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# Exploring Digital Sustainability Metrics: Developing a Comprehensive Framework to Measure Sustainable Digital Practices

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## ABSTRACT

Digital sustainability is inevitable for today's environment and sustainability. Digital technologies can help to manage sustainability effectively and efficiently. it's also important to understand the progress of sustainability and how technologies help to make digital sustainability practices successful. Measuring digital sustainability is a complex task and it requires consideration of all the influencing factors to have an accurate measurement of progress. It requires the standardization of sustainability components and factors across industries as technology changes and evolves rapidly. This research article explores the essential factors of environmental, social, and economic factors. We also considered technology factors as one of the determinants of measurement as it supports all other factors to make it successful and measurable. This paper also proposes a framework to measure the score of digital sustainability based on factors of each component. the significant factors, usage, and limitations and proposes a formula for calculating a Digital Sustainability Score. This framework can be customized, and factors can be prioritized based on business requirements. This measurement will help the companies to understand the status of digital sustainability practices, and this can be tuned based on sustainability goals. There are many challenges to measuring digital sustainability as it requires the collection of data for each factor, in-depth knowledge, and deployment of significant resources. While this framework is an attempt to understand all the major factors and requires a specific focus on industry. Though this paper addresses Social, environmental, economic, and digital technology factors, it requires a more comprehensive framework and a separate list of factors for each specific industry.

**Keywords:** digital sustainability, sustainability metrics, sustainable digital practices, framework, literature review, case study analysis, systematic review, environmental impact, ICT.

## INTRODUCTION

Digital sustainability is an emerging area that focuses on social, economic, and environmental impacts with the help of digital technology.

In today's era, it is crucial to use digital technologies like AI and IoT in the measurement process to gauge the impact of sustainability factors. It is effective and efficient to measure the current status and the gap to reach the milestone. Advanced technologies like machine learning and predictive algorithms can also help to understand the consequences of sustainability factors. A significant and integral part of digital sustainability is digital preservation, which has focused on one technical concern after another as issues and fashions have shifted over the last twenty years. Digital sustainability is demonstrated as providing an appropriate context for digital preservation because it requires consideration of the overall life cycle and technical, and socio-technical issues associated with the creation and management of digital items. (Bradley, 2007). Digital sustainability is a concept that draws huge attention due to rapid changes in technology and its support to manage sustainability effectively. It has huge potential to leverage the technologies for better collaboration and sharing. (Cybercom Group, 2021).

Digitization contributes a platform for innovations and an area where researchers or users can analyze and visualize complex data. Sustainability measurement requires the processing of massive data to understand the objective and to find the insight of collected data. It helps to understand and adopt new factors to measure progress accurately. According to a study published in Nature, AI could help achieve 79 % of the Sustainable Development Goals (SDGs). As we saw in the video, this technology could become a key tool for facilitating a circular economy and building smart cities that use their resources efficiently.(Vinuesa et al., 2020a).

Digitization sustainability is an approach to transform the potential of digital technologies to tune the sustainability factors that are responsible for positive effects on society and the environment. Digital technology can be helpful to drive positive change for the betterment of society and sustainable outcomes. The integration of sustainability and digital technology would be helpful to address the challenges we have to make it successful. Measurement is essential for the success of digital sustainability because it provides valuable insight into performance and milestones. Measurement also helps to understand whether we are in the right direction and if not then what could be the necessary improvements required. Measurement of digital sustainability helps to define the accountability of actions and their outcomes. As an organization, it helps to understand the strength and weaknesses of each factor of sustainability. Sustainability factors help to decide to prioritize the outcomes that are essential for digital sustainability. Measurement is the backbone and drives continuous improvement to make it better. The milestones are not final but its incremental and continuous optimization.

It may also be seen that the concept of sustainable development gave birth to new terms such as "societal responsibility" and "economic, social and environmental performance"("Our Common Future, Chapter 2: Towards Sustainable Development - A/42/427 Annex, Chapter 2 - UN Documents: Gathering a body of global agreements," n.d.). Social Metrics, Environmental Metrics, and Economic Metrics are three pillars of sustainability. Environmental and economic metrics are quantitative and Social Metrics are qualitative. Many papers discuss each pillar and its factors. But their little research has been done conspiring all the factors and how the measurement of these factors can be optimized with the help of digital technologies. Digital sustainability has one support component which is digital technology. This paper aims to address this gap by exploring the technology factor in Digital Sustainability. The proposed digital sustainability measurement framework will provide a base to measure the success of each metric. The systematic literature review has been conducted and a taxonomy of the key indicators for each metric has been captured for measurement framework. The core Digital Sustainability Metrics are proposed to measure and monitor Sustainable Digital Practices. The paper suggests integrating technology metrics into a comprehensive framework for Digital Sustainability as one of the major factors.

Research Questions:

- What are the most effective digital sustainability metrics to measure its progress?
- A comprehensive framework to cover all the indicators of Social, Environmental, Economic, and Technology metrics to measure digital sustainability progress.
- How the proposed framework can be applied to evaluate digital sustainability.

## LITERATURE REVIEW

The research paper aims to create a comprehensive framework to measure digital sustainability with the help of social, environmental, economic, and technological metrics. The main research questions to be addressed in this study are: What are the key components of digital sustainability metrics? How can these metrics be used to measure sustainable digital practices?

