (2026) 100907

Contents lists available at ScienceDirect

Journal of Innovation & Knowledge

journal homepage: www.elsevier.com/locate/jik

Beyond linearity: Quantifying SDG saturation in complex national innovation ecosystems

Giacomo Masali [a], Donato Morea [b,*], Carlo Giglio [c,d,e], Gianpaolo Iazzolino [c], Guido Perboli [a], Maria Elena Bruni [c]

[a] Department of Management and Production Engineering, Polytechnic of Turin, Italy
[b] Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo, 2, Cagliari, 09123, Italy
[c] Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy
[d] School of Economics, Business, accountancy and Actuary, University of Sao Paulo, Brazil
[e] School of Public Affairs, University of Science and Technology of China, Hefei, Anhui Province, PR China

ARTICLE INFO

JEL classifications:
Q01

Keywords:
Complexity
National innovation ecosystems
Sustainability
Sustainable development goals
SDGs
SDG saturation
Bass diffusion model
Predictive model

ABSTRACT

This study investigates the complex, nonlinear dynamics of the achievement of Sustainable Development Goals (SDGs) within national innovation ecosystems (NIEs), addressing a critical gap in understanding SDG saturation. Studying this topic is crucial because, despite the growing importance of sustainability issues in innovation ecosystem research driven by social and economic pressure, the literature remains fragmented and undecided, lacking a clear understanding of complex governance and operational frameworks in NIEs. Employing the Bass diffusion model, we analyze 22 years of SDG Index score data (2000–2021) from 177 countries/regions. The model quantifies SDG saturation time, accounting for complex interdependencies and threshold effects overlooked by traditional linear models. Findings reveal characteristic S-shaped adoption curves for most countries, indicating initial slow progress, acceleration driven by imitation, and eventual saturation. Geographical and socioeconomic clustering analyses highlight distinct patterns in SDG progress that depend on the peculiarities of complex systems in national contexts. High-income countries exhibit greater innovation efforts but lower saturation potential due to the proximity to SDG ceilings, while lower-income countries face complex structural constraints. The Bass model proves effective for forecasting SDG saturation and informing policy interventions in complex systems like NIEs, emphasizing the need for context-dependent governance and resource allocation to accelerate equitable sustainable development across the globe.

Introduction

National innovation ecosystems (NIEs) can accelerate technological, social, and economic progress toward achieving Sustainable Development Goals (SDGs) by fostering collaboration, innovation, and entrepreneurship (Azmat et al., 2023; Brás & Robaina, 2024; Iizuka & Hane, 2021; Liao et al., 2024; Liu & Stephens, 2019; Nylund et al., 2021). Specifically, a study on 131 countries demonstrates that NIEs improve the achievement of SDGs (Wei et al., 2025) through the development of eco-innovations and green technologies (Abdullai et al., 2022; Fatma & Haleem, 2023; Yikun et al., 2022) entrenched with the tackling of societal issues and grand challenges (Ritala, 2024).

Nevertheless, their effectiveness in regard to SDGs can be constrained by various barriers as well as complexity issues, including contingent approaches in innovation-as-a-context ecosystems, institutional inertia, resource (absorption) limitations, and inadequate and nonlinearly intertwined efforts among the multiple agents in NIEs (Gifford et al., 2020; Grama-Vigouroux et al., 2024; Huang et al., 2024; Ponsiglione et al., 2021; Ponta et al., 2023; Qiao et al., 2024). For instance, high-income nations show 2.3 times greater SDG progress per dollar invested in innovation activities than low-income countries, due to better institutional frameworks that mitigate the complexity of NIEs (Prokop et al., 2021). This trend is confirmed by the overall dominance of the agenda for implementing circular ecosystems in the Global North (Aryee et al., 2025). The same research shows that southern/emerging countries are underexplored and necessity-driven contexts for circular innovation ecosystems, as well as being more chaotic in their implementation. In fact, the main differences concern emergence,

* Corresponding author.
E-mail address: donato.morea@unica.it (D. Morea).

https://doi.org/10.1016/j.jik.2025.100907
Received 16 July 2025; Accepted 30 November 2025
Available online 5 December 2025
2444-569X/© 2025 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

orchestration, and governance dynamics. Telling examples relate to such sectors as: organic food in Brazil (Ferrari et al., 2023), textiles and apparel in Romania (Staicu & Pop, 2018), biochemical energy in India (Mukherjee et al., 2021), agriculture in China (Zhong et al., 2012), construction, and waste (Gyimah et al., 2024). Another research shows that NIEs in complex contexts, such as developing economies (e.g., Brazil, Pakistan), increase productivity in small and medium enterprises (SMEs) by 22–40 % and reduce resource waste by 15 % (Jan et al., 2025). On the other hand, the complexity of post-conflict Ukraine's ecosystem requires enhanced academic–business links to accelerate postwar SDG alignment (Kuzior et al., 2022).

Globally, the World Economic Forum (WEF) has shown that insufficient emphasis on sustainability-oriented innovation is linked to worsening performance in the achievement of SDGs (WEF, 2025a), whilst NIEs drive sustainability most effectively when integrating inclusive and more structured governance involving multiple agents in complex systems (Wei et al., 2025). Indeed, over the past decade, research on innovation ecosystems has focused primarily on understanding their structure, dynamics, and impact on economic growth (Ancona et al., 2023; Marinelli et al., 2023; Rabelo Neto et al., 2024; World Economic Forum, 2020; see also Spigel, 2017; Van de Ven, 1993) by adopting the lenses of complexity theory to investigate the set of actors, activities, and relations that determine the performance of ecosystems (Chatti et al., 2024; Granstrand & Holgersson, 2020; Isenberg, 2016; Russell & Smorodinskaya, 2018; Toth et al., 2024). Moreover, several definitory efforts have been undertaken in order to identify the differentiating elements of innovation ecosystems, such as actors' heterogeneity, actors' interdependence, and system-level outcomes, all of them calling for a specific focus on complexity issues. In fact, innovation ecosystems are shaped by coevolutionary microfoundations, whereas complex, nonlinear feedback loops among actors (e.g., firms, institutions) create emergent outcomes (Breslin et al., 2021) and varied system-level outcomes depending on the ecosystem typology—i.e., innovation ecosystem, business ecosystem, platform and technology ecosystems, entrepreneurial ecosystem, or knowledge and open innovation ecosystems. Similarly, Reed et al. (2025) criticize linear "innovation pipeline" models, advocating instead approaches that consider the impact of policy shocks and adaptive strategies in triggering cascading transformations across ecosystems. Zhang et al. (2023, 2024) prove that green innovation spreads through unequal connection nodes in complex networks, arising nonlinearly from actors' micro-interactions (e.g., firms, universities, policymakers) (Zhou & Li, 2024). Such interactions may include different agents' activities, such as pollution taxes or default costs altering opportunity costs, thus incentivizing green cooperation in NIEs, policy shifts, or startup disruptions. Moreover, they may trigger disproportionate impacts across the ecosystem (Zhang et al., 2024), learning and co-evolution dynamics among actors (firms, governments, universities) that create emergent behaviors challenging linear predictions (Miller et al., 2024) or self-organization properties to organically reconfigure around shared goals, driven by the growing emphasis on the sustainability transition in policy and business strategies (Han et al., 2019; Toth & Hary, 2024).

In fact, scholars have recently explored convergent topics related to innovation ecosystems and sustainability issues by emphasizing the importance of integrating sustainability and social issues into innovation practices, and reflecting the need for adaptive strategies when dealing with the complexity of innovative organizations and ecosystems (Pham & Vu, 2022; Pilelienė & Jucevičius, 2023; Ritala, 2024; Zeng et al., 2017). Sustainability issues are gaining momentum in innovation ecosystem research (Liu & Stephens, 2019; Ritala, 2024) due to the increasing recognition of environmental and social impacts stemming from cooperative innovation efforts (Nylund et al., 2021; Yin et al., 2020), the need for collaborative and cross-sectoral approaches—e.g., industrial symbiosis (Liu et al., 2024)—evolving policies and market demands in complex regulatory frameworks (Agasty et al., 2023; Zhang et al., 2023), and the importance of integrating sustainability into business models and regional development (Bakry et al., 2022; Oskam et al., 2020; Peñarroya-Farell et al., 2023). From the managerial and policy perspectives, sustainable innovation ecosystems impact the achievement of the goals set in the UN Agenda 2030 (United Nations, 2015) through collaboration among diverse stakeholders (Nylund et al., 2021), digital transformation and integration of emerging technologies (Dionisio et al., 2023; Liao et al., 2024; Springer et al., 2025), and supportive policies (Dmytrenko & Kuba, 2024), though their effectiveness can be hindered by barriers such as a lack of resources, networking, and institutional support (Grama-Vigouroux et al., 2024).

However, despite the growing number of publications on (sustainable) innovation ecosystems, field literature remains fragmented and lacks an understanding of the governance and operational frameworks of innovation ecosystems (Xu & Li, 2024), particularly in the context of sustainable development (Pilelienė & Jucevičius, 2023). Moreover, a systematization of the theoretical framework related to the complex, adaptive, nonlinear interactions occurring among actors in innovation ecosystems, as well as of their social, environmental, and economic sustainability dimensions, is still missing (Breslin et al., 2021; Ponsiglione et al., 2021; Ponta et al., 2023; Reed et al., 2025; Thomas et al., 2025). In addition, a strain of recent scientific literature highlighted the dark side of the relationship between innovation and innovation ecosystems, and SDGs, emphasizing how the former can have a negative impact on the achievement of sustainability goals (Berry et al., 2024; Islam, 2025; Yuan et al., 2023; Zhao et al., 2023). This pairs with the undecided discourse in the literature about whether the complexity of regulatory and cooperation frameworks in NIEs affects—positively or negatively—the capability of countries to achieve the SDGs, given the contrasting findings regarding high-income vs low-income countries, and developing vs war-torn/reconstruction economies (Grama-Vigouroux et al., 2024; Jan et al., 2025; Kuzior et al., 2022; Prokop et al., 2021).

Hence, existing studies concur that NIEs enable sustainability via collaboration (e.g., Nylund et al., 2021) but disagree on context-dependent and governance pathways (Pilelienė & Jucevičius, 2023; Xu & Li, 2024), which are influenced by nonlinear interactions among agents in complex systems (; Ponsiglione et al., 2021; Ponta et al., 2023; Thomas et al., 2025) and affected by the undecided role of ecosystem complementarities concurring with system-level value creation (Baldwin, 2024; Samuelson, 1974; Teece, 2018).

Finally, three critical research gaps emerge from these premises. First, there remains a significant lack of understanding about the comprehensive effects of complex governance models and actor dynamics on countries' achievement of SDGs in NIEs (Reed et al., 2025). Second, while studies increasingly recognize the impacts of innovation ecosystems on SDGs (e.g., through technological externalities or governance issues), there is insufficient empirical research on the extent, speed, and variability of those effects across different national contexts (Berry et al., 2024; Islam, 2025). Third, from the methodological perspective, quantitative studies are underutilized in the field of innovation ecosystems overall (Aryee et al., 2025). Moreover, most of the literature is skewed towards qualitative efforts like conceptual works or literature reviews (Pietrulla, 2022; Trevisan et al., 2022), thereby missing the potential complementary findings from statistical testing or hitherto unexplored applications of data-driven prediction efforts that our work aims to cover, at least partially (Aryee et al., 2025).

Hence, our research questions are: (1) Do national innovation ecosystems play a role in the achievement of Sustainable Development Goals in the 193 UN member countries, and if so, how?; and (2) What are the cross-country differences in terms of expected SDG saturation levels over time?

As such, this study aims to investigate the overall impact of sustainable innovation ecosystems on the achievement of country-level SDGs over time, from 2000 to 2021. More specifically, we aim to predict when each country will achieve saturation level (100 %), indicating when it is expected to achieve a satisfactory proportion of its SDG

fulfillment potential.

The relevance of this prediction is fourfold. First, it helps in understanding governance and policy integration, as sustainable innovation ecosystems align national policies with local actions through stakeholder interactions, e.g., governments and communities. Examples include the EU Green Deal's regional hubs (European Commission, 2023), Rwanda's decentralized energy systems supporting SDG 7 (UNDP, 2024), and Sweden's national ecosystem strategy for SDGs (Sachs et al., 2024), though measuring effectiveness remains challenging. Second, these ecosystems drive economic and technological progress impacting SDGs via the twin transition, such as Sweden's textile recycling reducing waste (Ellen MacArthur Foundation, 2023) and green tech leapfrogging in developing nations (World Bank, 2024). They contribute to SDGs 7–9 and 12 (UNEP, 2024) by creating resilient industries and boosting digital inclusion, as seen in Uganda's gender-inclusive tech hubs (ITU, 2023). Third, they promote social inclusion, e.g., Montreal's healthcare collaborations advancing SDG 3 (Larsson et al., 2024) and Chile's IoT water management empowering marginalized groups, but disparities and gender discrimination persist, calling for more equitable resource models and studies (African Development Bank, 2025; UN Women, 2024). Fourth, these ecosystems enhance resilience against challenges like Denmark's wind energy for climate action (IEA, 2023) and South Korea's digital health platforms during the pandemic (WHO, 2024), though systemic impact metrics need development (SDSN, 2024). More research is necessary to scale successful models across nations (World Economic Forum, 2025b).

This study presents the first framework to predict SDG saturation levels at the country level (Fig. 1). It integrates NIEs' governance and nonlinear dynamics for overall estimation of achievable sustainability goals. The study advances prior research by applying the Bass diffusion model to sustainability analysis for the first time. The Bass model quantifies SDG saturation time—the point when SDG progress nears its maximum (Bass, 1969)—and accounts for complex interdependencies and threshold effects overlooked by linear models. Findings show that the Bass model effectively describes national SDG progress by reinterpreting its parameters. SDG progress follows characteristic S-shaped curves: slow start, accelerated growth, and saturation phases. The framework fits most countries, except for 14 with complex instability that fail to show clear S-curves. The results reveal geographical and socioeconomic clusters with distinct SDG progress patterns. Innovation-driven policies, investment, and governance lead to earlier acceleration in SDG progress. High-income countries have higher innovation but lower saturation potential, being close to SDG ceilings, while low/middle-income countries face structural constraints, resulting in lower innovation and saturation potential.

