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Virtual connections, real responsibilities: a research agenda for sustainable virtual world development

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Abstract

Purpose – The objectives of this study are to understand the interdependencies between the metaverse and sustainable development. This study aims to integrate the existing body of literature within the research discipline and formulate a research agenda.

Design/methodology/approach – The current research applies bibliometric analysis to understand the evolution of the research area, the publication and citation patterns and the presence of prominent authors, countries and journals. In addition, the research will present clusters of key themes to present how concepts relate. A close inspection of the themes will reveal research gaps to guide future research.

Findings – It pinpoints the main trends in publication and citation, highlighting most contributors, such as top authors, countries and journals. This paper detects collaboration patterns among research and co-authorship networks and identifies major knowledge clusters shaping the domain. A detailed analysis of the latter enabled the study to detect lacunas in existing research and indicate clear directions for future studies.

Practical implications – Higher education institutions can enhance the learning in sustainability industries can adopt circular and artificial intelligence-based green practices, policy framers can use digital solutions for resilient cities and healthcare and can provide affordable maternal health solutions.

Originality/value – The article summarises the available literature to bring to the forefront the most influential authors, journals, geographies, seminal papers and publishing trends in the literature. This article also analyses the main research topics to uncover the research gaps and provide directions to researchers. This article is most helpful to a novice researcher.

Keywords Virtual world, Sustainability, Digital revolution, Urban modelling, Metaverse, Water sustainability, Climate adaptation, Resilient creation

Paper type Research article

1. Introduction

Sustainability has emerged as a key concern in the international business environment, with governments, non-governmental organisations and transnational corporations increasingly incorporating sustainable practices, especially through information and communication technologies (ICT) (Hilty *et al.*, 2006). The adoption of the United Nations (UN) Sustainable Development Goals (SDGs) in 2015 offered a global framework to address interlinked challenges like climate change, poverty and inequality, while underlining the enabling potential of ICT in sustainable development (United Nations, 2023). Sustainability has come to be acknowledged as a key business imperative in response to climate variability, resource constraints and mounting pressures on energy and food systems that impact organisational functioning (Guandalini, 2022).

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1.1 *The SDGs and sustainability*

Sustainable development is generally described as the fulfilment of current needs without compromising the ability of future generations to meet their needs (Guandalini, 2022). This is achieved by maintaining a balance among economic, social and environmental factors, using the triple bottom line approach. The SDGs were formulated to address global challenges such as climate change, environmental degradation, poverty and social inequality.

1.2 *Triple bottom line and the virtual world*

The virtual world, also known as the metaverse, is a digital environment that is made possible through the use of technologies such as artificial intelligence (AI), the Internet of Things and blockchain (Wang *et al.*, 2022). In today's business environment, there is a growing need for organisations to create economic value as well as meet their social and environmental responsibilities. The triple bottom line approach can be used to assess the sustainability implications of the development of virtual worlds.

1.3 *Sustainability and its intersection with the virtual world*

Duglio and Ivanov (2026) explored the mutual interconnectedness between the metaverse, a collective virtual shared space, and local development in the context of SDGs. Raman *et al.* (2024) explored the role of the metaverse in achieving SDG 3, which is good health and well-being; they explored how augmented reality (AR) and virtual reality technologies can help achieve SDGs. Current research points to the use of virtual world technology as a means of lowering environmental effects and contributing to sustainability efforts like carbon neutrality. As sustainability becomes an increasingly complex notion, organisations need to adjust their approach to deal with environmental, economic and social issues (Jauhiainen *et al*., 2022). Previous studies focus on specific areas; our study explored the vital role of the metaverse in sustainable development.

In view of these, several research questions emerge to consider in conducting a literature review for this research:

RQ1. What patterns can be observed in publication growth, citation impact, key contributors and collaborative linkages within virtual world and environmental sustainability?

RQ2. What unexplored dimensions of the virtual world offer opportunities for future research?

To answer the above research question, the present research performs:

(1) The performance analysis to uncover publication and citation trends and major contributors like prolific authors, countries, and journals of research domains.

(2) Thematic analysis to identify the relationship among keywords and knowledge clusters of the research domain.

(3) In-depth review of knowledge clusters to find the research gaps for future research in the research domain.

These questions are designed to unpack how the virtual world influences sustainable development and could affect environmental goals. To answer the research questions, this research adopts performance analysis and science mapping techniques, as they align with the exploratory aim of scrutinising the structure and advancement of research on the sustainability of virtual worlds and environments. This research study significantly contributes to the research area of virtual worlds and environmental sustainability. First, it examines existing literature using bibliometric methods, thereby enabling readers to gain insight into how the field has evolved. The performance analysis provides an overview of the publication and citation trends and major contributors. Science mapping provides insights into collaborative countries, co-authorship among the authors, and knowledge clusters of the research domain. At last, the study provides future research directions on the basis of an in-depth analysis of knowledge clusters in the research domain. Future scholars can explore the new findings in the domain and can make a significant contribution to the research domain.

The study is systematised as follows: Section 2 surveys existing literature, providing an overview of the research topic. Section 3 expresses the bibliometric analysis approach. Section 4 presents the performance analysis and scientific mapping findings, and Section 5 presents major results and conclusions.

2. Background

This section critically reviews earlier studies to chart the intellectual structure of the field. Although scholarly interest in the sustainable virtual world has accelerated in recent years, existing research remains fragmented and incomplete in several ways (Table 1). Prior bibliometric studies have provided valuable starting points but also reveal important limitations. For instance, Tiwari and Srivastava (2025) demonstrated the rapid rise in publications and leading outlets, but their performance analysis primarily focused on output

Table 1. List of review studies on virtual world and environmental sustainability

Sr. No.	Study	Focused area	Study type	Keywords used in search string
1	Johri *et al.* (2024)	Mapping, organising, and synthesising the emerging body of research on the intersection of the metaverse and sustainable development	Bibliometric and systematic literature review	"metaverse" OR "multiverse" OR "megadiverse" AND "sustainable development" OR "sustainability."
2	Tiwari and Srivastava (2025)	Sustainable metaverse performance analysis	Bibliometric analysis	metaverse," "virtual world," "virtual environment," "virtual reality," "augmented reality," "extended reality," and "sustainability", "tbl", "sustainable business model", "circular economy", and "green economy"
3	Sharif *et al.* (2025)	Review of co-benefits and trade-offs for sustainable development goals	systematic literature review	Not available
4	Jauhiainen *et al.* (2022)	Metaverse and sustainability performance analysis	Bibliometric analysis	"metavers" search query
5	Alabidi *et al.* (2024)	Metaverse and three dimensions	Bibliometric analysis	Not available
6	Mutlu Avinç and Yıldız (2025)	A bibliometric and systematic review of scientific publications on metaverse research in architecture: web of science (WoS)	Bibliometric analysis	"metaverse" AND "architect*" or "design" or "architectural studio" or "architectural education" or "building" or "architectural space" or "built environment" AND "virtual space" or "mixed reality" or "augmented reality" or "extended reality" or "cyberspace" or "virtual reality" or "virtual environment" or "virtual worlds" or "digital world"

and growth trends, offering limited insights into thematic or intellectual structures. Further advances include the grouping of the literature in the virtual world ecosystem and sustainable learning environment by Johri *et al.* (2024), although their categories function in seclusion from one another, offering little interlinking between governance and the environment. In addition, the virtual world and SDG relationships have also been investigated by Sharifi *et al.* (2024), revealing great concern regarding education, sustainable cities, innovation, and environmental sustainability. The sustainability issue has also been endorsed by Jauhiainen *et al.* (2022), revealing that sustainability studies are seldom the core in virtual world studies and are dominated in developed nations. In accumulation, Alabidi *et al.* (2024) emphasised the use of virtual worlds in promoting SDGs but acknowledged some digital divides, governance problems, and ecological threats that are still remotely understood. In the architectural field, the rise in building information modelling, cultural heritage, and digital twin studies has also been identified by Mutlu Avinç and Yıldız (2025), although in seclusion from sustainability issue factors such as carbon emissions, energy intensity, and equity.

Our research fills these research gaps by integrating performance evaluation, science mapping, and cluster analyses using the web of science (WoS) database to offer a holistic view of sustainable virtual world research. Whereas previous research assessed growth or body clusters exclusively, our research combines publication development, geographies of scholarship, and knowledge structure, hence allowing an understanding of the interrelations of the virtual world and sustainability. Accordingly, the research gap appears in the absence of holistic, interconnected, and geographically extended bibliometric studies on the sustainable virtual world. Our research bridges the gap by presenting an interconnected map that not only measures the increase in publications and the key journals but also identifies the silos, geographical inequities, and sustainability dimensions that remain uncharted.

3. Research methodology

In response to the research gaps acknowledged in the literature, this segment summarises the methodological framework adopted to examine the existing body of research. This section discusses the perspective and process involved in conducting a review concerning the role of the virtual world towards ensuring the sustainability of the environment. In this study, the researcher will benefit from a qualitative process that offers a wide and comprehensive understanding of the subject.

3.1 Search strategy and boundary definition

It is essential to make use of the appropriate database in carrying out a scientific literature review, as it affects the quality of the research output. Extraction of data can be carried out through the use of bibliometric databases such as the WoS, Scopus, Science Direct, or Google Scholar. The article makes use of the WoS as the primary source for the acquisition of bibliographic details due to its wide coverage and scientific standards. Rather than concentrating on precise scholars, the study embraced a keyword- and database-driven methodology, allowing dominant contributors to appear organically based on publication and citation patterns. Two steps of preliminary data analysis were carried out to evaluate and enhance the databases. The advanced search function, using operators like OR and AND, was applied across the database. In the first phase, search terms included keywords related to the metaverse. By using the search string "METAVERSE" OR "VIRTUAL REALITY" OR "VR" OR "3D" OR "AVTAR" AND "SDG" OR "SUSTAINABLE DEVELOPMENT GOALS" OR "SDGs", the results yielded were as follows: 350 articles.