The search for articles will be conducted using keywords related to digital sustainability metrics, sustainable digital practices, business performance, capabilities, and relevant theoretical approaches such as stakeholder theory and transaction cost theory. The search will be primarily based on the ScienceDirect and Google Scholar databases.

The proposed study's contribution to the field lies in developing a comprehensive framework to measure sustainable digital practices, which can be used by businesses to increase their performance and competitiveness in the digital age. The study will also help to fill the gap in the existing literature on digital sustainability metrics and sustainable digital practices.

**Methodology**

The present investigation was conducted following a meticulous and structured methodology, which builds upon earlier research studies. Specifically, we utilized a comprehensive systematic literature review approach to examine the metrics associated with digital sustainability and its underlying factors. This type of approach is highly advantageous when researchers endeavor to establish a clear and replicable process, as it enables us to thoroughly identify, assess, and summarize all pertinent literature on the subject matter at hand. By doing so, we can gain a comprehensive understanding of the topic and produce a more comprehensive analysis.

The first phase is Material Collection where the focus is to collect the relevant study material. The material collection phase includes two sub-phases: selection of database and targeted keyword to fetch the right research papers. The objective is to find the most relevant keywords to identify the research papers based on digital sustainability and components. The combination of keywords and Boolean operators is used to search the database for the right articles.

The next phase is article and material selection. This phase explains the qualification criteria to decide whether the article should be part of this study or not. The criteria make sure that the selected articles are relevant and would be helpful for research objectives.

***The next phase is research results where*** the findings are organized, and the review process started. It involves the selection of a database to search for the right literature. The Scopus database, google Scholar were chosen as it provides material from Science Direct, Emerald Insight, Springer Link, Wiley Online Library, and more. The below strings are used to search for articles.

Table 1 provides detailed information on the search string used and the total number of articles that were found.

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Insert Table 1 about here.
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Table 1: Strings used for the collection of articles

| Strings used for search | Number of Articles |
|---|---|
| Digital Sustainability, sustainability, digital sustainability metrics, social sustainability metrics, economic sustainability metrics, environmental sustainability metrics | 419 |

***Article Selection***

According to Table 1, the query on the above-mentioned database resulted in 378 articles. To ensure that only relevant articles were considered for the investigation, two selection criteria were defined. The first criterion involved screening the title and abstract of each article to check its adherence to the general topic of digital sustainability. For instance, papers that solely focused on digital sustainability metrics, social sustainability metrics, environmental sustainability metrics, and economic sustainability metrics. This screening process yielded a list of 246 articles. The second criterion involved reading the full text of the selected articles, resulting in the exclusion of an additional 42 papers. The results of the material selection phase are presented in Table 2.

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Insert Table 2 Article selection criteria
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Table 2: Article selection criteria

| Strings used for search | Number of Articles |
|---|---|
| Initial Sample | 378 |
| After title and abstract screening (Title and abstract screening is a preliminary step in the material selection phase of a review. It involves reading the title and abstract of each article to evaluate its relevance to the research topic and the inclusion and exclusion criteria. This step is essential in identifying articles that are irrelevant to the topic under investigation and excluding them from further consideration.) | 246 |
| After the full-text screening (It refers to the process of reading the entire text of selected articles during the material selection phase of a review. This step allows for a more thorough evaluation of the relevance of the article to the research topic and the inclusion and exclusion criteria.) | 204 |
| List of articles for final consideration | 204 |

**Digital Sustainability Metric and Its Components**

A metric is a quantitative measurement or indicator used to evaluate the performance, progress, or quality of a particular process, project, or system(“Metric - Wikipedia,” n.d.). Metrics are important because they provide a way to objectively measure and track progress toward specific goals or objectives. Without metrics, it would be difficult to determine whether a particular process or project is successful or whether improvements are needed. In the context of digital sustainability, metrics are crucial for assessing the environmental, social, and economic impact of digital technology usage and operations. These metrics will help organizations to focus and improve for better results to achieve digital sustainability. The metrics are useful for continuous improvement and to understand the difference from the objective. The status for each indicator helps to provide a warning to tune the process to make it effective and efficient. Additionally, the use of metrics facilitates benchmarking against other systems and effectively communicates ideas to stakeholders(Paula Ochôa & Pinto, 2014).

Furthermore, sustainability indicators aid in decision-making processes by providing a framework for formulating strategies and establishing improvement goals. By tracking progress, the metrics enable organizations to continuously improve their sustainability performance(Paula Ochôa & Pinto, 2014) It's worth noting that improvement can be categorized as Strong Sustainability, which refers to a scenario where at least one metric improves without the others declining. Alternatively, Weak Sustainability pertains to achieving an aggregate metric that aligns with targeted values in a process development context.

The adoption of the 2030 Agenda for Sustainable Development by the United Nations General Assembly represents a momentous turning point in the history of global development. This comprehensive strategy, consisting of 17 Sustainable Development Goals (SDGs), is aimed at transforming our world by eradicating poverty, reducing inequality, and combating climate change, among other pressing challenges(Weinberger, Rankine, Amanuma, Surendra, & Victoria Van Hull, 2015) The 2030 Agenda is not merely a lofty aspiration, but a concrete commitment by the global community to pursue sustainable development in a balanced and integrated manner, across all three dimensions: economic, social, and environmental. Achieving sustainable development is no small feat, but the integration of these dimensions is crucial to making progress toward this goal. While each of the SDGs represents a distinct area of focus, they are all interconnected, with progress in one area influencing progress in others. Thus, the pursuit of sustainable development requires a holistic approach that recognizes the complexity and interconnectedness of the challenges we face (Weinberger et al., 2015).