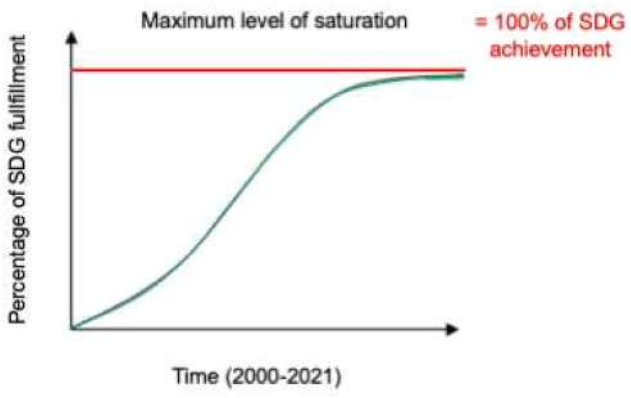


Fig. 1. Conceptual model.

Theoretical background

The bass diffusion model

The Bass diffusion model (Bass, 1969) helps in understanding innovation adoption processes within populations by analyzing commercial product uptake through its characteristic S-shaped adoption curve. This temporal pattern reflects the general transition from slow adoption to rapid acceleration and eventual market saturation across diverse innovation contexts. The model's theoretical foundation rests on two complementary adoption mechanisms: innovation-driven adoption (external influence parameter) and imitation-driven adoption (internal influence parameter).

It is important to situate the Bass model in relation to innovation diffusion theory, which conceptualizes the adoption of innovations through five adopter categories (innovators, early adopters, early majority, late majority, laggards) and emphasizes the role of communication channels, social systems, and time in shaping diffusion patterns. Rogers' framework is highly influential in providing a qualitative, sociological account of how innovations spread; however, it does not provide a direct quantitative mechanism for forecasting adoption dynamics or for estimating parameters from empirical data.

By contrast, the Bass model translates Rogers' qualitative insights into a parsimonious mathematical formulation. This quantitative specification allows researchers to fit empirical time series, estimate country-specific parameters, and make predictions about saturation dynamics, which is essential for the analysis of SDG trajectories.

The adaptation of the Bass diffusion model to SDGs represents a paradigmatic shift toward complex socioinstitutional transformation processes (Wonglimpiyarat, 2025). As such, this recontextualization requires careful consideration of the unique characteristics that distinguish SDG implementation from traditional innovation diffusion (Kanie et al., 2014).

The innovation parameter in the SDG context encompasses exogenous drivers, including governmental policy frameworks, complex international agreements and multilateral initiatives, and institutional mandates that independently promote SDG-aligned practices (Khalik et al., 2024). These external influences are manifested through mechanisms such as renewable energy subsidies, carbon pricing policies, environmental regulations, and international development assistance programs (Bitencourt et al., 2021).

The imitation parameter captures endogenous social dynamics, including policy coherence, knowledge spillovers, normative convergence, and complex cross-border learning processes, that increase SDG implementation through peer effects (Li et al., 2023). This parameter encompasses regional adoption of successful sustainability models, South–South cooperation mechanisms, and knowledge transfer networks that facilitate the diffusion of best practices (Collste et al., 2017).

The market potential translates to SDG saturation potential, i.e., the maximum feasible level of sustainable development achievement a country can attain given its structural constraints (Marzouk et al., 2022). These constraints may include economic capacity, institutional quality, natural resource endowments, demographic characteristics, and geopolitical complexity and stability.

Hence, the adapted Bass diffusion model provides a theoretically grounded foundation for modeling SDG achievement trajectories across heterogeneous country contexts (Fu et al., 2020). Its reformulation—incorporating dynamic saturation potentials, country-specific heterogeneities, and complex system feedback—enables robust predictions of SDG saturation timing and identifies leverage points for accelerating global sustainability transitions.

The relationship between innovation ecosystems and SDGs

While sustainable innovation ecosystems are increasingly framed as catalysts for the UN 2030 Agenda's 17 SDGs (United Nations, 2015),

their actual impact remains contingent on contested managerial and policy dynamics. Some scholars highlight multi-stakeholder collaboration (Nylund et al., 2021), digital tools (Dionisio et al., 2023; Liao et al., 2024), and policy incentives (Dmytrenko & Kuba, 2024) as drivers of socioeconomic and environmental progress, yet critics caution that structural barriers—including resource disparities, fragmented networks, and weak institutionalization (Grama-Vigouroux et al., 2024)—often dilute their transformative potential, revealing tensions between ecosystem rhetoric and implementation realities.

In fact, on the one hand, innovation ecosystems are aimed at: addressing climate change issues (SDGs 7, 13) by reducing CO_2 emissions through clean energy solutions and a circular economy (Brás & Robaina, 2024; George et al., 2020; Matos et al., 2022); achieving systemic collaboration (SDG 17) through multi-stakeholder partnerships exemplifying SDG-driven collaboration (Owen & Vedanthachari, 2022); implementing circular economy practices (SDG 12) for responsible production and consumption; supporting resilient supply chains and protecting biodiversity (SDGs 9, 15) through the sustainable use of natural resources (Albitar et al., 2023); scaling green innovations (SDG 9) such as digital/AI-driven solutions that cut emissions (George et al., 2020; Matos et al., 2022); addressing water scarcity worldwide (SDG 6) (Pandit & Sharma, 2023); promoting inclusive growth and reduced inequalities (SDG 10) by empowering SMEs and grassroots innovators (e.g., vertical farming startups) (Jütting, 2024; Mori et al., 2013; Song, 2025); enhancing policy implementation (SDG 16) like the EU Green Deal (Jütting, 2024); boosting economic competitiveness (SDG 8) as companies in sustainability ecosystems are 1.4 times more likely to achieve breakthroughs (Husainy et al., 2024); and fostering adaptive resilience (SDG 3) by ensuring good health and well-being (Mori et al., 2013; Pandit & Sharma, 2023).

By contrast, a strain of recent scientific literature highlighted possible negative impacts of innovation on the achievement of sustainability goals. For instance, in G7 countries, green innovation correlates negatively with SDG progress, particularly poverty eradication (SDG 1), due to high implementation costs displacing social investments (Islam, 2025). Circular innovations (e.g., textile recycling) advance SDG 12; however, they often prioritize economic efficiency over labor rights, undermining decent work (SDG 8) in supply chains (Berry et al., 2024; Islam, 2025). Digital innovation ecosystems in low-income countries exacerbate inequalities (SDG 10), as marginalized groups lack access to infrastructure, thereby worsening digital divides (Berry et al., 2024). Data-intensive innovations (e.g., AI) increase energy consumption (contradicting SDG 7) and carbon emissions, offsetting sustainability gains (Berry et al., 2024). Urban-centric innovation hubs widen rural–urban disparities (SDG 11), leaving rural communities behind in terms of access to healthcare (SDG 3) and education (SDG 4) (Yuan et al., 2023). Corporate-led innovation ecosystems, however, often prioritize profit over equity, sidelining SDGs 5 (gender equality) and 17 (partnerships) in governance (Berry et al., 2024). Pandemic-driven innovation (e.g., digital health), meanwhile, diverted resources from SDG 2 (zero hunger) and SDG 4 (education) in low-income regions (Henrysson et al., 2024; Yuan et al., 2023). As for resource-intensive R&D, clean-tech innovations in high-income countries rely on rare-earth mining, violating SDG 15 (life on land) in extractive regions (Berry et al., 2024; Islam, 2025). National innovation policies (e.g., subsidies for tech startups) often neglect local SDG priorities, such as water security (SDG 6) in arid regions (Zhao et al., 2023). Cascading effects of tech-driven growth (e.g., e-commerce) increase consumption (SDG 12) but exacerbate waste and inequality (SDG 10) (Berry et al., 2024; Yuan et al., 2023).

Data and methodology

Data

The dataset analyzed for this research is the online database for the Sustainable Development Report 2022 by Sachs et al. (2022), which is a yearly report that reviews the progress made periodically by UN member states with regard to the level of SDG achievement since their adoption. The data used for this study span 22 years, from 2000 to 2021, and the dataset contains 120 indicators covering the 17 SDGs, which generate the overall score for each country. Overall, 193 countries are included in the Sustainable Development Report 2022. The dataset includes several data on the SDGs, such as the overall results for all countries, including the index score, goal dashboard, and trend dashboard for all indicators and goals, spillover scores, raw values, normalized scores, dashboard ratings, trends, and goal scores. The SDG Index score and all other indicators are retroactively calculated across time using time series data. Missing data are treated by carrying forward time series data. Data come from international and rigorous organizations that operate extensive validation processes, like the World Bank, the Organisation for Economic Co-operation and Development, the World Health Organization, the Food and Agriculture Organization, and the International Labour Organization. Therefore, the dataset characteristics limit any biases related to single-source utilizations, and the complete coverage of UN members avoids sample selection issues (Alonso-Almeida et al., 2024). Finally, the quality of the data ensures the reliability of the results.

The mathematical framework of the bass diffusion model

The Bass diffusion model (Bass, 1969) is a mathematical framework for modeling the diffusion of innovation and new technologies over time. It describes cumulative adoption as an S-shaped curve (or S-curve), as the diffusion process starts slowly, initially accelerating until it fades out when it reaches the full market potential. Mathematically, the Bass model reads:

$$\frac{dF(t)}{dt} = (p + qF(t))(M - F(t)) \tag{1}$$

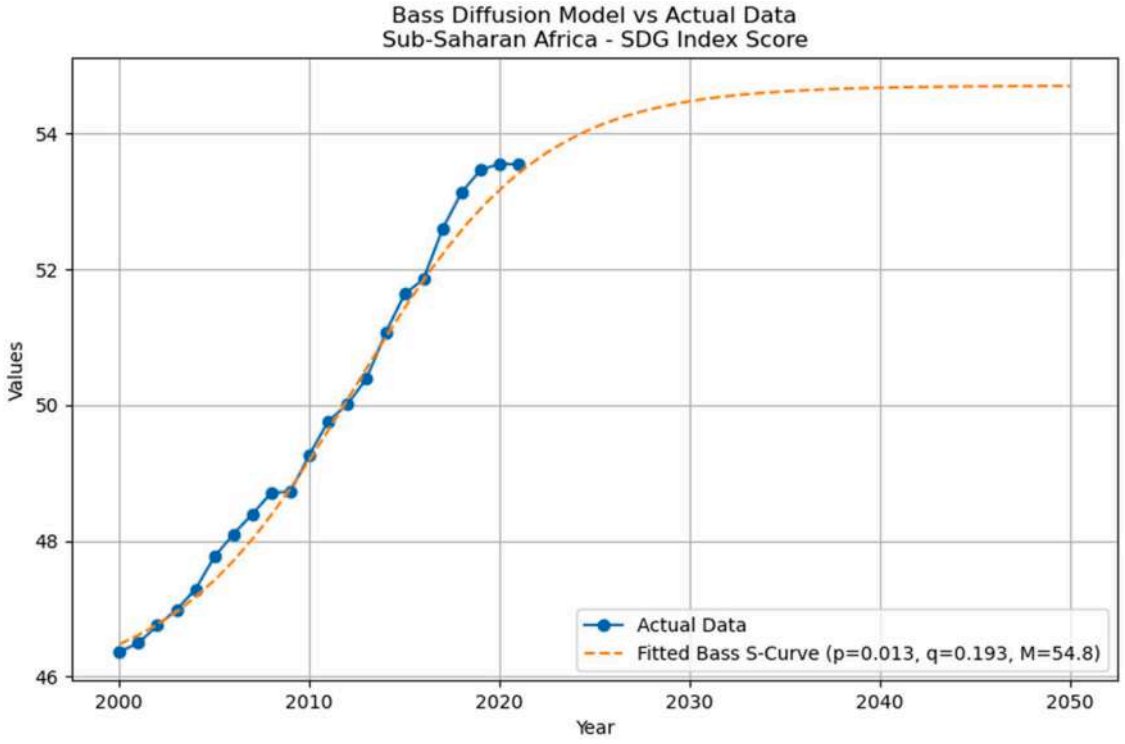
where $F(t)$ is the cumulative fraction of adopters at time t; p represents the proportion of adopters driven by forces exogenous to the social dynamics of diffusion, such as advertisement or personal inclination towards innovation; and q represents the proportion of adopters driven by social pressure, i.e., the fact that many other people have adopted. The parameters p and q are referred toas an innovation parameter and an imitation parameter, respectively. Parameter M is the market potential, i.e., the total amount of adoption registered at the end of the process.

The solution to this differential equation describes the S-curve, characterized by an initial period of slow adoption dominated by innovators, followed by rapid adoption driven by imitators, and finally a saturation phase when M is approached. The Bass model has traditionally been applied in contexts such as consumer product adoption, technology diffusion, and innovation management.

However, the overall flexibility of innovation diffusion models and theories—i.e., Bass, Rogers—enables adaptation to other domains where a diffusion-like process occurs (Wonglimpiyarat, 2025), including, for instance, innovative services and platforms in the urban mobility sector (Giglio & De Maio, 2022), electric vehicles (Brdulak et al., 2021; Kumar et al., 2022), and mobile banking services (Saeed & Xu, 2020). In this work, we have applied the Bass framework to data related to the SDGs for a large number of countries. The S-curve generated by the Bass model seems well suited to deriving insights into this process (Kanie et al., 2014). Similarly to innovation diffusion, national efforts toward SDG targets often begin slowly due to limited resources, institutional inertia, or other structural barriers, but over time, as progress accelerates through increased investment, policy implementation, and knowledge sharing, the rate of improvement may rise sharply before eventually stabilizing as the full potential of the country is approached.