A total of 350 articles were initially extracted. A document-type filter was then applied to exclude proceedings and conference papers. After applying this filtering, 48 articles were excluded. Following this, a language filter was used to remove any non-English articles, resulting in the exclusion of one paper in another language. Ultimately, 301 papers were retained for further analysis. The research extends a wide-ranging 25-year period (2000–2025), empowering a longitudinal indulgence in the advancement, trends, and intellectual structure of the research domain. This prolonged timeframe reinforces the study by encompassing both foundational developments and recent advancements, confirming robust and holistic insights. This study does not entitle universal exposure of all research in the domain. The dataset, while systematically built, is limited by database collection, keyword design, and inclusion criteria. Hence, the outcomes must be understood as representative rather than exhaustive. Figure 1 summarises the data retrieved from WoS.

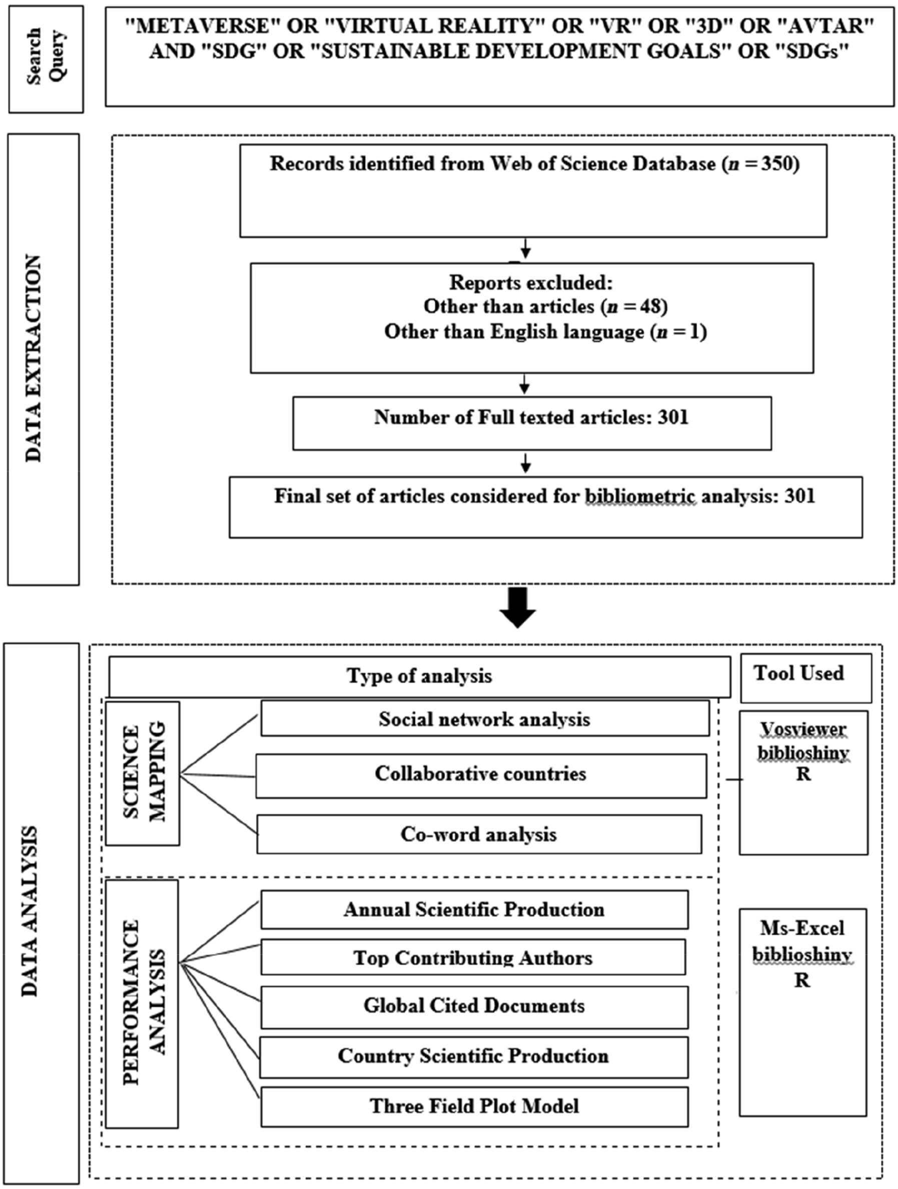

Figure 1. Flowchart demonstrating the procedure of identifying and selecting related literature for bibliometric analysis. Source: Created by authors

3.2 Data analysis technique

Firstly, the performance analysis technique was used to perform the analysis. To identify the most prolific writers, prominent nations, significant journals, and impactful publications, the study examined annual publishing patterns, the most productive authors and leading countries in the research domain. The second analytical approach used was scientific mapping. In this work, collaboration network analysis and co-occurrence analysis were used to investigate collaborative patterns and intellectual structures in the dataset.

This paper conducted a comprehensive bibliometric analysis using Biblioshiny and Vosviewer software. Biblioshiny is a user-friendly platform that enables researchers to perform a cultivated bibliometric analysis. VOSviewer is more preferable when considering the network analysis and visualisation of data.

3.3 Analysis framework

To answer the research questions, a bibliometric analysis was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework for guidance on search and literature selection. The PRISMA flow diagram depicts the identification process, inclusion, and exclusion of the analysed literature, together with exclusion justifications. PRISMA is beneficial in handling large volumes of data for the contribution to research questions. The present research aims to discard the virtual world's potential to sustain the environment; hence, a systematic review provides a more reliable answer compared to individual studies that can only give a few insights.

3.4 Justification of statistical methodology

This research adopts bibliometric analysis using performance analysis and science mapping techniques, as they align with the exploratory aim of scrutinising the structure and advancement of research on the sustainability of virtual worlds and environments. Science mapping techniques, such as co-citation and keyword co-occurrence analysis, provide visual insights into associations and thematic clusters, helping to discover the intellectual structure of the field. These methods confirm objectivity, reproducibility, and data-driven results, while effectively capturing emerging trends and research gaps. This methodology is suitable as it simplifies an inclusive, structured, and unbiased exploration of the research domain. Unlike traditional methods focused on hypothesis testing, bibliometric analysis enables systematic and quantitative evaluation of large volumes of literature, identifying key authors, themes, and publication trends.

The study works with keyword clustering techniques to categorise thematic structures within the literature. The present study uses network-based clustering that groups keywords based on the strength of their co-occurrence connections. Specifically, the clustering in this research was performed using VOSviewer, which employs a mapping-and-clustering technique based on a weighted, parameterised variant of modularity optimisation. This approach is predominantly appropriate for bibliometric data, as it detects the underlying intellectual linkages between research themes. Notably, clustering methods used in bibliometric analysis are non-parametric in nature, meaning they do not need assumptions about the normal distribution of data. This makes them extremely suitable for keyword co-occurrence data, which is typically skewed, sparse, and high-dimensional. The non-parametric property confirms strength and flexibility in detecting natural groupings in the data without imposing restrictive statistical assumptions. Overall, this methodology is appropriate as it facilitates a comprehensive, structured and unbiased understanding of the research domain.

4. Discussion and results

4.1 Performance analysis

This technique evaluates the total contribution of research components, including nations, journals and authors, using established review processes to represent individual performance indexes.

4.2 Main information

Table 2 delivers a forecast regarding research trends in the dataset from 2000 through 2025. Over the past 25 years, there has been substantial research advancement represented by 301 scholarly documents acquired from 199 sources. It also shows that there is a wide range of sources for scholarly works related to the research area. The research area shows a dramatic growth rate of 11.13% per year, making it attract more researchers. It takes a record-high average of 21.5 authors per paper in the research area.

4.3 Annual scientific production

Figure 2 reveals the increase in the number of publications over the years. There was a period, between 2000 and roughly 2017, when there were fewer publications, only a handful of publications happening annually. But since 2017, there has been exponential growth, with

Table 2. Main information

Main information about data	
Time	2000:2025
Sources	199
Number of documents	301
Annual growth rate	11.13
Document average age	3.72
Author’s keywords	1,504
Authors	5,381
Authors of single-authored docs	10
Single-authored docs	12
Co-authors per doc	21.5
International co-authorships	45.85

Source(s): Extracted from R Studio and compiled by the authors

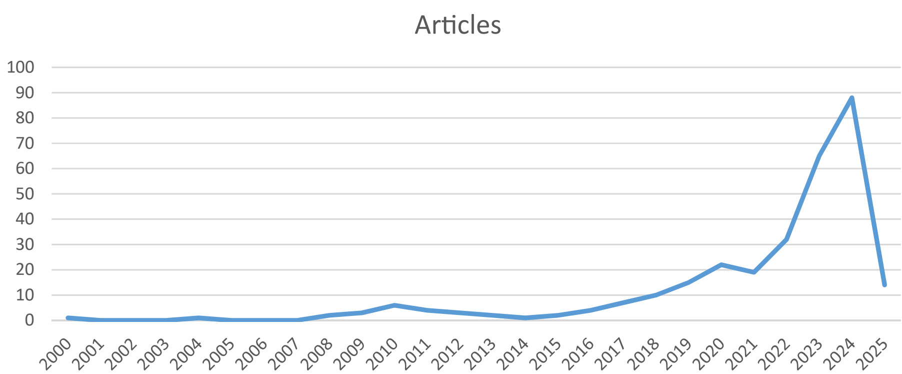

Figure 2. Shows the per annum research output in the field of virtual world and SDGs

nearly 88 publications happening annually by 2024. The dramatic rise would represent a sudden increase in publications, perhaps due to recent sources of funding, technological growth or the realisation of its significance. This would mean that there has been rapid growth in this region of study, perhaps due to the significance related to modern-day events or technological breakthroughs.