**Environmental Metrics and Its Factors**

The environmental metric is one of the key components of digital sustainability metrics. It asses the environmental effect. It is related to the use of natural resources (Input) and the generation of waste due to waste. The waste may harm the environment if there is no possibility of conversion to its earlier stage or no positive impact on the environment. Some important environmental indicators include water consumption, energy consumption, and e-waste generation. The measurement of energy consumption and tracking may help organizations to identify areas where they can decrease their carbon footprint and reduce energy consumption.

The goal of sustainability is to minimize the environmental impact of using non-renewable resources and generating waste and pollution. However, achieving this goal is often easier said than done, as every technology has its unique environmental costs and limitations(Fedkin, 2016).

That's why it's important to not only measure the actual environmental impact but also to evaluate the rate at which the environment can recover and absorb these impacts. This way, we can better understand the true sustainability of a particular technology or activity and take steps to minimize its negative effects.

Table showing how digital sustainability can help reduce the negative impact of the metrics listed in the previous table:

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Insert Table 3: Environmental Metrics and Its Factors

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Table 3: Environmental Metrics and Its Factors

| Metric | Negative Impact | How Digital Sustainability Can Help | Reference |
|---|---|---|---|
| **Energy Consumption** | Contributes to climate change | Use of renewable energy sources for digital infrastructure; optimization of energy usage through energy- | (Ergasheva, Khomyakov, Kruglov, & Succil, 2020a, 2020b; Faucheux & Nicolaï, 2011; S. Ma, Ding, Liu, Ren, & Yang, 2022; |

| | | | |
|---|---|---|---|
| | | efficient hardware and software | Pihkola, Hongisto, Apilo, & Lasanen, 2018) |
| **Raw Material Usage** | Depletes non-renewable resources | Recycling and reuse of electronics; development of the circular economy for electronics; use of alternative, sustainable materials | (Ekins et al., 2019; Patwa et al., 2021; Seif, Salem, & Allam, 2023; Williams, 2022) |
| **Water Consumption** | Depletes freshwater resources | Implementation of water-efficient practices and technologies; water recycling and reuse; use of non-potable water sources for cooling systems | (Design & Changes, n.d.; X. (Cissy) Ma, Xue, González-Mejía, Garland, & Cashdollar, 2015; Rodriguez et al., 2009; "Water Recycling and Reuse \| Region 9: Water \| US EPA," n.d.) |
| **Emissions of Greenhouse Gases (GHG)** | Contributes to climate change | Use of renewable energy sources; optimization of energy usage; use of carbon capture and storage technologies | (Abdallah & El-Shennawy, 2013a, 2013b; Edenhofer et al., 2011; Kabeyi & Olanrewaju, 2022; Terlouw, Treyer, Bauer, & Mazzotti, 2021) |
| **E-waste Generation** | Generates hazardous waste and pollutants | Designing products for easier repair, reuse, and recycling; promoting extended product lifetimes; developing a circular economy for electronics | (Abalansa, El Mahrad, Icely, & Newton, 2021; Althaf, Babbitt, & Chen, 2019; Turaga et al., 2019; Vishwakarma et al., 2022) |
| **Land Usage** | This can lead to habitat loss and fragmentation | Development of more compact and efficient digital infrastructure; use of brownfield sites and existing buildings for data centers | (Du et al., 2015; EEA, 2015; Huggins, 2018; "Planning and Resource Management Reference Materials," n.d.; "Reaping the Rewards of Sustainable Land Use," n.d.; "Towards Sustainable Land Use," 2020) |
| **Toxicity Potential** | Can harm human health and the environment | Use of safer materials and production processes; proper management of hazardous waste and pollutants; promoting transparency in supply chains | (Bandarra, Silva, Pereira, Martins, & Quina, 2022; "How Hazardous Waste Disposal Affects the Environment," n.d.; Metals et al., n.d.; Watts & Teel, 2003) |
| **Digital Inclusion** | Can exacerbate social and economic inequalities | Ensuring equitable access to digital products and services; promoting digital literacy and skills development; addressing the digital divide | ("How digital inclusion can improve people's lives and promote sustainable development \| ITCILO," n.d.; "This is how to finance digital inclusion \| World Economic Forum," n.d.; Nguyen, 2020a; O'Sullivan, Clark, Marshall, & MacLachlan, 2021) |

**Social Metrics and Its Factors**

Social metrics are concerned with the social impact of digital technology, including fair labor practices and ethical use of technology. According to the Western Australia Council of Social Services (WACOSS): "Social sustainability occurs when the formal and informal processes; systems; structures; and relationships actively support the capacity of current and future generations to create healthy and liveable communities. Socially sustainable communities are equitable, diverse, connected, and democratic and provide a good quality of life"(WACOSS, 2002).

According to Social Life, a UK-based social enterprise specializing in place-based innovation, Social sustainability is a process for creating sustainable successful places that promote wellbeing, by understanding what people need from the places they live and work. Social sustainability combines the design of the physical realm with the design of the social world – infrastructure to support social and cultural life, social amenities, systems for citizen engagement, and space for people and places to evolve(Woodcraft, Bacon, And, & Hackett, 2012).

