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ORIGINAL PAPER

Bridging the Divide: Assessing Digital Infrastructure for Higher Education Online Learning

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Abstract
Modern life and society are heavily reliant on technology. Technology has the potential to revolutionize educational access by transcending geographical barriers and catering to diverse learning needs, paving the way for equitable and inclusive education for all. Various studies have confirmed that use of technology tools in education would democratize access, personalize learning experiences, enhance engagement and promote learning opportunities. Background digital infrastructure is a critical enabler of educational technology tools. This study is such an attempt. It tries to systematically evaluate the digital infrastructure ecosystem, needed to advance technology in education. Specifically, the study tries to assess the status of digital infrastructure for online learning in higher education. We focused this study on India, which has the third largest higher education system in the world. A composite index was developed with the use of Principal Component Analysis (PCA) to evaluate the IT infrastructure by relying on relevant secondary data. Based on this index score, digital infrastructure status of various States of the country was determined. Results suggested regional disparities in digital infrastructure and areas to focus to strengthen digitally enabled higher education. The study's findings have implications for reducing the digital divide by improving digital infrastructure and designing policy interventions, particularly in developing countries.

Keywords Digitalization · IT Infrastructure · Digital gap · Digital Divide · Higher Education · Developing Country

1. Introduction

The higher education sector is witnessing a complex tapestry of social and structural changes, from diverse student demographics to evolving technological advances. Global access to information was made possible by the digital revolution, and education is moving towards new frontiers due to the increased use of digitalization (Greenhow et al., 2022). It is argued that, to pick up with the digital transformation and disruptive technological advancements, the higher education system needs to make use of digital tools to stay competitive and offer quality instruction (Alenezi et al., 2023). Besides, the demands of rising student enrolment may be met by implementing digital technologies in teaching and learning (Tulinayo et al., 2018). Digital technologies encompass various tools, services, applications, and hardware/software combinations (Rice, 2003). Learning Management Systems (LMSs), Massive Open Online Courses (MOOCs), synchronous and asynchronous online learning and learning dashboards are some of the commonly used technology applications in education (Bordoloi et al., 2020; Chaw & Tang, 2018; Farahmand et al., 2020; Mishra et al., 2020). Digital technology offers opportunities that speed up online, blended, and e-learning in higher education (Rahman, 2021). Notably, online learning emerged as a

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prominent and acceptable approach, characterising the sector's digital transformation in higher education (Bao, 2020; Mishra et al., 2020; Sarkar et al., 2021). It allows for individualized learning paths that cater to individual learning styles, paces and needs (Dziuban et al., 2018). A study by the Organization for Economic Cooperation and Development [OECD] (2016) demonstrates significant growth in online learning enrolment worldwide, indicating increased access for students with diverse backgrounds and schedules. However, the use and implementation of online learning are not devoid of challenges (Haleem et al., 2022). Online learning is dependent on the accessibility and affordability of technological devices and the Internet (Pokhrel & Chhetri, 2021). The other considerations include the quality of the content, technological infrastructure and pedagogical concerns (Tømte et al., 2019). These issues are especially pertinent for students from low-income families or those who attend school in rural areas (Coman et al., 2020). This became more apparent during the recent COVID-19-led disruptions in the higher educational sector (Selvaraj et al., 2021).

This study attempted to understand the digital infrastructure ecosystem of a developing country, India, for online learning. With 1040 universities and 39,800 colleges, India boasts one of the largest higher education systems in the world, with over 38.5 million students enrolled (Shamika & Gupta, 2019; Mittal & Pani, 2020). Graduate-level learners constitute the highest share (79.53%) of total enrolment in the higher education sector, followed by post-graduate learners (11.2%) in the country with a Gross Enrolment Ratio (GER) of 27.1(Department of Higher Education, 2020). To meet the educational demands of the second-largest population in the world, a robust higher education system is paramount (Singh & Kumar, 2020). In response to this demand, capacity is growing steadily to serve the burgeoning student population in the country (Tobenkin, 2022). However, the higher education sector is fraught with a multitude of challenges. Quality, equity and access to higher education are essential concerns (Verma et al., 2024). In addition, the country's educational infrastructure needs to be improved to cater to the needs of the vast majority of its learners (Sheikh, 2017). Further, 40 per cent of universities and 61 per cent of higher education institutions are located in rural areas (Roy & Brown, 2022). In such a context, academic institutions quickly realised that digital transformation is a viable long-term growth strategy to ensure inclusiveness and equitable access to learning. The National Education Policy (2020) acknowledges that technology can play a transformative role in improving access to quality education, enhancing teaching and learning processes, and bridging the digital divide. The recent outbreak of the COVID-19 pandemic necessitated a sudden shift to digitalized educational approaches in the country (Vishnu et al., 2022). This unanticipated occurrence further pushed for efforts to digitalize higher education more quickly. Nevertheless, the country's Information Technology (IT) infrastructure preparedness for such a transition was poorly understood. Besides, there is little evidence of the regional disparities in switching to online learning approaches.

