Journal of Open Innovation: Technology, Market, and Complexity 11 (2025) 100540

Contents lists available at ScienceDirect

Journal of Open Innovation: Technology, Market, and Complexity

journal homepage: www.sciencedirect.com/journal/journal-of-open-innovation-technology-market-and-complexity

Digitalisation dynamics: Developing a global index for digital pioneers, adapters, and followers

Ushan Kumara [a,1], Dilan Wijerathna [a,2], Ruwan Jayathilaka [b,3,*]

[a] SLIIT Business School, Sri Lanka Institute of Information Technology, New Kandy Road, Malabe, Sri Lanka
[b] Department of Information Management, SLIIT Business School, Sri Lanka Institute of Information Technology, New Kandy Road, Malabe, Sri Lanka

ARTICLE INFO

Keywords:
Digitalisation
Composite Index
Principal Component Analysis
Digital Transformation
Digital divide

ABSTRACT

Digitalisation has become a transformative force revamping economies, societies, and governance systems. It has fostered innovation and enhanced global competitiveness in an interconnected world. This study aims to construct a composite index for digitalisation to evaluate global digitalisation levels and categorise nations as digital pioneers, adapters, and followers. The index is developed using a Principal Component based on Factor Analysis, utilising secondary data gathered from World Development Indicators from 2010 to 2022. The study highlights that the United States, Hong Kong, Singapore, China, and Korea dominate the top tier as digital pioneers through adopting emerging fourth-industrial revolution technologies such as artificial intelligence, blockchain, etc. Moreover, nations like Japan, Switzerland, Estonia, Czechia, and Iceland are categorised as digital adapters due to less digital investments in digital technologies and building digital ecosystems. At the same time, Madagascar, Paraguay, Ecuador, Guatemala, and Egypt remain at the bottom of the index as digital followers due to existing digital gap and digital literacy and skills among the population. This evidence provides digitalisation index an effective tool for policymakers and researchers to assess each nation's digitalisation levels and technological readiness, to formulate strategies and policies to enhance digital interaction, foster innovation, and promote economic growth.

1. Introduction

1.1. Background of the study

Digitalisation has become a significant driver of global economic growth (Calderon-Monge and Ribeiro-Soriano, 2024) and innovation, fostering the transformation of organisations, institutions, and societies (Kraus et al., 2021). Over the past two decades, global behaviours, work, and communication have been transformed, driven by improvements in ICT, especially the Internet and mobile technologies. These innovations have stimulated innovation, new market channels, and organisational complexities (Myovella, Karacuka, and Haucap, 2020).

Terms like "digitalisation" and "digitisation" are fundamental concepts in digital technology and innovation (Gradillas and Thomas, 2025). Digitalisation is the advancement and execution of ICT systems connected to organisational changes by transforming socio-technical frameworks enabled earlier by non-digital tools to systems facilitated by digital technology (Yoo, Lyytinen, Boland, and Berente, 2010). These technologies and data boost revenue, enhance business operations, replace traditional processes, and conduct digital, serving digital information at the top (i-SCOOP, 2024); it also involves capturing and generating innovative ways by implementing digital technologies and digitising information (Gobble, 2018). Digitisation is essential to achieve digitalisation, which could lead to digital transformation and transform businesses towards digital businesses. Digitisation develops digital objects through various technical methods like conversion, representation, and enhancement (Gradillas and Thomas, 2025). Further, digitisation is a technical process of transforming analogue data into a digital format that instantly makes digital content shareable, programmable, accessible, and traceable (Fähndrich, 2023).

Many businesses face challenges in digital transformation, and digitalisation has become an essential factor in achieving it. Constructs like

* Corresponding author.
E-mail addresses: ushankumaras86@gmail.com (U. Kumara), harshanadilan2000@gmail.com (D. Wijerathna), ruwan.j@sliit.lk (R. Jayathilaka).
[1] ORCID: 0009–0008-1618–7179
[2] ORCID: 0009–0009-7768–6710
[3] ORCID: 0000–0002-7679–4164

https://doi.org/10.1016/j.joitmc.2025.100540
Received 28 February 2025; Received in revised form 13 April 2025; Accepted 22 April 2025
Available online 25 April 2025

"digitisation" and "digitalisation" are both critical to the process of digital transformation(Leonardi and Treem, 2020). The method of applying a set of information, computation, communication, and connectivity technologies that bring improvements and transformative changes to an entity's properties is digital transformation (Vial, 2019). Such transformations would lead to enhanced inventions, efficiency within operations, and improved business satisfaction. Besides companies, digital transformations positively impact various government sectors and increase efficiency (Yang, Gu, and Albitar, 2024). Reduction of administrative inefficiencies and enhanced service delivery result from adapting digital technologies for government operations.

Digitalisation is considered a powerful driver that affects economic growth (Calderon-Monge and Ribeiro-Soriano, 2024), management control (Fähndrich, 2023), innovation process (Urbinati, Manelli, Frattini, and Bogers, 2022) and digital transformation (Saarikko, Westergren, and Blomquist, 2020)—many scholarly studies state digitalisation as a key driver that enhances economic development (Mwananziche, Myovella, Karacuka, Haucap, and Moshi, 2023; Myovella et al., 2020). Meanwhile, mobile technology, fixed broadband and mobile subscriptions, internet users, and secure internet servers are fundamental enablers of digitalisation and digital services. Advancements in these technologies would lead to a reduction in the digital gap and an increase in digital literacy and skills among the global population. The digital divide is called the disparities in access, use, and effectiveness of digital resources, highlighting the gap between people who benefit from digital resources and those who do not (Vassilakopoulou and Hustad, 2023). At present, transformative technologies such as AI, cloud computing, blockchain, IoT and big data analytics revolutionise connectivity, automation, and data-driven decision-making to drive digitalisation across industries.

Developing a composite index for digitalisation fills a significant gap in internationally comparable digitalisation metrics, the current work presents a timely and pertinent contribution in this regard. The methodology created here promotes evidence-based policy actions to promote inclusive and innovation-driven digital growth in addition to benchmarking national digital capacity.

1.2. Research objective

The researchers have been able to formulate the generic and specific objectives clearly before conducting the research study. The generic objective and specific objectives could be defined as follows: Generic Objective: To develop a composite index for digitalisation utilising Principal components based on factor analysis to measure the degree of digitalisation across nations from 2010 to 2022 and classify them as digital pioneers, digital adapters, and digital followers.

Specific Objective:

1. To identify the key variables influencing digitalisation based on a comprehensive literature review.
2. To apply principal component analysis to construct the robust digitalisation index.
3. To evaluate the trends, contributions, and relationships under digitalisation variables across nations.
4. To classify nations into digital pioneers, adopters, and followers based on their digitalisation scores.
5. To provide actionable insights and policy recommendations for the digital divide and promote sustainable digital growth.

1.3. Existing research gap

This study aims to fill a critical gap in the literature by constructing a composite index for digitalisation, measuring the degree of digitalisation among 71 nations for 12 years. Certain studies have developed digitisation indices, sub-indices related to ICT, and digitalisation indices to discover the impact on economic growth and the labour force; thereby, studies have not been able to develop a composite index for digitalisation integrating variables that define digitalisation. The uniqueness of this study would be the methodological approach and integration of variables utilised to construct the index. Certain variables were employed in developing indices like Global Connectivity and Innovation indices at the global level. Therefore, the need for the index could be utilised to analyse economic effects for governments, educate decision-makers within enterprises, and conduct future research for researchers since the digital transition has occurred in many countries.

1.4. Structure of the research paper

The article's structure is organised thus: the "Literature Review" section highlights existing literature on selected variables related to digitalisation; the "Data & Methodology" section outlines the data sources and methodological approach used to construct the index; the "Results and Discussion" section presents and analyses empirical findings; and the "Conclusion" section summarises the key takeaways along with policy implications, recommendations, and guidelines for future research.

2. Literature review

2.1. Introduction

The researchers have incorporated publications on digitalisation, ICT, and economic growth published between 2018 and 2024 in their analysis. To construct the literature review, they accessed several electronic research databases, such as Science Direct, Springer, Emerald Insight, Research Gate, and IEEE.

2.2. Theoretical & empirical background on digitisation, digitalisation & competitiveness

Digitisation is the core concept that leads towards digitalisation, thereby this process leads to achieving digital competitiveness. The initial step enables content to be stored, shared, and accessed more efficiently, allowing ultimately for programmability and traceability (Fähndrich, 2023). However, upon this foundation, digitalisation encompasses a broader transformation, where digital technologies are integrated into business models, public services, and socio-economic processes. Thereby such transformations tend to improve task efficiency, management control, standardization, etc. According to scholarly articles like (Saarikko et al., 2020), digitalisation is inseparable from digital transformation, and entire societies (Kraus et al., 2021).

The integration of digital technologies into organizational processes has accelerated the evolution of ICT systems. Thereby these frameworks support structural changes once handled by analogue tools (Yoo et al., 2010), however, this could also lead to enhanced revenue potential, streamlined operations, and replacement of traditional procedures with digital alternatives. Consideration of all these digital competitiveness could emerge as an outcome of digitisation and digitalisation. Concerning the study, nations' should reflect on the ability to utilise digital technologies for sustainable development, societal progress and reach competition. The globally developed indices like the Digital Opportunity Index and ICT readiness measures developed by ITU evaluate a country's digital maturity. According to IMD World Digital Competitiveness Rankings, competitiveness is shaped by elements such as knowledge, technology, and future readiness that directly contribute to national economic resilience while measuring digital capabilities and adaptability (IMD, 2024). However, digital competitiveness results from strategic and well-integrated digital efforts by initiating digitisation the digital journey, and digitalization transforms systems and institutions.

2.3. Theoretical background on digitalisation index variables

2.3.1. Internet users

Digitalisation has been widely researched, with significant literature highlighting its role in economic growth. Internet usage significantly impacted economic development in Africa. Early studies suggest that most Internet users are interconnected. However, digital growth should be promoted, and economic development, including education, health, and knowledge, should be sustained (Myovella, Karacuka, and Haucap, 2021; Njoh, 2018). Internet usage has also been linked to poverty reduction and economic growth in SADC and G-20 regions. Several studies have underlined the need to improve Internet connectivity to achieve development, with access to the Internet being a priority in ICT infrastructure (Olamide, Ogujiuba, Maredza, and Semosa, 2022; Soomro, Kumar, and Kumari, 2022).

In Asia, Internet users contributed positively to economic growth. China and South Asia contributed most of the contributions towards economic rates through innovations such as Internet banking (Huong Yong Jing and Ab-Rahim, 2020; M. A. Kurniawati, 2022; Nipo, Lily, Idris, Pinjaman, and Bujang, 2024). Between later periods, OECD countries such as Denmark, Iceland, Japan, and Norway attained near-universal coverage and showed a strong relationship between digital connectivity and economic growth (Habibi and Zabardast, 2020; Myovella et al., 2020; Nair, Pradhan, and Arvin, 2020). However, poor ICT infrastructure in the Middle East negatively impacted the economic benefits and bi-directional relationship in the influence of Internet usage on trade and economic expansion (Appiah-Otoo and Song, 2021; H. S. Lee, Sia, Low, and Chong, 2020; P. Singh and Siddiqui, 2023). Despite these, the Internet has dramatically influenced economic growth worldwide, especially in the case of vulnerable sections and both developed and developing countries.

2.3.2. Mobile & Fixed broadband subscriptions

Fixed broadband and mobile subscriptions have increased economic growth, especially in accessing the Internet globally (Myovella et al., 2021). In Europe, this improved considerably from an early stage. Several studies (Adejumo, Adejumo, and Aladesanmi, 2020; Mwananziche et al., 2023; Njoh, 2018) also provide evidence of this fact, with the G-20 nations illustrating substantial economic benefits accruing from fixed broadband and ICT infrastructure.

Empirical research from OECD nations found that fixed broadband increased GDP per capita across 135 countries (Edquist, Goodridge, Haskel, Li, and Lindquist, 2018; Habibi and Zabardast, 2020). In addition, evidence of mobile subscriptions, especially in the early period, was closely linked to higher economic growth due to increased technological penetration (M. Kurniawati, 2020; Nair et al., 2020).

The share of mobile subscriptions is higher, while fixed broadband is more advantageous (H. S. Lee et al., 2020; Maneejuk and Yamaka, 2020) in developed economies. ICT was known to significantly impact the economic development of SSA, MENA, and LAAC, hence increasing subscriptions (Charles Shaaba Saba, Ngepah, and Odhiambo, 2024). Broadband and mobile subscriptions increased access to financial activities in 20 developing and developed nations (Appiah-Otoo and Song, 2021; Batool and Hasan, 2023; Dzator, Acheampong, Appiah-Otoo, and Dzator, 2023). In 2018, broadband boosted economic growth in global regions, and associated technologies revolutionised economies worldwide. They are now widely recognised as essential drivers of modern economic growth.

2.3.3. Patent applications by residents & non-residents

Specific studies and citizens' patent applications contribute to economic growth, demonstrating the significance of innovation in national economies. Several studies have linked the number of patent applications to other necessary measures of financial success (Maneejuk and Yamaka, 2020). Interestingly, resident patent applications have a proven tendency to boost economic growth; it is essential to note that the extent of this benefit will undoubtedly vary depending on each nation's level of development, with a more significant impact on technical advancement and growth (H. S. Lee et al., 2020; Nguyen and Doytch, 2022; P. Singh and Siddiqui, 2023).

Both resident and non-resident actors are equally significant because, rather than merely improving local markets, resident patent applications boost economic development, competitiveness, and innovations in many nations around the world (Nguyen and Doytch, 2022). It seems contradictory that non-resident patent applications and financial success are related. Non-resident patent activity, for instance, involves filing patents and competing with different resident firms (M. Kurniawati, 2020; H. S. Lee et al., 2020). Additionally, research shows that non-resident patents foster rivalry among local businesses to be creative, boosting the local technology base and establishing a knowledge market (Yuan et al., 2021).