As the world becomes increasingly digital, the concept of sustainability has evolved to include not just environmental and economic factors, but also social dimensions. Social sustainability refers to the ability of societies to maintain healthy and liveable communities that are equitable, diverse, connected, and democratic. However, measuring social sustainability can be a challenge, as the metrics are often qualitative and hard to quantify. In this context, the use of digital technologies can play a crucial role in improving social sustainability, by facilitating the measurement and monitoring of social metrics.

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Insert Table 4: Social Metrics and Its Factors

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Table 4: Social Metrics and Its Factors

| Metric | Negative Impact | How Digital Sustainability Can Help | Reference |
|---|---|---|---|
| **Quality of life** | Basic needs not being met; low quality of life for some groups | Monitoring and measurement of social indicators; targeted interventions | (Barykin et al., 2023; Comitee, 2011; FY2010, 2010; Grum & Kobal Grum, 2020; Mondejar et al., 2021a; Musarat, Sadiq, Alaloul, & Abdul Wahab, 2023) |
| **Equity** | Unequal opportunities and outcomes for different groups | Promoting inclusivity and diversity; targeted interventions | (Brenner & Hartl, 2021a, 2021b; Cooper, 2021; “Pursuing Sustainability with Social Equity Goals \| icma.org,” n.d.; WACOSS, 2002) |
| **Diversity** | Lack of understanding and acceptance of diverse groups | Promoting cross-cultural communication and awareness | (Jankelová, Joniaková, Procházková, & Blštáková, 2020; Segerstedt & Abrahamsson, 2019; “Social Challenge 8 – Diversity & Inclusion Why it matters \| Maximizing well-being for all \| Sustainability \| NTT,” n.d.; “Why is Diversity and Inclusion Important for Sustainability?,” n.d.; Syed, 2014; WACOSS, 2002) |

| | | | |
|---|---|---|---|
| **Democracy and governance** | Lack of transparency and accountability in decision-making processes | Promoting open and participatory governance through digital tools | ("Part I : Background of the Development of HSM ---for the first reader of HSM theory, this part is prepared," n.d.; Tulchin, Varat, Ruble, & Woodrow Wilson International Center for Scholars. Comparative Urban Studies Project., 2002; WACOSS, 2002; Westall, 2023; Wydra & Pülzl, 2013, 2015) |
| **Maturity** | Lack of personal growth and development | Providing access to education and learning resources through digital tools | (authorPerson:McKeown, 2002; CooperGibson Research, 2022; Daniela, Visvizi, Gutiérrez-Braojos, & Lytras, 2018; Napal, Mendióroz-Lacambra, & Peñalva, 2020; WACOSS, 2002) |

Note: The above table is a summary of the social metrics and their dimensions discussed in the text. The negative impacts and ways in which digital sustainability can help address them are based on the analysis presented in the paper.

**Economic Metrics and Its Factors**

Economic metrics are concerned with the economic impact of digital technology usage and operations. These metrics evaluate the economic benefits or costs of digital technology usage and operations. For example, an organization might measure the cost savings associated with the adoption of digital technology. Other important economic metrics include the economic impact of digital technology on local communities, the cost of transitioning to a sustainable digital economy, and the potential economic benefits of digital sustainability.

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Insert Table 5: Economic Metrics and Its Factors

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Table 5: Economic Metrics and Its Factors

| **Metric** | **Negative Impact** | **How Digital Sustainability Can Help** | **Reference** |
|---|---|---|---|
| Competitiveness | Inability to keep up with competitors | Digital sustainability can help companies innovate and streamline their processes to stay ahead of competitors | (Delgosha, Saheb, & Hajiheydari, 2021; Kisel'áková, Šofranková, Gombár, Cabinová, & Onuferová, 2019; Kukushkina, Mursaliev, Krupnov, & Alekseev, 2022; Möbius & Althammer, 2020; Popescu, Sima, Nica, & Gheorghe, 2017) |
| Customization | Wasted materials and resources in producing | Digital sustainability can enable more efficient and targeted production of | (Chen, Despeisse, & Johansson, 2020a, 2020b; Cricelli & Strazzullo, 2021a; Han et al., 2023a) |