4.4 Three-field plot

Figure 3 provides information about the link between the important topics, the different countries, and particular sources. The different countries appear on the left side, in which the respective countries, like the USA, Iran, India, and China, appear to be actively involved in the research area of the virtual world. The keywords for the authors appear in the centre, and the different sources on the right side specify that "*Sustainability*," "*International Journal of Production Research*" and "The *Lancet*" refer to the detailed research sources in the particular area relating to the area of research. This fantasy demonstrates the link between the different countries and the topics, resulting in the highlighting of the diversity area in the particular subject.

4.5 Most relevant sources

Also, Table 3 illustrates the top journals containing influential research within the virtual world application for the fulfilment of the SDGs. The top influential journals are led by the *Sustainability Journal*, which contains a huge 30 publications, making it a prolific source of information for this particular research. Secondly, "*The Journal of Cleaner Production*" has seven publications, which clearly signify its importance in the publication process for further research. Thirdly, *Water*, which contains six publications. The remaining top 10 journals include the *International Journal of Production Research*, with publications amounting to five, and *Land*, with a similar five publications. The table further holds information about the H-index for sources, as well as the citation count for the respective journals.

4.6 Most relevant authors

Table 4 focuses on the most prolific authors in the area. KUMAR stands out as the top author, with nine publications, including the highest value for both H-Index and G-Index, addressing a broad spectrum of topics related to sustainability, climate change and technology. Following

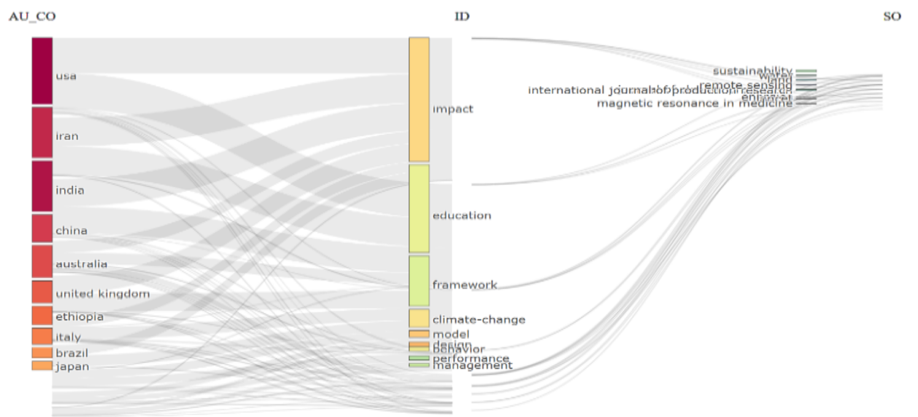

Figure 3. Shows the three field plots in the area of virtual-world SDGs, which define the relationship between countries, keywords and sources

Table 3. Most devoted sources in the research domain

Rank	Source	Articles	H index	Total citations
1	*"Sustainability"*	30	10	469
2	*"Journal of Cleaner Production"*	7	4	540
3	*"Water"*	6	4	151
4	*"International Journal of Production Research"*	5	4	51
5	*"Land"*	5	3	30
6	*"Energies"*	4	2	28
7	*"Lancet"*	4	4	3,273
8	*"Magnetic Resonance in Medicine"*	4	4	201
9	*"Remote Sensing"*	4	3	54
10	*"Sustainable Cities and Society"*	4	3	16

Source(s): Compiled by authors

Table 4. Most influential authors

Rank	Author name	Documents	H index	G index	M index	Citations	PY start
1	Kumar	9	7	9	0.875	3,500	2018
2	Avtar Ram	9	6	9	0.857	149	2019
3	Kumar.Pankaj	7	6	7	0.857	153	2019
4	A	5	5	5	0.313	1,680	2010
5	Ali	5	5	5	1.667	283	2023
6	Nezafat Reza	5	5	5	0.294	150	2009
7	J	4	4	4	0.5	1,241	2018
8	Kissinger Kraig V	4	4	4	0.235	92	2009
9	M	5	4	5	0.667	230	2020
10	S	5	4	5	0.5	1,474	2018

Source(s): Prepared by authors from the Web of Science database

closely are authors such as "AVTAR RAM", KUMAR PANKAJ, and "A", who follow KUMAR with more than five publications, including high values for both H-Index and G-Index. This indicates that these authors actively collaborate in defining the research aspect and contribute diverse ideas. The area of research is enhanced by a third group consisting of five authors, with all authors contributing more than four publications, adding diverse ideas to the spectrum of research.

4.7 Scientific production of countries

Table 5 displays the scientific production of countries in this field, reflecting the impact and quality of research produced by each. The United States of America ranks first, with a notable 4,502 citations, indicating its strong influence and high-quality contributions. The United Kingdom holds the second position with 427 citations, followed by Germany, China, Japan, Sweden, Italy, Brazil, India and Korea, all of which rank within the top 10. These citation counts highlight the prominence of these countries in driving research and innovation in this area. The table also highlights the information on collaboration within the countries. China is the leading country in terms of document production, followed by the USA and India. The USA is on top with an average of 118.5 citations, followed by Germany and the United Kingdom.

Table 5. Scientific contribution of countries

Rank	Country	Documents	Single country production	Multiple country production	Total citation	Average citation
1	China	47	32	15	274	5.80
2	USA	38	19	19	4,502	118.50
3	India	28	18	10	158	5.60
4	United Kingdom	23	12	11	427	18.60
5	Japan	16	5	11	240	15.00
6	Sweden	13	2	11	182	14.00
7	Italy	11	5	6	112	10.20
8	Korea	10	6	4	145	14.50
9	Brazil	9	5	4	24	2.70
10	Germany	7	1	6	389	55.60

Source(s): Prepared by authors

4.8 Most globally cited documents

Table 6 presents the most globally referenced articles in this field. Leading the list is Liu L. *et al.*'s 2016 article in *The Lancet*, which has amassed an impressive 2,141 citations, making it the most cited work at the global level. Following this is Lozano R.'s 2018 paper, also published in *The Lancet*, with 320 citations. The chart highlights the top 10 most-cited articles, with *The Lancet* contributing the majority of these influential publications. This underscores the journal's significant role in shaping impactful research in this area.

While the performance analysis delivers an outline of publication trends and dominant contributors, the science mapping investigation offers deeper insights into the intellectual and thematic structure of the field.

4.8.1 Science mapping. This approach provides network maps to examine the links between several study components. It investigates the structural association and intellectual isolation within the study area. This work examines co-authorship analysis, collaboration analysis between countries and co-occurrence analysis.

4.9 Co-authorship analysis

Figure 4 shows how researchers working on the virtual world are associated through co-authorship. Each circle denotes an author, and the larger the circle, the more publications that person has in this area. The lines among circles show when two authors have worked together on a paper, and thicker lines mean they've collaborated more often.

Table 6. List of global cited documents

Paper	Total citations	TC per year	Normalised TC
Liu, L., 2016, Lancet	2,141	237.89	5.00
Lozano, R., 2018, Lancet	320	45.71	3.50
Leal Filho, W., 2019, J Clean Prod	315	52.50	7.15
Mondejar, M.E., 2021, Sci Total Environ	271	67.75	7.64
Colorado, H.A., 2020, J Mater Res Technol-JMRT	150	30.00	4.88
FerrarI, A.J., 2024, Lancet	147	147.00	42.38
Albareda-Tiana, S., 2018, Int J Sustain High Educ	143	20.43	1.56
Rijal, G., 2016, Biomaterials	139	15.44	0.32
Crapser, J., 2016, Aging-US	125	13.89	0.29
Matharu, A.S., 2016, Bioresour Technol	124	13.78	0.29

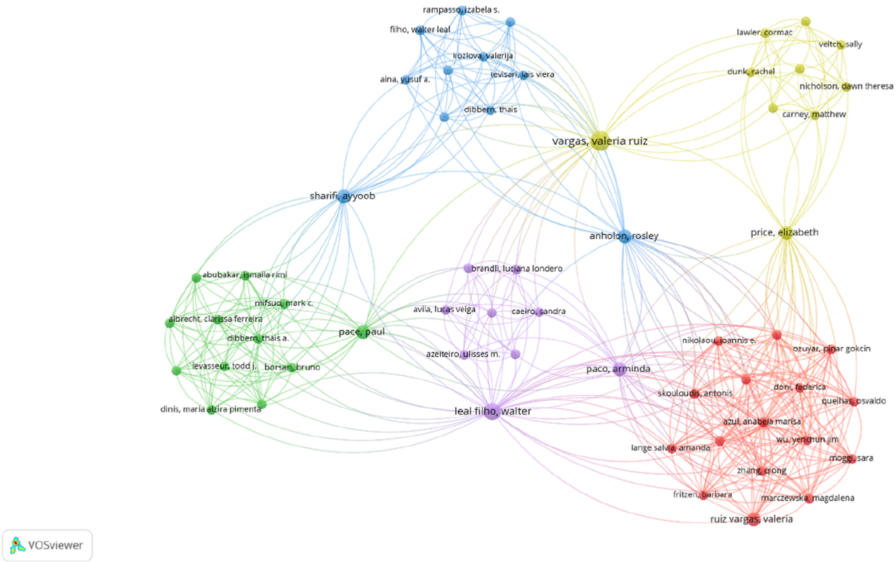

Figure 4. Co-authorship network

The colours group together researchers who tend to work closely with each other:

(1) Blue group: Led by *Sharifi, Ayoob*, this team contains people like Rampasso, Izabela S., Kozlova, Valerija and Dibbern. They have strong links within the group.