The adaptation of the bass diffusion model

To carry out this analysis, we fitted the Bass curve (1) to the time series of the SDG results for each country. The dataset includes datasets for the aggregate SDG Index score as well as indicators for the 17 different goals. The database also contains highly granular data with time series for single measures contained in each goal, but no analysis has been carried out for these subgoals. The time span of the dataset covers 22 years, from 2000 to 2021, with one data point for each year corresponding to the level of fulfillment of the SDG on a scale ranging from 0 to 100. With respect to the SDG Index score time series, we performed a curve fitting of the S-curve produced by the Bass model using nonlinear least squares. In particular, this means searching for the set of parameters (*p, q, M*) that produces the S-curve that minimizes the



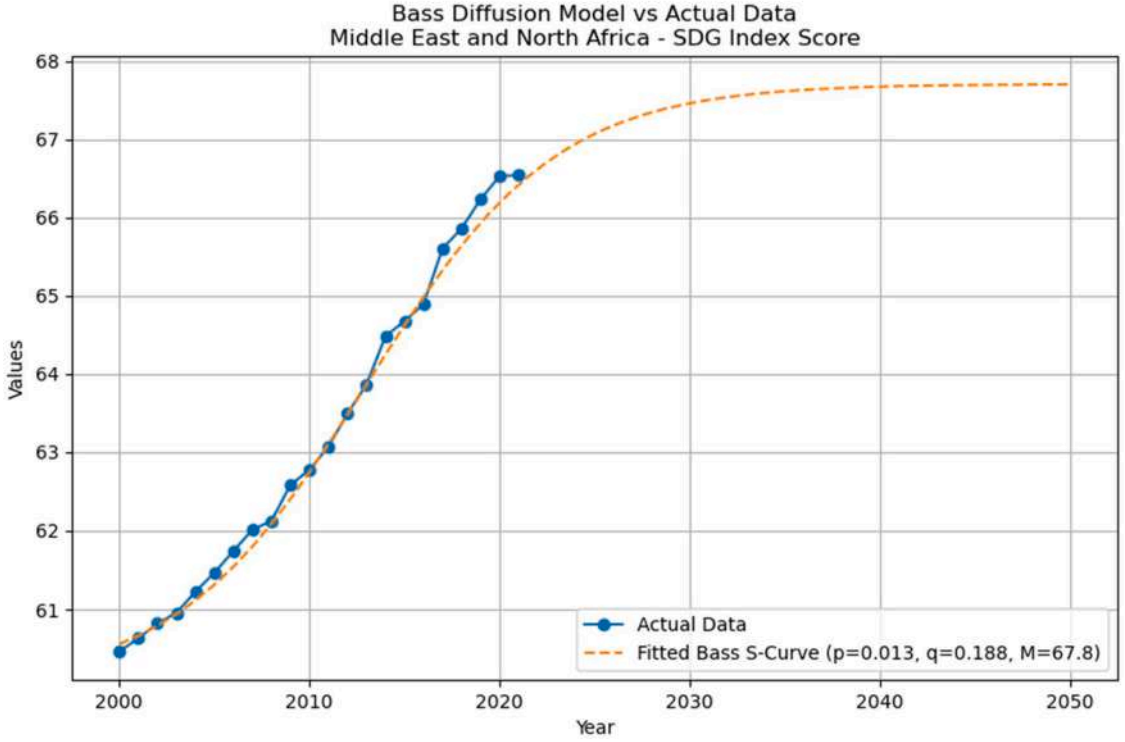
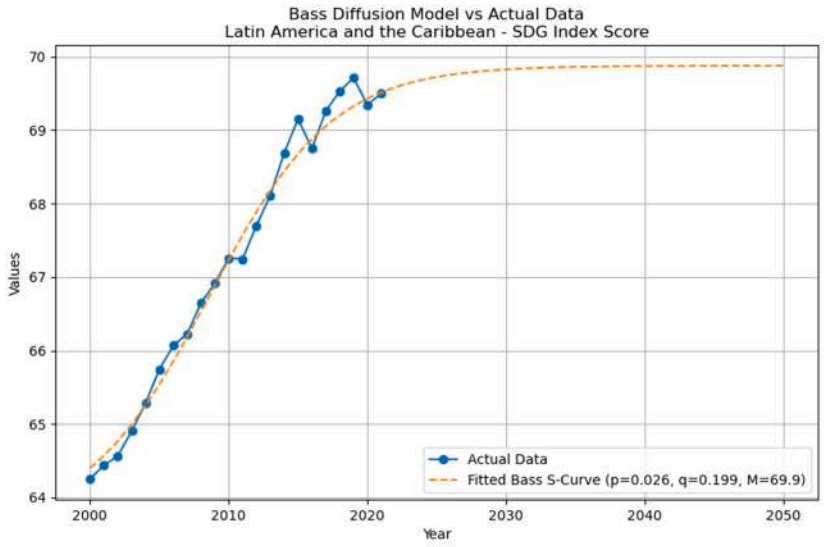
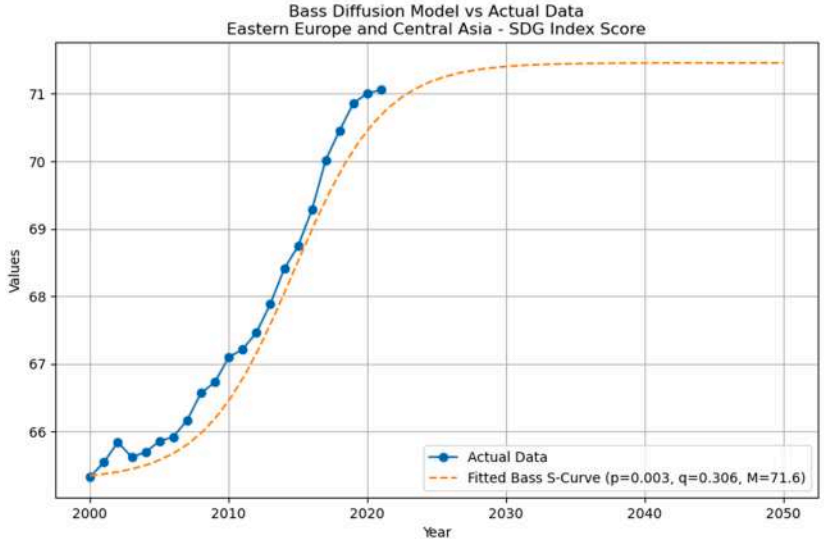


Fig. 2. a, 2.b, 2.c, 2.d, 2.e. Geographic clustering.





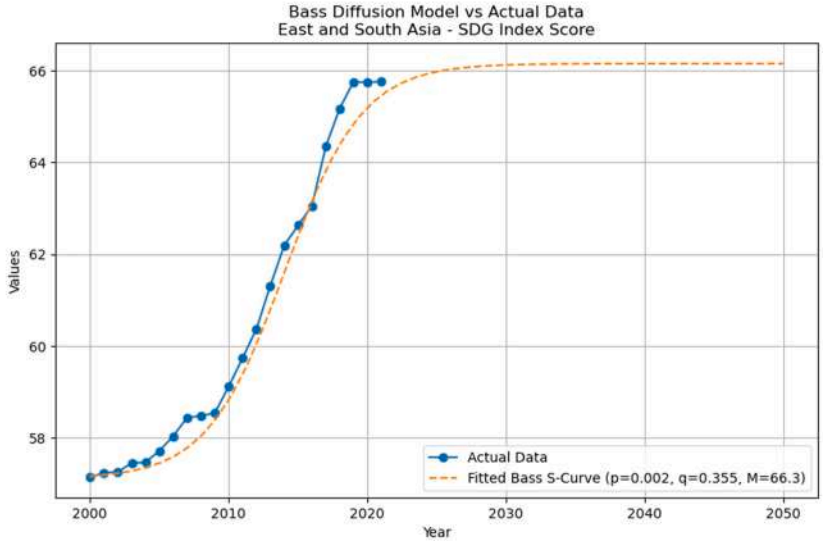


Fig. 2. (*continued*).

squared difference between the curve itself and the data points of the time series. It should be noted here that the canonical Bass has null initial condition and grows to M. Hence, to apply the Bass framework in this case, we had to shift the SDG Index score properly and later readjust the fulfillment potential level *M*. Depending on the case and on the quality of the fitting, some precautions have been adopted to ensure the best fitting of the data points.

First, a Monte Carlo exploration of the space of the parameters was performed in case of an unsatisfactory result of the fitting for stiffer cases.

In some cases, the high fluctuations in the data resulted in poor fitting of the curve. In these cases, a moving average smoothing or an exponential smoothing was performed prior to the application of the least squares algorithm, depending on which led to the best

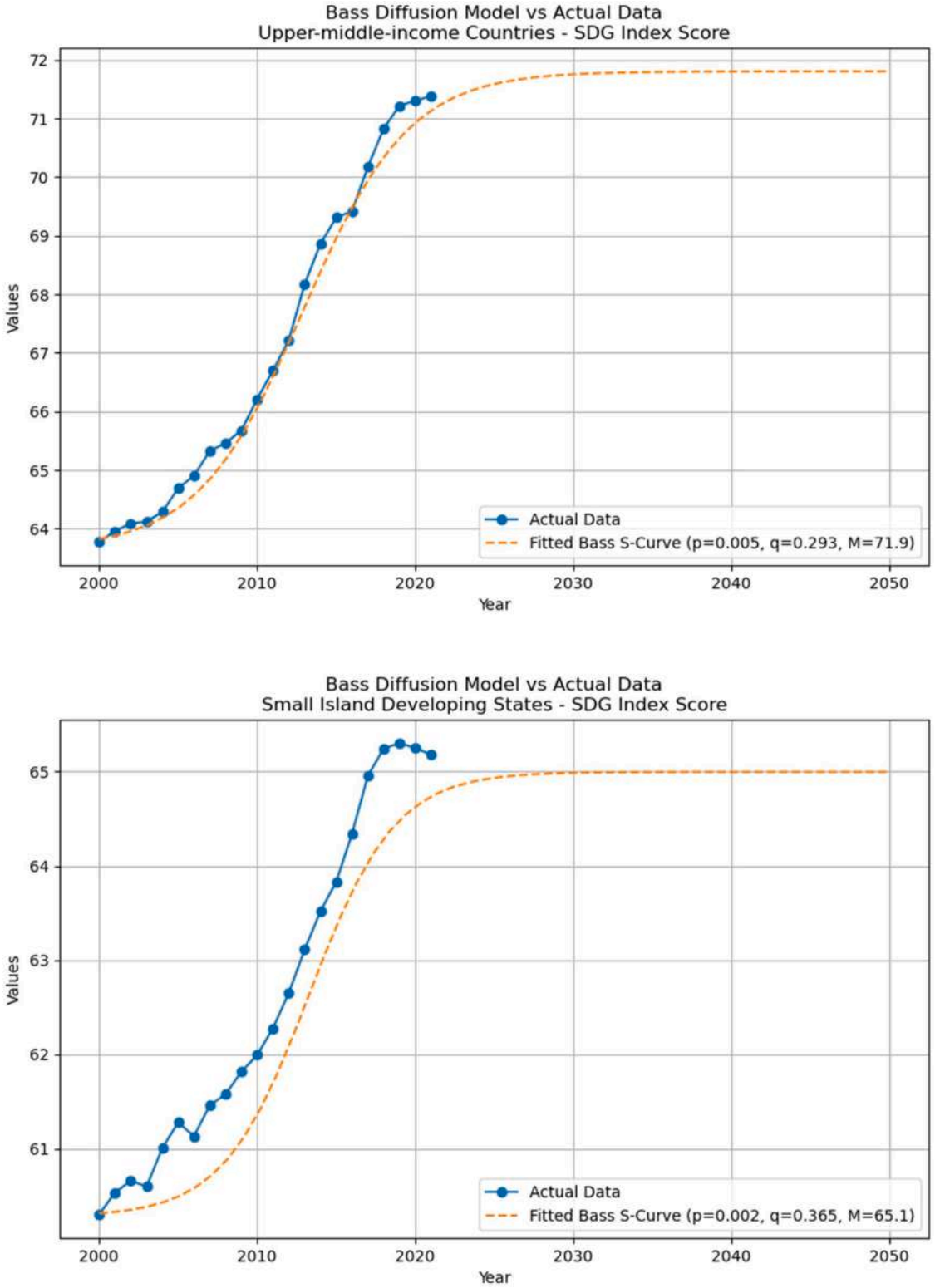


Fig. 3. a, 3.b, 3.c, 3.d, 3.e, 3.f, 3.g. Socioeconomic clustering.