| | | | |
|---|---|---|---|
| | customized products | customized products, reducing waste and saving resources | |
| Economic development | Harmful environmental impacts from economic growth | Digital sustainability can promote sustainable economic growth through reduced resource consumption and increased efficiency | (Cricelli & Strazzullo, 2021b; International Labour Organisation (ILO), 2020; Kunkel & Tyfield, 2021; Mondejar et al., 2021b; Y. Q. Zhang, Li, Sadiq, & Chien, 2023; Zhong et al., 2022) |
| Efficiency | Inefficient processes lead to wasted resources and increased emissions | Digital sustainability can optimize processes to increase efficiency and reduce resource consumption and emissions | (Beier, Kiefer, & Knopf, 2022; Bibri, 2009; "Digital Sustainability (2023): Importance & Top 5 Digital Solutions," n.d.; "Digitalization and Energy – Analysis - IEA," n.d.; "Energy and Climate Protection - BASF Report 2021," n.d.; Gupta Kirti & Effraimidis Georgios, 2021) |
| Extension of product/equipment life cycle | Discarded products/equipment leading to waste and pollution | Digital sustainability can facilitate the repair, repurposing, and recycling of products/equipment to extend their life cycle and reduce waste | (Berg et al., 2020; Chauhan, Parida, & Dhir, 2022; Dassault Systemes, 2021; *Environment at a Glance Indicators*, 2023; Han et al., 2023b; Šipka, 2021) |
| Fostering innovation and entrepreneurship | Limited resources and opportunities for innovation and entrepreneurship | Digital sustainability can open up new opportunities for innovation and entrepreneurship by promoting sustainable practices and creating new markets | (Van den Breul et al., 2018; Cricelli & Strazzullo, 2021c; Ely, Fressoli, & Van Zwanenberg, 2017; Filser, Kraus, Roig-Tierno, Kailer, & Fischer, 2019; Nations, 2022; Veleva, 2021; Yan, Gu, Liang, Zhao, & Lu, 2018) |
| Reduction of material consumption | Excessive use of materials leads to waste and depletion of resources | Digital sustainability can reduce material consumption through optimized production processes, waste reduction, and the use of sustainable materials | (Cricelli & Strazzullo, 2021c; Fredrick Royan, 2021; Mont, Lehner, & Dalhammar, 2022; Piscicelli, 2023a; Turan et al., 2022) |
| Production costs reduction | High production costs due to inefficient processes and wasted resources | Digital sustainability can reduce production costs through increased efficiency, waste reduction, and the use of sustainable materials | (Bai, Quayson, & Sarkis, 2021; Cricelli & Strazzullo, 2021c; Eyman, 2021; "Innovation needs in the Sustainable Development Scenario – Clean Energy Innovation – Analysis - IEA," n.d.; Nakicenovic et al., 2019; Palacká, Krechovská, & Číž, 2021; Ri & Automation, n.d.) |
| Productivity | Low productivity | Digital sustainability can increase | (American & Outlook, 2020; Cricelli & Strazzullo, 2021c; Field, Management, Services, & Performance, n.d.; |

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|---|---|---|---|
| | due to inefficient processes | productivity through optimized processes, automation, and the use of digital tools | Moghrabi, Bhat, Szczuko, AlKhaled, & Dar, 2023; OECD, 2019a; I. Paper, 2019; Samadhiya et al., 2022; Santiago, 2021; United Nations, 2023) |
| **Profitability of investments** | Unsustainable investments lead to financial losses | Digital sustainability can improve the profitability of investments by promoting sustainable practices and reducing environmental risks | ("2022 sustainability consumer research: Sustainability and profitability \| IBM," n.d.; Cricelli & Strazzullo, 2021c; Merrill, Schillebeeckx, & Blakstad, 2019; United Nation Environment Programme, 2022; World Economic Forum, 2021a) |
| **Reduction of delivery times** | Slow or inefficient delivery processes | Digital sustainability can improve delivery times through the optimization and automation of delivery processes | (Cricelli & Strazzullo, 2021c; Klein & Popp, 2022; World Economic Forum, 2021b) |
| **Reduction of energy consumption** | Excessive energy consumption leads to environmental harm and high costs | Digital sustainability can reduce energy consumption through increased efficiency, the use of renewable energy sources, and the optimization of energy systems | (Cricelli & Strazzullo, 2021c; Haiwei & Wang, 2009; Lange, Pohl, & Santarius, 2020; Strielkowski, Kovaleva, & Efimtseva, 2022; The Shift Project, 2020; Verma et al., 2020) |
| **Reduction of transportation costs** | High transportation costs due to inefficient transportation processes | Digital sustainability can reduce transportation costs through the optimization of transportation routes and modes, and the use of digital tools | (Akbari & Hopkins, 2022; Kayikci, 2018; Palkina, 2021; UNCTAD, 2018; UNECE, 2011; *UNECE Nexus: Sustainable Mobility and Smart Connectivity*, 2021; U.S. Department of Energy, U.S. Department of Transportation, U.S. Environmental Protection Agency, & U.S. Department of Housing and Urban Development, 2050) |
| **Reduction of waste costs** | High waste disposal costs due to excessive waste production | Digital sustainability can reduce waste costs through waste reduction, reuse, and recycling | (Bendix, Le, Vito, & Vrancken, 2019; C40 Cities Climate Leadership Group, 2015; Maciej Serda et al., 2021; Mattila, Mesiranta, & Heikkinen, 2020; Truong, 2022) |
| **Reduction of water consumption** | Excessive water consumption leads to environmental harm and high costs | Digital sustainability can reduce water consumption through increased efficiency, water recycling, and the use of alternative water sources | (Andrić, Vrsalović, Perković, Aglić Čuvić, & Šolić, 2022; Banerjee, Bhaduri, & Saraswat, 2022; Batista, Franco, Fakury, Porto, & Braga, 2022; Hubert, Wang, Alonso, & Minguez, 2020; Liu, Yang, & Yang, 2021; Maestu, 2015; Sachidananda et al., 2016) |

**Digital Technology Metrics and Its Factors**

The world we live in is becoming increasingly digital, and with that comes a wealth of opportunities to address some of the most pressing societal and environmental issues. Digital technologies provide access to vast amounts of data that can be used to solve problems and create a more sustainable future. However, to make the most of these opportunities, we need to consider several key factors.