(2) Green group: Centred on Pace, Paul, with members like Abubakar, Ismaila Rimi, Mifsud, Mark C. and Levasseur, showing tight-knit collaboration.

(3) Yellow group: Around Price, Elizabeth, with close partners such as Lawler, Cormac, Veitch and Nicholson, Dawn Theresa.

(4) Purple group: Connected to Leal Filho, Walter, along with Avila, Lucas Veiga, Caeiro, Sandra and Azeiteiro, Ulisses M. – a group that also links to several other teams.

(5) Red group: A large, highly connected network with Paco, Arminda, Ruiz Vargas, Valeria, Zhang, Qiong and Magdalena Marczewska among its most active members.

Overall, this network displays that virtual-world research is very collaborative. A few key individuals serve as connectors between different research groups, facilitating the flow of ideas and knowledge throughout the entire network.

4.10 Co-word analysis

According to Donthu *et al*. (2021), co-word analysis is an effective tool to recognise and uncover evolving topics and associations between variables in the research domain. It also helps to expose the conceptual structure and knowledge gaps in the research domain for forthcoming research. To perform co-word analysis, a threshold of the least occurrence of the keyword was chosen to be two occurrences. Out of 1,361 keywords, 107 met the selected criteria. Based on the analysis, eleven clusters were identified, which include eligible keywords. The cluster was differentiable by colour and categorised with a name based on the keywords of the cluster (Figure 5). Furthermore, most dominant studies of the respective clusters have been reviewed to reveal the knowledge structure and connections between

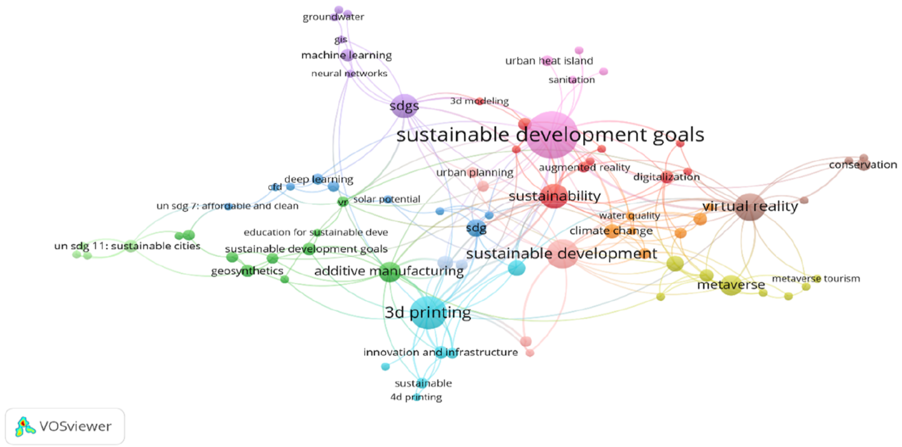

Figure 5. Co- word analysis

variables in the research domain. Table 7 provides an overview of the clusters, along with their respective keywords and representative studies.

4.10.1 Cluster 1: Digital immersion and sustainability. Cluster 1 includes 10 keywords labelled as "digital immersion and sustainability," presented with red-coloured bubbles in the network. In light of the cluster's theme, Akinradewo *et al.* (2024) examined the key drivers of AR for education and training, finding that it significantly improves educational outcomes by enhancing task accuracy and mitigating misinformation. Hoosain *et al.* (2020) analysed the sway of digital technologies on the UN SDGs, concluding that digital technologies have a positive impact on the environment and economy. Makrakis (2024) inspected the self-efficacy and transformative teaching beliefs of teachers in adopting ICT technologies in teaching and found that both variables are significant. Filho *et al.* (2023) highlighted the prominence of implementing SDGs in teaching in universities. Giovanni (2023) delivers a path to manage the transition to Industry 5.0 through digital transformation tools like the metaverse.

4.10.2 Cluster 2: green engineering and manufacturing. Cluster 2 comprises 10 keywords categorised as "green engineering and manufacturing." As the name suggests, it focuses on green engineering. Almeida *et al.* (2024) examined the feasibility of using industrial waste in the production of highly porous 3D-printed geopolymeric lattices for wastewater treatment applications. Additionally, Mukherjee *et al.* (2024) focused on SDG 6, which is clean water and sanitation and the need to prevent water pollution through the solvothermal method. Gössling (2020) investigated the role of technology and ICT in the tourism sector in fostering SDGs and concluded that ICT and technology significantly led to a positive influence on achieving SDGs. Dostatni *et al.* (2024) concentrated on enhancing sustainability by reducing particulate matter emissions through optimising 3D printing with the application of neural networks.

4.10.3 Cluster 3: computational urban energy modelling. Cluster 3 represents "computational urban energy modelling", which includes nine keywords and is shown with a sky blue colour in the network. As per this theme, Santos *et al.* (2021) evaluated the clout of urban growth spatial patterns on sustainable development. They discovered that the urban growth pattern led to a more sustainable urban region. Shehadeh *et al.* (2024) investigated the role of digital twin technologies in achieving the SDGs in urban areas, which combines real-time data and community insights through machine learning. Skrzypczak *et al.* (2022) scrutinised the modelling of buildings through laser scanning 3D technology. They proposed that the laser scanning technique provides many advantages in architecture.

Table 7. Knowledge clusters of research domain

Cluster	Representative keywords	Representative studies
1. Digital Immersion & Sustainability **(Red Colour)**	3d Modelling (2), Augmented Reality (3), Built Environment (2), Digital Transformation (2), Digitalization (4), Higher Education (4), Management (2), Sustainability (13), Teaching (2), Tourism (2)	Akinradewo *et al*. (2024), Hoosain *et al*. (2020), Makrakis (2024), Filho *et al*. (2019), Giovanni (2023), Akram *et al*. (2022), Choi and Kim (2023)
2. Green Engineering & Manufacturing **(Green Colour)**	Additive Manufacturing (9), Education for Sustainable Development (2), Geosynthetics (4), Innovation (3), Piles & Piling (3), Stiffness (2), Sustainable Development (16), Un Sdg 9 (3), VR (3), Waste (2)	Almeida *et al*. (2024), Mukherjee *et al*. (2024), Tiana *et al*. (2018), Gifford and McKelvey (2019), Gossling (2020), Dostani *et al*. (2024)
3. Computational Urban Energy Modelling **(Sky Blue Colour)**	Cfd (2), Computational Fluid Dynamics (2), Deep Learning (3), Sdg (7), Solar Potential (2), Transfer Learning (2), Un Sdg 7: Affordable and Clean Energy (2), Unmanned Aerial Vehicle (3), Urban Growth (2)	Santos *et al*. (2021), Ahsan *et al*. (2024), Shehadeh *et al*. (2024), Skrzypczak *et al*. (2022), Ryali *et al*. (2024)
4. ***AI & Metaverse Tourism*** ***(Yellow Colour)***	Artificial Intelligence (6), Digital Twin (4), Metaverse (9), Metaverse Tourism (2), Sdg 9: Industry, Innovation and Infrastructure (2), Sustainable Development Goals (36), Sustainable Tourism (2), Virtual Tourism (2)	Gossling (2020), Dolgui and Ivanov (2024), Raman *et al*. (2024), Go and Kang (2023), Giovanni (2023)
5. Data-Driven Water Sustainability **(Purple Colour)**	Gis (2), Groundwater (2), Machine Learning (4), Neural Networks (2), Sdgs (12), Vietnam (2), Water Quality Index (2)	Molekoa et al. (2019), Duc *et al*. (2023), Spiller *et al*. (2023), Hathat *et al*. (2024)

6. *Green Printing Technologies (Light Blue Colour)*	3d Printing (20), 4d Printing (2), Covid-19 (6), Green Synthesis (2), Innovation and Infrastructure (4), Sdg 9: Industry (3), Sustainable (3)	Bednarski *et al*. (2024), Parr (2022), Higginbotham (2021), Sanassee and Henrage (2024), Alami *et al*. (2023)
7. Climate Adaptation Strategies (Orange Colour)	Climate Change (5), Climate Change Adaptation (2), Diversity (2), Education (4), Renewable Energy (3), Sustainable Development Goals, Sdg (4), Water Quality (2)	Saraswat (2019), Pimental and Kalyanaraman (2023), Kumar *et al*. (2020), Kazak and Swiader (2018), Wamsler and Johannessen (2020), Elizabeth *et al*. (2024)
8. Virtual Sustainability Learning (Brown Colour)	Biodiversity (2), Conservation (4), Education For Sustainable Development (2), Un Sustainable Development Goals (2), Virtual Reality (15)	Filho et al. (2023), Aasar *et al*. (2024), Hsiao and Su (2021), Rahman *et al*. (2021), Dasgupta *et al*. (2023)
9. Maternal Health and Climate (Pink Colour)	Maternal Mortality (2), Sanitation (2), Sustainable Development (16), Uganda (2), Urban Heat Island (3)	Candidori *et al*. (2024), Bauserman *et al*. (2020), Friedrich *et al*. (2020), Assefa *et al*. (2018), Biermann *et al*. (2023)
10. Urban Planning & Microanalysis (Light Pink)	Sample Preparation (3), Sustainable Development Goal (2), Transmission Electron Microscopy (2), Urban Planning (3), Urban Resilience (3)	Esenarro *et al*. (2023), He *et al*. (2024), Whitemore (2023), Rahman *et al*. (2021), Biljecki (2024)
11. Resilient Construction Solutions (Light Green)	Concrete Technology & Manufacture (2), Un Sdg 11: Sustainable Cities And Communities (4), Un Sdg 9: Industry Innovation and Infrastructure (2), Construction (2)	Bei *et al*. (2024) , Pinusorachai *et al*. (2024), Xiao *et al*. (2018), Kalyavaradhan *et al*. (2024), Dorostkar and Najarsadeghi (2023)

4.10.4 Cluster 4: AI and virtual-world tourism. Cluster 4, denominated as “AI and virtual-world tourism”, which covers eight keywords of co-word analysis and is expressed by the yellow colour in the network. According to the subject of the cluster, Gössling (2020) examined the role of information technology in the tourism sector to achieve SDGs and concluded that technology and ICT significantly contribute to achieving SDGs. Dolgui and Ivanov (2025) inspected the clout of the Internet of behaviour (IoB) on supply chain and operation management and concluded that IoB has significant clout on supply chain management. Go and Kang (2023) investigated the role of virtual-world tourism for achieving sustainable tourism and recommended that virtual-world products can enhance sustainable tourism by providing profitable resources. Giovanni (2023) evaluated the sustainability of the virtual world to drive the transition to Industry 5.0.