2.3.4. Researchers in R&D & R&D Expenditures

To uncover the processes of innovation and its effects on economic development, it is essential to consider the interactions between researchers engaged in R&D and patent applications (Benitez Hurtado et al., 2024). Further, as more patents are filed in R&D environments, the concomitant relationships between R&D investment, ICT infrastructure development, and economic growth support the significance of strict patent rules (Nair et al., 2020). However, empirical evidence indicates that more patent filings are associated with higher financial returns from research and development (H. S. Lee et al., 2020). On the other hand, factors like innovation, trade openness, and ICT penetration significantly correlate with economic growth (P. Singh and Siddiqui, 2023). Even when R&D and patenting efforts are conducted, the results indicate that the practical links between these activities are not well known, which makes it challenging to apply them when formulating policy.

Additionally, it has been demonstrated that innovation outcomes are linked to R&D expenditure (Batool and Hasan, 2023; Horvath, 2011; M. Kurniawati, 2020). However, since this relationship depends on both country and policy, it is evident that not all strategies in one would work in another (H. S. Lee et al., 2020; Wang, Luo, Sari, and Shao, 2020). Based on this complexity, modifying the tactics employed to guarantee that the anticipated returns from the R&D investments are realised under various conditions is necessary.

2.3.5. ICT goods & service exports

In several studies of central economies, ICT services and goods trade highlighted a worldwide trend towards bilateral trade with major economies. These nations enjoy more robust competitive advantages, and the overall network density has decreased, underscoring developing countries' difficulties in overcoming policy, cost, and technology constraints (Moreno-Hurtado, Plascencia, Lozano, and Cano, 2020; Y. Zhang, Xu, and Yang, 2024). In developed nations, digitalised service levels significantly impact exports of digital services trade (Jiang and Jia, 2022; Oliinyk et al., 2023). The success of ICT services exports is influenced considerably by economic complexity and human capital. Higher export capacities are exhibited by nations with more human capital, with middle-income countries showing the most benefit (Moreno-Hurtado et al., 2020; Oliinyk et al., 2023).

Economic complexity, technology exports, and digitally delivered services strongly correlate (Diego, Elisa, Gabriela, and Gabriela, 2023; Li, Han, and Xu, 2023), underscoring digital innovations' vital role in boosting international trade competitiveness. Exporting ICT services improves environmental practices while using renewable energy improves the management of natural resources (H. Zhang, Liu, and Wei, 2023; Z. Zhou, Long, and Xin, 2024).

Adopting digital technology has raised the domestic value-added ratio in exports for Asian companies, especially in eastern regions and processing trade (Arvin, Pradhan, and Nair, 2021; Ndubuisi, Otioma, and Tetteh, 2021; Pang, Li, and Wang, 2024). In competitive

marketplaces, these advantages are magnified by cost savings and technology advancements (Diego et al., 2023; H. Zhang et al., 2023)It takes sophisticated tactics adapted to situations to close these gaps, and replication has been essential to growth, with the help of foreigners and multinational companies that promote international ties (Rao and Balasubrahmanya, 2017). Future expansion depends on fostering innovation and enhancing ICT infrastructure. Strategic policies encouraging digital adoption and competitive market environments are crucial to improving ICT export goods and services.

2.3.6. Secure internet servers

Some empirical findings show that developments in IoT network security frameworks have introduced new methods for improving security. Identity-based encryption (Calderon-Monge and Ribeiro-Soriano, 2024) and Certificate-Less Digital Signatures (CLDS) are used in a less trust architecture to solve the security issues with marine IoT (Al-Khalidi, Al-Zaidi, Ali, Khan, and Bashir, 2025). Implementing Elliptic Curve Cryptography (ECC) significantly reduces processing times and key sizes. Additional ECC parameter optimisation with a genetic algorithm (Diego et al.) and Particle Swarm Optimisation (PSO) improved resistance to ECC attacks and reduced parameter generation time by more than 40 % (S. K. Singh and Kumari, 2023; Soomro et al., 2022).

For resource-constrained IoT devices, the suggested authentication-enabled privacy Protection Scheme (APPS) exhibits strong security, exhibiting resistance to replay, anonymity, and untrace ability. According to the performance study, the system operates efficiently with a detection rate of 0.85, memory use of 0.497 MB, and computational and turnaround times of 112.79 and 131.91 s, respectively (Benitez Hurtado et al.). High-income countries (HICs) are reaping a disproportionately more significant advantage than low-income countries (LICs). These findings underscore the role of innovative security frameworks and ICT advancements in enhancing secure server operations and driving economic growth (Ranjan and Kumar, 2024).

In the latest studies encrypting DNS transmission, DNS over HTTPS lowers the possibility of third-party interception and enhances end-user privacy and security. However, because it gets around more established safeguards like firewalls, it presents problems for network security experts and makes them more susceptible to attackers (Nistor and Zadobrischi, 2022; S. K. Singh and Kumari, 2023). These results guide the significance of developing IoT, ICT, and cyber security frameworks to support strong and sustained growth, highlighting the junction of digital innovation and secure server practices.

Each selected variable within the index reflects a critical dimension of digitalisation—ranging from infrastructure (e.g., internet and broadband access), innovation capacity (e.g., patent applications, R&D), to digital economic integration (e.g., ICT exports, secure servers). These dimensions are underpinned by both theoretical and empirical research linking them to digital transformation and economic advancement.

What distinguishes this index from existing measures is the integration of a broader range of variables—such as resident and non-resident patent applications and secure internet servers—offering a more comprehensive understanding of digital maturity across countries.

2.4. Past literature on indices developed

A comprehensive literature review was conducted on previous indices and methodologies for developing them. Several past studies have developed indices on digitisation (Cámara and Tuesta, 2017; Katz, Koutroumpis, and Callorda, 2014), the digital divide (Bruno, Diglio, Piccolo, and Pipicelli, 2023), poverty (Siddhisena and Jayathilaka, 2006), energy efficiency (Dolge, Kubule, and Blumberga, 2020), and digitalisation to measure the impact on the labour force (Androniceanu, Georgescu, Tvaronaviciene, and Androniceanu, 2020) and sub-indices on ICT (M. A. Kurniawati, 2021) to measure the effects of economic growth. However, several well-recognized institutions have also successfully developed more comprehensive indices on innovation (WIPO, 2023), mobile connectivity (Huawai Technologies Co..., 2021), and network readiness (Portulans Institute., 2023).

2.5. Global trends in digitalisation

This section discovers the global trends between digitalisation index variables, the publications conducted based on digitalisation and within nations, and the interests captured by researchers from 2018 to 2024.

Fig. 1 shows the number of publications from 2018 to 2024 in this bar chart, which focuses on digitalisation index variables. Thirty-two articles were published in 2020, focusing on connectivity-related variables, including Internet users, mobile subscriptions, and fixed broadband subscriptions, which primarily reflected during the COVID-19 epidemic due to the transformation towards digital solutions. The number of publications has moderately decreased after 2020, showcasing consistent interest in ICT exports of goods and services among the researchers.

With 15 articles published in 2024, there is a slight decline, by maintaining secure internet servers still for 33 % out of all publications. Noticeably, some limited publications were conducted in 2018 and 2019, with contributions spread equally across all variables. This trend suggests that research interests change with new technological developments.

Fig. 2 depicts the distribution of research publications conducted by researchers utilising the digitalisation index variables from 2018 to 2024. Notably, many studies have been conducted utilising variables like internet users and mobile and fixed broadband subscriptions among pioneers, adapters, and followers like Mexico, Madagascar, and Egypt, investigating digitalisation and economic growth (Myovella et al., 2020), digital infrastructure, employment (Ndubuisi et al., 2021), and the digital divide (Mignamissi and Djijo T, 2021). Meanwhile, other variables have been used less to conduct studies for all respective nations by researchers from 2018 to 2024. The count of studies conducted on digitalisation index variables from 2018 to 2024 is provided in the S3 appendix.

Fig. 3 reveals eight distinct clusters indicating terms like economic growth, digitalisation, digital economy, and ICT that dominate at the top of those clusters. Themes like economic growth, ICT, and digitalisation show strong links focusing on the convergence of digital technologies and financial outcomes. However, many studies have proven that digitalisation (Myovella et al., 2020; Sinha, Roy, and Tirtosuharto, 2024) & ICT (Appiah-Otoo and Song, 2021; Fernández-Portillo, Almodóvar-González, and Hernández-Mogollón, 2020) could be defined as a driver which boosts economic growth.

Some major emerging areas, such as development in ICT, Industry 4.0, e-commerce, digital economy (Murthy, Kalsie, and Shankar, 2021), and digital technologies, indicate a growing interest in digital transformation. Such transformations could increase innovation capacity and growth in economic activities within nations (M. Kurniawati, 2020; M. A. Kurniawati, 2021; H. S. Lee et al., 2020).

Fig. 4 reveals some significant topics discussed and clustered into eight with distinct colours from 2018 to 2024. Terms like challenges, Africa, economic growth, co-integration, China, developing countries, FDI, and India are positioned at the top within the clusters since they have occurred often. Researchers have moderately used many terms or keywords like globalisation and the internet for publications. In contrast, terms like economic growth, digital technology, digitalisation, and digital economy have been used most, showing higher keyword concentration within the period.

Digitalisation plays a foundational role in fostering open innovation dynamics, particularly by enabling collective intelligence, platform-based service delivery, and digitally facilitated business model innovation. Recent research has highlighted the importance of digital infrastructure and services in enabling open innovation across domains such as mobile payments, car sharing, and SME ecosystems (Chesbrough and

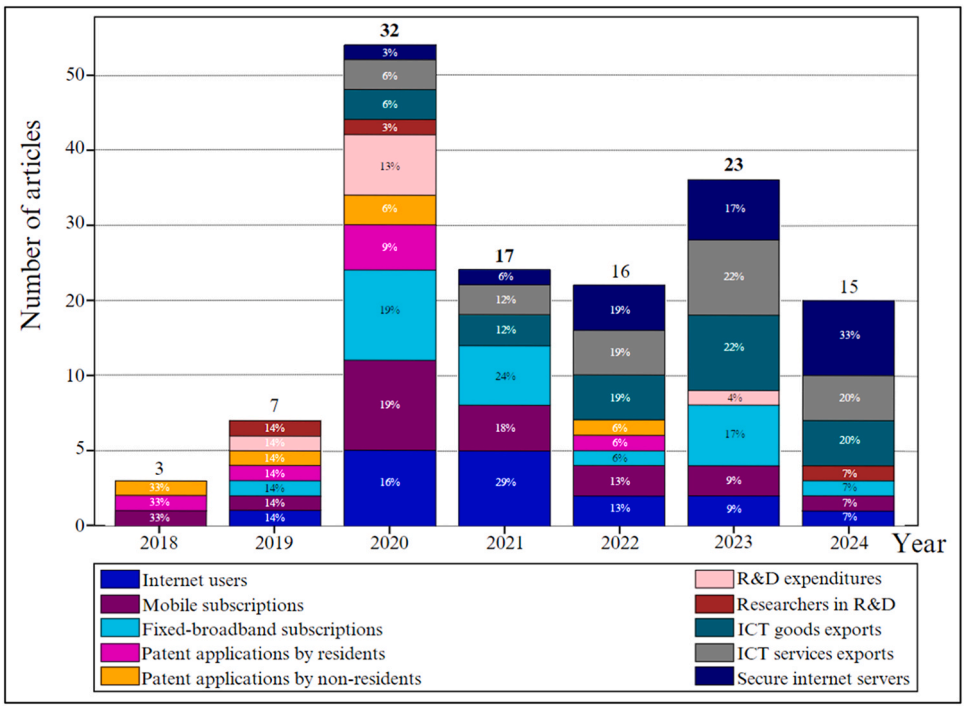

Fig. 1. Distribution of research articles on digitalisation index variables over time, 2018–2024.
Source: Authors' compilations based on past literature through Python.

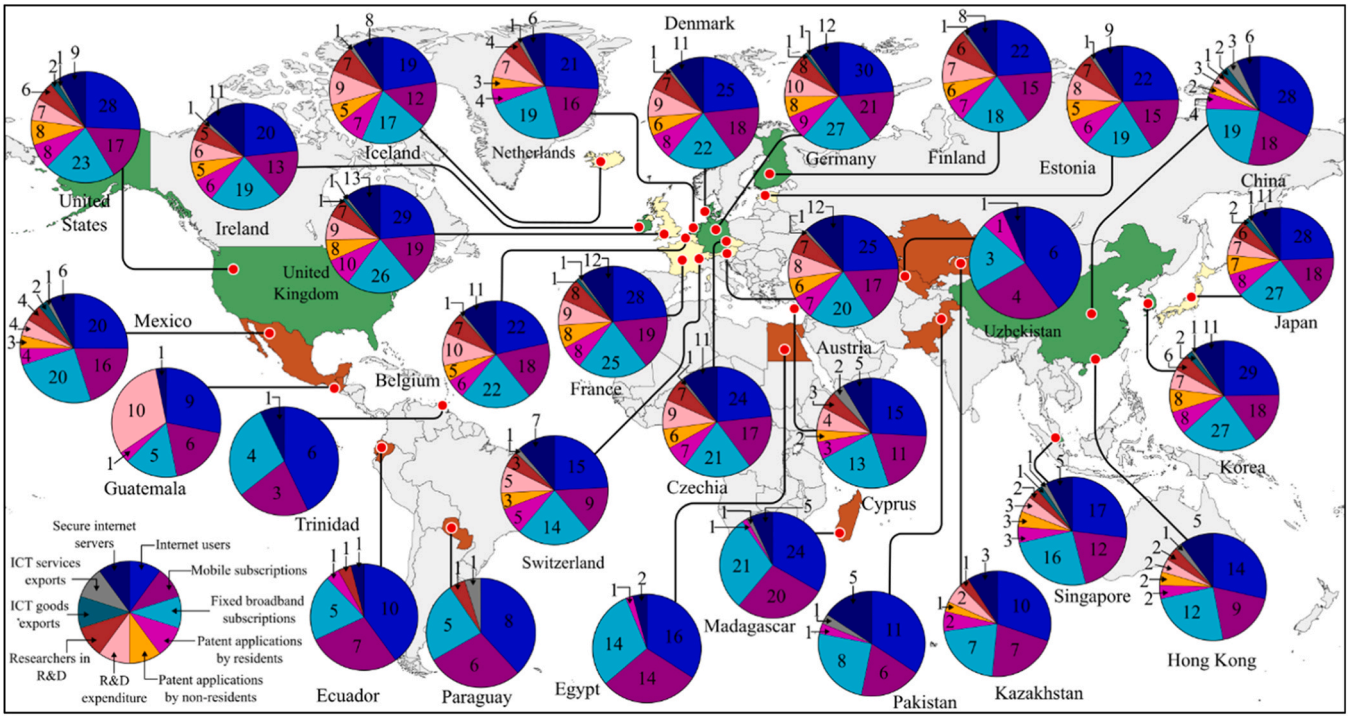

Fig. 2. Distribution of research publications focused on digitalisation index variables from 2018 to 2024.
Source: Authors' compilation based on past literature & created through OriginPro 2024 and Inkscape software.