Recently, there has been a proliferation in the number of studies which investigate the growing use of technology in higher education (Chugh et al., 2023; Cabaleiro-Cerviño & Vera, 2020; Ignatyeva, 2015). Few studies focused on selected aspects of the digital infrastructure, neglecting a holistic perspective and thus overlooking crucial interdependencies. For example, a recent survey by QS IGUAGE (2020) raised concerns about the internet infrastructure and power supply, which are essential for online learning. Similarly, a recent study by the Internet and Mobile Association of India [IAMAI], (2022) found that only 37 per cent of Indians have access to the Internet and a significant portion of those with access face connectivity issues and slow speeds. The success of online learning largely hinges on steady access to digital technologies and supporting infrastructure (Chakraborty et al., 2020), and critical gaps in this regard minimise the active learning participation of learners (Maity et al., 2020). Inadequate digital infrastructure is exacerbating the country's digital divide, affecting learners from rural areas disproportionately (Naik et al., 2021; Telecom Regulatory Authority of India [TRAI], 2020). From this discourse, it is clear that insufficient digital infrastructure is one of the critical challenges associated with the transition to online learning (Rahman, 2021). In addition to that, concerns about the digital divide and inequitable access shaped by socio-economic imbalances cannot be overlooked. According to IAMAI (2019), there are variations in socioeconomic class and gender when accessing the Internet. For instance, while 67 per cent of men in India have access to the Internet, this is only 33 per cent of women, signalling the gender dimension of the digital divide (IAMAI, 2019).

Conversely, few other studies argue that digital infrastructural gaps accentuate the rural-urban divide and social inequalities in the effort to transform the educational sector (Kumar Jha & Singh, 2020; Oxford University Press, 2021). Hence, it becomes pertinent to understand the status of digital infrastructure for enabling online learning by higher education learners. In addition, higher education institutions in the country are increasingly moving towards blended learning approaches by suitably integrating virtual learning methods in traditional physical classrooms (University Grants Commission, 2020). There are several studies on the effectiveness of online learning from developed countries, while there is a severe shortage of similar comparative studies in developing countries. Weak infrastructure, lack of financial resources and technical support, as well as modest IT skills for instructors and students, are the main challenges to online learning adoption (Bozkurt et al., 2020; Rashid

& Yadav, 2020; Sintema, 2020; Tembo & Mwale, 2019) in the developing world. Despite the significance of all these challenges, addressing the foundational element – digital infrastructure – remains paramount. This is because disparities in infrastructure can significantly exacerbate the existing digital divide (Kloza, 2023). Hence, this paper is built on the critical argument that digital infrastructure is the fundamental prerequisite for inclusive digital education. Though this argument is suitable for all levels of learners, we were specifically interested in the case of higher education scholars. Hence, this study aims to understand India's level of preparedness regarding her digital infrastructure for online learning for higher education learners. With this background, the study concentrates on the following objectives.

1. To develop a Digital Infrastructure Index (DII) to assess the digital infrastructure status of Indian States.
2. To compare and analyze the various dimensions contributing to DII.

2. Methodology

The study was based on secondary data sources published in the last five years by government departments and private firms. Of the twenty eight states in India, twenty one states were considered for this study, as the relevant data were available only for these states. However, the analysis would likely reflect the country's scenario of the digital infrastructure ecosystem since most states were included, ensuring adequate regional representation. This study developed a new composite index, the DII, by conducting a rigorous literature review and consultation with subject matter specialists. The DII has three overarching dimensions: Digital Asset Possession, Network Access and Electricity Supply. These dimensions were represented by relevant indicators and were computed separately (Table 1).