4.10.5 Cluster 5: data-driven water sustainability. Cluster 5 involves seven keywords pigeonholed as "data-driven water sustainability," exposed with the colour purple in the network. The theme of the cluster focuses on water sustainability. Molekoa *et al.* (2019) evaluated water quality status and hydro-chemical processes in South Africa by performing a hydro-geochemical analysis of groundwater samples to calculate the water quality index. Similarly, Duc *et al.* (2023) examined the variation in surface water quality to provide information about sustainable water resource management. Spiller *et al.* (2023) inspected the generalisation of the capability of four neural networks: (1) fully connected, (2) one-dimensional CNN, (3) two-dimensional CNN and (4) three-dimensional CNN and offered that the fully connected model has more generalisation capability.

4.10.6 Cluster 6: green printing technologies. Cluster 6, entitled "green printing technologies," which embraces seven keywords presented by the light blue colour in the network. In the context of this theme, Bednarski *et al.* (2025) performed a systematic review on the influence of geopolitical disruptions on the supply chain to identify key themes of the research domain. Parr (2022) explored the target to prepare national capacity for any pandemic preparations by the SDGs. Higginbotham (2021) reconnoitred the role of immersive technologies like virtual reality and AR in improving global neurosurgery. Sanassee and Henrage (2024) analysed the transformation of polyethene terephthalate bottles into filaments for 3D printing.

4.10.7 Cluster 7: climate adoption strategies. Cluster 7 is categorised as "climate adoption strategies," which includes seven keywords and is shown by orange-coloured bubbles in the network. This cluster emphasises climate change and adaptation strategies. As the theme represents, Saraswat *et al.* (2019) investigated the hydro-chemical features of groundwater in Surat City, India, and examined the suitability of water. Pimentel and Kalyanaraman (2023) developed a "virtual climate scientist" through virtual reality to educate students about palaeoclimatology. Kumar *et al.* (2020) used a combination of two techniques – participatory approach and computer simulation modelling – for water resource management and discovered that population growth is a foremost reason for water quality deterioration. Kazak and Świader (2018) advanced a tool called "SOLIS" for the assessment of solar radiation.

4.10.8 Cluster 8: virtual sustainability learning. Cluster 8 contains five keywords characterised as "virtual sustainability learning," revealed by the brown colour in the network. As per this theme, Filho *et al.* (2023) examined the connection between governance and sustainable development in higher education institutions. They performed a bibliometric analysis and identified the extent to which governance impacts sustainable development in higher education institutions. Hsiao and Su (2021) analysed the clout of science, technology, engineering, the arts and mathematics (STEAM) education on student motivation to learn and found that the combined use of virtual reality and STEAM education can foster learning satisfaction among students. Dasgupta *et al.* (2023) explored the indigenous and local knowledge and practices (ILKPS) connected with shifting cultivation for sustainable development and concluded that upholding ILKPS has a strong role in achieving SDGs.

4.10.9 Cluster 9: maternal health and climate. Cluster 9 comprises five keywords categorised as "maternal health and climate," epitomised by pink-coloured bubbles in the network. Candidori *et al.* (2024) executed experimental research to examine the performance of a medical device named "BAMBI," which is an alternative to the condom balloon tamponade technique. Similarly, Bauserman *et al.* (2020) reviewed maternal mortality data from six countries over 8 years to identify risk factors and trends. Friedrich *et al.* (2020)

examined the increasing use of latrines in rural areas of Karnataka by applying psychological theory to evaluate scalable behaviour change for promoting latrine use in rural India. Assefa *et al.* (2018) developed a water security assessment framework for the assessment of water supply, sanitation, and hygiene factors and discovered that sanitation and hygiene factors were at a poor level.

4.10.10 Cluster 10: urban planning and microanalysis. Cluster 10 represents "urban planning and microanalysis," with four keywords and is shown by light pink-coloured bubbles in the network. As the theme represents, Esenarro *et al.* (2023) developed an architectural design for an interpretation centre in Peru for the revaluation of the flora and fauna by using climate analysis and biochemical design strategies and designed an ecological network. Whitmore (2023) designed a small vibrational polishing machine (MiniViP), which was constructed through 3D printing and may help research labs to reach SDGs. Rahman *et al.* (2021) developed a new technique for the identification of building types in Dhaka. Macatulad and Biljecki (2024) implemented a systematic review of urban disaster risk management and highlighted the growth of research on urban resilience.

4.10.11 Cluster 11: resilient construction solutions. Cluster 11 includes four keywords pigeonholed as "resilient construction solutions," shown by light green-coloured bubbles in the network. In light of the theme of the cluster, Xiao *et al.* (2018) emphasised the role of geo-informatics technologies such as photogrammetry and remote sensing in conserving cultural heritage. SDGs also focus on protecting and safeguarding cultural heritage and promoting sustainable tourism. Ambily *et al.* (2024) inspected the influence of sand gradations on fresh properties of printable concrete mixtures. Dorostkar and Najarsadeghi (2023) analysed the impact of the virtual world on urban planning and underlined that the virtual world is an innovative method to reduce the influence of greenhouse gases in cities all over the world.

4.11 Collaboration network

Figure 6 proposes an international collaboration network in virtual-world research, where each node denotes a country, and the extent of the node represents the volume of research production. Countries have been clustered into coloured clusters based on their patterns of collaboration. The blue cluster, led by India, includes Italy, Spain, South Africa and Brazil. The level of interconnectedness among these countries should be quite high. The green cluster,

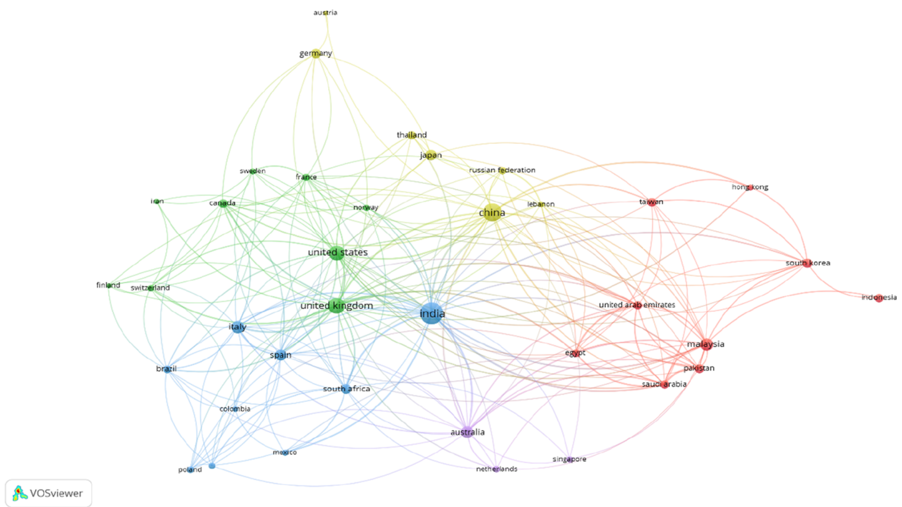

Figure 6. Collaboration network of countries

anchored by the United States of America and the United Kingdom, includes Canada, France and other Western countries. It is amazingly well-knit. The yellow cluster, centred on China, also has Germany, Japan and Russia. The strong intra-Asian and intra- and European collaborations are reflected in this cluster. The red cluster embraces Malaysia, South Korea, Saudi Arabia and the United Arab Emirates. The map underlines the global and interconnected nature of virtual-world research, with India, the United States of America, China and Malaysia as key centres connecting different regional networks.

5. Key findings

The findings of the research address the research questions to a large degree in this research because of the way in which they connect to the theoretical elements.

> RQ1: What patterns can be detected in the development of publications, citing influence, major authors or cooperative associations in virtual worlds and environmental sustainability issues?

Publications on metaverse studies and environmental sustainability have dramatically accelerated from 2017 to nearly 88 pieces per year by 2024. With regard to the number of citations, publications are primarily in the USA, followed by other international nations such as the UK, Germany and China, and led by prestigious journals such as "*Sustainability*" and "*The Journal of Cleaner Production*". Preeminent authors such as "Kumar" and "Avtar Ram" have played an important role in metaverse and sustainability research, emphasising views on climate change and educating others. Top collaboration country indices show China's prominent role in producing research, coupled with the USA's citation impact. Major research institutions such as Harvard University, Hokkaido University and others emphasise the global relevance of this ever-expanding body of research.