Sustainable development goals must be at the forefront of our thinking. By using digital technologies to promote sustainability, we can create a more equitable, ecologically sustainable, and healthy society. We also need to focus on digital technologies for socioeconomic development, equitable growth, and sustainable process for a better society. Digital technologies are essential components in the value chain to integrate common sustainability metrics and gauge efficiency.

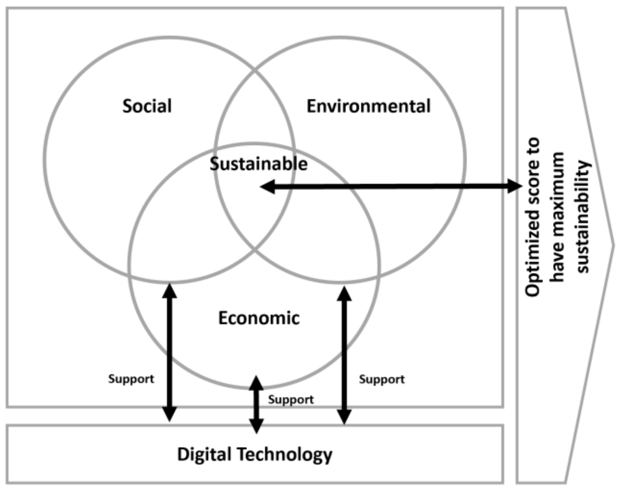


Figure 1. Adopted from sustainable development(see Brundtland Report 1987)

Table showing the list of digital technology factors that can support digital sustainability across the social, economic, and environmental dimensions, along with their uses:

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Insert Table 6: Digital Technology Metrics and Its Factors

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Table 6: Digital Technology Metrics and Its Factors

| **Technology Factor** | **Tools or Digital Technology** | **How it supports Environmental Metric** | **How it supports Social Metric** | **How it supports Economic Metric** | **Reference** |
|---|---|---|---|---|---|
| Internet of Things (IoT) | Environmental Sensors | Real-time monitoring of resource usage, emissions, and waste | Improves health and safety, and promotes sustainable consumption | Reduces costs and promotes sustainable business practices | (Era & Era, 2021; Ibrahim, 2022; Rosca, Nicolae, Sanda, & Madan, 2021; World Economic Forum, 2018) |

| | | | | | |
|---|---|---|---|---|---|
| | | | and production | | |
| Artificial Intelligence (AI) | Machine Learning Algorithms | Optimizes resource usage and reduces waste, and predicts environmental impact | Improves public services and enhances decision-making for social development | Increases efficiency and productivity, and enables innovation | (Galaz et al., 2021; Thamik & Wu, 2022; Vincent Pedemonte, 2020; Vinuesa et al., 2020b) |
| Blockchain | Distributed Ledger Technology | Provides transparency and traceability for supply chain management, and reduces fraud and corruption | Promotes fair trade and social responsibility, and ensures ethical business practices | Reduces transaction costs and enables secure and efficient financial transactions | (*Harnessing blockchain for sustainable development*, 2021; Joshi, Tewari, Kumar, & Singh, 2023; Khanfar, Iranmanesh, Ghobakhloo, Senali, & Fathi, 2021; Mhlanga, 2023; OECD, 2019b) |
| Renewable Energy | Solar, Wind, and Hydro Power | Reduces greenhouse gas emissions and dependence on fossil fuels | Provides access to clean energy and promotes energy security, especially in rural areas | Creates jobs and generates economic growth in the renewable energy sector | (Dekeyrel & Fessler, 2023; El, Abdelli, & Shahbaz, 2023; Mihai, Aleca, Stanciu, Gheorghe, & Stan, 2022; Wei, Li, Löschel, Managi, & Lundgren, 2021) |
| Big Data Analytics | Data Processing and Visualization Tools | Identifies patterns and insights for optimizing resource usage and reducing waste | Enhances public services and promotes evidence-based decision-making for social development | Enables market insights and enhances business competitive ness | (Raut et al., 2019; Şerban, 2017; D. Zhang, Pee, Pan, & Cui, 2022) |
| Digital Platforms | Collaborative Platforms and Apps | Facilitates collaboration across the value chain for sustainability and aligns on | Promotes social participation and engagement, and enhances access to | Enables new business models and creates new markets for sustainable | (Calabrese, Sala, Fuller, & Laudando, 2021; Caughie, 2013; Łobejko & Bartczak, 2021; Stepanova, Vorotnikov, |