2.1 Composite Index Construction

The composite index helps measure multidimensional concepts that cannot be captured by a single indicator (OECD, 2008; Saisana & Tarantola, 2002). The composite index construction includes inductive, deductive, index or fuzzy normalization approaches (Reckien, 2018). This study followed an inductive approach, which involves identifying various indicators contributing to making a sub-index and adding them up to get the variable of interest. Under this approach, multiple steps for index construction include indicator selection, transformation, scaling, weighting, and aggregation (Tate, 2012). The three dimensions of the composite index and indicators under each of these dimensions are given below (Table 2).

Several factors, such as the unavailability of recent data, lack of state-level data, and pay wall restrictions, delimited adding more valuable indicators under various dimensions. However, every effort has been made to collate and integrate the latest data sources to get realistic information about the status of Indian states in terms of digital infrastructure. Most of these indicators were obtained from official data sources from the Government of India (GoI) or published reports of relevant private sector firms. The state-level data was represented either as percentage values or in absolute numbers. Since various indicators were measured on different levels, normalization was performed to make the data comparable across the indicators, following Weziak-Bialowolska (2014). This rescaling transformed the entire range of values between 0 and 1.

$$y_{in} = x_{in} - min(x_{in})/max(x_{in}) - min(x_{in}) \quad (1)$$

Subsequently, these normalized values were input for running Principal Component Analysis (PCA). This step was performed to derive weights for each indicator.

$$I = \frac{\sum_{i=1} XiWi}{\sum_{i=1} Wi} \quad (2)$$

where, I, index for each state; Xi, normalized value of i^{th} indicator;

Wi, weight of the i^{th} Indicator $=\sum|L_{ij}|E_j$; $L_{ij,}$ factor loading value of the i^{th} state on the j^{th} factor;
Ej, Eigen value of the j^{th} factor; i, 1, 2, 3,…0.20 indicators; j, 1,2,3 …factors

After assigning the weights, the aggregate value across each dimension was computed using mean values. Finally,

Table 1 Dimensions of Digital Infrastructure Index (DII)

Digital Asset Possession Sub index (DAPSi)	Network Access Sub index (NASi)	Electricity Supply Sub index (ESSi)
• % of households with access to computer • Smartphone penetration (%) • % of households with access to Television	• % of households with access to internet • % of households with 4G availability • Internet penetration (%) • Wireless subscription base (in million)	• % of households connected to Grid electricity • Average daily electricity supply (in hours) • Share of households dissatisfied with grid electricity

Table 2 Dimensions and indicators of the DII

Dimension	Indicator	Source of the indicator	Source of data*
Digital Asset Sub-index	Proportion of households with computer (%)	Hanafizadeh et al. (2009), ITU (2017), ITU (2007)	NSSO (2020)
	Smart phone penetration (%)	Hanafizadeh et al. (2009), Katz et al. (2014)	Cyber Media Research India (2018)
	Proportion of households with Television (%)	Hanafizadeh et al. (2009)	Statista (2021)
Network Access Sub- index	Proportion of households with internet (%)	Hanafizadeh et al. (2009), ITU (2017), ITU (2007)	NSSO (2020)
	4G availability (% of times)	Katz et al. (2014)	Open Signal (2020)
	Internet penetration (%)	Hanafizadeh et al. (2009)	IAMAI, (2019)
	Wireless subscription base (number in million)	Hanafizadeh et al. (2009), ITU (2017), ITU (2007)	TRAI (2020)
Electricity Access Sub-index	Average daily electricity supply (in hours)	Martín and Ramos (2022)	Agarwal et al. (2020)
	Share of households dissatisfied with grid electricity (%)	Identified and selected by authors	Agarwal et al. (2020)
	Proportion of households with connected to grid electricity (%)	Martín and Ramos (2022)	Ministry of Power (2021)

*Details of the data sources are given in the Appendix 1

the composite index was derived as the geometric mean of all three dimensions following Majerová (2018).

$$DII = 3\sqrt{DASi.NASi.EASi} \quad (3)$$

In this approach, the composite index value is more sensitive to the performance variation in any dimension or indicator (Talukder et al., 2017). The final index, DII, reflects the digital infrastructure status of the country or region under consideration. Data analysis and visualization were conducted using IBM SPSS Statistics® (Version 23, © 2015 IBM Corporation) and Microsoft Excel® 2019 (© Microsoft Corporation, 2018).