> RQ2: What are the new research questions and knowledge areas emerging in the virtual world and environmental sustainability research?

There are some prominent research and practical aspects covered under the 11 clusters that have been exposed through the co-word analysis. Regarding digital immersion and sustainability, research has principally stayed exploratory, leading less towards comparisons and long-term impacts of digital transformation. Practically, there are opportunities to implement immersion technology for learning and for governments to promote ICT for sustainable innovation. Green engineering and manufacturing are lagging in scaling experimental results and implementing AI for optimisation, and there are chances for industries to utilise industrial waste and for universities to advance green start-ups. Computational urban energy modelling remains fragmented, with limited integration of digital twins, AI and cross-regional applications. Urban planners can address this by adopting digital tools for renewable energy mapping and infrastructure management. In AI and metaverse tourism, ethical implications and sustainability remain underexplored, though tourism boards and supply chains can leverage these technologies to reduce environmental footprints and improve customer engagement. Table 8 presents all the identified research gaps derived from the clusters.

6. Implications

6.1 Theoretical implications

The gap analysis in research for the 11 clusters throws up several critical implications for furthering the global sustainability and digital transformation agenda. The results suggest a critical need for further levels of integration among digital technology, environment and social behavioural studies for more holistic frameworks for sustainability innovation (Dostatni *et al.*, 2024). Although much progress has been made in digital immersion platforms such as

Table 8. Research gap based on knowledge clusters

Sr. No.	Application area	Research gap
1	Cluster 1: Digital Immersion & Sustainability	• Limited integration of digital immersion technologies (e.g., AR/VR, metaverse) into mainstream educational curricula; most studies are exploratory (Akinradewo *et al*., 2024; Makrakis, 2024) • Lack of cross-country comparative studies on teachers' self-efficacy in ICT adoption (Makrakis, 2024) • Insufficient research on the long-term sustainability effects of digital transformation in industry and higher education (Hossain *et al*., 2020; Giovanni, 2023)
2	Cluster 2: Green Engineering & Manufacturing	• Need for scaling experimental solutions (e.g., 3D-printed geo-polymeric lattices) into real-world industrial adoption (Almeida *et al*., 2024) • Lack of interdisciplinary approaches linking knowledge-intensive entrepreneurship with SDGs implementation (Gifford and McKelvey, 2019) • Few studies investigate AI-driven optimisation of sustainable production processes (Dostani *et al*., 2024)
3	Cluster 3: Computational Urban Energy Modelling	• Scarce research integrating digital twin frameworks with AI/ML models for large-scale urban sustainability planning (Shehadeh *et al*., 2024) • Insufficient empirical studies on the impact of solar energy modelling in developing economies (Ryali *et al*., 2024) • Limited comparative evidence on urban energy models across diverse climatic zones (Santos *et al*., 2021)
4	Cluster 4: AI & Metaverse Tourism	• Inadequate frameworks for measuring the sustainability of metaverse tourism beyond profitability (Go and Kang, 2023) • Lack of studies connecting Internet of Behaviour (IoB) with sustainable operations in tourism supply chains (Dolgui and Ivanov, 2025) • Absence of research on ethical implications of AI-driven tourism experiences in metaverse settings (Raman *et al*., 2024)
5	Cluster 5: Data-Driven Water Sustainability	• Scarce longitudinal datasets for predictive modelling of water quality trends (Molekoa *et al*., 2019; Duc *et al*., 2023) • Limited integration of neural network models with hydro-geochemical processes for decision-making (Spiller *et al*., 2023) • Lack of research connecting climate change impacts with agricultural water sustainability (Hathat *et al*., 2024)
6	Cluster 6: Green Printing Technologies	• Limited exploration of circular economy practices in additive manufacturing (Sanasee and Hwang, 2024) • Lack of cross-sectoral studies on the impact of 3D printing on SDG achievement (Alami *et al*., 2023) • Need for empirical research on geopolitical disruptions and supply chain resilience in green printing (Bednarski *et al*., 2025)
7	Cluster 7: Climate Adaptation Strategies	• Limited evidence on community-based climate adaptation strategies in developing countries (Kumar *et al*., 2020) • Need for evaluation of VR-based climate education tools in real classrooms (Pimental and Kalyanaraman, 2023) • Scarce studies addressing barriers to disaster risk reduction technologies across different governance contexts (Wamsler and Johannessan, 2020)

(*continued*)

Table 8. Continued

Sr. No.	Application area	Research gap
8	Cluster 8: Virtual Sustainability Learning	• Lack of research on long-term learning outcomes of VR and STEAM integration in sustainability education (Hsiao and Su, 2021) • Limited exploration of indigenous knowledge systems and their integration into virtual learning platforms (Dasgupta *et al.*, 2023) • Few bibliometric studies on the role of governance in sustainable learning environments (Filho *et al.*, 2023)
9	Cluster 9: Maternal Health & Climate	• Lack of scalable studies validating low-cost maternal health technologies (Candidoiri *et al.*, 2024) • Few interdisciplinary investigations linking climate variability with maternal health outcomes (Assefa *et al.*, 2018) • Scarce studies addressing sanitation and hygiene behaviour change interventions in rural contexts (Friedrich *et al.*, 2020)
10	Cluster 10: Urban Planning & Microanalysis	• Limited application of AI/3D technologies in micro-scale urban resilience planning (He *et al.*, 2024; Macatuld and Biljicki, 2024) • Need for more case studies on eco-architectural designs and biodiversity conservation (Esenarro *et al.*, 2023) • Few empirical studies connect urban microanalysis with climate adaptation outcomes (Whitmore, 2023)
11	Cluster 11: Resilient Construction Solutions	• Scarce empirical evidence on the adoption of AI-driven geotechnical mapping in developing countries • Lack of studies integrating resilient construction technologies with cultural heritage preservation (Xiao *et al.*, 2018) • Few explorations on the metaverse's potential in sustainable urban planning (Dorostkar and Najarasadeghi, 2023)

augmented and virtual reality and metaverse platforms, even they lack many concrete scientific studies and global comparisons. This requires greater emphasis and more pragmatic application levels for AI-based technologies in both the industrial and higher education sectors for long-term sustainability benefits (Hoosain *et al.*, 2020; Giovanni, 2023). However, AI and data analytics-based technologies have unexplored levels of predictive analytics capabilities for energy sustainability and urban resilience but have largely been inadequate in terms of integration with broader decision-making and governance frameworks for sustainability (Shehadeh *et al.*, 2024; Spiller *et al.*, 2023). Furthermore, as made evident in the current state of literature, one area that has been left untouched by research pertains to the ethics and social aspects of digital transformation and AI-led tourism experiences and metaverse-based learning environments (Candidori *et al.*, 2024). Likewise, additional studies regarding AI-led solutions for resilient construction projects and environmental mapping will be immensely valuable for urban adaptability and disaster risk (Xiao *et al.*, 2018). Closing this research gap will allow for not only additional theoretical knowledge regarding digital immersion and sustainability and their relation to human experiences, among others, but also contribute meaningfully to the attainment of the UN SDGs (Filho *et al.*, 2023).

6.2 Implications for management and economics

The study embraces a bibliometric and science-mapping approach and underwrites meaningfully to the management and economics domains by systematically synthesising the intellectual structure, evolution and developing trends at the intersection of the metaverse, virtual worlds and sustainable development. From a management outlook, our research recognises key thematic clusters such as digital immersion and sustainability, AI and metaverse tourism, green engineering and manufacturing, data-driven water sustainability, green printing technologies, climate adaptation strategies and virtual sustainability learning. These intuitions are directly significant to managerial decision-making, predominantly in areas such as strategic adoption of metaverse technologies, designing immersive customer experiences and incorporating sustainability into digital business practices. By plotting prominent authors, journals and collaboration networks, the study also aids management scholars in appreciating the knowledge base and research gaps, thereby guiding future empirical investigations.

From an economic standpoint, the convergence of the metaverse and sustainability announces new magnitudes of value creation and resource allocation. Virtual atmospheres have the potential to shrink physical resource consumption (e.g. travel and physical infrastructure), thereby contributing to environmental sustainability. At the same time, they produce new economic opportunities through digital assets, virtual goods and immersive services, reshaping traditional market structures. This study adds to the mounting discourse on virtual economies, digital assets and the role of metaverse platforms in modelling new procedures of economic interaction and value exchange. In short, the paper underwrites by connecting policy-oriented discussions on sustainability with actionable understandings and research directions applicable to management and economics scholars and practitioners.

7. Conclusion

This study provides precious insights into the research landscape on "virtual-world in advancing environmental sustainability" with the help of a bibliometric analysis of 301 articles extracted from the WoS database. This article shows an 11.13% annual growth rate in the research domain. The publication has been prominent in the research field since 2024. The "*Sustainability*" journal is the top contributing journal in the research field with 30 articles. The biggest prolific authors of the research domain are "Kumar" with 9 articles and 3,500 citations, followed by "Avtar Ram" with 9 articles and good H-Index and G-Index. The USA is the top contributing country, followed by China and India. Hokkaido University is the top contributor, with 23 documents, followed by Harvard University with 22 documents. The study also names the top ten articles of the research domain, which the researchers globally cite. Through science mapping, the research highlights the co-occurrence network of keywords, which represents the interconnectedness between topics. The study also reveals the emerging trending topics of the research field in which future research can be carried out. Through bibliometric coupling, the study highlights the interconnectedness between topics that express the depth of the research domain. At last, the study yields precious apprehension about the collaboration network of nations in the research domain. In short, the study demonstrates the growing significance of research on the virtual world with a notable increase in publications in the research domain.