| | | | | | |
|---|---|---|---|---|---|
| | | common metrics and goals | public services | products and services | Doronin, & Vorotnikov, 2020) |
| Renewable Energy | Solar Panels, Wind Turbines | Reduces greenhouse gas emissions and dependence on fossil fuels | Increases energy access and affordability for underserved communities | Creates jobs in the renewable energy industry | (Keim, 2017; Latifah, 2020; UNCTAD, 2019; Yu, Tsai, Jin, & Zhang, 2022) |
| Sustainable Agriculture | Precision Farming Technologies, Drones | Reduces water and fertilizer usage, minimizes soil erosion, and preserves biodiversity | Improves food security and access to nutritious food, promotes rural development | Increases productivity and profitability for farmers | (Basso & Antle, 2020; Hrustek, 2020a, 2020b; Lajoie-O'Malley, Bronson, van der Burg, & Klerkx, 2020; Satpathy, 2022) |
| Smart Buildings | IoT sensors, Building Automation Systems | Reduces energy consumption and carbon footprint through optimized heating, cooling, and lighting | Enhances indoor air quality and comfort, promotes health and wellbeing | Lowers operational costs and increases asset value | (Froufe et al., 2020; Yang, Lv, & Wang, 2022) |
| Circular Economy | Blockchain, IoT, Digital Twins | Promotes reuse and recycling of materials, reduces waste and pollution | Facilitates transparency and traceability in supply chains, fosters collaboration and innovation | Generates economic value from waste and unused resources | (Bressanelli, Adrodegari, Pigosso, & Parida, 2022; Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Piscicelli, 2023b; Wirtz, 2022) |
| Digital Inclusion | Digital Literacy Programs, Community Networks | Improves digital access and skills for marginalized communities, promotes social equity and inclusion | Enables participation in the digital economy and civic engagement, enhances the quality of life | Boosts economic productivity and innovation through a diverse and skilled workforce | (Erturk & Purdon, 2022; KIDD & LEE, 2018; Madon, Reinhard, Roode, & Walsham, 2006; Nguyen, 2020b; Nosratabadi & Atobishi, 2023) |
| Green Transportation | Electric Vehicles, Autonomous Vehicles | Reduces greenhouse gas emissions and air pollution, promotes sustainable mobility | Enhances safety and accessibility for all users, reduces traffic congestion and travel time | Stimulates innovation and investment in the transportation industry | (Li, Yang, Gao, & Han, 2022; P. Paper, 2022; "Sustainable Transport, Sustainable |

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|---|---|---|---|---|---|
| | | | | | Development," 2021) |
| Sustainable Packaging | Biodegradable Materials, Smart Labels | Reduces waste and pollution, enhance product safety and quality | Promotes consumer awareness and responsible consumption, fosters brand loyalty and trust | Improves supply chain efficiency and reduces costs | (Frank, 2022; Santi, Garrone, Iannantuoni, & Del Curto, 2022; Versino et al., 2023; Wandosell, Parra-Meroño, Alcayde, & Baños, 2021) |
| Water Management | IoT sensors, Water Treatment Technologies | Reduces water consumption and pollution, promote efficient water use and conservation | Improves access to safe and clean water, mitigates water-related risks and conflicts | Increases productivity and competitiveness in water-intensive industries | (Helena M. Ramos & Pérez-Sánchez, 2019; International Water Management Institute, 2019) |

## PROPOSED FRAMEWORK

The four components of environmental sustainability, economic sustainability, social sustainability, and technological sustainability are considered for the proposed framework to measure digital sustainability. Each component has multiple factors or indicators which will be considered based on the literature review. This framework is generic but based on the weightage of factors, the result can be tuned based on industry usage.

The environmental sustainability component and its factors are focused on the reduction of the impact on environmental aspects like energy consumption, carbon footprint, and waste generation. The economic sustainability component focuses on the financial performance of the organization like cost savings, revenue growth, and profitability. The social sustainability component focuses on the impact on society like the well-being of employees, customers, and communities. The weightage can be modified according to the priority of the organization and industry.

The technology component focuses on emerging technologies like artificial intelligence, blockchain, and the Internet of Things which supports the above components. Overall, the proposed framework provides a comprehensive and holistic approach to measuring the factors that can be used by organizations and policymakers to evaluate and improve their digital sustainability performance.

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Insert Table 7: Four Components of Digital Sustainability

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Table 7: Four Components of Digital Sustainability

| Components | Description |
|---|---|
| **Environmental** | Focuses on minimizing the negative impact on the environment through measures. |
| **Economic** | Focuses on economic viability and sustainability. |
| **Social** | Focuses on social and ethical implications. |

| | |
|---|---|
| **Technological** | Focuses on emerging technologies to support Social, environmental, and economic components to increase performance. |

The four components are interconnected and interdependent. It provides more accurate results when we consider together for digital sustainability.

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Insert Table 8: Weighted variables for four components of Digital Sustainability

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Table 8: Weighted variables for four components of Digital Sustainability

| Factor | Variable | Variable Name | Weighted Variable |
|---|---|---|---|
| **Social** | Quality of life | QOL | w1 * QOL |
| | Equity | EQ | w2 * EQ |
| | Diversity | DIV | w3 * DIV |
| | Democracy and governance | DEM | w4 * DEM |
| | Maturity | MAT | w5 * MAT |
| **Environmental** | Energy Consumption | EN | w1 * EN |
| | Raw Material Usage | RMU | w2 * RMU |
| | Water Consumption | WC | w3 * WC |
| | Emissions of Greenhouse Gases (GHG) | GHG | w4 * GHG |
| | E-waste Generation | EWG | w5 * EWG |
| | Land Usage | LU | w6 * LU |
| | Toxicity Potential | TP | w7 * TP |
| **Digital Technology** | Internet of Things (IoT) | IoT | w1 * IoT |
| | Artificial Intelligence (AI) | AI | w2 * AI |
| | Blockchain | BC | w3 * BC |
| | Renewable Energy | RE | w4 * RE |
| | Big Data Analytics | BDA | w5 * BDA |
| | Digital Platforms | DP | w6 * DP |
| | Sustainable Agriculture | SAG | w7 * SAG |
| | Smart Buildings | SBLD | w8 * SBLD |
| | Circular Economy | CEC | w9 * CEC |
| | Digital Inclusion | DI | w10 * DI |
| | Green Transportation | GT | W11*GT |
| | Sustainable Packaging | SP | W12*SP |
| | Water Management | WM | W13*WM |
| **Economic** | Competitiveness | COMP | w1 * COMP |
| | Customization | CUST | w2 * CUST |
| | Economic development | ED | w3 * ED |
| | Efficiency | EFF | w4 * EFF |
| | Extension of product/equipment life cycle | EXL | w5 * EXL |
| | Fostering innovation and entrepreneurship | INN | w6 * INN |
| | Reduction of material consumption | RMC | w7 * RMC |
| | Production costs reduction | PCR | w8 * PCR |