Bogers, 2014; S. G. Lee, Trimi, and Kim, 2013; Urbinati, Chiaroni, Chiesa, and Frattini, 2020; Yun, Zhao, Jung, and Yigitcanlar, 2020). Moreover, digital platforms support open innovation engineering, crowd-based ideation, and complex problem-solving in sectors like mobility (e.g., e-bikes), hospitality, and digital commons. Therefore, the proposed digitalisation index also offers valuable insights into a country's readiness to participate in and benefit from open innovation ecosystems.

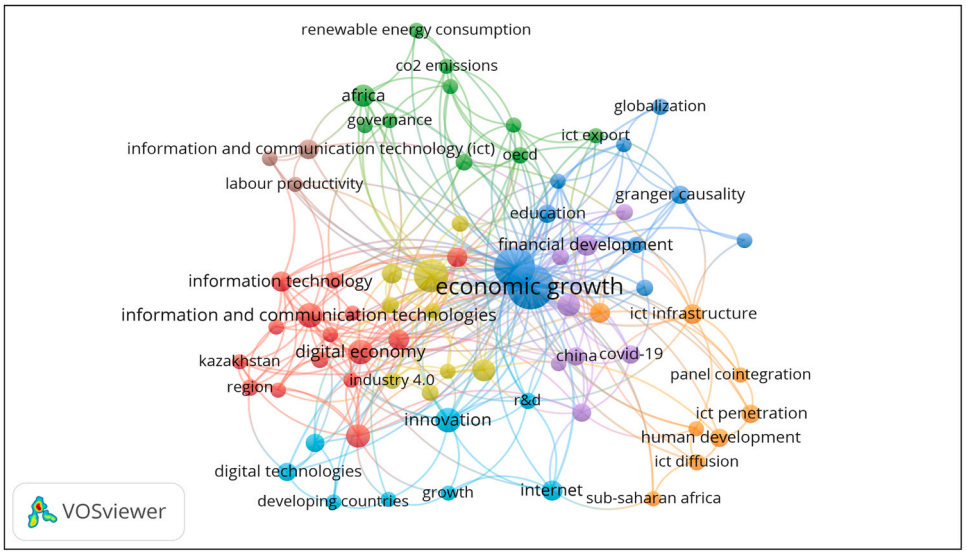

Fig. 3. Network visualisation indicating authors' keyword co-occurrence network from 2018 to 2024.
Source: Authors' Compilation based on bibliographic data from Scopus & created through VOSviewer software.

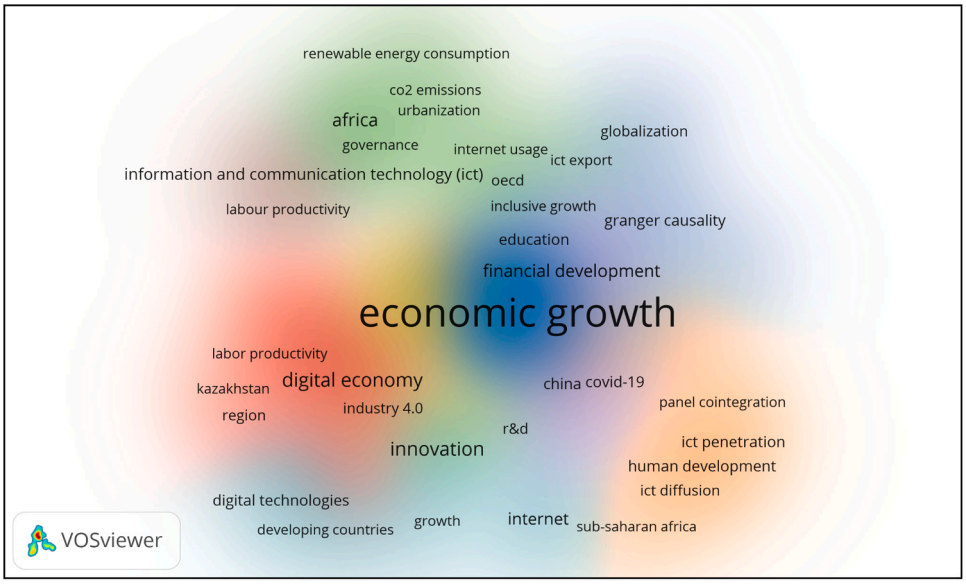

Fig. 4. Cluster density visualisation determining authors' keywords discussed within each cluster from 2018 to 2024.
Source: Authors' Compilation based on bibliographic data from Scopus & created through VOSviewer software.

3. Data and methodology

3.1. Data

This study utilises annual time series data for 71 nations to create a composite index for digitalisation from 2010 to 2022 to measure the current digital progression and variations taken place within the nations. The secondary data are extracted from the World Bank Development Indicator for analysis (see S1 Appendix to be added).

3.2. Definition of variables

To develop the index, this study has employed ten indicators: Internet users, mobile subscriptions, fixed broadband subscriptions, the number of patent applications by residents and non-residents, research and development expenditures, researchers in research and development, ICT goods exports, ICT service exports, and secure internet

Table 1
Definition of variables.

Variable	Unit of Measure
Internet users	Per 100 inhabitants
Mobile subscriptions	Per 100 inhabitants
Fixed broadband subscriptions	Per 100 inhabitants
Patent applications by residents	Per 100 inhabitants
Patent applications by non-residents	Per 100 inhabitants
R&D Expenditure	% of the GDP
Researchers in R&D	Per one million people
ICT goods exports	% of total goods exports
ICT service exports	% of service exports, BoP
Secure internet servers	Per one million people

Source: Authors' compilations based on the World Development Indicators.

servers. Table 1 will provide more details, such as the measurement units of the respective variables.

3.3. Data processing

During the study, a few feasible statistical approaches, such as regression (linear and polynomial regression) and average values, were used to estimate the absence of data values for the respective variables among the selected nations. There were some instances in which negative values were generated while employing these techniques; in such cases, the most recent available year's value was carried forward until a valid data point was reached. To ensure a reasonable level of accuracy and reliability, countries were only included if at least 50 % of the data points were available for the selected variables.

However, we acknowledge that variations in data quality, collection methods, and reporting standards across countries may influence the robustness of the constructed digitalisation index. Although our methodological choices aimed to mitigate these effects, the interpretation of results should consider these limitations. Future research could enhance robustness by conducting PCA separately for subgroups of nations based on regional or economic classifications, or by incorporating alternative data sources such as the ITU or OECD databases.

3.4. Methodological approach

The principal component based on factor analysis is utilised to construct the index for digitalisation by incorporating the ten variables. A past research study has been successful in creating a composite index utilising Principal Components based on Factor Analysis for Poverty (Siddhisena and Jayathilaka, 2006), digital divide (Bruno et al., 2023), labour force (Androniceanu et al., 2020) and several research papers (M. Kurniawati, 2020; M. A. Kurniawati, 2021) have also discussed generating indices through Principal Component Analysis at present. Several institutions have also successfully developed indices like Global Connectivity & Innovation indices to measure a country's performance over time in digital connectivity and innovation output areas (Huawai Technologies Co..., 2021; WIPO, 2023).

This approach ensures that the level of digitalisation can be accurately measured using quantitative measures to facilitate cross-country comparisons. This study could also be adopted as a quantitative research philosophy grounded in the positivism paradigm to construct the digitalisation index.

3.4.1. Principal Component based on factor analysis

This analytical technique could be derived as a multivariate technique utilised for transforming a set of variables relative to a defined or latent variable to decrease the complexity of data by reducing the number of variables (Sabine Landau, 2004). This technique is employed to normalise selected variables, weighting through principal components based on factor analysis and aggregating them to construct a comprehensive index for digitalisation. Several research publications have gone over the specifics of the PCA method used to generate indices and sub-indices for several research studies in the past (Bruno et al., 2023; M. A. Kurniawati, 2021; Siddhisena and Jayathilaka, 2006). Fig. 5 demonstrates the workflow hierarchy, including eight chronological steps in developing the composite index for digitalisation.

3.4.2. Defining the conceptual framework

The foundation for comprehending and choosing which factors to include in a composite index is provided through a theoretical framework (Nardo et al., 2008). A conceptual framework (see Fig. 6) is essential and developed to identify the variables utilised when developing the index, thereby the study is developed based on a thorough review of prior research that created indices related to digitalisation and e-readiness indices (M. Hanafizadeh, Hanafizadeh, and Saghaei, 2009; M. R. Hanafizadeh, Saghaei, and Hanafizadeh, 2009; P. Hanafizadeh, Hanafizadeh, and Khodabakhshi, 2009b; Huawai Technologies Co..., 2021; M. A. Kurniawati, 2021; C. Saba, David, and Voto, 2024; Charles S. Saba, Asongu, Ngepah, and Ngoungou, 2024; Charles Shaaba Saba and David, 2020; WIPO, 2023), including the Digital Economy and Society Index (European Commission, 2022), the ICT infrastructure and access index (M. R. Hanafizadeh et al., 2009; P. Hanafizadeh, Hanafizadeh, and Khodabakhshi, 2009a).The selection of variables to develop the digitalisation index was utilised referring to the above past studies conducted. However, reviewing and inclusion of these models allows for a deeper understanding of technological preparedness and readiness and how it is measured within nations.

3.4.3. Data collection and processing of selected variables

By examining data availability, secondary data of ten variables were utilised to develop the digitalisation index for 71 nations. Some indicators were omitted due to the unavailability of data for a more extended period.

3.4.4. Normalisation of the variables

Normalisation is essential to reduce the ambiguity of the indicators and achieve more accurate and reliable results. The purpose of normalising data before developing an index is to convert different scales of indicators to a standard scale. Therefore, we have utilised the min-max transformation technique to normalise the variables. Since the index scores should be meaningful to the reader and should lie within the range from −10–15, previous studies suggest that min-max, rank, or standardisation could also be more applicable when comparing studies (Dolge et al., 2020). The digitalisation index variables were normalised using the below equation.

$$I_n = I_{act} - I_{\min} / I_{\max} - I_{\min}$$

$$I_n = \textit{Normalized Indicator}$$

$$I_{act} = \textit{Actual value of the Indicator}$$

$$I_{\min} = \textit{Minimum value of the indicator}$$

$$I_{\max} = \textit{Maximum value of the indicator}$$

3.4.5. Classification of the variables into dimensions

Classifying variables into dimensions was performed using Principal Components based on Factor Analysis. The varimax rotation technique was utilised to identify how far the variables are explained through the extracted principal components, and a co-relation matrix was extracted to determine the strength and direction between variables. Finally, factor analysis was employed for all the selected variables to identify significant factors (Eigen values greater than 1 were identified as dimensions) to the respective dimensions, and factor scores were saved through the regression method.

3.4.6. Weighting and Aggregating of the indicators

As stated in specific handbooks, the weighting methodology adopts several methods, such as equal and expert weighting, when constructing indices (Nardo et al., 2008). Finally, based on the factor scores received, the respective eigenvalues of (greater than one) factors were weighted, and the summation of those weighted dimensions was aggregated to be used as the final measure of digitalisation index scores (Bruno et al., 2023; Siddhisena and Jayathilaka, 2006).Assigning weights to digitalisation indicators was conducted utilising Principal Component Analysis. Thereby always we considered the first, second, or third principal components that capture the highest variance from the dataset and reflect the most significant underlying structure of digitalisation across nations. However, with the support of the below equation, the weights were computed.

$$PC_1 = \propto_1 Z_1 + \propto_2 Z_2 + \propto_3 Z_3 + \propto_4 Z_4 + \propto_5 Z_5$$

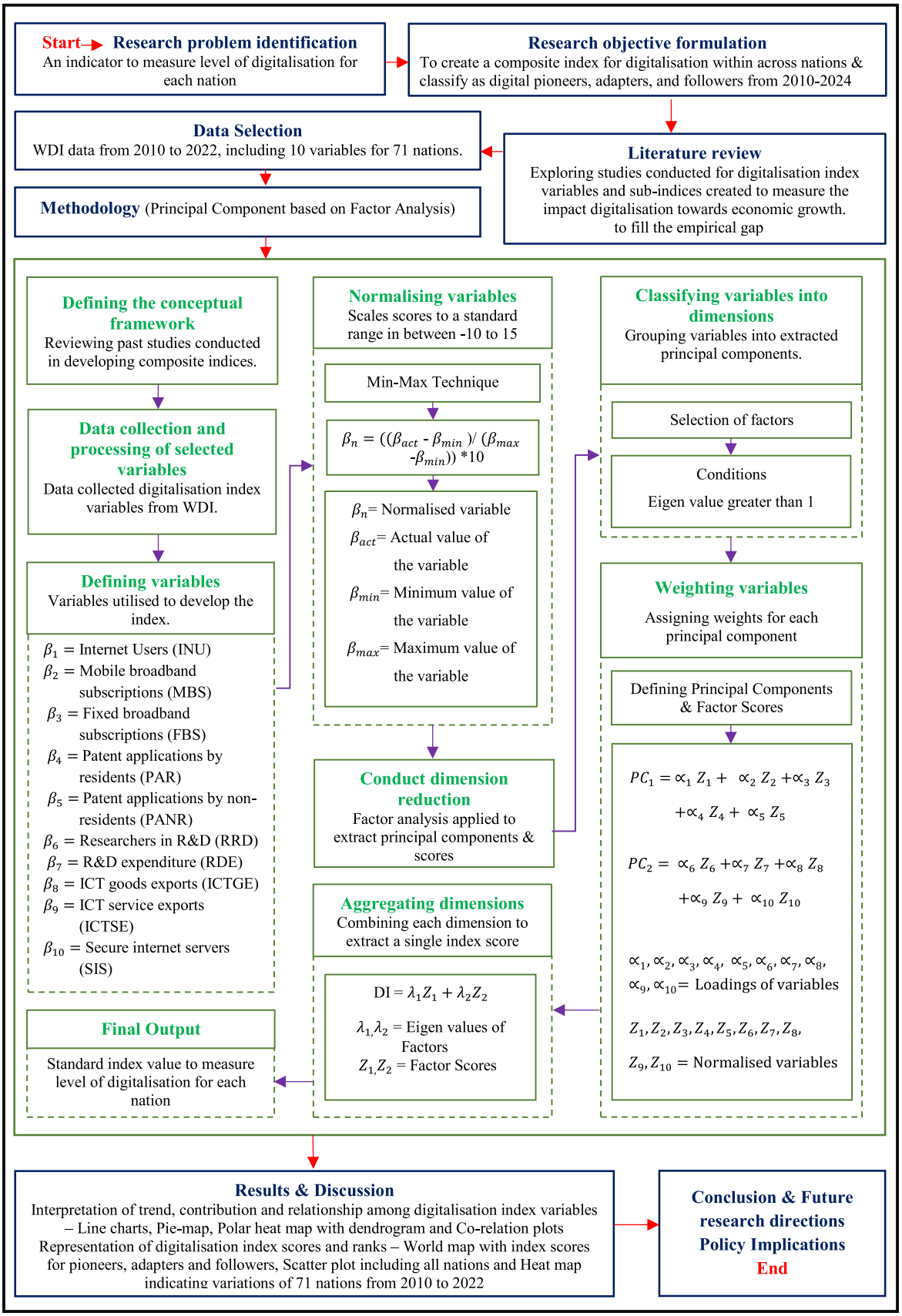

Fig. 5. Workflow hierarchy of developing the digitalisation index.
Source: Authors' compilation.