8. Limitations and future research

The study has a few constraints that must be acknowledged. Firstly, this research includes articles that are extracted from the WoS database. It may be possible that some other useful articles in the research domain are published in journals that are not registered in the WoS database. Future scholars can explore more databases to seek the depth of the research domain. Second, the study relies on predefined keywords and search strings, which, although wisely raised, may omit relevant studies using alternative terminologies. Future researchers can expand search strategies with broader and alternative keywords. Future researchers can explore this domain by applying advanced text-mining or machine learning techniques to reveal unseen patterns. Thirdly, this study includes only articles that are published in the

English language. Future researchers can add more language articles to explore the research domain and contribute more significantly to it. Table 8 also provides research gaps in the research domain based on knowledge clusters. Future scholars can explore the domain and fill the research gaps in it.

Author contributions

All authors contributed to the study conception and design. All authors have read and approved the final manuscript.

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References

Akinradewo, O., Hafez, M., Aigbavboa, C., Ebekozien, A., Adekunle, P. and Otasowie, O. (2024), "Innovating built environment education to achieve SDG 4: key drivers for integrating augmented reality technologies", *Sustainability*, Vol. 16 No. 19, p. 8315, doi: 10.3390/su16198315.

Alabidi, S., Alarabi, K., Khurma, O.A., Alarabi, A. and Taani, R. (2024), "Sustainability in three dimensions: mapping the metaverse's blueprint on sustainable development goals (SDGs) through a bibliometric journey", *Proceedings of the 25th International Arab Conference on Information Technology (ACIT 2024)*, IEEE, pp. 1-7.

Alami, A.H., Olabi, A.G., Alashkar, A., Alasad, S., Aljaghoub, H., Rezk, H. and Abdelkareem, M.A. (2023), "Additive manufacturing in the aerospace and automotive industries: recent trends and role in achieving sustainable development goals", *Ain Shams Engineering Journal*, pii/S2090447923004057?via%3Dihub.

Almeida, M.M., Gonçalves, N.P., Gameiro, T., Alves, Z., Labrincha, J.A. and Novais, R.M. (2024), "3D-printing bauxite residue/fly ash-containing geopolymers as promising metal sorbents for water treatment", *Waste Management*, Vol. 190, pp. 35-44, doi: 10.1016/j.wasman.2024.09.007.

Ambily, P.S., Kaliyavaradhan, S.K., Sebastian, S. and Shekar, D. (2024), "Mixing approach for 3D printable concrete: method of optimisation of superplasticiser dosage", *Magazine of Concrete Research*, Vol. 76 No. 11, pp. 574-590.

Assefa, Y.T., Babel, M.S., Sušnik, J. and Shinde, V.R. (2018), "Development of a generic domestic water security index, and its application in Addis Ababa, Ethiopia", *Water*, Vol. 11 No. 1, p. 37, doi: 10.3390/w11010037.

Bauserman, M., Thorsten, V.R., Nolen, T.L., Patterson, J., Lokangaka, A., Tshefu, A., Patel, A.B., Hibberd, P.L., Garces, A.L., Figueroa, L., Krebs, N.F., Esamai, F., Nyongesa, P., Liechty, E.A., Carlo, W.A., Chomba, E., Goudar, S.S., Kavi, A., Derman, R.J., Saleem, S., Jessani, S., Billah, S.M., Koso-Thomas, M., McClure, E.M., Goldenberg, R.L. and Bose, C. (2020), "Maternal mortality in six low and lower-middle income countries from 2010 to 2018: risk factors and trends", *Reproductive Health*, Vol. 17 No. Suppl 3, p. 173, doi: 10.1186/s12978-020-00990-z.

Bednarski, L., Roscoe, S., Blome, C. and Schleper, M.C. (2025), "Geopolitical disruptions in global supply chains: a state-of-the-art literature review", *Production Planning & Control*, Vol. 36 No. 4, pp. 536-562.

Candidori, S., Dozio, N., Osouli, K., Graziosi, S., Zanini, A.A., Costantino, M.L. and De Gaetano, F. (2024), "Improving maternal safety: usability and performance assessment of a new medical device for the treatment of postpartum haemorrhage", *Applied Ergonomics*, Vol. 117, 104223, doi: 10.1016/j.apergo.2023.104223.

Dasgupta, R., Dhyani, S., Basu, M., Kadaverugu, R., Hashimoto, S., Kumar, P., Johnson, B.A., Takahashi, Y., Mitra, B.K., Avtar, R. and Mitra, P. (2023), "Exploring indigenous and local knowledge and practices (ILKPs) in traditional jhum cultivation for localizing sustainable development goals (SDGs): a case study from Zunheboto district of Nagaland, India", *Environmental Management*, Vol. 72 No. 1, pp. 147-159, doi: 10.1007/s00267-021-01514-6.

Dolgui, A. and Ivanov, D. (2025), "Internet of behaviors: conceptual model, practical and theoretical implications for supply chain and operations management", *International Journal of Production Research*, Vol. 63 No. 1, pp. 1-8, doi: 10.1080/00207543.2024.2372008.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N. and Lim, W.M. (2021), "How to conduct a bibliometric analysis: an overview and guidelines", *Journal of Business Research*, Vol. 133, pp. 285-296, doi: 10.1016/j.jbusres.2021.04.070.

Dorostkar, E. and Najarsadeghi, M. (2023), "Sustainability and urban climate: how the virtual world can influence urban planning?", *Environment and Planning B: Urban Analytics and City Science*, Vol. 50 No. 7, pp. 1711-1717, doi: 10.1177/23998083231181596.

Dostatni, E., Osiński, F., Mikołajewski, D., Sapietová, A. and Rojek, I. (2024), "Neural networks for prediction of 3D printing parameters for reducing particulate matter emissions and enhancing sustainability", *Sustainability*, Vol. 16 No. 19, p. 8616, doi: 10.3390/su16198616.

Duc, N.H., Kumar, P., Lan, P.P., Kurniawan, T.A., Khedher, K.M., Kharrazi, A., Saito, O. and Avtar, R. (2023), "Hydrochemical indices as a proxy for assessing land-use impacts on water resources: a sustainable management perspective and case study of Can Tho City, Vietnam", *Natural Hazards*, Vol. 117 No. 3, pp. 2573-2615, doi: 10.1007/s11069-023-05957-4.

Duglio, S. and Ivanov, S.H. (2026), "Metaverse, sustainable development goals and local development: a mutually beneficial relationship?", *Foresight*, Vol. 28 No. 2, pp. 203-222, doi: 10.1108/fs-07-2025-0149.

Esenarro, D., Vasquez, P., Morales, W. and Raymundo, V. (2023), "Interpretation center for the revaluation of flora and fauna in Cusco, Perú'", *Buildings*, Vol. 13 No. 9, p. 2345, doi: 10.3390/buildings13092345.

Filho, W.L., Abubakar, I.R., Mifsud, M.C., Eustachio, J.H.P.P., Albrecht, C.F., Dinis, M.A.P., Borsari, B., Sharifi, A., Levesque, V.R., Ribeiro, P.C.C., LeVasseur, T.J., Pace, P., Trevisan, L.V. and Dibbern, T.A. (2023), "Governance in the implementation of the UN sustainable development goals in higher education: global trends", *Environment, Development and Sustainability*, Vol. 27 No. 9, pp. 1-24, doi: 10.1007/s10668-023-03278-x.

Friedrich, M., Balasundaram, T., Muralidharan, A., Raman, V.R. and Mosler, H.-J. (2020), "Increasing latrine use in rural Karnataka, India using the risks, attitudes, norms, abilities, and self-regulation approach: a cluster-randomized controlled trial", *Science of the Total Environment*, Vol. 707, 135366, doi: 10.1016/j.scitotenv.2019.135366.

Gifford, E. and McKelvey, M. (2019), "Knowledge-intensive entrepreneurship and S3: conceptualizing strategies for sustainability", *Sustainability*, Vol. 11 No. 4824, pp. 1-16, doi: 10.3390/su11184824.

Giovanni, P.D. (2023), "Sustainability of the virtual world: a transition to Industry 5.0", *Sustainability*, Vol. 15 No. 7, p. 6079.

Go, H. and Kang, M. (2023), "Virtual world tourism for sustainable tourism development: tourism agenda 2030", *Tourism Review*, Vol. 78 No. 2, pp. 381-394, doi: 10.1108/tr-02-2022-0102.

Gössling, S. (2020), "Technology, ICT and tourism: from big data to the big picture", *Journal of Sustainable Tourism*, Vol. 29 No. 5, pp. 849-858, doi: 10.1080/09669582.2020.1865387.

Guandalini, I. (2022), "Sustainability through digital transformation: a systematic literature review for research guidance", *Journal of Business Research*, Vol. 148, pp. 456-471, doi: 10.1016/j.jbusres.2022.05.003.

Hathat, Z.E., Venkatesh, V.G., Sreedharan, V.R., Zouadi, T., Manimuthu, A., Shi, Y. and Srinivas, S.S. (2024), "Leveraging greenhouse gas emissions traceability in the groundnut supply chain: blockchain-enabled off-chain machine learning as a driver of sustainability", *Information Systems Frontier*, pp. 2059-2076, doi: 10.1007/s10796-024-10514-w.

He, W., Cao, S., Du, M., Meng, X., Yang, Z. and Yang, Y. (2024), "The effect of urban form parameters on annual and diurnal cycles of land surface temperature with 30-meter hourly resolution", *Sustainable Cities and Society*, Vol. 115.