| | | | |
|---|---|---|---|
| | Productivity | PROD | w9 * PROD |
| | Profitability of investments | PROF | w10 * PROF |
| | Reduction of delivery times | DTIME | w11 * DTIME |
| | Reduction of energy consumption | ECON | w12 * ECON |
| | Reduction of transportation costs | TNC | w13 * TNC |
| | Reduction of waste costs | WAC | w14 * WAC |
| | Reduction of water consumption | WASC | w15 * WASC |

To calculate the score for each factor, we need to sum up the weighted variables for each factor.

Here are the calculated scores for each factor:

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Insert Table 9: Overall Digital Sustainability score

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Table 9: Overall Digital Sustainability score

| Metric | Score calculation |
|---|---|
| **Social Score (SS)** | (w1 * QOL) + (w2 * EQ) + (w3 * DIV) + (w4 * DEM) + (w5 * MAT) |
| **Environmental Score (ENS)** | (w1 * EN) + (w2 * RMU) + (w3 * WC) + (w4 * GHG) + (w5 * EWG) + (w6 * LU) + (w7 * TP) + (w11GT)+(W12SP)+(W13*WM) |
| **Digital Technology Score (DTS)** | (w1 * IoT) + (w2 * AI) + (w3 * BC) + (w4 * RE) + (w5 * BDA) + (w6 * DP) + (w7 * SAG) + (w8 * SBLD) + (w9 * CEC) + (w10 * DI) |
| **Economic Score (ECS)** | (w1 * COMP) + (w2 * CUST) + (w3 * ED) + (w4 * EFF) + (w5 * EXL) + (w6 * INN) + (w7 * RMC) + (w8 * PCR) + (w9 * PROD) + (w10 * PROF) + (w11 * DTIME) + (w12 * ECON) + (w13 * TNC) + (w14 * WAC) + (w15 * WASC) |

Note that the weights (w1, w2, etc.) represent the importance of each variable within its respective factor. Organizational priority and objective influence the value of wights. More priority will take more percentage of weight. Weights are tuned based on relative importance with other factors.

**Digital Sustainability Score** = (w1 * SS) + (w2 * ENS) + (w3 * ECS) + (w4 * DTS)

where w1, w2, w3, and w4 are the weights assigned to each of the four scores.

The weights will depend on the organizational context and priorities to measure digital sustainability. For example, if an organization has priority on social equity, then the social core will have a higher weight. Whereas, if an organization is focused on reducing environmental impact, then Environmental Score will have a higher weight. Digital Sustainability Score will help the organization to have insight into the areas where it is doing well and areas that need to improve. This insight can be used as feedback to tune the weights and digital sustainability strategy. The score can be standardized as a benchmark for peers and other organizations operating in the same segment.

## LIMITATIONS

Several limitations make this framework challenging because of the evolution of new factors and technologies. One component may have a direct or indirect effect on other components. The success of one factor may decrease the success rate of another factor. Fee factors can be measured in both quantitative and qualitative ways. Few are only through qualitative measurement. The final score is a mix of qualitative and quantitative measurements.  This framework may not contain all the necessary factors and the addition of more indicators will provide more robust results. Standardization measurement scales are not done, and this may be necessary if the scales are different for environmental factors for any organization. The lack of a standardized set of components and metrics for measuring digital sustainability makes it difficult to compare performance across industries, or regions. This is because technology and areas are constantly evolving, and few factors may not be significant over the period. The unavailability of data is another limitation as organizations may not have the latest technology or process to capture the measurement for all factors. The development of a comprehensive framework requires significant effort, expertise, time, and budget. This may not be possible for smaller organizations.

## CONCLUSION

This research is based on systematic literature search to create a conceptual framework with the most critical indicators. The digital technology and new factors that impact the society and environment are constantly changing. The landscape also changing, and components are breaking into new subcomponents. The framework needs to be updated with the pace of technology and inclusion of new metrics. The primary objective of organisation is making profit but keeping these indicators in mind will make the process optimised for society and environment. These metrics can be used by organizations or industries to assess their digital sustainability performance and recognize areas for enhancement. Measurement leads to an understanding of the gap from the goal, and it will help to promote the best practices to reduce negative impact and will enhance sustainability.

This can be possible with collaboration and effort from all stakeholders across the industry and organization. This framework is a skeleton and provides a base for organizations but there is a need for further research to refine and expand. Digital technologies can have a significant impact on all the sustainability components in both positive and negative directions. Technology may create more waste and at the same time, it can be used as a tool to mitigate any negative impacts.  Technology can only provide the platform to gain insight, but it is up to us to act and prioritize the metrics to optimize digital sustainability performance.

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