3. Results

The study was set to develop a comprehensive DII to have a deeper understanding of the level of preparedness of different states in India for higher education learners in the digital mode. From the sub-index values, it is evident that there is a regional-level variation about various dimensions of DII (Table 3). The variation in the values under the dimension DAPSi signalled varying levels of access to digital devices by the learners. Digital devices include smartphones, computers, and television sets. Access to these digital devices may help the learners to access learning resources more effectively.

Further, the Coefficient of Variation (CoV) of the measure is 51.39 per cent, indicating a substantial level of variation among the Indian states with regard to this measure. The NASi dimension denotes mobile and internet network access and its quality parameters. The effective use of any IT device primarily hinges on the availability of both mobile and internet coverage. Hence, higher scores under this dimension imply a favourable digital ecosystem to access learning resources. CoV was found to be significantly high (74.37%), implying high variability among the States focused. About the third dimension, viz. EASi, CoV was 32.57 per cent, the least among the three dimensions. The scores under this dimension represent relative position with regard to basic electricity access, a necessary condition for charging digital devices. A systematic pattern was observed in relation to the status of the States across the three dimensions of DII. Finally, the composite index scores were computed for all the states. Delhi, Kerala, and Punjab emerged as the leading states, while Assam, Bihar, and Odisha were identified as the lagging performers. The CoV for the composite index measure was 52.27 per cent, indicating a considerable disparity in the aggregate measure among the States.

Results signalled that of the three dimensions, the highest level of variability was exhibited by states about EASi, followed by DASi and NASi. The map shows regional variation in the DII scores in India (Fig. 1).

Further, the composite index score also enabled the categorization of various regions in India. Quartile scores were used to decide the classes. Six of the 21 states were coming under the *Extremely Low* category, while four were in *Moderately Low* and four in *Moderately High moderately high* categories. Seven States figured in the *High* score group. Such a categorization would enable inter-regional comparison with regard to IT infrastructure and highlight the weak and strong points (Table 4).

Table 3 Dimension-wise scores of Indian states

Sl. No.	State	Digital Asset Sub-index (DASi)	Network Access Sub- index (NASi)	Electricity Access Sub- index (EASi)
1	Andhra Pradesh	0.382	0.397	0.800
2	Assam	0.219	0.376	0.143
3	Bihar	0.152	0.413	0.215
4	Chhattisgarh	0.237	0.364	0.430
5	Delhi	0.452	0.602	0.889
6	Gujarat	0.388	0.489	0.950
7	Haryana	0.359	0.489	0.215
8	Himachal Pradesh	0.375	0.480	0.775
9	Jharkhand	0.201	0.362	0.000
10	Karnataka	0.384	0.457	0.543
11	Kerala	0.454	0.531	0.910
12	Madhya Pradesh	0.273	0.411	0.467
13	Maharashtra	0.381	0.598	0.683
14	Odisha	0.271	0.336	0.543
15	Punjab	0.398	0.505	0.862
16	Rajasthan	0.279	0.458	0.540
17	Tamil Nadu	0.420	0.496	0.853
18	Telangana	0.335	0.416	0.758
19	Uttarakhand	0.221	0.402	0.567
20	Uttar Pradesh	0.236	0.585	0.063
21	West Bengal	0.279	0.443	0.607

4. Discussion

Global higher education is one of the industries experiencing a significant digital transformation (Dwivedi et al., 2020). The COVID-19 pandemic has accelerated the adoption of digital technologies in higher education (Hodges et al., 2020). Against such a backdrop, this study tried to assess the status of the digital infrastructure ecosystem for higher education by developing a composite index, DII. Some studies focused on cross-country comparisons of access to Information and Communication Technology (ICT) tools and e-readiness (Bui et al., 2003; Hanafizadeh et al., 2009). Furthermore, studies on digital infrastructure for higher education have primarily examined the IT infrastructure of particular universities rather than the digital ecosystem for higher education (Rajendran, 2022; Singh & Mishra, 2022). This study mainly tried to scrutinize the digital infrastructure to switch to digital technology-led educational approaches such as online learning. Its novel approach and insightful findings can potentially inform policy decisions and improve academic outcomes. The findings also revealed regional imbalances in IT infrastructure, which has implications for higher education learners' access to learning resources. A recent study by the International Telecommunication Union (ITU) confirmed this, which found that access to ICT infrastructure and skills varies significantly across regions (ITU, 2019). To support learners who belong to geographically diverse regions with varied learning demands, the deployment of digital technologies is indispensable. Nevertheless, research shows a concerning digital divide, particularly in rural areas, where network coverage and device accessibility are limited (Goswami et al., 2021). These concerns are further supported by studies in other developing countries (UNSECO, 2022; Mathrani et al., 2022). Adding to these challenges, affordability remains a significant concern for learners from marginalized communities (IEEE CTU, 2021).