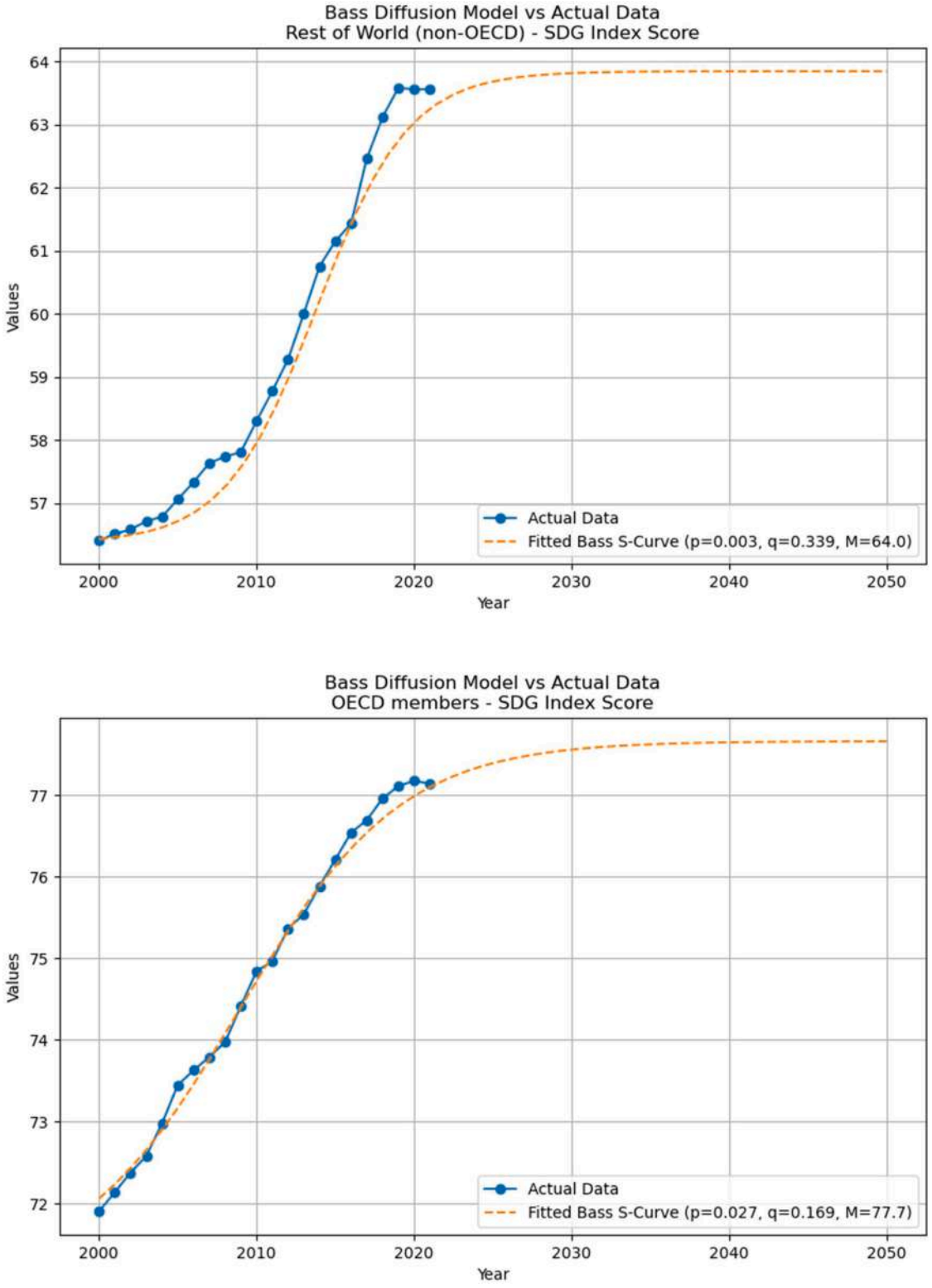
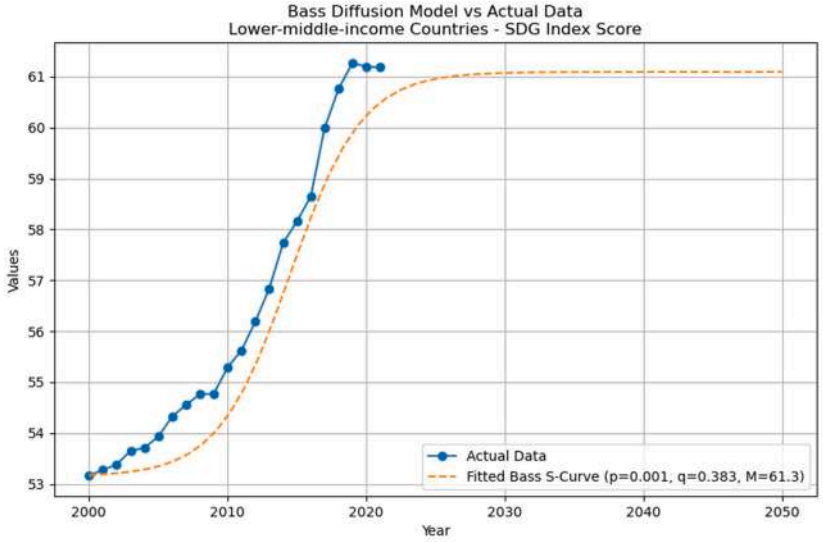


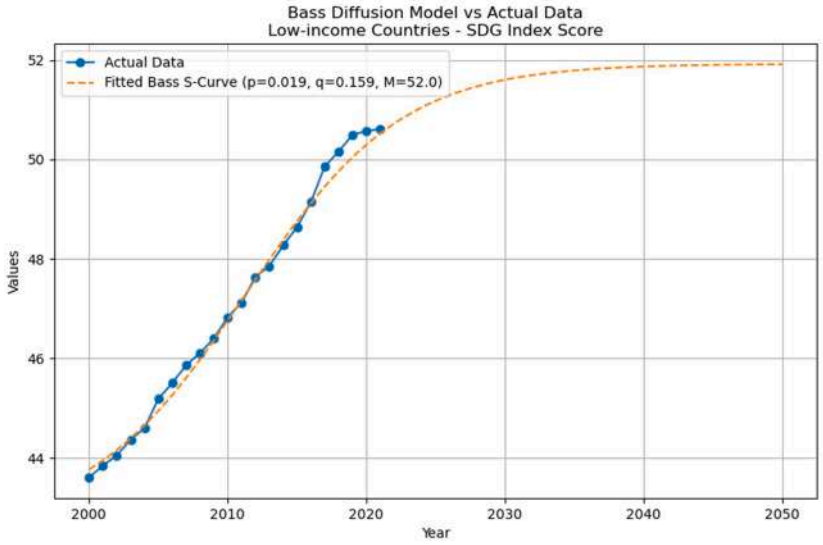
Fig. 3. (*continued*).

performance.

For a minority of countries, the best fitting curve seems to underestimate the actual curve, likely due to idiosyncrasies in the trajectories of the Index score. For these countries, we applied a case-specific fine-tuning of the parameters—a common practice when fitting Bass curves to real data. For a small subset of countries, the time series appears highly linear. In these cases, the least squares method over the full set of parameters (*p, q, M*) led to a meaningless overestimation of parameter *M*, which far exceeded the cap value of 100. For these countries, we forced the market potential to 100.

Moreover, for some countries, the trajectory of the SDG Index score does not follow an S-shaped growth. For these nations, it is pointless to apply the described method as one cannot retrieve useful insights from the Bass framework. For each country, after having applied the





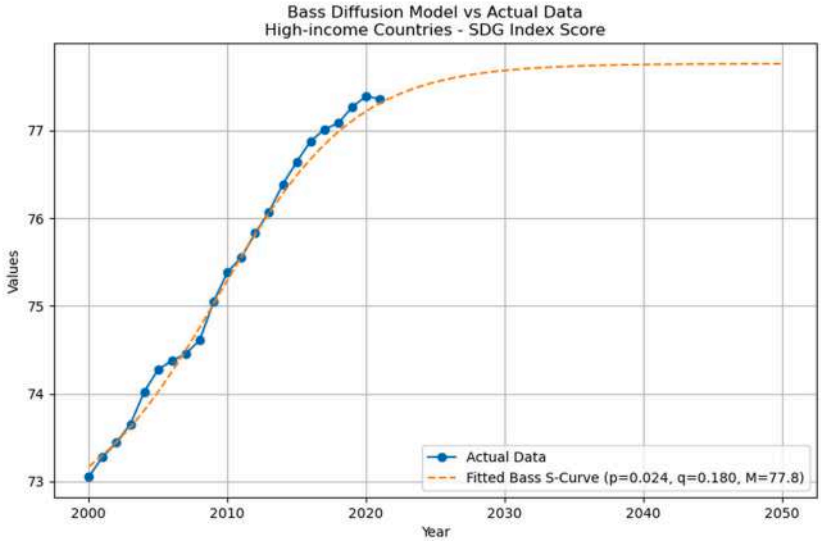


Fig. 3. (*continued*).

corrections and assessed the best fit parameters, the time of the peak in the performance and the expected saturation time were computed. The former refers to the time—which can be either in the past or in the future—when the maximum increase in the year-to-year score is detected. Since this refers to the Bass S-curve rather than the real data, it is not influenced by random fluctuations in the dataset. The latter refers to the time in which the country is expected to reach a satisfactory proportion of its fulfillment potential. In this work, the satisfaction threshold for computing the saturation time is 100 %, but of course, this can be modified to be less demanding. This method can be applied in the same way to the time series for the single goals for the countries in the dataset. Due to these case-by-case exceptions, though, doing so is time-consuming. As a preliminary study, we report in the next section some results derived from the application of this method only to the aggregated SDG Index score. If needed, more granular analysis can be performed.

Results

The results are reported in Figs. 2a–e, 3a–g, and in the Appendix (Table A.1). Findings suggest that the Bass framework is well suited to explaining the majority of the trajectories in the fulfillment of the SDGs. As a very general remark, few countries do not exhibit a clear S-shaped trajectory (14 out of 177 entities), and they have often experienced very severe sociopolitical instability in recent decades. Another 12 countries show and underestimation by the Bass curve. The prediction for the remaining 151 countries does not present such issues, which suggests that the Bass paradigm can still be useful in this application even if it fails in some specific cases. Various clusterings, both geographical (East and South Asia, Eastern Europe and Central Asia, etc.) and sociopolitical (low-income countries, OECD members, etc.), present some variability.

As for the parameter estimates and distributions, the Bass diffusion model revealed substantial heterogeneity across entities. The innovation parameter (p) demonstrated a mean value of 0.012705 with a range spanning from −0.004975 to 0.081554. The imitation parameter (q) exhibited a higher magnitude with a mean of 0.308457 and considerably wider variation, ranging from −1.087885 to 3.899236. The market potential parameter (M) showed extreme variability with a mean of 229.16 and a range extending from −2.92 to 19,789.91.

Geographical clustering

Model fit quality assessment based on the residual sum of squares (RSS) indicated mixed performance across entities. Excellent model fit (RSS < 1) was achieved for 29 entities (16.4 %), while good fit (RSS 1–2) characterized 35 (19.8 %). Moderate fit (RSS 2–3) was observed in 44 entities (24.9 %), and poor fit (RSS ≥ 3) affected 69 (39.0 %). The best-performing models included Denmark (RSS = 0.107025), the United States (RSS = 0.124277), Mauritius (RSS = 0.184018), high-income countries (RSS = 0.191918), and the Philippines (RSS = 0.230923). Conversely, the worst-performing models were Estonia (RSS = 13.317756), Venezuela (RSS = 11.644583), São Tomé and Príncipe (RSS = 10.460178), Angola (RSS = 7.248241), and Mauritania (RSS = 6.897939).

Several entities demonstrated parameter estimates that deviate from theoretical expectations. One entity (South Sudan) exhibited a negative innovation parameter, while five (Azerbaijan, Cuba, Gabon, Luxembourg, and South Sudan) showed negative imitation parameters. Three entities (the Central African Republic, Syria, and Venezuela) yielded negative market potential estimates, and two (Djibouti and New Zealand) displayed extremely high market potential values exceeding 19,000, indicating potential overfitting or data quality concerns.

Socioeconomic clustering

A comparison between estimated market potential (M) and actual market potential (M_real) revealed some underestimation across the dataset. No entities demonstrated overestimation with ratios exceeding 2.0. The highest innovation parameter was observed in Cuba (p = 0.081554), while Barbados exhibited the highest imitation parameter (q = 3.899236), and Djibouti demonstrated the highest estimated market potential (M = 19,789.91). These extreme values suggest either unique diffusion dynamics or potential model specification issues requiring further investigation case by case.

Peak adoption years ranged from 1995 to 2194, with a median peak year of 2012. Saturation years spanned from 2000 to 2198, with a median saturation year of 2033. Four out of 177 entities exhibited invalid peak estimates (Azerbaijan, Cuba, Gabon, and Luxembourg), while three showed saturation projections beyond 2100 (Cuba, Gabon, and Luxembourg). This shows the overall validity of the Bass model application.

Regional aggregates and income-based groupings generally demonstrated better model fit than individual countries, with high-income countries and OECD members being among the top-performing entities. This pattern suggests that aggregated data may smooth individual country volatility and provide more stable parameter estimates for Bass model application.

The minor proportion of entities with poor model fit indicates that the standard Bass diffusion model may have relevant applicability to SDG Index score diffusion patterns. By contrast, those cases presenting an underestimation of market potential and the occurrence of negative parameter values suggest that SDG achievement dynamics sometimes does not conform to traditional product diffusion assumptions, necessitating model modifications or alternative theoretical frameworks for accurate representation of SDG adoption patterns.

Discussion

Clustering analyses based on socioeconomic and geographic criteria reveal nuanced and complementary insights into the diffusion and saturation patterns of SDGs across countries and regions. Socioeconomic clustering distinctly segments countries into developmental tiers–high-income, middle-income, and low-income groups–reflecting fundamental differences in economic capacity, institutional quality and complexity, and human capital that critically shape SDG achievement trajectories. This finding aligns with research emphasizing that sustainable innovation ecosystems and SDG progress are deeply contingent on economic wealth, education, and institutional robustness and complexity, which drive innovation capacity and imitation effects (Dmytrenko & Kuba, 2024; Nylund et al., 2021). The heterogeneity in Bass diffusion model parameters across socioeconomic clusters supports the hypothesis that these foundational conditions strongly influence the pace and extent of SDG adoption.

Geographic clustering highlights regional cohesion and policy spillovers, reflecting shared cultural, political, and environmental contexts that facilitate knowledge transfer and normative convergence (Owen & Vedanthachari, 2022). However, the persistence of substantial intraregional disparities indicates that geographic proximity alone cannot overcome complex structural barriers such as resource disparities, governance fragmentation and complexity, and social inequality (Grama-Vigouroux et al., 2024). This confirms critiques in the literature that ecosystem collaboration rhetoric often confronts complex implementation challenges due to uneven capacities and institutional weaknesses (Berry et al., 2024). Thus, while regional cooperation mechanisms (SDG 17) can catalyze diffusion through multi-stakeholder partnerships and policy harmonization (Owen & Vedanthachari, 2022), the underlying socioeconomic context remains the predominant determinant of SDG diffusion success.