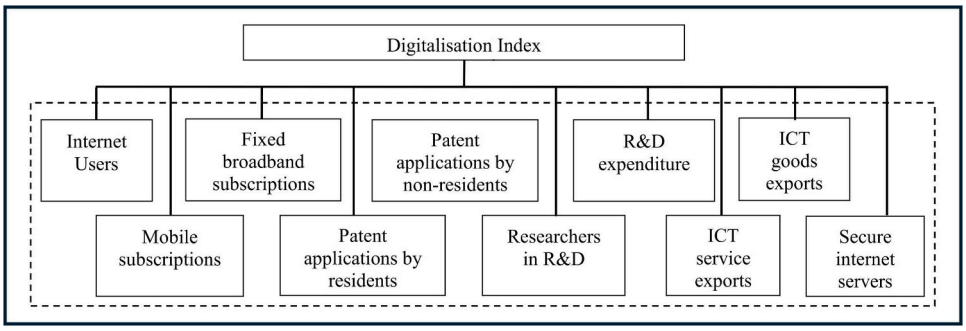

Fig. 6. Conceptual framework designed before developing the index.
Source: Authors' Compilation.

PC_1 = First principal component score

$\propto_1, \propto_2, \propto_3, \propto_4, \propto_5, \propto_6, \propto_7, \propto_8, \propto_9, \propto_{10}$ = Loadings of variables

$Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8, Z_9, Z_{10}$ = Normalised variables

$PC_2 = \propto_6 Z_6 + \propto_7 Z_7 + \propto_8 Z_8 + \propto_9 Z_9 + \propto_{10} Z_{10}$

The weighting of components in the index is not arbitrarily assigned but derived using Principal Component based on Factor Analysis (PCA-Factor). This ensures the construction of the index is grounded in data-driven relationships and reflects the actual contribution of each variable. This reallocation of weights based on factor loadings offers a methodological advancement over traditional indices by empirically identifying which digitalisation components contribute most to inter-country variation. The below equation was utilised to compute the final digitalisation index scores.

$DI = \lambda_1 Z_1 + \lambda_2 Z_2$

λ_1, λ_2 = Eigen values of Factors

Z_1, Z_2 = Factor Scores

3.4.7. Validation and testing of the digitalisation index

The digitalisation index developed was examined through internal and external validation techniques. Various techniques were utilised such as using different normalization and weighting methods, sensitivity analysis was carried out, and correlation analysis was used to look at the correlations analysis was used to look at the correlations between the variables. The digitalization index was further confirmed by contrasting its rankings with those of well-known indices, such as the ICT development index (ITU, 2024) and the Global Competitiveness Index (World Economic Forum, 2020). The created index's validity is confirmed by the findings, which show that it closely matched these benchmarks.

3.5. Tools & software used

All the computations related to PCA and developing the digitalisation index were made using the IBM SPSS Statistics 27 software package. The maps and line charts were drawn using different software packages, such as Microsoft Excel, Map Chart, Inkscape, OriginPro 2024, and Python.

4. Results & discussion

This section explores the results and their implications related to the examined literature by exploring how digitalisation index variables contribute to the digitalisation index among digital pioneers, adapters, and followers. Furthermore, some specific comparative analyses will be conducted later in this section to investigate the levels of digitalisation among nations. The discussion further contextualises these results, drawing comparisons to past studies and exploring the potential drivers behind the observed trends.

4.1. Development of the Composite Index

After reviewing comprehensive literature on digitalisation index variables, indices were created, and the scores were extracted through Principal components based on factor analysis. Later, based on the digitalisation index scores, the nations were classified into digital pioneers, adapters, and followers, and comparative analyses were conducted to conclude. The computed digitalisation index scores from 2010 to 2022 are provided in the S4 appendix.

4.2. Digitalisation index variable trends captured over

Figs. 7 and 8 explain how the trends of the digitalisation index variables fluctuated over time and how variations occurred in the rankings of nations according to the computed digitalisation index scores.

Fig. 7 represents the average values of digitalisation index variables from 2010 to 2022 before developing the index, showcasing a significant increase in digitalisation globally within this period. The number of internet users, mobile subscriptions, and fixed broadband subscriptions have steadily increased throughout the years, showing consistent growth in internet access, mobile phone penetration, and access to high-speed internet connections while positively affecting economic development (Hussain, Batool, Akbar, and Nazir, 2021). This reflects growth and investments in digital connectivity, bridging the digital divide, particularly in underserved regions (Canazza, 2009; Kongaut and Bohlin, 2016). The variables such as patent applications by residents and non-residents, researchers in R&D, and R&D expenditure demonstrate a positive trend globally, indicating significant investments and a thriving workforce dedicated to research & development activities aimed at building an innovation ecosystem (M. A. Kurniawati, 2021; H. S. Lee et al., 2020).

Meanwhile, ICT exports of goods and services have steadily increased with the global production and trade of technological-related products, indicating a growing international market for technology services. The upward trend in secure internet servers in the middle phase suggests that this will result in an increasing emphasis on cyber security and data protection. The average digitalisation index variables score from 2010 to 2022 is provided in the S2 appendix.

Fig. 8 represents a heat map that illustrates the pace of digitalisation levels across nations from 2010 to 2022 based on the digitalisation index rankings. Digital Pioneers like the United States, Korea, Denmark, and China have remained at the top rankings, demonstrating strong digital growth and innovation towards the green end of the spectrum. These nations typically have adopted widespread internet access and advanced digital infrastructure while maintaining a strong digital economy (Y. Zhou and Ye, 2017).

Nations like Croatia, Ireland, Czechia, and Estonia have emerged

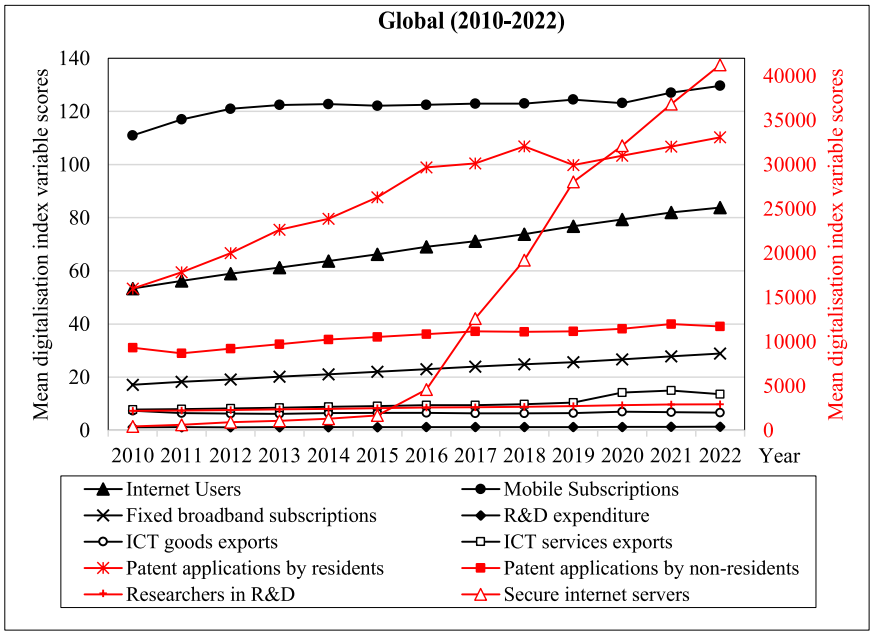

Fig. 7. Line chart indicating the mean digitalisation index variable scores: A comparison (2010–2022).
Source: Authors' compilation based on WDI data.

from adapters to pioneers through bridging the digital divide and adopting digital infrastructure and resources. Therefore, the implication of policies focusing on technological adoption, broadband access, and digital economy advancements has likely contributed to these improvements. According to the red end of the spectrum indicated in Fig. 8, nations like Madagascar, South Africa, and Mauritius indicate lower digitalisation scores, demonstrating that a strong divide exists with low penetration of ICT within those nations (Binuyo, 2015).

4.3. Identification of key relationships among digitalisation index variables

An investigation was conducted to identify the association between the digitalisation index variables before developing the index and the relationship between the variables and nations selected to create the index.

Figures 09 (A) and (B) depict correlation plots for 2010 and 2022, revealing shifts in the relationships between digitalisation index variables over time. According to Fig. 9 (A) & (B), the internet user's variable is highly correlated with fixed broadband subscriptions, stating that broadband technology significantly supported internet penetration in 2010 & 2022, while mobile technology contributed to expanding internet access moderately, reflecting less contribution within both periods. Many studies state that the penetration of telecommunication infrastructure and internet users promotes economic growth (David, 2019; Hussain et al., 2021). The positive correlations between Researchers in R&D and R&D expenditure have significantly strengthened from 2010 to 2022, enabling research & development activities to showcase advancements in innovation ecosystems.

Meanwhile, secure internet servers have become a primary factor in driving internet adoption in many nations at the early stage but not in later periods. Notably, the association between mobile subscriptions and secure internet servers is weak across both years, reflecting that mobile technology often occurs independently from secure internet servers. Also, secure internet servers are a significant driver in R&D expenditure, and researchers in R&D have a positive relationship above a 1 % significance level in both years, according to Fig. 9 (A) & (B).

Figure 10 (A) and (B) depict the polar heatmap with a dendrogram indicating the clustering of nations with similar digitalisation index variable correlations. This highlights distinct patterns of digital competitiveness and reflects advancements in digitalisation over time. Figure 10 (A) represents positive relationships between researchers in R&D and patent applications by non-resident digitalisation index variables in 2010, while Figure 10 (B) represents positive relationships between patent applications by residents and non-residents and secure internet servers in 2022. Thus, patent applications by non-residents show consistently positive relationships in both years, showcasing them as a strong indicator of digitalisation.

Secure internet servers have strongly influenced two clusters of internet users in 2022, reflecting that secure internet servers have a significant impact and contribution towards the index later. Figure 10 (A) indicates that ICT service & goods exports, R&D expenditure, and fixed broadband subscriptions had no significant variations in 2010. At the same time, there were no variations within ICT goods export, R&D expenditure, fixed broadband subscriptions, and internet users in 2022 within any nation, according to Figure 10 (B). This states that these indicators have contributed less towards the digitalisation index within those respective years.

4.4. Contribution of digitalisation index variables among digital pioneers, adapters, and followers

The contribution of each digitalisation index variable is denoted as percentages for digital pioneers, adapters, and followers between 2018 & 2022, as shown in Figure 11 & 12.

Figure 11 shows the percentage distribution overlaid with pie charts representing key digitalisation index variables across nations classified as digital pioneers, adapters, and followers in 2010. According to Figure 11 (A), many nations show the dominance of mobile subscriptions as the primary access mode to digital services while showing a limited proportion of broadband infrastructure. However, it has been proved that the enhancement of mobile subscriptions positively affects economic growth for nations (M. A. Kurniawati, 2021; Majumder and Miah, 2022). Considering ICT penetration as a combination of internet users and mobile and fixed broadband subscriptions would lead to enhanced economic development and economic advantages driven by knowledge for nations (Hussain et al., 2021).