Research studies have shown that digitalization holds promise for raising educational standards and promoting equity (Haleem et al., 2022; Johnson et al., 2021). Improved IT infrastructure enhances online access and engagement in digital classrooms, even in rural areas, leading to better educational outcomes (Deshmukh & Kale, 2022). This became particularly apparent during the post-pandemic phase, with the growing use of digital resources and technologies more rigorously than before (Mishra et al., 2020). However, studies by UNESCO (2022) and the World Bank (2020) highlight the underinvestment in IT infrastructure for higher education, particularly in developing countries. This hinders the ability of the learners to have a seamless and reliable online learning experience. In the Indian context, two-thirds of the colleges are located in rural areas (Department of Higher Education, 2020). Hence, regional imbalances in the IT infrastructure may affect rural learners disproportionately compared to urban learners. This argument is supported by other studies which suggest that students from low-income families often share devices and struggle with limited bandwidth, affecting their ability to participate effectively in online classes and access learning materials (Singh & Kumar, 2020; Mittal et al., 2021). While socioeconomic disadvantage presents significant challenges for participation in online higher education (Méndez-Domínguez et al., 2023), there are also opportunities to leverage technology to improve access and reach to the learners. Towards this purpose, specific interventions can be planned to improve the digital infrastructure, which forms the enabling environment for technology-enabled learning approaches in general. This would be an essential step in developing an inclusive online learning environment to ensure that online higher education benefits all learners, regardless of their socioeconomic background.