Higginbotham, G. (2021), “Virtual connections: improving global neurosurgery through immersive technologies”, *Frontiers in Surgery*, Vol. 8, 629963, doi: 10.3389/fsurg.2021.629963.

Hilty, L.M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M. and Wäger, P.A. (2006), “The relevance of information and communication technologies for environmental sustainability: a prospective simulation study”, *Environmental Modelling & Software*, Vol. 21 No. 11, pp. 1618-1629, doi: 10.1016/j.envsoft.2006.05.007.

Hoosain, M.S., Paul, B.S. and Ramakrishna, S. (2020), “The impact of 4IR digital technologies and circular thinking on the United Nations sustainable development goals”, *Sustainability*, Vol. 12 No. 23, 10143, doi: 10.3390/su122310143.

Hsiao, P.W. and Su, C.H. (2021), “A study on the impact of STEAM education for sustainable development courses and its effects on student motivation and learning”, *Sustainability*, Vol. 13 No. 7, p. 3772, doi: 10.3390/su13073772.

Jauhiainen, J.S., Krohn, C. and Junnila, J. (2022), “Metaverse and sustainability: systematic review of scientific publications until 2022 and beyond”, *Sustainability*, Vol. 15 No. 1, p. 346, doi: 10.3390/su15010346.

Johri, A., Joshi, P., Kumar, S. and Joshi, G. (2024), “Metaverse for sustainable development: a bibliometric analysis and systematic literature review”, *Journal of Cleaner Production*, Vol. 435, 140610, doi: 10.1016/j.jclepro.2024.140610.

Kazak, J.K. and Świąder, M. (2018), “SOLIS—a novel decision support tool for the assessment of solar radiation in ArcGIS”, *Energies*, Vol. 11 No. 8, p. 2105, doi: 10.3390/en11082105.

Kumar, P., Johnson, B.A., Dasgupta, R., Avtar, R., Chakraborty, S., Kawai, M. and Magcale-Macandog, D.B. (2020), “Participatory approach for more robust water resource management: case study of the Santa Rosa sub-watershed of the Philippines”, *Water*, Vol. 12 No. 4, p. 1172, doi: 10.3390/w12041172.

Macatulad, E. and Biljecki, F. (2024), “Continuing from the Sendai Framework midterm: opportunities for urban digital twins in disaster risk management”, *International Journal of Disaster Risk Reduction*, Vol. 102, 104310, doi: 10.1016/j.ijdrr.2024.104310.

Makrakis, V. (2024), “Teachers’ resilience scale for sustainability enabled by ICT/metaverse learning technologies: factorial structure, reliability, and validation”, *Sustainability*, Vol. 16 No. 17, p. 7679, doi: 10.3390/su16177679.

Molekoa, M.D., Avtar, R., Kumar, P., Minh, H.V.T. and Kurniawan, T.A. (2019), “Hydrogeochemical assessment of groundwater quality of Mokopane area, Limpopo, South Africa using statistical approach”, *Water*, Vol. 11 No. 9, p. 1891, doi: 10.3390/w11091891.

Mukherjee, A., Dhak, P., Mandal, D. and Dhak, D. (2024), “Solvothermal synthesis of 3D rod-shaped Ti/Al/Cr nano-oxide for photodegradation of wastewater micropollutants under sunlight: a green way to achieve SDG 6”, *Environmental Science and Pollution Research*, Vol. 31 No. 46, pp. 56901-56916, doi: 10.1007/s11356-023-30112-8.

Mutlu Avinç, G. and Yıldız, A. (2025), “A bibliometric and systematic review of scientific publications on metaverse research in architecture: web of science (WoS)”, *International Journal of Technology and Design Education*, Vol. 35 No. 2, pp. 825-849, doi: 10.1007/s10798-024-09918-1.

Parr, S.F. (2022), “When indicators fail: SPAR, the invisible measure of pandemic preparedness”, *Policy and Society*, Vol. 41 No. 4, pp. 528-540, doi: 10.1093/polsoc/puac024.

Pimentel, D. and Kalyanaraman, S. (2023), “Virtual climate scientist: a VR learning experience about paleoclimatology for underrepresented students”, *Interactive Learning Environments*, Vol. 31 No. 7, pp. 4426-4439, doi: 10.1080/10494820.2021.1969582.

Rahman, M.M., Avtar, R., Ahmad, S., Inostroza, L., Misra, P., Kumar, P., Takeuchi, W., Surjan, A. and Saito, O. (2021), “Does building development in Dhaka comply with land use zoning? An analysis using nighttime light and digital building heights”, *Sustainability Science*, Vol. 16, pp. 1323-1340, doi: 10.1007/s11625-021-00923-0.

Raman, R., Hughes, L., Mandal, S., Das, P. and Nedungadi, P. (2024), "Mapping metaverse research to the sustainable development goal of good health and well-being", *IEEE Access*, Vol. 12, pp. 180631-180651, doi: 10.1109/access.2024.3502171.

Ryali, N.S.D., Tripathi, N.K., Ninsawat, S. and Singh, J.G. (2024), "Geospatial assessment of solar energy potential: utilizing MATLAB and UAV-derived datasets", *Buildings*, Vol. 14 No. 6, doi: 10.3390/buildings14061781.

Sanassee, L. and Henrage, K. (2024), "Production of 3D printing filament from plastic bottles waste using a low-income settings extruder as an opportunity to reduce plastic pollution in small island developing states", *Journal of Material Cycles and Waste Management*, Vol. 26 No. 5, pp. 2841-2852, doi: 10.1007/s10163-024-02005-6.

Santos, T., Deus, R., Rocha, J. and Tenedório, J.A. (2021), "Assessing sustainable urban development trends in a dynamic tourist coastal area using 3D spatial indicators", *Energies*, Vol. 14 No. 16, p. 5044, doi: 10.3390/en14165044.

Saraswat, C., Kumar, P., Dasgupta, R., Avtar, R. and Bhalani, P. (2019), "Sustainability assessment of groundwater quality in western India to achieve urban water security", *Applied Water Science*, Vol. 9 No. 4, p. 73, doi: 10.1007/s13201-019-0956-2.

Sharifi, A., Allam, Z., Bibri, S.E. and Khavarian-Garmsir, A.R. (2024), "Smart cities and sustainable development goals (SDGs): a systematic literature review of co-benefits and trade-offs", *Cities*, Vol. 146, 104659, doi: 10.1016/j.cities.2023.104659.

Sharifi, A., Amirzadeh, M. and Khavarian-Garmsir, A.R. (2025), "The metaverse as a future form of smart cities: a systematic literature review of co-benefits and trade-offs for sustainable development goals", *Cities*, Vol. 161, 105879, doi: 10.1016/j.cities.2025.105879.

Shehadeh, A., Alshboul, O. and Arar, M. (2024), "Enhancing urban sustainability and resilience: employing digital twin technologies for integrated WEFE nexus management to achieve SDGs", *Sustainability*, Vol. 16 No. 17, p. 7398, doi: 10.3390/su16177398.

Skrzypczak, I., Oleniacz, G., Leśniak, A., Zima, K., Mrówczyńska, M. and Kazak, J.K. (2022), "Scan-to-BIM method in construction: assessment of the 3D buildings model accuracy in terms of inventory measurements", *Building Research & Information*, Vol. 50 No. 8, pp. 859-880, doi: 10.1080/09613218.2021.2011703.

Spiller, D., Carbone, A., Amici, S., Thangavel, K., Sabatini, R. and Laneve, G. (2023), "Wildfire detection using convolutional neural networks and PRISMA hyperspectral imagery: a spatial–spectral analysis", *Remote Sensing*, Vol. 15 No. 19, p. 4855, doi: 10.3390/rs15194855.

Tiwari, S. and Srivastava, R. (2025), "Performance analysis of sustainable metaverse: a bibliometric analysis", *Benchmarking: An International Journal*, Vol. 32 No. 6, pp. 2276-2300.

United Nations (2023), "Take action for the sustainable development goals", available at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed 31 May 2023).

Wamsler, C. and Johannessan, A. (2020), "Meeting at the crossroads? Developing national strategies for disaster risk reduction and resilience: relevance, scope for, and challenges to, integration", *International Journal of Disaster Risk Reduction*, pii/S2212420919309239?via%3Dihub.

Wang, Y., Su, Z., Xing, R., Liu, D., Luan, T.H. and Shen, X. (2022), "A survey on the metaverse: fundamentals, security, and privacy", *IEEE Communications Surveys & Tutorials*, Vol. 25 No. 1, pp. 32-64, doi: 10.1109/COMST.2022.3202047.

Whitmore, L. (2023), "A mini vibrational polishing machine produced by 3D printing", *Ultramicroscopy*, Vol. 243, 113630.

Xiao, W., Mills, J., Guidi, G., Rodríguez-González, P., Barsanti, S.G. and González-Aguilera, D. (2018), "Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals", *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 142, pp. 389-406, doi: 10.1016/j.isprsjprs.2018.01.001.

Further reading

Anderson, J. (2022), *The Virtual World in 2040*, Pew Research Center.

De Giovanni, P. (2023), "Sustainability of the virtual world: a transition to Industry 5.0", *Sustainability*, Vol. 15 No. 7, p. 6079, doi: 10.3390/su15076079.

Liu, Y. (2023), "Ecological thinking about the metaverse from a posthumanist perspective", *Critical Arts*, Vol. 38 Nos 2-3, pp. 86-103, doi: 10.1080/02560046.2023.2276423.

United Nations (2015), *Transforming Our World: The 2030 Agenda for Sustainable Development*, United Nations, New York.

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