Nations like Finland, India, Sri Lanka, Moldova, and Guatemala have

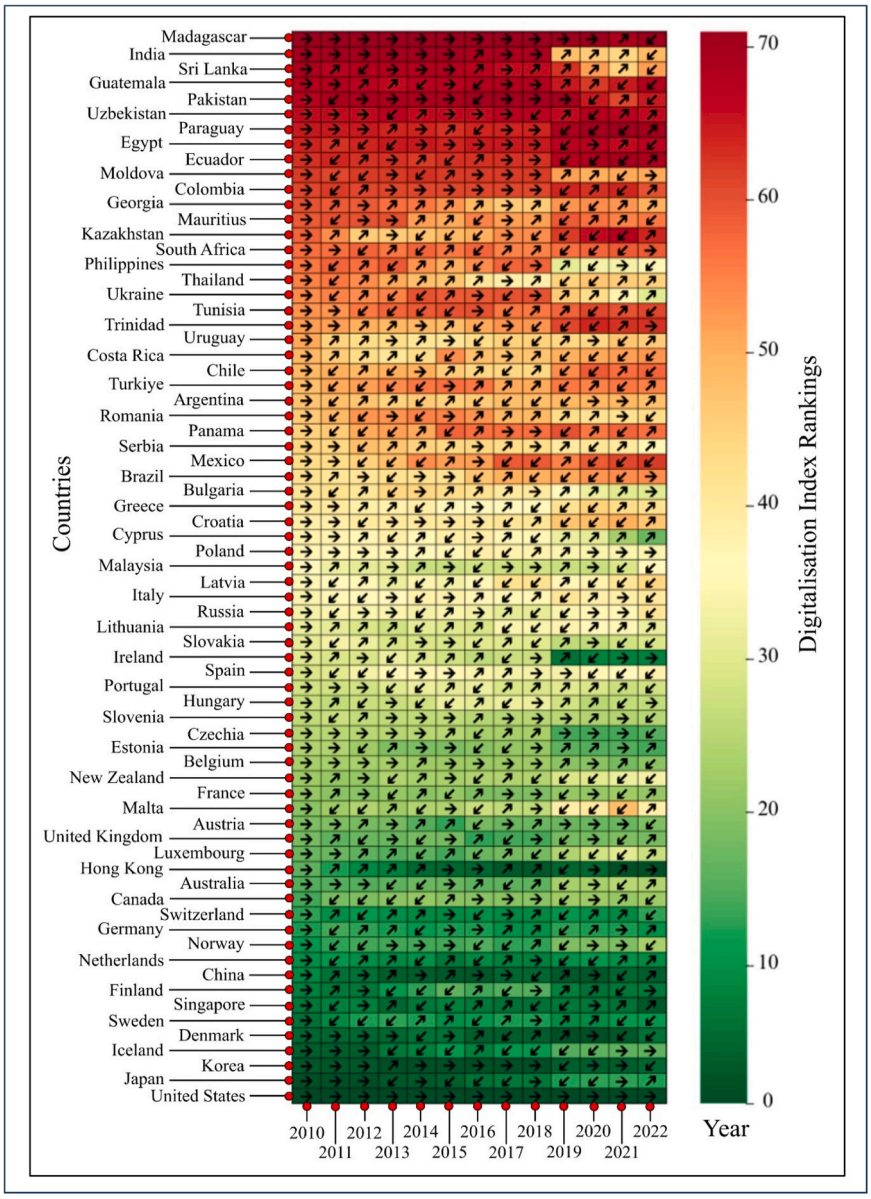

Fig. 8. Heat map identifying variations within nations according to digitalisation index ranks from 2010 to 2022.
Source: Authors' compilation based on digitalisation index ranks through Python & Canva. Note: " → " country ranked constant, " ↗ " country rank increased, " ↘ " country rank decreased.

a notable portion of ICT service exports, showcasing their reliance on digital services as an economic driver. Some nations exhibit a lower percentage of R&D expenditure, highlighting the need for a policy focusing on ICT and innovation to enhance digital competitiveness and economic development. However, investments in ICT and innovation could promote economic growth (H. S. Lee et al., 2020).

Pioneers like Iceland, Netherlands, Sweden, Finland, and Denmark exhibit a high share of secure internet servers, indicating that they have a robust digital security infrastructure, according to Figure 11 (B). The contribution of patent applications by residents and non-residents is notably lower than the other four variables of the respective nations. This suggests that a strong focus should be reflected on domestic investments and openness to foreign innovations to build an innovation ecosystem. Some studies highlight that resident patent applications negatively affect economic growth (H. S. Lee et al., 2020) since most patent applications are filed by wealthy people, which may cause unequal distribution of national wealth.

Pioneers and Adapters like the United States, China, Japan, Korea, France, and the United Kingdom showcase higher proportions of researchers in R&D, demonstrating a strengthened workforce in R&D that leads towards the development of innovation and digital competitiveness. Apart from the United States, Asian nations like China and Korea lead in ICT export goods, demonstrating strong production and export-oriented goods in the ICT sector. At the same time, many digital followers like India, Sri Lanka, Pakistan, Madagascar, Ecuador, and Paraguay also showcase higher proportions of ICT export goods, according to Figure 11 (B).

Figure 12 shows the percentage distribution overlaid with pie charts representing key digitalisation index variables across various nations classified as Digital pioneers, adapters, and followers in 2022. According to Figure 12 (A), mobile subscriptions have become significant among all nations, contributing to digitalisation by expanding access to digital services and fostering socio-economic development. Therefore, the global shift towards 5 G mobile subscriptions will drive digitalisation by supporting emerging technologies like digital Inclusion, smart cities, and artificial intelligence.

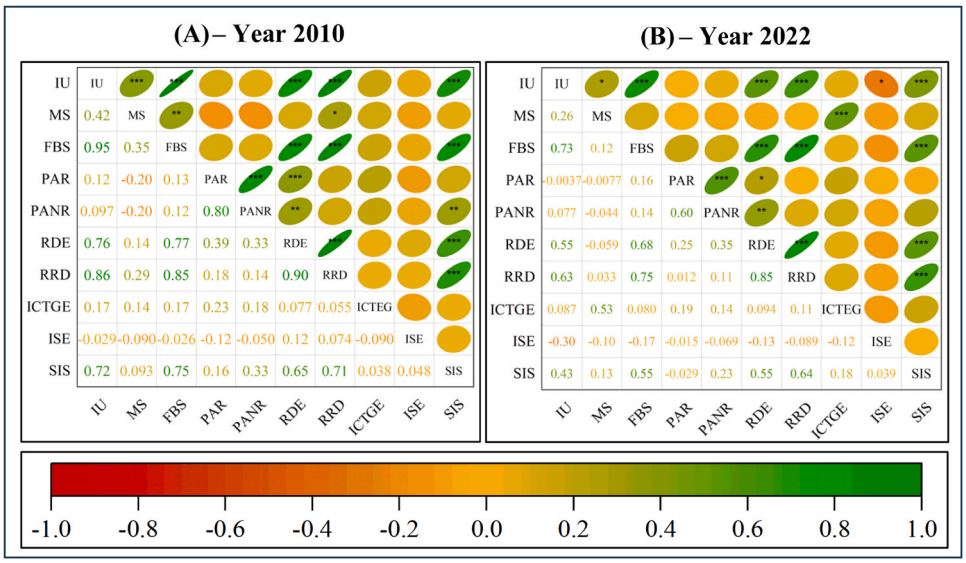

Fig. 9. Correlation ellipse matrix identifying the association between digitalisation index variables for the years 2010 & 2022. Note: * indicates 5 % significance level; * * indicates 10 % significance level; * ** indicates 1 % significance level.
Source: Authors' compilation based on WDI data through OriginPro 2024 software.

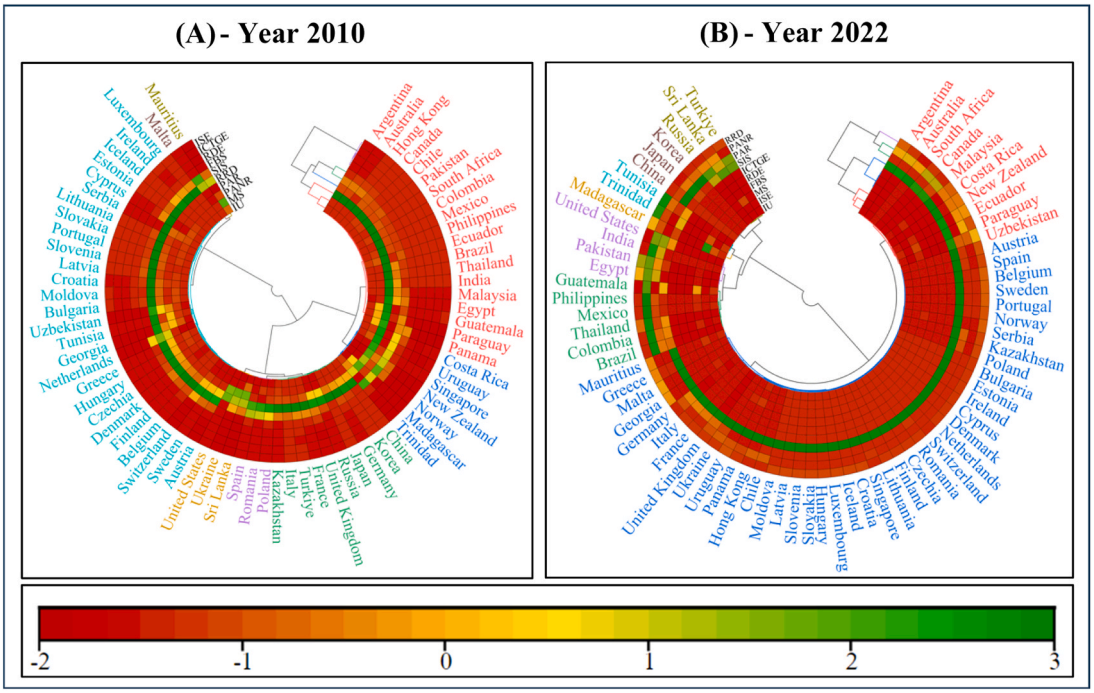

Fig. 10. Polar heatmap with dendrogram identifying the relationship between digitalisation index variables within nations for the years 2010 & 2022.
Source: Authors' compilation based on WDI data through OriginPro 2024 software.

The proportion of Internet users has emerged, reflecting how individuals and societies benefit from digital technologies. Yet fixed broadband significantly contributes to various nations and is the backbone infrastructure, complementing mobile networks to increase internet access. Nations like Finland, Ireland, Pakistan, and Madagascar have significant contributions as 12.6 %, 18.5 %, 25.8 %, and 20.4 % from ICT service exports, providing digital services as a key driver towards a digital economy.

Many nations classified under pioneers, adapters, and followers achieved a higher proportion of patent applications by non-residents in 2022 than in 2010, indicating the growing importance of the global innovation network, as shown in Figure 12 (B). Asian nations like China, Japan, and Korea have captured higher percentages in the workforce in R&D at 90.3 %, 69 %, and 75.5 %, respectively, while other Asian nations also contributed moderate amounts. In 2010, digital pioneering nations such as Iceland, Netherlands, Denmark, and Finland significantly contributed to the global share of secure internet servers. However, this contribution has dropped dramatically in 2022.

4.5. 4.5 Comparison of digital pioneers, adapters, and followers

Nations' computed digitalisation index scores are classified into digital pioneers, adapters, and followers and visualised for 2010 and 2022, as illustrated in Figure 13. Later, all nations are visualised to the

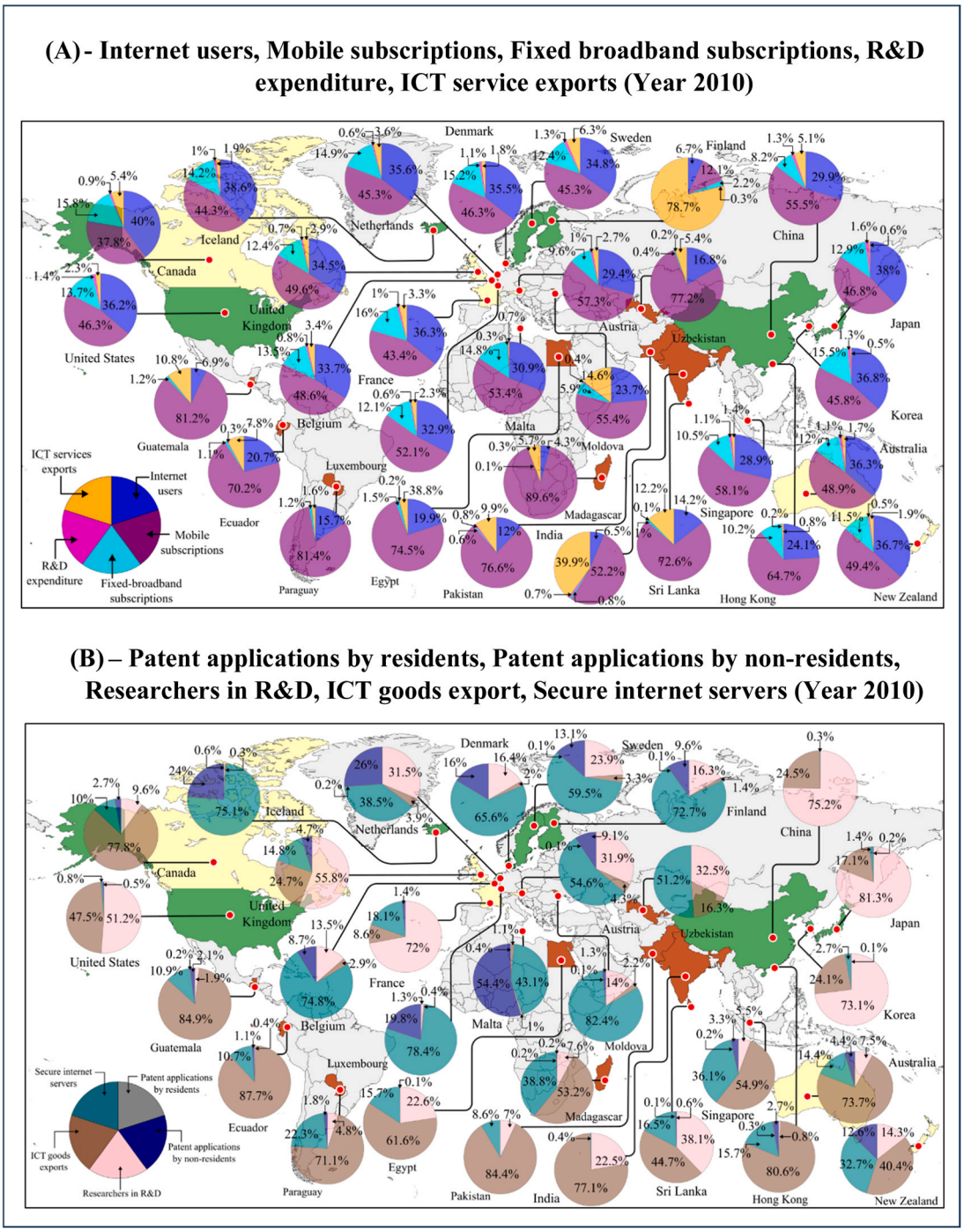

Fig. 11. World Map indicating digitalisation index variable percentages for digital pioneers, adapters, and followers for the year 2010.
Source: Authors' compilation based on WDI data through Inkscape and Map Chart.

latest period to draw cross-country comparisons, as shown in Figure 14.