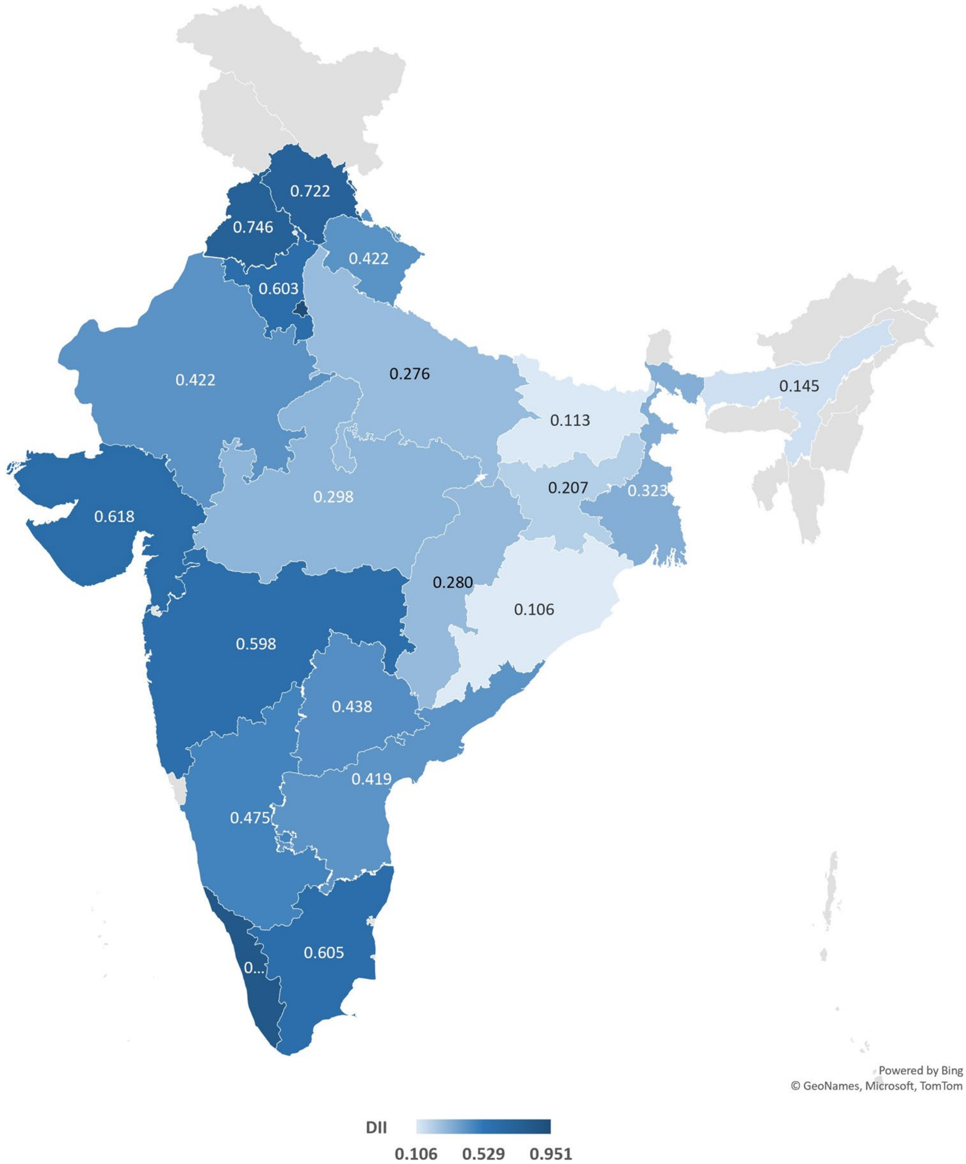

Fig. 1 Variation in the DII scores of Indian states Caption: This figure represents the variation in the composite index score (DII) of various States in India

Table 4 Classification of states based on composite index scores in DII

Sl. No.	Category	Number of states	Name of the states
1	*Extremely low* (DII ≤ 0.28)	6	Jharkhand, Uttar Pradesh, Assam, Bihar, Chhattisgarh, Odisha
2	*Moderately Low* (DII > 0.281 ≤ 0.421)	4	Madhya Pradesh, Rajasthan, West Bengal, Andhra Pradesh
3	*Moderately High* (DII > 0.422 and ≤ 0.6)	4	Karnataka, Telengana, Maharashtra, Uttarakhand
4	*High* (DII > 0.6)	7	Delhi, Punjab, Tamil Nadu, Gujarat, Kerala, Himachal Pradesh, Haryana

5. Conclusion

This study focuses on the adequacy of digital infrastructure for higher education in developing countries. This is a relatively under-explored area with significant educational equity and access implications. By drawing on the case of India, it tried to understand the enabling environment needed for advancing digital learning approaches. A composite index, meticulously constructed using relevant indicators, was employed to systematically evaluate the digital infrastructure ecosystem. By encompassing various facets of digital infrastructure, the DII offers a comprehensive analysis of the enabling environment for online learning and the development of a resilient learning ecosystem. This tool can be used in similar settings to draw meaningful inferences to guide policy interventions. The index also helps to compute the performance of various dimensions of digital infrastructure and to check the regional variation. Performance can be evaluated across all index dimensions to determine the strong and weak points of the digital infrastructure. Further, in developing country settings, this composite index can enable cross-country and regional comparisons. In this research, the case of India serves to demonstrate this utility. Consistency in performance across all dimensions is essential for achieving a higher DII score, establishing it as a valuable analytical tool for deriving meaningful insights into digital infrastructure. Any gaps in the digital infrastructure could contribute to the digital divide and disadvantage students by converging with socioeconomic inequality. Hence, in light of the findings, it can be argued that the ongoing debates on the prospects of technology in higher education should primarily address the concerns of digital infrastructure and ways to strengthen it.

Our study is not without limitations. While it primarily assessed the digital infrastructure for online learning in higher education, we acknowledge the importance of additional factors for a holistic understanding. These factors include educational resources, learner support services, and more. In addition to these supply side factors, demand side factors of online learning can also be explored. Future studies could build upon our findings by incorporating a wider range of variables at a more granular level. This may encompass faculty training programs, learners' digital competencies, and the implementation of learning management systems at the institutional level. Such a comprehensive approach would enable a more robust evaluation of online learning preparedness.

Appendix

Data sources of the study.

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Author Contributions Sreeram Vishnu (SV): Conceptualization and design of the study; Drafting the manuscript

Mahesh B Tengli (MBT): Data gathering and Analysis

Sendhil Ramadas(SR): Data gathering, wrangling and analysis

Archana Raghavan Sathyan (ARS): Manuscript drafting and refinement

Archana Bhatt (AB): Language Editing and Proof checks

Data Availability We have not generated any data sets for this study. The study is based on secondary data, and the same is accessed from publicly accessible open sources. The links to the same are provided in the Appendix section.

Declarations

Competing Interests The authors have no competing interests to declare relevant to this article's content.

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