The clustering results further suggest that high-income countries and OECD members, which cluster socioeconomically, exhibit stronger Bass model fits and greater saturation potential, reflecting their advanced innovation ecosystems and complex policy infrastructures (Husainy

et al., 2024; Jütting, 2024). Conversely, many low-income countries, even when geographically proximate to better-performing neighbors, remain in lower diffusion clusters, in line with documented digital divides and resource constraints that exacerbate SDG inequalities (Yuan et al., 2023). This supports the hypothesis that innovation ecosystems, while pivotal for progress on climate action (SDGs 7, 13), a circular economy (SDG 12), and inclusive growth (SDG 10), are highly contingent on overcoming structural barriers (Brás & Robaina, 2024; Song, 2025).

Moreover, the clustering patterns may reflect the uneven spatial distribution of innovation benefits, where urban-centric innovation hubs concentrate resources and capabilities, leaving rural and marginalized populations behind, thus reinforcing spatial inequalities (Yuan et al., 2023). Digital innovation ecosystems in low-income clusters may exacerbate social exclusion due to infrastructural deficits, limiting the imitation-driven diffusion of sustainable practices. The findings also highlight the risk of misaligned national innovation policies that neglect local SDG priorities, such as water security or biodiversity conservation, which are critical in resource-constrained regions (Albitar et al., 2023; Zhao et al., 2023).

Importantly, these results echo the dual nature of innovation ecosystems described in recent literature. On the one hand, innovation ecosystems foster systemic collaboration (SDG 17), green technology scaling (SDG 9), and adaptive resilience (SDG 3) through multistakeholder partnerships, digital tools, and policy incentives (Dmytrenko & Kuba, 2024; Liao et al., 2024; Nylund et al., 2021). On the other hand, they may inadvertently exacerbate inequalities (SDG 10), environmental trade-offs (SDGs 7, 15), and social exclusion, particularly in low-income and marginalized contexts (Berry et al., 2024; Islam, 2025). For example, green innovations in G7 countries have been found to correlate negatively with poverty eradication due to high costs displacing social investments (Islam, 2025), a dynamic that may be reflected in the clustering of diffusion parameters.

In summary, the clustering analyses substantiate the complex interplay between socioeconomic capacity and geographic factors in shaping SDG diffusion pathways. They confirm that while innovation ecosystems are critical enablers of the 2030 Agenda, their transformative potential is mediated by multilevel governance dynamics, resource distribution, and equity considerations (Dionisio et al., 2023; Grama-Vigouroux et al., 2024; United Nations, 2015). These insights suggest that effective policy interventions should simultaneously strengthen socioeconomic foundations and foster regional cooperation to accelerate equitable and widespread diffusion of sustainable development innovations across the globe.

Conclusions

This study demonstrates that the Bass diffusion model can be effectively adapted to analyze national progress toward Sustainable Development Goals, capturing the characteristic S-shaped adoption curves of SDG achievement across diverse countries. The model's parameters reveal significant heterogeneity influenced by socioeconomic and geographic factors, reflecting the complex dynamics of innovation ecosystems. While high-income countries tend to approach saturation earlier, lower-income nations face structural constraints limiting their SDG fulfillment potential. These findings highlight the importance of innovation ecosystems and governance in accelerating sustainable development. Overall, the Bass model provides a valuable quantitative framework for forecasting SDG saturation timing and informing policy interventions.

Theoretical implications

The application of the Bass diffusion model in this study extends its traditional use from product and technology adoption to the complex domain of achieving SDGs at the national level (Bass, 1969; Wonglimpiyarat, 2025). The model's foundational premise—that adoption dynamics arise from two complementary mechanisms, namely innovation-driven external influences and imitation-driven internal social interactions—offers a parsimonious yet powerful lens through which to understand the nonlinear progression of SDG fulfillment (Kanie et al., 2014). By reinterpreting the market potential parameter as the SDG saturation potential, this adaptation accounts for structural constraints and capacities that are unique to each country, such as economic resources, institutional quality, and geopolitical stability (Marzouk et al., 2022).

Theoretically, this reformulation bridges innovation diffusion theory with complexity science by acknowledging that SDG progress emerges from the interplay of multiple heterogeneous agents within national innovation ecosystems (Breslin et al., 2021; Ponta et al., 2023). These ecosystems are characterized by adaptive, nonlinear feedback loops among governments, firms, and civil society actors, which influence the acceleration and eventual saturation of sustainable development efforts (Reed et al., 2025; Toth et al., 2024). The Bass model's S-shaped curve effectively captures the transition from initial slow progress—often hindered by institutional inertia and resource limitations (Grama-Vigouroux et al., 2024)—to rapid acceleration driven by policy coherence, knowledge spillovers, and normative convergence (Collste et al., 2017; Li et al., 2023), culminating in a plateau as countries near their fulfillment ceilings.

Moreover, the model's parameters provide insight into the relative strength of external policy drivers versus internal social dynamics across different socioeconomic and geographic clusters, highlighting the importance of context-dependent governance frameworks (Husainy et al., 2024; Nylund et al., 2021). This aligns with the emphasis of complexity theory on emergent behaviors arising from microlevel interactions within complex adaptive systems (Granstrand & Holgersson, 2020; Miller et al., 2024). While the Bass model simplifies some aspects of these interactions by aggregating adopters, its successful application here suggests that even relatively simple diffusion models can yield meaningful insights into complex socioinstitutional transformations when carefully adapted.

Theoretically, this study invites further integration of the Bass framework with network-based and agent-based models that explicitly capture heterogeneity and multilevel interactions (Zhang et al., 2024; Zhou & Li, 2024), enhancing the understanding of how innovation ecosystems evolve and influence SDG trajectories. It also underscores the need to consider dynamic saturation potentials and threshold effects to better reflect the evolving capacities and constraints within innovation ecosystems. In sum, this work contributes to the theoretical literature by demonstrating the Bass model's flexibility and relevance for modeling complex, multi-actor sustainability transitions in national contexts.

Practical implications

From a practical standpoint, the adapted Bass diffusion model offers policymakers, innovation managers, and development practitioners a quantitative tool for forecasting the timing and extent of national SDG achievement, enabling more informed strategic planning (Sachs et al., 2024). By estimating the innovation and imitation parameters, decision-makers can discern the relative impact of external policy initiatives versus internal social dynamics, guiding the allocation of resources and the design of interventions to accelerate sustainable development (Dmytrenko & Kuba, 2024; Nylund et al., 2021).

For instance, a higher innovation parameter suggests that strengthening external drivers—such as regulatory frameworks, subsidies for green technologies, and international cooperation—can effectively stimulate early SDG adoption (Bitencourt et al., 2021; European Commission, 2023). Conversely, a higher imitation parameter highlights the critical role of endogenous factors like peer learning, knowledge spillovers, and regional cooperation networks, suggesting that fostering

collaborative governance and multi-stakeholder partnerships can increase progress (Collste et al., 2017; Owen & Vedanthachari, 2022). Understanding these dynamics allows governments to tailor policies to their specific contexts, focusing on either enhancing policy incentives or facilitating social diffusion mechanisms (Dionisio et al., 2023; Liao et al., 2024).

The ability of the model to predict saturation times also assists in setting realistic targets and monitoring progress, as it helps to identify countries or regions at risk of stagnation due to structural barriers or governance challenges (Grama-Vigouroux et al., 2024; Zhao et al., 2023). This insight supports the prioritization of capacity-building efforts, institutional reforms, and investment in innovation ecosystems where they are most needed (Jütting, 2024; UNDP, 2024). Furthermore, recognizing the heterogeneity of diffusion patterns across socioeconomic clusters enables international organizations and donors to customize support strategies, addressing disparities between high-income and low-income countries (World Bank, 2024).

In addition, the Bass model's framework can inform private sector actors and innovation hubs by signaling market readiness and potential demand for sustainable technologies, thereby optimizing investment decisions and scaling strategies (Husainy et al., 2024; Song, 2025). It also aids in anticipating the impact of disruptive events or policy shocks on SDG trajectories, enabling the use of adaptive management in complex and uncertain environments (Reed et al., 2025).

Overall, this practical application of the Bass diffusion model equips stakeholders with a robust, data-driven approach to enhance coordination, improve policy coherence, and accelerate the diffusion of sustainability innovations within national innovation ecosystems, ultimately advancing the global 2030 Agenda (Nylund et al., 2021; United Nations, 2015).

Limitations and future research directions

Despite its valuable insights, this study acknowledges several limitations inherent in applying the Bass diffusion model to complex socioinstitutional phenomena like SDG achievement. The model's assumption of homogeneous adopter populations and constant parameters over time simplifies the diverse and evolving nature of national innovation ecosystems. Some countries exhibited poor model fit or anomalous parameter estimates, reflecting sociopolitical instability or data quality issues that the model cannot fully capture.

Moreover, the model used in this research needs to be complemented by Rogers' model when considering investigating the maturity stages of a subgroup of more consolidated innovation ecosystems as well as the consequences of for platform design and governance (Rogers, 2003; Rogers et al., 2014; Springer et al., 2025).

Future research should explore methodological enhancements by integrating the Bass framework with agent-based and network diffusion models to explicitly represent heterogeneous actors, multilevel governance structures, and dynamic feedback loops. Incorporating time-varying parameters would enable the model to better reflect changing policy environments, shocks, and adaptive behaviors. Additionally, leveraging richer, higher-frequency data sources, such as real-time policy implementation metrics or social network analyses, could improve parameter estimation and model validation.

Further empirical studies could extend the analysis to subnational levels or specific SDGs to uncover more granular diffusion patterns and contextual factors. Investigating the interplay between innovation ecosystems and negative externalities, such as inequality or environmental trade-offs, would also deepen understanding of the "dark side" of innovation.

Additional research is needed to uncover the differences in sustainability-related dynamics, governance patterns, and structural factors of B2B innovative industrial ecosystems vs B2C ones, thus calling for a multigroup comparison of B2B vs B2C ecosystems (Springer et al., 2025; see also Ritala & Jovanovic, 2024).

Future research efforts should also be devoted to coordination-level efforts in platform ecosystems and innovation ecosystems in general, with a view to grand challenge resolution. Possible research questions to address include: (1) How can pro-environmental or prosocial actors be combined with profit-oriented ones in innovation ecosystems?; (2) How can these different kinds of actors be incentivized?; (3) How can brokerage among those actors help in reducing the overall complexity and uncertainty in innovation ecosystems? (Ritala, 2024; see also Samuelson, 1974).

Finally, interdisciplinary approaches combining complexity science, behavioral economics, and sustainability transitions theory hold promise for refining theoretical frameworks and developing more comprehensive models to guide policy and practice in achieving sustainable development.

Funding

This work was partly supported by:

- The Ministry of Science and Technology of China through the University of Science and Technology of China, Hefei, Anhui, P.R. China (Project number: DL2023200001L, project title: "Research on Regional Innovation Ecosystem of China in the New era").
- The Brazilian Federal Agency for Support and Evaluation of Graduate Education - CAPES under the PRINT - Institutional Internationalization Program through the University of São Paulo, Brazil (Project number: 88,887.936506/2024–00).

CRediT authorship contribution statement

Giacomo Masali: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Donato Morea:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Carlo Giglio:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Gianpaolo Iazzolino:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Guido Perboli:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Elena Bruni:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

We have nothing to declare.

Appendix

Table A.1
Best fitting parameters, the corresponding sum of squares error, the peak and saturation times and the re-adjusted fulfillment potential per each country.

Country	p_least_squares	q_least_squares	M_least_squares	RSS_least_squares	Peak	Saturation	M real
Afghanistan	1,13864E-05	0,699785628	6,089420845	0,829995243	2015	2033	50,90850746
Albania	0,01542901	0,258028958	8,290141953	6,839464783	2010	2028	71,83034307
Algeria	0,018283443	0,218681079	9,715793158	4,172398488	2010	2031	72,04329848
Angola	0,001355098	0,796154922	4,328220356	7,24824067	2007	2017	50,80627652
Argentina	0,018203105	0,242534455	6,743017457	2,988414281	2009	2028	73,14608137
Armenia	0,020454587	0,143956786	6,363761807	1,860877556	2011	2041	71,92382538
Australia	0,02315452	0,190570467	4,822288441	1,361707151	2009	2031	75,97629383
Austria	0,018210041	0,1992056	5,882978404	1,981110843	2011	2033	82,75608817
Azerbaijan	0,019461335	-0,019478668	34,47663192	4,552042517	Invalid	2000	97,20875436
Bahrain	3,22202E-05	0,701413642	2,482158516	4,346062073	2014	2030	64,17366895
Bangladesh	0,000338163	0,415795142	10,63995774	3,269711201	2017	2038	63,9387632
Barbados	1,99426E-23	3,899236279	1,021232044	3,52095925	2013	2015	68,31640871
Belarus	0,020709038	0,108574226	8,692930492	2,551025587	2012	2050	78,28964843
Belgium	0,040722506	0,134444228	7,126558248	3,679143062	2006	2031	80,21066261
Belize	0,019595172	0,220118448	6,256975711	2,167548183	2010	2030	65,83510446
Benin	0,011719941	0,212317564	5,819656152	2,212172322	2012	2036	52,03480067
Bhutan	0,015971014	0,196734831	12,9913294	2,502161694	2011	2035	72,01702192
Bolivia	0,016704936	0,171226396	10,12056274	3,413567335	2012	2038	69,10183642
Bosnia and Herzegovina	0,006098272	0,249467084	6,68328377	2,423353368	2014	2037	72,60912163
Botswana	7,21147E-05	0,657453847	5,695918017	1,135931396	2013	2030	60,98163097
Brazil	0,031493876	0,130975112	6,151692341	2,957110632	2008	2036	73,54155109
Brunei Darussalam	0,000667361	0,505458357	3,415337488	4,587032836	2013	2029	66,15572434
Bulgaria	0,044650194	0,295909329	6,846127225	6,676136021	2005	2017	73,63245052
Burkina Faso	0,003993005	0,313666029	8,17763783	4,339831703	2013	2033	54,66390022
Burundi	0,025400976	0,191186515	7,718164912	2,4829326	2009	2030	54,47353893
Cambodia	0,002675952	0,325419321	14,85637618	3,330775819	2014	2035	63,60050747
Cameroon	0,006559417	0,308504545	7,07459376	1,342755314	2012	2031	55,49963942
Canada	0,023430313	0,19559211	2,958054055	0,332887379	2009	2031	77,91081477
Central African Republic	0,000600282	0,505294214	-0,589044194	1,204398301	2013	2000	38,29491302
Chad	0,000910255	0,564302408	2,026822465	2,629952317	2011	2025	41,06416343
Chile	0,006221331	0,268890361	8,251619566	1,368872512	2013	2035	78,3844237
China	0,002490427	0,357079894	9,493388646	0,907824051	2013	2033	72,91483157
Colombia	0,034924128	0,101534259	9,636317588	6,076669723	2007	2040	71,64208643
Congo, Dem. Rep.	0,001550144	0,378928283	4,366261011	1,996624758	2014	2033	50,380415
Congo, Rep.	0,00113846	0,515782011	5,454876764	0,460286921	2011	2026	51,99652102
Costa Rica	0,023366705	0,143228145	5,182123829	2,306239722	2010	2039	74,53049393
Cote d'Ivoire	0,000172216	0,493948466	8,567049634	1,869340405	2016	2035	58,33718584
Croatia	0,000659887	0,528835034	6,181447601	0,624719402	2012	2028	77,76242522
Cuba	0,081553771	-0,081550714	7,546582779	2,754970236	Invalid	2100+	76,47032718
Cyprus	0,027745259	0,079031031	10,55400579	4,1134898	2009	2053	77,23651898