Figure 13 (A) shows the digitalisation index scores for 2010, classifying them under Digital pioneers, adapters, and followers. According to 2010 scores, digital pioneers such as the United States, Japan, Korea, Iceland, and Denmark dominate the top tier of the digitalisation index by transforming towards advanced digital infrastructures, digital technologies, and innovations. Digital adapters, including Japan and Iceland, showed moderate progress in digitalisation, indicating growing digital adoption with ongoing challenges.

Nations like Paraguay, Ecuador, Guatemala, and Mexico remain at the bottom of the index with scores near −12 due to slow progress in adopting digital technologies and innovations. In 2022, the digitalisation index score classification continued to highlight significant disparities. The United States, Korea, China, Finland, and Ireland are regarded as the top-performing nations in the digitalisation index; country stations like Hong Kong and Germany have also been able to join the Digital pioneers, as shown in Figure 13 (B). When comparing both years, middle performers like Austria, Belgium, the United Kingdom, and France remain as digital adapters comparing both years.

Figure 14 represents a scatter plot indicating nations classified as digital pioneers, adapters, and followers in 2022. The United States, Hong Kong, Singapore, and Korea are ranked in the top tier in 2022, showcasing high scores and high levels of digital adoption. The United States and Germany are still dominating as pioneers due to their shared

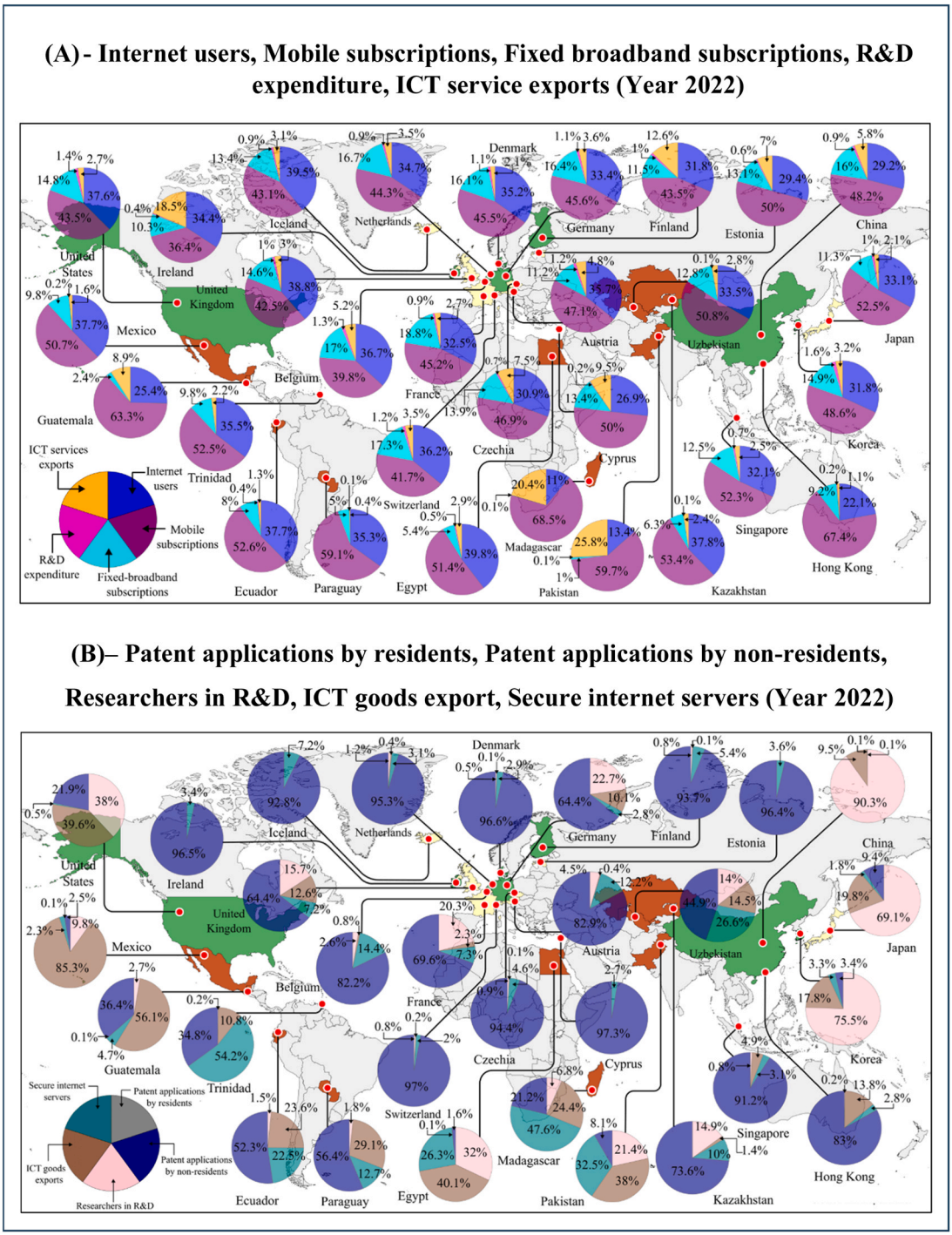

Fig. 12. World Map indicating digitalisation index variable percentages for digital pioneers, adapters, and followers for the year 2022.
Source: Authors' compilation based on WDI data through Inkscape and Map Chart.

higher proportion of ICT export goods (Murthy, Kalsie, and Shankar, 2021) and digital infrastructure. Korea has been regarded as a digitalised nation since it is meant to be a leader in E-government (Paul, Upadhyay, and Dwivedi, 2020) and E-commerce (Murthy et al., 2021).

Many nations like Luxembourg, Italy, Romania, Thailand, and Greece, classified as adapters, should be supported to bridge the existing digital divide and expand their digital infrastructure to reach the top tier. Followers like Madagascar, Guatemala, Ecuador, and Paraguay have been left at the bottom, with low scores indicating challenges in adopting digital infrastructure and lower levels of digital adoption. Most African nations like Madagascar and South Africa need to implement policies to enhance improvements in the telecommunication sector to minimise the digital divide and promote economic growth (David, 2019).

5. Conclusion

5.1. Summary of findings

This study investigates measuring the level of digitalisation by creating a composite index for digitalisation for 71 nations using ten variables from 2010 to 2022. Later, the nations are classified as digital

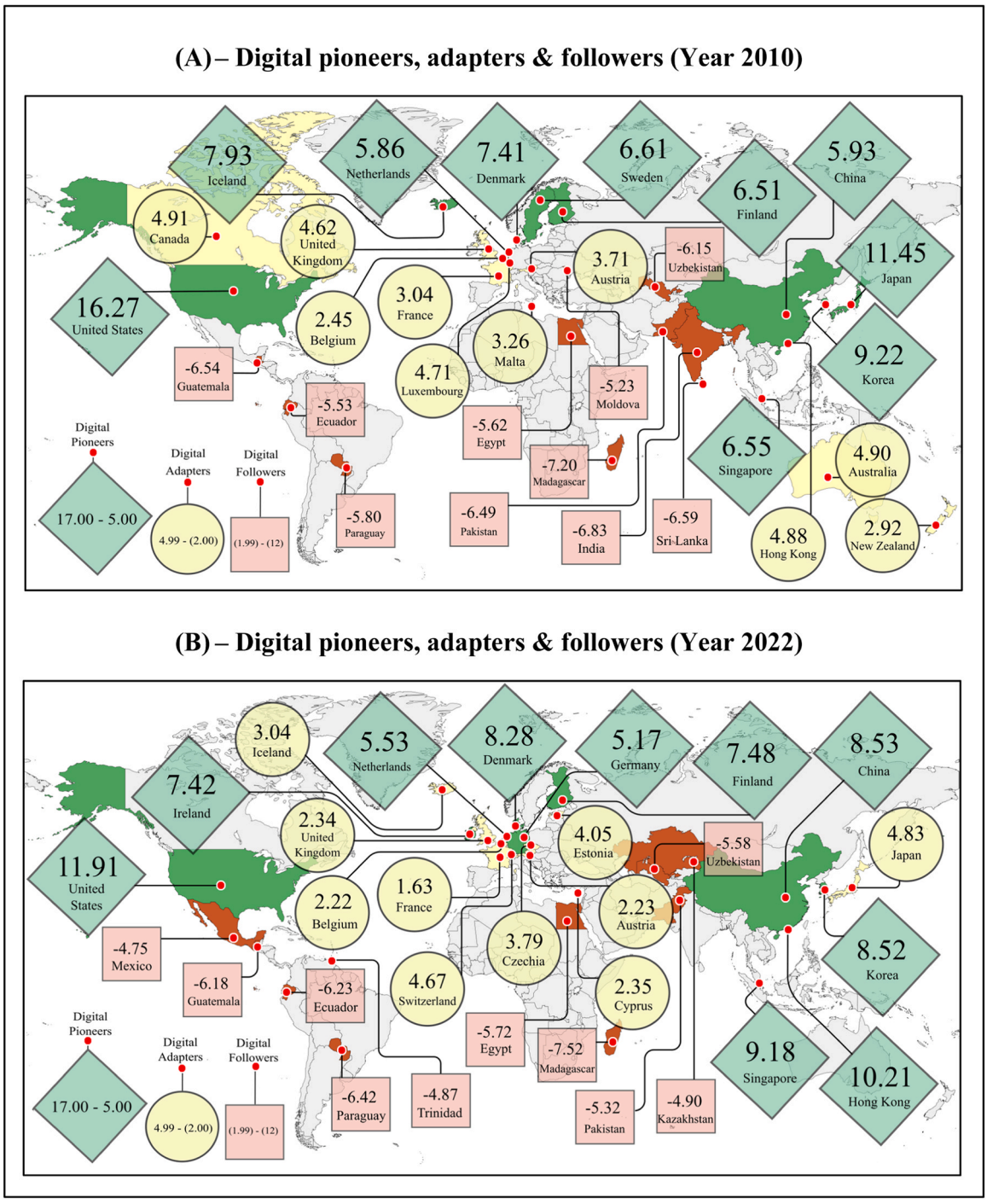

Fig. 13. World map classifying digital pioneers, adapters & followers based on the digitalisation index score (2010 & 2022).
Source: Authors' compilation based on digitalisation index scores through Inkscape and Map Chart.

pioneers, adapters, and followers based on their digitalisation index scores. However, findings reveal that advanced economies dominate as digital pioneers at early and later stages. This could result from higher adoption of digital infrastructure, technology development, and innovation capacities. Nations like Madagascar, Guatemala, Colombia, Egypt, and Uzbekistan remain digital followers due to lower adoption of digital technologies and digital literacy and with the existing digital divide. Many developing nations have been classified as digital adapters due to fewer practices of adopting advanced technologies and importing existing technologies rather than creating groundbreaking innovations. However, these findings reveal that strong digital ecosystems are associated with higher technological competence and the ability to support innovation and sustainability and promote economic growth. At the same time, followers could find it difficult to reach up due to existing economic imbalance and digital gap.

The results of the correlation analysis state that fixed broadband subscriptions have significantly contributed to accessing the internet more than mobile subscriptions within both periods. However, telecommunication technologies could tend to stimulate economic growth (David, 2019). Notably, strong positive relationships have also been captured between researchers in R&D and R&D expenditure within both periods through retaining researchers by funding projects and offering

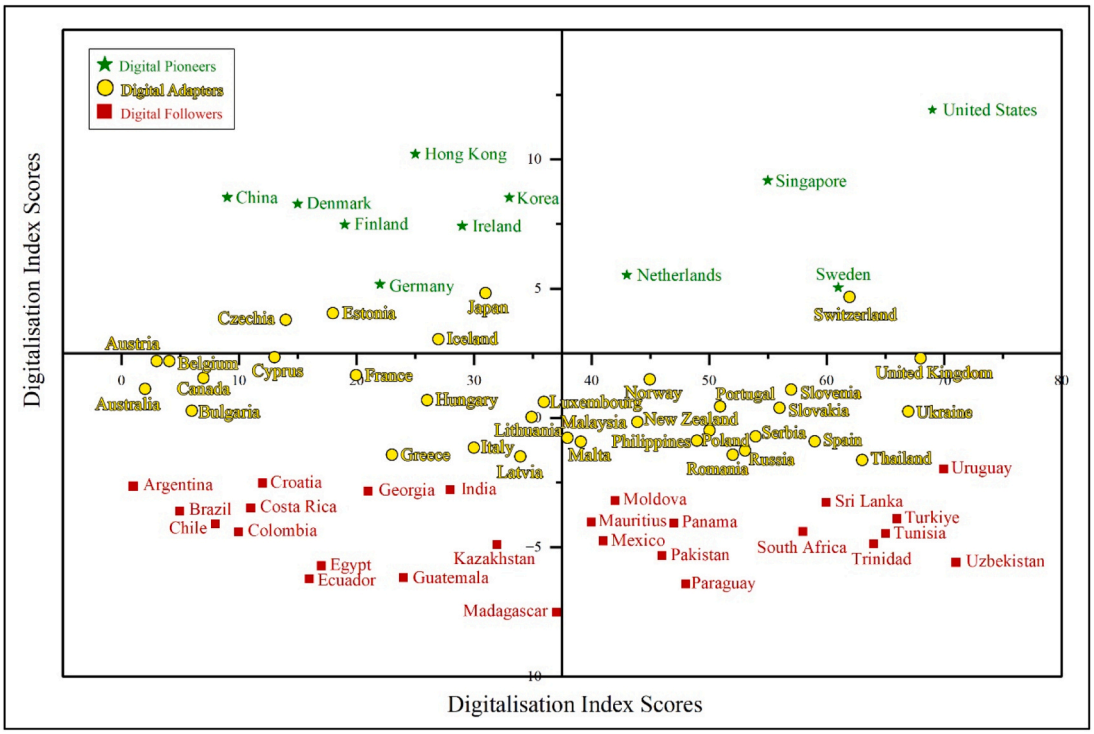

Fig. 14. Scatter plot classifying digital pioneers, adapters & followers based on the digitalisation index scores, including all nations for the year 2022. Source: Authors' compilation based on digitalisation index scores through OriginPro 2024 software.

advanced facilities. This also ensures that other variables have contributed to measuring the level of digitalisation among nations.

5.2. Future directions

However, the created digitalisation index could be used as an effective tool to track progress and guide focused initiatives to promote innovation and connectivity among nations. The digitalisation scores would also offer important insights to formulate policies to promote ICT, prioritising investing and adopting sophisticated digital infrastructure. Therefore, future research studies could be conducted by researchers to investigate the impact on economic growth, environmental pollution, and innovation by utilising the developed digitalisation index. The index would be re-developed utilising additional indicators like digital literacy, e-governance, and cyber security by using alternative data sources. Methodologically it would be interesting to conduct utilising advanced analytical techniques like multiple corresponding analysis to develop a new index for regions or nations to gain more valuable insights in developing policies and strategies for different stakeholders.

5.3. Limitations of the study

This comprehensive index uses ten variables and secondary data extracted from World Bank Development Indicators. A significant limitation of this study is the long-term data availability for selected variables. Regardless of the period, this also impacted some nations because some quantitative data for selected variables were missing. Additionally, the classification of nations into digital pioneers, adapters, and followers may oversimplify of the complex and dynamic nature of digital transformation.

Moreover, differences in data quality, reporting standards, and statistical capacities across countries may have influenced the robustness of the index outcomes. Although steps were taken to ensure data consistency—such as applying a 50 % data availability threshold and using estimation methods for missing values—future research could enhance robustness by conducting subgroup analyses or employing alternative data sources such as ITU or OECD datasets. These could be significant limitations that should be acknowledged when interpreting the results and developing future indices.

6. Policy implications

6.1. Recommendations

The research findings would be efficient for policymakers, researchers, and other stakeholders. First, digital pioneers should enhance their innovation capacities, further maintaining global leadership in digitalisation. Pioneers like Hong Kong, Singapore, Denmark, Finland, Ireland, and the Netherlands should prioritise more on emerging technologies like artificial intelligence, block chain, Internet of things, quantum computing, and developing telecommunication infrastructure. However, the emergence of these Fourth Industrial Revolution technologies highlights the existing gaps in certain regulatory frameworks for each area. It presents innovative approaches that governments could adopt to support and advance these transformative technologies (Forum, 2021). Meanwhile, certain programs like the Digital Europe Programme are providing funding to implement quantum technologies to develop and reinforce digital competency (Commission, 2023).

Second, digital adapters should focus more on expanding existing digital infrastructure, investing in digital skill development, and incentivising domestic innovation. Adapters like Portugal, Estonia, and Slovenia should invest more in mobile and fixed broadband infrastructure that helps to close the internal digital divide in underserved regions and enable access to digital services for both rural and urban populations. To create digital environment digital investments are essential to sustain and be competitive in such environments. Therefore, enabling an ecosystem and policy assistance to finance and skill gaps is a European vision that could accelerate the pace of digital innovations and adoption (European Investment, 2023). Adapters should implement policies to promote digital literacy and technical skills within the workforce that integrate into a better global economy. They also prioritise incentivising domestic innovations by supporting and

encouraging private sector R&D investments, implementing policy measures like tax incentives for tech start-ups, and subsidies for digital innovation that support the transition towards the pioneer stage.

Finally, digital followers must initially address the challenges in building basic digital infrastructure, including mobile networks, internet access, and other ICT facilities, to bridge the digital divide among rural regions. To expand their digital reach, followers should regulate pricing and subsidy policies for low-income households and incentivise internet service providers to offer affordable packages that promote digital inclusivity. Certainly, the United Nations Broadband Commission for Sustainable Development aims to make broadband prices affordable to the population of developing nations by 2025. This initiative would increase the no. of users' access to the Internet and reduce the digital divide existing in certain developing regions (Union, 2021).

6.2. Global and regional co-operation for digital development

At present, rapid digital development and transformation are taking place among nations globally. This section showcases how global and regional cooperation contributes to future digital development. Digital pioneers could play a significant role by sharing their best practices, technical expertise, and policy frameworks that have effectively advanced digitalisation among adapters and followers. Further, establishing regional platforms for collaborative knowledge-sharing will allow adapters and followers to benefit from global technological advancements. Finally, nations can benefit from standardising policies on cyber security, data protection, and digital trade, which promote building a global digital ecosystem while making digital interactions and economic transactions smoother across borders.

Given the strong connection between digital readiness and open innovation capacity, our findings can guide policymakers and firms—especially SMEs—on how to cultivate open innovation culture and manage complexity by investing in the digital enablers identified in our index.

Funding Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical Statement

This article does not involve any studies with human or animal participants.

CRediT authorship contribution statement

Jayathilaka Ruwan: Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Formal analysis, Conceptualization, Supervision, Visualization. **Wijerathna Dilan:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization, Formal analysis, Validation. **Kumara Ushan:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.joitmc.2025.100540.

References

Adejumo, O.O., Adejumo, A.V., Aladesanmi, T.A., 2020. Technology-driven growth and inclusive growth- implications for sustainable development in Africa. Technol. Soc. 63, 1–8. https://doi.org/10.1016/j.techsoc.2020.101373.

Al-Khalidi, M., Al-Zaidi, R., Ali, T., Khan, S., Bashir, A.K., 2025. AI-optimized elliptic curve with Certificate-Less Digital Signature for zero trust maritime security. Ad Hoc Netw. 166, 1–13. https://doi.org/10.1016/j.adhoc.2024.103669.

Androniceanu, A.-M., Georgescu, I., Tvaronaviciene, M., Androniceanu, A., 2020. Canonical Correlation Analysis and a New Composite Index on Digitalization and Labor Force in the Context of the Industrial Revolution 4.0. Sustainability 12, 1–20. https://doi.org/10.3390/su12176812.

Appiah-Otoo, I., Song, N., 2021. The impact of ICT on economic growth-Comparing rich and poor countries. Telecommun. Policy 45 (2), 1–15. https://doi.org/10.1016/j.telpol.2020.102082.

Arvin, M.B., Pradhan, R.P., Nair, M., 2021. Uncovering interlinks among ICT connectivity and penetration, trade openness, foreign direct investment, and economic growth: The case of the G-20 countries. Telemat. Inform. 60, 1–25. https://doi.org/10.1016/j.tele.2021.101567.

Batool, R., Hasan, H., 2023. The Effect of Education, R&D, and ICT on Economic Growth of Middle-Income Countries. J. Manag. Pract., Humanit. Soc. Sci. 7 (3), 35–47. https://doi.org/10.1109/ICETAS51660.2020.948421310.33152/jmphss-7.3.5.

Benitez Hurtado, S.R., Tenesaca-Martínez, K., Torres-Diaz, V., Quito, B., Ojeda, C., Ochoa-Moreno, S., 2024. Assessing the influence of GDP, globalization, civil liberties, and foreign direct investment on researchers in R&D per country: Dynamic Panel Cointegration Analysis for Latin American countries. Soc. Sci. Humanit. Open 10, 1–8. https://doi.org/10.1016/j.ssaho.2024.100929.

Binuyo, A., 2015. ICT Adoption and Economic Growth Nexus: Evidence from Leading African Economies. J. Econ. Behav. Stud. 7, 43–54. https://doi.org/10.22610/jebs.v7i5(J).605.

Bruno, G., Diglio, A., Piccolo, C., Pipicelli, E., 2023. A reduced Composite Indicator for Digital Divide measurement at the regional level: An application to the Digital Economy and Society Index (DESI). Technol. Forecast. Soc. Change 190, 1–16. https://doi.org/10.1016/j.techfore.2023.122461.

Calderon-Monge, E., Ribeiro-Soriano, D., 2024. The role of digitalization in business and management: a systematic literature review. Rev. Manag. Sci. 18 (2), 449–491. https://doi.org/10.1007/s11846-023-00647-8.

Cámara, N., & Tuesta, D. (2017). *DiGiX: The Digitization Index DiGiX: the Digitization Index. Retrieved from BBVA Research*:

Canazza, M. (2009). *Global effort on bridging the digital divide and the role of ICT standardization. Paper presented at the Kaleidoscope Academic Conference, Mar del Plata, Argentina.* ⟨https://ieeexplore.ieee.org/document/5338914⟩.

Chesbrough, H., Bogers, M., 2014. Explicating open innovation: Clarifying an emerging paradigm for understanding innovation. New Frontiers in Open Innovation. Oxford University Press, Forthcoming, *Oxford*, pp. 3–28.

Commission, E. (2023). Quantum Technologies Flagship. Retrieved from ⟨https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship⟩.

David, O.O., 2019. Nexus between telecommunication infrastructures, economic growth and development in Africa: Panel vector autoregression (P-VAR) analysis. Telecommun. Policy 43 (8), 1–17. https://doi.org/10.1016/j.telpol.2019.03.005.

Diego, O.J., Elisa, T., Gabriela, C., & Gabriela, J.L. (2023). *Stochastic convergence of information and communication technology goods exports. Evidence for developing countries*. Paper presented at the 2023 18th Iberian Conference on Information Systems and Technologies (CISTI).

Dolge, K., Kubule, A., Blumberga, D., 2020. Composite index for energy efficiency evaluation of industrial sector: sub-sectoral comparison. Environ. Sustain. Indic. 8, 1–9. https://doi.org/10.1016/j.indic.2020.100062.

Dzator, J., Acheampong, A.O., Appiah-Otoo, I., Dzator, M., 2023. Leveraging digital technology for development: Does ICT contribute to poverty reduction? Telecommun. Policy 47 (4), 1–34. https://doi.org/10.1016/j.telpol.2023.102524.

Edquist, H., Goodridge, P., Haskel, J., Li, X., Lindquist, E., 2018. How important are mobile broadband networks for the global economic development? Inf. Econ. Policy 45, 16–29. https://doi.org/10.1016/j.infoecopol.2018.10.001.

European Commission. (2022). The Digital Economy and Society Index. Retrieved from https://digital-strategy.ec.europa.eu/en/policies/desi.

European Investment, B, 2023. Digitalisation in Europe 2022-2023 – Evidence from the EIB investment survey. European Investment Bank.

Fähndrich, J., 2023. A literature review on the impact of digitalisation on management control. J. Manag. Control 34 (1), 9–65. https://doi.org/10.1007/s00187-022-00349-4.

Fernández-Portillo, A., Almodóvar-González, M., Hernández-Mogollón, R., 2020. Impact of ICT development on economic growth. A study of OECD European union countries. Technol. Soc. 63, 1–9. https://doi.org/10.1016/j.techsoc.2020.101420.

Forum, W.E. (2021). *Global Technology Governance Report 2021: Harnessing Fourth Industrial Revolution Technologies in COVID-19 World*. Retrieved from Switzerland: https://www.weforum.org/publications/global-technology-governance-report-2021/.

Gobble, M.M., 2018. Digitalization, Digitization, and Innovation. Res. -Technol. Manag. 61 (4), 56–59. https://doi.org/10.1080/08956308.2018.1471280.