(*continued on next page*)

Table A.1 (*continued*)

Czech Republic	0,028309905	0,134023988	8,898644217	1,210594425	2009	2037	81,68866343
Denmark	0,001208209	0,445470088	2,846306441	0,107024673	2013	2030	85,0729911
Djibouti	6,39641E-06	0,045662928	19789,90699	5,933782555	2194	2000	19835,18624
Dominican Republic	0,026640557	0,13317632	11,04602367	5,99103156	2010	2038	72,48442353
East and South Asia	0,001953578	0,355468267	9,175236112	1,230560144	2014	2034	66,32818044
Eastern Europe and Central Asia	0,002787344	0,306279861	6,240785556	0,498493212	2015	2037	71,57561214
Ecuador	0,007120801	0,335059115	9,7863047	2,097584423	2011	2028	72,29620914
Egypt, Arab Rep.	0,005365941	0,119689979	12,83995117	2,917501683	2024	2073	76,5505121
El Salvador	0,015770736	0,277298771	9,139270999	2,531241568	2009	2027	69,91401764
Estonia	0,045967409	0,079189618	11,5025532	13,31775605	2004	2038	82,09241216
Eswatini	0,020892493	0,260903155	7,021628817	3,914761816	2008	2026	54,61844658
Ethiopia	0,009159205	0,128767965	18,93171668	2,858603908	2019	2059	66,13175631
Fiji	0,000683667	0,407913554	5,752515536	3,355272835	2015	2035	72,6598385
Finland	0,025120621	0,302638525	4,31396779	2,87784164	2007	2021	86,34964748
France	0,027100292	0,135653236	7,977748285	1,876821601	2009	2037	82,40671838
Gabon	0,020623751	-0,020629905	22,54906048	6,149646843	Invalid	2100+	78,12393898
Gambia, The	0,001729922	0,360960487	9,705108961	3,541705278	2014	2034	59,5360257
Georgia	0,007082317	0,253761609	8,403770275	1,338938967	2013	2036	74,0724438
Germany	0,028028429	0,152850795	7,617510438	1,757654438	2009	2034	83,05026065
Ghana	0,009006515	0,242677204	9,18221511	6,12809496	2013	2035	64,03975594
Greece	0,011073114	0,020431309	31,45800161	2,805471061	2019	2087	100
Guatemala	0,006937194	0,259701022	6,565234772	3,359863934	2013	2035	61,29950559
Guinea	0,019310492	0,200538871	5,42722793	1,961857377	2010	2032	51,73793899
Guyana	0,004827736	0,190540507	7,254916078	2,359403769	2018	2050	65,63096126
Haiti	0,000398417	0,545812354	3,557145103	0,720436635	2013	2029	52,94121365
High-income Countries	0,023945374	0,179854444	4,743238992	0,191917651	2009	2032	77,7986967
Honduras	0,01400707	0,276353637	6,053427301	4,614179107	2010	2028	63,1186844
Hungary	0,017929321	0,042978248	11,80071117	2,040549168	2014	2097	85,32091456
Iceland	0,003692814	0,378465331	3,579454892	2,73182897	2012	2029	78,62389728
India	4,2179E-05	0,597642093	7,219958031	2,447684836	2015	2034	58,8185613
Indonesia	0,002511464	0,313877416	10,85799104	2,584054357	2015	2037	70,10729522
Iran, Islamic Rep.	0,002248601	0,348637825	7,787842054	1,586528672	2014	2034	68,63044107
Iraq	0,013603885	0,192870149	5,035629268	5,122665624	2012	2037	62,60210924
Ireland	0,035695547	0,291334612	4,99175561	2,314833301	2006	2019	80,32272347
Israel	0,00071124	0,426947879	4,024709434	1,422034742	2014	2034	73,42504381
Italy	0,030973135	0,209730591	6,858124369	2,531957838	2007	2026	78,46314818
Jamaica	0,012830485	0,246497744	3,363099099	1,134746387	2011	2031	68,95083663
Japan	0,006654147	0,014431169	24,23535133	0,62157373	2036	2121	100
Jordan	0,000336508	0,401123057	2,237378148	2,892922044	2017	2039	69,55273718
Kazakhstan	0,006779311	0,359749159	5,480322215	2,915313815	2010	2027	71,38819153
Kenya	0,003044503	0,288328303	8,863036502	0,385472049	2015	2038	60,8184509
Korea, Rep.	0,033795188	0,14553384	5,134412558	1,210415456	2008	2032	78,24305857
Kuwait	0,001939366	0,30815095	1,389774935	2,548698629	2016	2039	63,41290056
Kyrgyz Republic	0,006298209	0,279692057	6,914155756	4,344503521	2013	2034	74,09527316
Lao PDR	0,001294277	0,409045878	10,20915496	2,340507801	2014	2032	62,2188381

(*continued on next page*)

Table A.1 (*continued*)

Latin America and the Caribbean	0,025715693	0,199023131	5,665169674	1,148184333	2009	2029	69,91854089
Latvia	0,022941179	0,148735244	8,91707319	3,3234034	2010	2038	81,41613846
Lebanon	0,020859443	0,248701977	3,500745064	5,872435858	2009	2027	65,22553162
Lesotho	0,022869982	0,148480805	9,089074146	4,194351784	2010	2038	56,38675678
Liberia	0,02908123	0,153114739	6,123447834	1,337975016	2009	2033	50,58104643
Lithuania	0,051816127	0,169562897	7,251718395	4,141259464	2005	2023	75,22287169
Lower-middle-income Countries	0,001193522	0,383086548	8,084962656	1,256982632	2015	2034	61,25056364
Low-income Countries	0,019192535	0,158896512	8,41251011	0,448918409	2011	2039	52,01850073
Luxembourg	0,042937998	-0,042855676	11,29616678	3,05477392	Invalid	2100+	81,2561582
Madagascar	0,005176378	0,01299285	56,84713172	3,327110644	2050	2198	100
Malawi	0,013512508	0,231392768	5,380800299	1,917856461	2011	2032	53,66290751
Malaysia	0,003173776	0,333063874	6,616241478	2,186271306	2013	2033	70,63737047
Maldives	0,010329047	0,231112769	9,082462549	2,499735798	2012	2035	72,01800176
Mali	0,013456648	0,222526275	8,885575393	2,83738678	2011	2033	54,84025305
Malta	0,010088872	0,185788379	10,09842788	2,661327678	2014	2042	78,91690916
Mauritania	0,01730227	0,213091747	11,55058845	6,897938732	2010	2032	56,49178803
Mauritius	0,002640867	0,214940864	5,544938858	0,184018446	2020	2051	70,11218702
Mexico	0,020273693	0,128279635	10,28137186	2,964836196	2012	2044	72,53625183
Middle East and North Africa	0,012503208	0,187869806	7,342163304	0,415424162	2013	2039	67,80833354
Moldova	0,03150764	0,116009385	7,895799779	1,408866415	2008	2039	74,97293006
Mongolia	1,76025E-06	0,928427435	3,553289816	5,732263796	2014	2029	63,41775853
Montenegro	2,34522E-10	2,666285967	1,73682177	5,673297839	2008	2000	66,86658718
Morocco	0,024948238	0,182232267	11,07379717	2,59782481	2009	2031	69,71824913
Mozambique	0,024632496	0,108400471	11,46572494	5,024890596	2011	2046	56,23934077
Myanmar	0,000227955	0,533712566	9,710442038	6,12321136	2014	2032	64,77468511
Namibia	0,000687703	0,537106327	7,394644237	3,327595459	2012	2027	62,70189153
Nepal	0,009835794	0,26090807	14,48525193	4,364186091	2012	2032	67,00570976
Netherlands	0,012504422	0,263766336	3,312304639	0,74103119	2011	2030	80,03215422
New Zealand	1,11819E-06	0,096215015	19381,9524	1,948663981	2118	2000	19458,55624
Nicaragua	0,025337994	0,201039212	9,417471222	4,70654501	2009	2029	67,72718511
Niger	0,013041256	0,212283906	8,404888836	6,232253017	2012	2035	53,07943984
Nigeria	0,014107209	0,092852783	9,89279555	4,445837917	2017	2065	58,64098397
North Macedonia	0,000863801	0,480187459	6,104227133	1,780627418	2013	2029	71,46927913
Norway	0,034273217	0,117179774	4,258340089	2,124348616	2008	2037	82,84939233
Oceania	9,06611E-05	0,500022583	0,590953496	0,970942157	2017	2037	51,2277176
OECD members	0,026624298	0,169304266	5,794414908	0,285499065	2009	2032	77,70325531
Oman	0,00077232	0,461410247	8,034029655	4,464005782	2013	2031	69,10774667
Pakistan	0,000964077	0,409715308	5,849783304	1,440741103	2014	2033	59,47253681
Panama	0,000324276	0,501066521	3,735598941	5,41274863	2014	2032	63,94913487
Papua New Guinea	0,001550303	0,29854012	0,655199284	0,941917796	2017	2042	53,15164091
Paraguay	0,014950925	0,216868045	6,911210299	3,933323408	2011	2033	67,71181228
Peru	0,020492597	0,174390393	10,04203446	2,676450409	2010	2035	73,19483404
Philippines	0,002536724	0,262937674	8,765101524	0,230922699	2017	2043	67,56208474
Poland	0,016428555	0,196284374	9,057866746	4,082989024	2011	2035	81,59287284
Portugal	0,027017686	0,135431962	10,15591215	3,042183284	2009	2038	80,69851586

(*continued on next page*)

Table A.1 (*continued*)

Qatar	0,021785237	0,201462558	9,99079157	4,898345423	2009	2031	67,35797938
Rest of World (non-OECD)	0,002533407	0,338582453	7,578022881	0,796433529	2014	2034	63,98530747
Romania	0,017333582	0,298929412	8,567609357	4,977871144	2009	2024	77,45432724
Russian Federation	0,000976437	0,383281155	7,163875698	2,398640719	2015	2036	73,98104937
Rwanda	0,014915907	0,211248545	12,86794624	5,426926677	2011	2034	60,48697731
Sao Tome and Principe	0,026773915	0,344450117	7,629540594	10,46017846	2006	2019	59,76791289
Saudi Arabia	0,000249409	0,43729572	7,666015922	2,937265501	2017	2038	66,80100989
Senegal	0,018680479	0,156634357	10,83251007	4,420843671	2012	2040	60,55013899
Serbia	0,001214559	0,360666694	6,748515099	3,315400853	2015	2036	75,97324987
Sierra Leone	0,001603258	0,391928693	8,414624172	2,847766126	2013	2032	53,36514945
Singapore	0,049335148	0,143962735	2,910013114	3,8759477	2005	2026	71,88493464
Slovak Republic	0,026724764	0,143235875	8,304656056	1,94321724	2009	2036	79,52568578
Slovenia	0,030910034	0,18062074	7,580134935	3,646792163	2008	2029	80,39648213
Small Island Developing States	0,002276363	0,365230156	4,778447869	0,563796815	2013	2032	65,08844105
Somalia	0,000120842	0,539501017	2,975673465	1,857018804	2015	2034	45,0034891
South Africa	0,004682688	0,269702176	7,144118681	3,336864257	2014	2037	64,65382512
South Sudan	-0,004975129	-1,087884921	0,512654222	0,757189324	1995	2000	38,9620739
Spain	0,021570211	0,045532779	12,88592042	2,302965959	2011	2084	86,0237215
Sri Lanka	0,000830774	0,422471004	5,776398191	2,055091087	2014	2033	69,57057858
Sub-Saharan Africa	0,013400636	0,192873493	8,459877278	0,66439278	2012	2038	54,82136341
Sudan	0,018975447	0,165172253	5,994373775	3,436867877	2011	2038	50,51364534
Suriname	0,004317655	0,243298391	8,863951538	0,511491555	2016	2041	72,91059382
Sweden	0,008354024	0,638857843	1,664426105	1,128147922	2006	2015	85,16765558
Switzerland	0,009389513	0,308378575	3,947365756	0,924592956	2010	2028	80,57276322
Syrian Arab Republic	0,000724318	0,504599983	-2,922587002	4,248065464	2012	2000	54,33503564
Tajikistan	0,018903763	0,139683393	9,716994341	3,612013855	2012	2043	71,06388457
Tanzania	0,002965083	0,340441485	8,034076966	1,839462235	2013	2033	56,87593887
Thailand	0,010739892	0,213704749	5,851714048	1,663011242	2013	2037	74,90938004
Togo	6,73418E-05	0,548500189	6,47129348	3,03112011	2016	2035	54,39811715
Trinidad and Tobago	0,022693327	0,239960878	4,498717219	2,436315475	2008	2026	65,55660259
Tunisia	0,026921686	0,126800131	8,092916953	1,107594245	2010	2039	71,93300911
Turkey	0,007994389	0,4396096	4,579407666	3,472174025	2008	2021	69,50372204
Turkmenistan	0,000275381	0,500304469	1,275664968	1,791802382	2014	2033	64,300275
Uganda	0,009582692	0,191462754	9,360769607	2,19005924	2014	2042	56,74791645
Ukraine	0,003046742	0,101681645	30,43001078	3,379479031	2033	2049	100
United Arab Emirates	0,001925456	0,352291358	10,46029189	4,585360339	2014	2034	68,82908479
United Kingdom	0,003153957	0,366211101	4,819452291	0,278325054	2012	2031	80,65273501
United States	0,005646285	0,421816487	2,962780346	0,124277325	2010	2024	74,23811235
Upper-middle-income Countries	0,005345913	0,292849993	8,170387212	0,716371048	2013	2033	71,94886903
Uruguay	0,006602334	0,268444452	8,098798815	3,239161673	2013	2034	77,8602026
Uzbekistan	0,007193206	0,117279263	19,65946753	1,428718327	2022	2068	80,49907961
Venezuela, RB	5,23436E-05	0,499993671	-2,155636371	11,64458346	2018	2000	58,248276
Vietnam	0,0109058	0,224755678	9,154400285	3,155046513	2012	2035	73,4607

(*continued on next page*)

Table A.1 (*continued*)

World	0,003445866	0,313707941	7,11825795	0,630684824	2014	2034	66,47987042
Yemen, Rep.	0,02245508	0,671028772	2,611804882	2,975153874	2004	2012	52,11193579
Zambia	0,005074963	0,358429225	6,066391043	4,441458524	2011	2028	54,55764195
Zimbabwe	7,13553E-05	0,814190253	4,299354586	3,889007059	2011	2024	57,24531798

Legend:

Good fit
Bad fit, no S-shape or too fluctuating
Under-estimated by Bass curve
Smoothed data (moving average)
Smoothed data (exponential)
M parameter forced to 100

References

Abdullai, L., Porras, J., & Haque, S. (2022). Building a National Smart Campus to support sustainable business development: An ecosystem approach. *Environmental Science, Business, Engineering*. https://doi.org/10.48550/arXiv.2209.13613

African Development Bank. (2025). *Equitable resource distribution in innovation ecosystems: A global south perspective*.

Agasty, S., Tarannum, F., & Narula, S. (2023). Sustainability innovation index for micro, small and medium enterprises and their support ecosystems based on an empirical study in India. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.137793

Albitar, K., Al-Shaer, H., & Liu, Y. (2023). Corporate commitment to climate change: The effect of eco-innovation and climate governance. *Research Policy*. https://doi.org/10.1016/j.respol.2022.104697

Ancona, A., Cinelli, M., Ferraro, G., & Iovanella, A. (2023). Network-based principles of entrepreneurial ecosystems: A case study of a start-up network. *Small Business Economics, 61*, 1497–1514.

Aryee, R., Kanda, W., Geissdoerfer, M., & Kirchherr, J. (2025). Circular ecosystems: Past, present, and future research directions. 29(4), 1364–1381. 10.1111/jiec.70061.

Azmat, F., Lim, W., Moyeen, A., Voola, R., & Gupta, G. (2023). Convergence of business, innovation, and sustainability at the tipping point of the sustainable development goals. *Journal of Business Research*. https://doi.org/10.1016/j.jbusres.2023.114170

Bakry, D., Daim, T., Dabić, M., & Yesilada, B. (2022). An evaluation of the effectiveness of innovation ecosystems in facilitating the adoption of sustainable entrepreneurship. *Journal of Small Business Management, 62*, 763–789. https://doi.org/10.1080/00472778.2022.2088775

Baldwin, C. Y. (2024). *Design rules, volume 2: How technology shapes organizations*. MIT Press Ltd. https://doi.org/10.7551/mitpress/7374.001.0001

Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science, 15*(5), 215–227.

Berry, E. M., Burlingame, B., & le Coutre, J. (2024). Partnerships for the sustainable development goals: A call for more science. *Frontiers in Nutrition, 11*, Article 1347593. https://doi.org/10.3389/fnut.2024.1347593

Bitencourt, L., Abud, T., Santos, R., & Borba, B. (2021). Bass diffusion model adaptation considering public policies to improve electric vehicle sales: A Brazilian case study. *Energies, 14*(17), 5435. https://doi.org/10.3390/en14175435

Brás, G., & Robaina, M. (2024). National innovation systems and sustainable environmental performance: A cross country analysis. *Environmental challenges*. https://doi.org/10.1016/j.envc.2024.100978

Brdulak, A., Chaberek, G., & Jagodziński, J. (2021). BASS model analysis in "crossing the chasm" in E-cars innovation diffusion scenarios. *Energies, 14*, 3216. https://doi.org/10.3390/EN14113216

Breslin, D., Kask, J., Schlaile, M., & Abatecola, G. (2021). Developing a coevolutionary account of innovation ecosystems. *Industrial Marketing Management, 98*, 59–68. https://doi.org/10.1016/j.indmarman.2021.07.016

Chatti, R., Drabo, M., & Gagnon, D. (2024). Innovation ecosystem performance indicators: Review of the literature. Statistics Canada, catalogue no. 11-633-X — No. 052, ISSN 2371-3429, ISBN 978-0-660-73268-8.

Collste, D., Pedercini, M., & Cornell, S. E. (2017). Policy coherence to achieve the SDGs: Using integrated simulation models to assess effective policies. *Sustainability Science, 12*(6), 921–931. https://doi.org/10.1007/s11625-017-0457-x

Dionisio, M., De Souza, S., Paula, F., & Pellanda, P. (2023). The role of digital social innovations to address SDGs: A systematic review. *Environment, development and sustainability* (pp. 1–26). https://doi.org/10.1007/s10668-023-03038-x

Dmytrenko, D., & Kuba, O. (2024). Governmental policies and sustainable outcomes in EU: How innovations change the game?. In *Proceedings of the European conference on innovation and entrepreneurship*. https://doi.org/10.34190/ecie.19.1.2744

Ellen MacArthur Foundation. (2023). Circular economy in innovation ecosystems: The Swedish textile case study. https://ellenmacarthurfoundation.org.

European Commission. (2023). *The EU green deal regional innovation hubs: Policy coordination case studies*. Publications Office of the European Union.

Fatma, N., & Haleem, A. (2023). Exploring the nexus of eco-innovation and sustainable development: A bibliometric review and analysis. *Sustainability, 15*, Article 12281. https://doi.org/10.3390/su151612281

Ferrari, A. G., Jugend, D., Armellini, F., Barbalho, S. C. M., & de Carvalho, M. M. (2023). Crossing actors' boundaries towards circular ecosystems in the organic food sector: Facing the challenges in an emerging economy context. *Journal of Cleaner Production, 407*, Article 137093.

Fu, B., Zhang, J., Wang, S., & Zhao, W. (2020). Classification–coordination–collaboration: A systems approach for advancing sustainable development goals. *National Science Review, 7*(5). https://doi.org/10.1093/nsr/nwaa048

George, G., Merrill, R., & Schillebeeckx, S. (2020). Digital sustainability and entrepreneurship: How digital innovations are helping tackle climate change and sustainable development. *Entrepreneurship Theory and Practice, 45*, 999–1027. https://doi.org/10.1177/1042258719899425

Gifford, E., McKelvey, M., & Saemundsson, R. (2020). The evolution of knowledge-intensive innovation ecosystems: Co-evolving entrepreneurial activity and innovation policy in the West Swedish maritime system. *Industry and Innovation, 28*, 676. https://doi.org/10.1080/13662716.2020.1856047

Giglio, C., & De Maio. (2022). A structural equation model for analysing the determinants of crowdshipping adoption in the last-mile delivery within university cities. *International Journal of Applied Decision Sciences, 15*(2), 117–142.

Grama-Vigouroux, S., Saidi, S., Uvarova, I., Cīrule, I., & Sellami, M. (2024). Drivers and barriers of national innovation ecosystems for implementing sustainable development goals: A Latvian case study. *IEEE Transactions on Engineering Management, 71*, 4188–4204. https://doi.org/10.1109/TEM.2022.3233859

Granstrand, O., & Holgersson, M. (2020). Innovation ecosystems: A conceptual review and a new definition. *Technovation, 90–91*, Article 102098.

Gyimah, S., Owusu-Manu, D. G., Edwards, D. J., Buertey, J. I. T., & Danso, A. K. (2024). Exploring the contributions of circular business models towards the transition of green economy in the Ghanaian construction industry. *Smart and Sustainable Built Environment, 14*(3), 85–9880.

Han, J., Ruan, Y., Wang, Y., & Zhou, H. (2019). Toward a complex adaptive system: The case of the Zhongguancun entrepreneurship ecosystem. *Journal of Business Research, 128*, 537–550.

Henrysson, M., Swain, R. B., Swain, A., et al. (2024). Sustainable development goals and wellbeing for resilient societies: Shocks and recovery. *Humanities and Social Sciences Communications, 11*, 1513. https://doi.org/10.1057/s41599-024-03973-8

Huang, Y., Kang, A., Jiang, Z., Li, J. Y., Gan, X., & Zhou, B. (2024). An approach based on ecosystem services for assessing progress towards sustainable development goals at both national and provincial levels in China. *Scientific Reports, 14*. https://doi.org/10.1038/s41598-024-78632-8

Husainy, A., Mangave, S., Ingale, A., Patil, Y., & Koganole, M. (2024). Innovation ecosystems and green building techniques for a sustainable future: Leveraging advanced technologies. *The Asian review of civil engineering*. https://doi.org/10.70112/tarce-2024.13.2.4233

Iizuka, M., & Hane, G. (2021). Towards attaining the SDGs: Cases of disruptive and inclusive innovations. *Innovation and Development, 11*, 343–364. https://doi.org/10.1080/2157930X.2021.1954751

International Energy Agency (IEA). (2023). *Denmark's wind energy transition: A resilience case study*. OECD Publishing.

International Telecommunication Union (ITU). (2023). Digital inclusion through innovation ecosystems: Uganda's gender-inclusive tech hubs. https://www.itu.int.

Isenberg, D. J. (2016). Applying the ecosystem metaphor to entrepreneurship: Uses and abuses. *The Antitrust Bulletin, 61*(4), 564–573.

Islam, H. (2025). Nexus of economic, social, and environmental factors on sustainable development goals: The moderating role of technological advancement and green innovation. *Innovation and Green Development, 4*(1), Article 100183.

Jan, S. Q., Junfeng, J., Iqbal, M. B., Raza, A., Naz, M., & Bhatt, T. K. (2025). The impact of entrepreneurial ecosystems and sustainable digital innovation on business performance: A study of Gilgit-Baltistan Pakistan. *Frontiers in Sustainability, 6*, Article 1485680. https://doi.org/10.3389/frsus.2025.1485680

Jütting, M. (2024). Crafting mission-oriented innovation ecosystems: Strategic levers for directing collaborative innovation toward the grand challenges. *IEEE Transactions on Engineering Management, 71*, 12053–12067. https://doi.org/10.1109/TEM.2022.3171735

Kanie, N., Abe, N., Iguchi, M., Yang, J., Kabiri, N., Kitamura, Y., Managi, S., Miyazawa, I., Olsen, S., & Tasaki, T. (2014). Integration and diffusion in sustainable development goals: Learning from the past, looking into the future. *Sustainability, 6*(4), 1761–1775. https://doi.org/10.3390/su6041761

Khalik, I., Sapei, A., Hariyadi, S., & Anggraeni, E. (2024). Development of clean water supply policies to achieve SDG 6 targets in Bengkulu City. In *Proceedings of the IOP conference series: Earth and environmental science, volume 1359, frontier in sustainable agromaritime and environmental development conference 14/12/2023 –15/12/2023 Bogor, Indonesia. IOP Publishing Ltd.*. https://doi.org/10.1088/1755-1315/1359/1/012102

Kumar, R., Guha, P., & Chakraborty, A. (2022). Comparative assessment and selection of electric vehicle diffusion models: A global outlook. *Energy*. https://doi.org/10.1016/j.energy.2021.121932

Kuzior, A., Pidorycheva, I., Liashenko, V., Shevtsova, H., & Shvets, N. (2022). Assessment of national innovation ecosystems of the EU countries and Ukraine in the interests of their sustainable development. *Sustainability, 14*(14), 8487. https://doi.org/10.3390/su14148487

Larsson, A., Tremblay, M., & Chen, Y. (2024). Healthcare innovation ecosystems: Montreal's collaborative model for SDG 3. *Journal of Social Innovation, 12*(3), 45–67.