Gradillas, M., Thomas, L.D.W., 2025. Distinguishing digitization and digitalization: A systematic review and conceptual framework. J. Prod. Innov. Manag. 42 (1), 112–143. https://doi.org/10.1111/jpim.12690.
Habibi, F., Zabardast, M.A., 2020. Digitalization, education and economic growth: A comparative analysis of Middle East and OECD countries. Technol. Soc. 63, 1–9. https://doi.org/10.1016/j.techsoc.2020.101370.
Hanafizadeh, M., Hanafizadeh, P., Saghaei, A., 2009. The Pros and Cons of Digital Divide and E-Readiness Assessments. Int. J. E-Adopt. 1 (3), 1–29. https://doi.org/10.4018/jea.2009092901.
Hanafizadeh, M.R., Saghaei, A., Hanafizadeh, P., 2009. An index for cross-country analysis of ICT infrastructure and access. Telecommun. Policy 33 (7), 385–405. https://doi.org/10.1016/j.telpol.2009.03.008.
Hanafizadeh, P., Hanafizadeh, M.R., Khodabakhshi, M., 2009b. Taxonomy of e-readiness assessment measures. Int. J. Inf. Manag. 29 (3), 189–195. https://doi.org/10.1016/j.ijinfomgt.2008.06.002.
Hanafizadeh, P., Hanafizadeh, M.R., Khodabakhshi, M., 2009a. Extracting Core ICT Indicators Using Entropy Method. Inf. Soc. 25 (4), 236–247. https://doi.org/10.1080/01972240903028490.
Horvath, R., 2011. Research & development and growth: A Bayesian model averaging analysis. Econ. Model. 28 (6), 2669–2673. https://doi.org/10.1016/j.econmod.2011.08.007.
Huawai Technologies Co., L. (2021). 2020 Global Connectivity Index. Retrieved from https://www.huawei.com/minisite/gci/en/country-rankings.html.
Huong Yong Jing, A., Ab-Rahim, R., 2020. Information and Communication Technology (ICT) and Economic Growth in ASEAN-5 Countries. J. Public Adm. Gov. 10 (2), 20–33. https://doi.org/10.5296/jpag.v10i2.16589.
Hussain, A., Batool, I., Akbar, M., Nazir, M., 2021. Is ICT an enduring driver of economic growth? Evidence from South Asian economies. Telecommun. Policy 45 (8), 1–12. https://doi.org/10.1016/j.telpol.2021.102202.
IMD. (2024). *IMD World Digital Competitiveness Ranking. Retrieved from* https://www.imd.org/centers/wcc/world-competitiveness-center/rankings/world-digital-competitiveness-ranking/.
i-SCOOP. (2024). Digitization, digitalization, digital and transformation: the differences. Retrieved from https://www.i-scoop.eu/information-management/moving-digitization-digitalization/.
ITU. (2024). *The ICT Development Index 2024*. Retrieved from Switzerland, Geneva: https://www.itu.int/hub/publication/d-ind-ict_mdd-2024-3/.
Jiang, M., Jia, P., 2022. Does the level of digitalized service drive the global export of digital service trade? Evidence from global perspective. Telemat. Inform. 72, 1–14. https://doi.org/10.1016/j.tele.2022.101853.
Katz, R., Koutroumpis, P., Callorda, F., 2014. info. Using a Digit. Index Meas. Econ. Soc. Impact Digit. Agendas 16 (1), 32–44. https://doi.org/10.1108/info-10-2013-0051.
Kongaut, C., Bohlin, E., 2016. Investigating mobile broadband adoption and usage: A case of smartphones in Sweden. Telemat. Inform. 33 (3), 742–752. https://doi.org/10.1016/j.tele.2015.12.002.
Kraus, S., Jones, P., Kailer, N., Weinmann, A., Chaparro-Banegas, N., Roig-Tierno, N., 2021. Digital Transformation: An Overview of the Current State of the Art of Research. Sage Open 11 (3). https://doi.org/10.1177/21582440211047576.
Kurniawati, M., 2020. The role of ICT infrastructure, innovation and globalization on economic growth in OECD countries, 1996-2017. J. Sci. Technol. Policy Manag. 11 (2), 193–215. https://doi.org/10.1108/JSTPM-06-2019-0065.
Kurniawati, M.A., 2021. ICT infrastructure, innovation development and economic growth: a comparative evidence between two decades in OECD countries. Int. J. Soc. Econ. 48 (1), 141–158. https://doi.org/10.1108/IJSE-05-2020-0321.
Kurniawati, M.A., 2022. Analysis of the impact of information communication technology on economic growth: empirical evidence from Asian countries. J. Asian Bus. Econ. Stud. 29 (1), 2–17. https://doi.org/10.1108/JABES-07-2020-0082.
Lee, H.S., Sia, B.K., Low, C.W., & Chong, S.C. (2020). *Impacts of ICT and innovation on economic growth in advanced countries*. Paper presented at the 2020 IEEE 7th International Conference on Engineering Technologies and Applied Sciences (ICETAS), Kuala Lumpur, Malaysia.
Lee, S.G., Trimi, S., Kim, C., 2013. Innovation and imitation effects' dynamics in technology adoption. Ind. Manag. Data Syst. 113 (6), 772–799. https://doi.org/10.1108/IMDS-02-2013-0065.
Leonardi, P.M., Treem, J.W., 2020. Behavioral Visibility: A new paradigm for organization studies in the age of digitization, digitalization, and datafication. Organ. Stud. 41 (12), 1601–1625. https://doi.org/10.1177/0170840620970728.
Li, H., Han, J., Xu, Y., 2023. The effect of the digital economy on services exports competitiveness and ternary margins. Telecommun. Policy 47 (7), 1–12. https://doi.org/10.1016/j.telpol.2023.102596.
Majumder, S., Miah, M.M., 2022. ICT and its Impact on Economic Growth in SAARC Countries. Usak Univ. J. Soc. Sci. 3, 123–142.
Maneejuk, P., Yamaka, W., 2020. An analysis of the impacts of telecommunications technology and innovation on economic growth. Telecommun. Policy 44 (10), 1–19. https://doi.org/10.1016/j.telpol.2020.102038.
Mignamissi, D., Djijo, T., A.J., 2021. Digital divide and financial development in Africa. Telecommun. Policy 45 (9), 1–18. https://doi.org/10.1016/j.telpol.2021.102199.
Moreno-Hurtado, C., Plascencia, A., Lozano, A., & Cano, J. (2020). *ICT exports: the role of human capital and economic complexity. Paper presented at the 2020 15th Iberian Conference on Information Systems and Technologies (CISTI)*.
Murthy, K.V.B., Kalsie, A., Shankar, R., 2021. Digital economy in a global perspective: is there a digital divide? Transnatl. Corp. Rev. 13 (1), 1–15. https://doi.org/10.1080/19186444.2020.1871257.
Mwananziche, J., Myovella, G., Karacuka, M., Haucap, J., Moshi, G., 2023. Is digitalization a booster for economic growth in Africa? Short run and long run evidence from Tanzania. Telecommun. Policy 47 (10), 1–12. https://doi.org/10.1016/j.telpol.2023.102679.
Myovella, G., Karacuka, M., Haucap, J., 2020. Digitalization and economic growth: A comparative analysis of Sub-Saharan Africa and OECD economies. Telecommun. Policy 44 (2), 1–12. https://doi.org/10.1016/j.telpol.2019.101856.
Myovella, G., Karacuka, M., Haucap, J., 2021. Determinants of digitalization and digital divide in Sub-Saharan African economies: A spatial Durbin analysis. Telecommun. Policy 45 (10), 102224. https://doi.org/10.1016/j.telpol.2021.102224.
Nair, M., Pradhan, R.P., Arvin, M.B., 2020. Endogenous dynamics between R&D, ICT and economic growth: Empirical evidence from the OECD countries. Technol. Soc. 62, 1–12. https://doi.org/10.1016/j.techsoc.2020.101315.
Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., Giovannini, E., 2008. *Handbook on Constructing Composite Indicators and User Guide*. OECD Publishing, Paris. https://doi.org/10.1787/9789264043466-en.
Ndubuisi, G., Otioma, C., Tetteh, G.K., 2021. Digital infrastructure and employment in services: Evidence from Sub-Saharan African countries. Telecommun. Policy 45 (8), 1–9. https://doi.org/10.1016/j.telpol.2021.102153.
Nguyen, C.P., Doytch, N., 2022. The impact of ICT patents on economic growth: An international evidence. Telecommun. Policy 46 (5), 102291. https://doi.org/10.1016/j.telpol.2021.102291.
Nipo, D., Lily, J., Idris, S., Pinjaman, S., Bujang, I., 2024. Information and Communication Technology (ICT) on Economic Growth in Asia: A Panel Data Analysis. Int. J. Bus. Manag. 17 (12), 18–23. https://doi.org/10.5539/ijbm.v17n12p18.
Nistor, A., Zadobrischi, E., 2022. Analysis and Estimation of Economic Influence of IoT and Telecommunication in Regional Media Based on Evolution and Electronic Markets in Romania. Telecom 3 (1), 195–217. https://doi.org/10.3390/telecom3010013.
Njoh, A.J., 2018. The relationship between modern Information and Communications Technologies (ICTs) and development in Africa. Uti. Policy 50, 83–90. https://doi.org/10.1016/j.jup.2017.10.005.
Olamide, E., Ogujiuba, K.K., Maredza, A., Semosa, P., 2022. Poverty, ICT and Economic Growth in SADC Region: A Panel Cointegration Evaluation. Sustainability 14 (15). https://doi.org/10.3390/su14159091.
Oliinyk, A., Molchanova, E., Sierova, L., Kulyk, Y., Huliaieva, L., Tkachenko, I., 2023. ICT Services Market's Impact on ICT-Enabled Services Market: Comparative Cross-Country Analysis. Pap. Presente 2023 13th Int. Conf. Adv. Comput. Inf. Technol. (ACIT).
Pang, S., Li, Z., Wang, Y., 2024. Digital technology and domestic value-added ratio in export: Evidence from China's pilot zones for integrating informatization and industrialization. Econ. Anal. Policy 84, 424–439. https://doi.org/10.1016/j.eap.2024.08.030.
Paul, M., Upadhyay, P., Dwivedi, Y., 2020. Roadmap to digitalisation of an emerging economy: a viewpoint. Transform. Gov.: People, Process Policy. https://doi.org/10.1108/TG-03-2020-0054.
Portulans Institute (2023). Trust in a Network Society: A crisis of the digital age? Retrieved from.
Ranjan, A.K., Kumar, P., 2024. APPS: Authentication-enabled privacy protection scheme for secure data transfer in Internet of Things. Ad Hoc Netw. 164, 1–13. https://doi.org/10.1016/j.adhoc.2024.103631.
Rao, P.M., Balasubrahmanya, M.H., 2017. The rise of IT services clusters in India: A case of growth by replication. Telecommun. Policy 41 (2), 90–105. https://doi.org/10.1016/j.telpol.2016.11.006.
Saarikko, T., Westergren, U.H., Blomquist, T., 2020. Digital transformation: Five recommendations for the digitally conscious firm. Bus. Horiz. 63 (6), 825–839. https://doi.org/10.1016/j.bushor.2020.07.005.
Saba, C., David, O., Voto, T., 2024. Institutional quality effect of ICT penetration: Global and regional perspectives. South Afr. J. Econ. Manag. Sci. (SAJEMS) 27, 1–14. https://doi.org/10.4102/sajems.v27i1.5180.
Saba, C.S., David, O.O., 2020. Convergence patterns in global ICT: Fresh insights from a club clustering algorithm. Telecommun. Policy 44 (10), 1–28. https://doi.org/10.1016/j.telpol.2020.102010.
Saba, C.S., Asongu, S.A., Ngepah, N., Ngoungou, Y.E., 2024. Governance in the exploration of global and regional determinants of ICT development. Int. J. Innov. Stud. 8 (2), 132–153. https://doi.org/10.1016/j.ijis.2024.02.002.
Saba, C.S., Ngepah, N., Odhiambo, N.M., 2024. Information and Communication Technology (ICT), Growth and Development in Developing Regions: Evidence from a Comparative Analysis and a New Approach. J. Knowl. Econ. 15 (3), 14700–14748. https://doi.org/10.1007/s13132-023-01571-8.
Sabine Landau, B.S.E., 2004. A Handbook of Statistical Analyses using SPSS. Chapman & Hall/CRC Press LLC, Boca Ranton, Florida.
Siddhisena, P., Jayathilaka, R., 2006. Identification of the Poor in Sri Lanka: Development of Composite Indicator and Regional Poverty Lines. SSRN Electron. J. https://doi.org/10.2139/ssrn.891782.
Singh, P., Siddiqui, A.A., 2023. Innovation, ICT penetration, trade and economic growth in developing and developed countries: a VECM approach. Compét. Rev.: Int. Bus. J. 33 (2), 395–418. https://doi.org/10.1108/CR-05-2021-0074.
Singh, S.K., & Kumari, R. (2023). *ICT Influence on Economic Growth of Low-Income Countries with the Participation of HICs*.
Sinha, M., Roy, S., Tirtosuharto, D., 2024. Digitalization and economic development: lessons from globalized developing countries. Stud. Econ. Financ. https://doi.org/10.1108/SEF-12-2023-0701.
Soomro, A., Kumar, J., Kumari, J., 2022. The Dynamic Relationship Between FDI, ICT, Trade Openness, and Economic Growth: Evidence from BRICS Countries. J. Asian Financ. Econ. Bus. 9 (2), 295–303. https://doi.org/10.13106/jafeb.2022.vol9.no2.0295.

Union, I.T. (2021). *Measuring digital development: Facts and figures 2021*. Retrieved from https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2021.pdf.

Urbinati, A., Chiaroni, D., Chiesa, V., Frattini, F., 2020. The role of digital technologies in open innovation processes: an exploratory multiple case study analysis. Rd Manag. 50 (1), 136–160.

Urbinati, A., Manelli, L., Frattini, F., Bogers, M.L.A.M., 2022. The digital transformation of the innovation process: orchestration mechanisms and future research directions. Innovation 24 (1), 65–85. https://doi.org/10.1080/14479338.2021.1963736.

Vassilakopoulou, P., Hustad, E., 2023. Bridging Digital Divides: a Literature Review and Research Agenda for Information Systems Research. Inf. Syst. Front. 25 (3), 955–969. https://doi.org/10.1007/s10796-020-10096-3.

Vial, G., 2019. Understanding digital transformation: A review and a research agenda. J. Strateg. Inf. Syst. 28 (2), 118–144. https://doi.org/10.1016/j.jsis.2019.01.003.

Wang, L., Luo, G.-l, Sari, A., Shao, X.-F., 2020. What nurtures fourth industrial revolution? An investigation of economic and social determinants of technological innovation in advanced economies. Technol. Forecast. Soc. Change 161, 1–7. https://doi.org/10.1016/j.techfore.2020.120305.

WIPO. (2023). *Global Innovation Index 2023 Retrieved from Geneva*: www.wipo.int/global_innovation_index.

World Economic Forum. (2020). *The Global Competitiveness Report. Retrieved from* https://www.weforum.org/publications/the-global-competitiveness-report-2020/.

Yang, C., Gu, M., Albitar, K., 2024. Government in the digital age: Exploring the impact of digital transformation on governmental efficiency. Technol. Forecast. Soc. Change 208, 1–12. https://doi.org/10.1016/j.techfore.2024.123722.

Yoo, Y., Lyytinen, K., Boland, R., Berente, N., 2010. The Next Wave of Digital Innovation: Opportunities and Challenges: A Report on the Research Workshop 'Digital Challenges in Innovation Research. SSRN Electron. J. https://doi.org/10.2139/ssrn.1622170.

Yuan, S., Musibau, H.O., Genç, S.Y., Shaheen, R., Ameen, A., Tan, Z., 2021. Digitalization of economy is the key factor behind fourth industrial revolution: How G7 countries are overcoming with the financing issues? Technol. Forecast. Soc. Change 165, 1–7. https://doi.org/10.1016/j.techfore.2020.120533.

Yun, J.J., Zhao, X., Jung, K., Yigitcanlar, T., 2020. In. In: The culture for open innovation dynamics, 12. MDPI, p. 5076.

Zhang, H., Liu, Q., Wei, Y., 2023. Digital product imports and export product quality: Firm-level evidence from China. China Econ. Rev. 79, 1–19. https://doi.org/10.1016/j.chieco.2023.101981.

Zhang, Y., Xu, J., Yang, W., 2024. Analysis of the evolution characteristics of international ICT services trade based on complex network. Telecommun. Policy 48 (3), 1–17. https://doi.org/10.1016/j.telpol.2023.102697.

Zhou, Y., Ye, L., 2017. An empirical analysis of the impact of Internet finance on China's economic growth: From the perspective of information and communication technology and financial inclusion. Pap. Presente 2017 Int. Conf. Serv. Syst. Serv. Manag.

Zhou, Z., Long, D., Xin, Y., 2024. Combining the management of natural resources with the management of environmental resources: Modeling the impact of high-tech and ICT service export. Resour. Policy 95, 1–7. https://doi.org/10.1016/j.resourpol.2024.105192.