Li, F., Zhang, H., Zhang, D., & Yan, H. (2023). Structural diffusion model and urban green innovation efficiency: A hybrid study based on DEA-SBM, NCA, and fsQCA. *Sustainability, 15*(17), Article 12705. https://doi.org/10.3390/su151712705

Liao, A., Pan, C., & Wu, Z. (2024). Digital transformation and innovation and business ecosystems: A bibliometric analysis for conceptual insights and collaborative practices for ecosystem innovation. *International Journal of Innovation Studies*. https://doi.org/10.1016/j.ijis.2024.04.003

Liu, H., Li, W., Jiang, J., & Zhang, Q. (2024). Regional innovation ecosystem and local firms' outward foreign direct investment: An empirical study based on symbiosis perspective. *Technology analysis & strategic management*. https://doi.org/10.1080/09537325.2024.2304224

Liu, Z., & Stephens, V. (2019). Exploring innovation ecosystem from the perspective of sustainability: Towards a conceptual framework. *Journal of Open Innovation: Technology, Market, and Complexity*. https://doi.org/10.3390/JOITMC5030048

Marinelli, L., Bartoloni, S., Pascucci, F., Gregori, G. L., & Farina Briamonte, M. (2023). Genesis of an innovation-based entrepreneurial ecosystem: Exploring the role of intellectual capital. *Journal of Intellectual Capital, 24*(1), 10–34. https://doi.org/10.1108/JIC-09-2021-0264

Marzouk, M., Azab, S., & Elshaboury, N. (2022). Modeling COVID-19 effects on SDGs using system dynamics in Egypt. *Environmental Science and Pollution Research, 29*, 59235–59246. https://doi.org/10.1007/s11356-022-20019-1

Matos, S., Viardot, E., Sovacool, B., Geels, F., & Xiong, Y. (2022). Innovation and climate change: A review and introduction to the special issue. *Technovation*. https://doi.org/10.1016/j.technovation.2022.102612

Miller, C., Mills, A., Charite, D., Routh, A., & Keyal, A. (2024). Nurturing ecosystems to supercharge innovation. Deloitte Center for Government Insights, Deloitte United States. Retrieved May 6, 2025, from https://www2.deloitte.com/us/en/insights/industry/public-sector/government-trends/2024/governments-role-in-achieving-innovation-at-scale.html.

Mori, A., Spies, T., Sudmeier-Rieux, K., & Andrade, A. (2013). Reframing ecosystem management in the era of climate change: Issues and knowledge from forests. *Biological Conservation, 165*, 115–127. https://doi.org/10.1016/J.BIOCON.2013.05.020

Mukherjee, A., Zaveri, P., Patel, R., Shah, M. T., & Munshi, N. S. (2021). Optimization of microbial fuel cell process using a novel consortium for aromatic hydrocarbon bioremediation and bioelectricity generation. *Journal of Environmental Management, 298*, Article 113546.

Nylund, P., Brem, A., & Agarwal, N. (2021). Innovation ecosystems for meeting sustainable development goals: The evolving roles of multinational enterprises. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.125329

Oskam, I., Bossink, B., & De Man, A. (2020). Valuing value in innovation ecosystems: How cross-sector actors overcome tensions in collaborative sustainable business model development. *Business & Society, 60*, 1059–1091. https://doi.org/10.1177/0007650320907145

Owen, R., & Vedanthachari, L. (2022). Exploring the role of U.K. government policy in developing the university entrepreneurial finance ecosystem for Cleantech. *IEEE Transactions on Engineering Management*, 1–14. https://doi.org/10.1109/TEM.2022.3153319

Pandit, J., & Sharma, A. (2023). A comprehensive review of climate change's imprint on ecosystems. *Journal of Water and Climate Change*. https://doi.org/10.2166/wcc.2023.476

Peñarroya-Farell, M., Miralles, F., & Vaziri, M. (2023). Open and sustainable business model innovation: An intention-based perspective from the Spanish cultural firms. *Journal of Open Innovation: Technology, Market, and Complexity*. https://doi.org/10.1016/j.joitmc.2023.100036

Pham, Q. H., & Vu, K. P. (2022). Digitalization in small and medium enterprise: A parsimonious model of digitalization of accounting information for sustainable innovation ecosystem value generation. *Asia Pacific Journal of Innovation and Entrepreneurship, 16*(1), 2–37. https://doi.org/10.1108/APJIE-02-2022-0013

Pietrulla, F. (2022). Circular ecosystems: A review. *Cleaner and Circular Bioeconomy, 3*, Article 100031.

Pilelienė, L., & Jucevičius, G. (2023). A decade of innovation ecosystem development: Bibliometric review of Scopus database. *Sustainability*. https://doi.org/10.3390/su152316386

Ponsiglione, C., Cannavacciuolo, L., Primario, S., Quinto, I., & Zollo, G. (2021). The ambiguity of natural language as resource for organizational design: A computational analysis. *Journal of Business Research, 129*, 654–665.

Ponta, L., Puliga, G., Lazzarotti, V., Manzini, R., & Cincotti, S. (2023). To copatent or not to copatent: An agent-based model for firms facing this dilemma. *European Journal of Operational Research, 306*(3), 1349–1363.

Prokop, V., Hajek, P., & Stejskal, J. (2021). Configuration paths to efficient national innovation ecosystems. *Technological Forecasting and Social Change, 168*. https://doi.org/10.1016/j.techfore.2021.120787. Article 120787.

Qiao, Z., Xu, X., Zou, W., & Huang, Y. (2024). Urban sustainable development goals and ecosystem services: Pathways to achieving coordination. *Land Use Policy*. https://doi.org/10.1016/j.landusepol.2024.107317

Rabelo Neto, J., Figueiredo, C., Coelho Gabriel, B., & Valente, R. (2024). Factors for innovation ecosystem frameworks: Comprehensive organizational aspects for evolution. *Technological Forecasting and Social Change, 203*, Article 123383.

Reed, J., Svedberg, P., & Nygren, J. (2025). Enhancing the innovation ecosystem: Overcoming challenges to introducing information-driven technologies in health care. *Journal of Medical Internet Research, 27*, Article e56836. https://doi.org/10.2196/56836

Ritala, P. (2024). Grand challenges and platform ecosystems: Scaling solutions for wicked ecological and societal problems. *Journal of Product Innovation Management, 41*(2), 168–183.

Ritala, P., & Jovanovic, M. (2024). Platformizers, orchestrators, and guardians: Three types of B2B platform business models, business model innovation. *Game Changers and Contemporary Issues*, 91–125. https://doi.org/10.1007/978-3-031-57511-2_4

Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). Free Press.

Rogers, E. M., Singhal, A., & Quinlan, M. M. (2014). Diffusion of innovations. *An integrated approach to communication theory and research* (pp. 432–448). Routledge.

Russell, M. G., & Smorodinskaya, N. V. (2018). Leveraging complexity for ecosystemic innovation. *Technological Forecasting and Social Change, 136*, 114–131.

Sachs, J., Lafortune, G., & Fuller, G. (2024). *Sustainable development report 2024: National ecosystem strategies for SDG implementation*. Cambridge University Press.

Sachs, J., Lafortune, G., Kroll, C., Fuller, G., & Woelm, F. (2022). *From crisis to sustainable development: The SDGs as roadmap to 2030 and beyond. Sustainable development report 2022*. Cambridge University Press.

Saeed, K., & Xu, J. (2020). Understanding diffusion of information systems-based services: Evidence from mobile banking services. *Internet Research, 30*, 1281–1304. https://doi.org/10.1108/intr-01-2019-0008

Samuelson, P. A. (1974). Complementarity: An essay on the 40th anniversary of the Hicks-Allen revolution in demand theory. *Journal of Economic Literature, 12*(4), 1255–1289.

SDSN. (2024). Metrics for assessing systemic impacts of innovation ecosystems on SDGs. *Sustainable Development Solutions Network*.

Song, J. (2025). The intersection of climate technology and public diplomacy: Insights into policy and implementation. *Sustainable futures*. https://doi.org/10.1016/j.sftr.2025.100465

Spigel, B. (2017). The relational organization of entrepreneurial ecosystems. *Entrepreneurship Theory and Practice, 41*(1), 49–72.

Springer, V., Randhawa, K., Jovanovic, M., Ritala, P., & Piller, F. T. (2025). Platform design and governance in industrial markets: Charting the meta-organizational logic. *Research Policy, 54*, Article 105236. https://doi.org/10.1016/j.respol.2025.105236

Staicu, D., & Pop, O. (2018). Mapping the interactions between the stakeholders of the circular economy ecosystem applied to the textile and apparel sector in Romania. *Management & Marketing. Challenges for the Knowledge Society, 13*(4), 1190–1209.

Teece, D. J. (2018). Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy, 47*(8), 1367–1387. https://doi.org/10.1016/j.respol.2017.01.015

Thomas, L. D. W., Ritala, P., Karhu, K., & Heiskala, M. (2025). Vertical and horizontal complementarities in platform ecosystems. *Innovation, 27*(3), 369–393. https://doi.org/10.1080/14479338.2024.2303593

Toth, C., Fehervolgyi, B., Kovacs, Z., & Hary, A. (2024). Complexity theory approach to innovation ecosystems. *Revista De Gestão Social E Ambiental, 18*(4), Article e08051. https://doi.org/10.24857/rgsa.v18n4-188

Toth, C., & Hary, A. (2024). A comprehensive model for innovation ecosystems. *Triple Helix, 11*(2), 170–191. https://doi.org/10.1163/21971927-bja10050

Trevisan, A. H., Castro, C. G., Gomes, L. A. V., & Mascarenhas, J. (2022). Unlocking the circular ecosystem concept: Evolution, current research, and future directions. *Sustainable Production and Consumption, 29*, 286–298.

United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations. https://sdgs.un.org/2030agenda.

United Nations Development Programme (UNDP). (2024). Decentralized energy systems in Rwanda: SDG 7 implementation case study. https://www.undp.org.

United Nations Environment Programme (UNEP). (2024). Long-term impacts of sustainable innovation ecosystems. https://www.unep.org.

U.N. Women. (2024). Innovation ecosystem participation and gender equality (SDG 5): Research gaps. https://www.unwomen.org.

Van de Ven, A. H. (1993). The development of an infrastructure for entrepreneurship. *Journal of Business Venturing, 8*(3), 211–230.

Wei, Y., Zhong, F., Song, X., & Huang, C. (2025). Achieving sustainable development through national innovation: Evidence from 131 countries. *Environmental Impact*

Assessment Review, 115, Article 108046. https://doi.org/10.1016/j.eiar.2025.108046

Wonglimpiyarat, J. (2025). Achieving the United Nations sustainable development goals: Innovation diffusion and business model innovations. *Foresight (Los Angeles, Calif.), 27*(1), 101–119. https://doi.org/10.1108/FS-11-2023-0233

World Bank. (2024). Green technology leap-frogging in developing nations. https://www.worldbank.org.

World Economic Forum. (2025a). *From tech-first to climate-first: Why we must redefine how innovation is measured*. Retrieved July 6, 2025, from https://www.weforum.org/stories/2025/06/climate-tech-innovation-progress-measurement/.

World Economic Forum. (2025b). *Scaling innovation ecosystem models across national contexts*. Retrieved July 6th, 2025, from https://www.weforum.org.

World Economic Forum (2020). *Global competitiveness report special edition 2020: How countries are performing on the road to recovery. Section 4: Innovation ecosystem. Full report published on Dec. 16th, 2020*. July 6th, 2025, https://www.weforum.org/publications/the-global-competitiveness-report-2020/in-full/section-4-innovation-ecosystem/.

World Health Organization (WHO). (2024). Digital health platforms and pandemic resilience: South Korea's ecosystem approach. https://www.who.int.

Xu, Y., & Li, Y. (2024). A bibliometric review of innovation ecosystem. *Systems Research and Behavioral Science*. https://doi.org/10.1002/sres.3042

Yikun, Z., Woon Leong, L., Cong, P. T., Abu-Rumman, A., Al Shraah, A., & Hishan, S. S. (2022). Green growth, governance, and green technology innovation. How effective towards SDGs in G7 countries? *Economic Research-Ekonomska Istraživanja, 36*(2). https://doi.org/10.1080/1331677X.2022.2145984

Yin, D., Ming, X., & Zhang, X. (2020). Sustainable and smart product innovation ecosystem: An integrative status review and future perspectives. *Journal of Cleaner Production, 274*, Article 123005. https://doi.org/10.1016/j.jclepro.2020.123005

Yuan, H., Wang, X., Gao, L., et al. (2023). Progress towards the sustainable development goals has been slowed by indirect effects of the COVID-19 pandemic. *Communications Earth & Environment, 4*, 184. https://doi.org/10.1038/s43247-023-00846-x

Zeng, D., Hu, J., & Ouyang, T. (2017). Managing innovation paradox in the sustainable innovation ecosystem: A case study of ambidextrous capability in a focal firm. *Sustainability, 9*(11), 2091. https://doi.org/10.3390/su9112091

Zhang, R., Liu, J., & Cao, Z. (2023). Green innovation ecosystems: Spatial organization mode and associated network renewal under coupling effect. *Journal of Cleaner Production, 422*. https://doi.org/10.1016/j.jclepro.2023.138539. Article 138539.

Zhang, R.-J., Tai, H.-W., Cao, Z.-X., Wei, C.-C., & Cheng, K.-T. (2024). Green innovation ecosystem evolution: Diffusion of positive green innovation game strategies on complex networks. *Journal of Innovation & Knowledge, 9*(3), Article 100500. https://doi.org/10.1016/j.jik.2024.100500. Article.

Zhao, M., Meng, Z., Xu, B., Yu, D., Wu, S., & Li, R. (2023). Prior goal setting of SDGs based on the interaction correlation. *Frontiers in Sustainability, 4*, Article 1214615. https://doi.org/10.3389/frsus.2023.1214615

Zhong, Z. M., Weng, B., Huang, Q. L., Huang, X., Chen, Z., & Feng, D. (2012). Evaluating the ecosystem sustainability of circular agriculture based on the emergy theory: A case study of the Xingyuan circular agriculture demonstration site in Fuqing City, Fujian. *Shengtai Xuebao/Acta Ecologica Sinica, 32*(18), 5755–5762.

Zhou, J., & Li, H. (2024). Review and prospects of green innovation ecosystems from the perspective of value emergence. *Systems, 12*(6), 206. https://doi.org/10.3390/systems12060206