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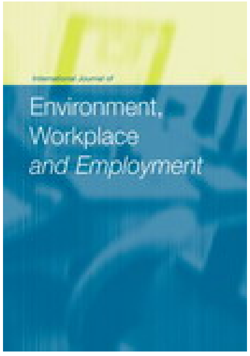

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An examination of the environmental and climatic consequences stemming from the integration of the Metaverse into converging digital ecosystems

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Abstract: This paper delves into the environmental and climatic consequences stemming from the integration of the Metaverse into converging digital ecosystems. Current literature on the impacts of the Metaverse on the environment and climate change does not offer practical solutions and approaches to mitigate these impacts within the context of digital ecosystems. The research methodology adopted was an integrative literature review design in which multiple sources were analysed to provide a comprehensive understanding of the topic. Findings revealed five critical areas in which the Metaverse is most likely to have a notable impact on environmental sustainability and the climate: 1) energy consumption; 2) e-waste; 3) rare earth metals and conflict minerals; 4) changes in physical travel; 5) encouraging

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sustainable behaviours. The findings underscore the role of renewable and alternative resources, recycling initiatives, and cross-sector collaboration in mitigating the relevant negative impacts.

Keywords: environment; climate; climate change; Metaverse; sustainability; digital ecosystem; energy; e-waste; conflict minerals; travel.

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1 Introduction

When Facebook renamed itself Meta in 2021, the Metaverse quickly became a topic of intense social discussion and business investment (Meta, 2022). The Metaverse has been defined as a space where digital and physical worlds are merged to create a shared virtual space where users explore three-dimensional virtual worlds and interact with each other (Jauhiainen et al., 2023). Some experts consider the Metaverse as the next level of evolution of the internet, where characteristics of social media, gaming, and cryptocurrency are combined to create a new reality where users can socialise, shop, work, and engage in entertainment through avatars (Kraus et al., 2023). This experience is enabled by the use of augmented reality (AR), virtual reality (VR), and extended reality (XR) technologies. Experts predict that the Metaverse will likely become an industry worth up to $5 trillion by 2030 (McKinsey & Company, 2022).

As with every new technology that promises to disrupt social and economic systems, the Metaverse has crucial implications for sustainability, climate change, the global environment, and society (Esposito et al., 2023). Technologies that form the foundations of the Metaverse, such as VR headsets, cloud computing, blockchain-based cryptocurrency, and NFTs, are all powered by electricity and physical infrastructure, such as data centres (Stoll et al., 2022). These technologies consume far more energy than non-Metaverse technologies and result in highly increased carbon emissions – for example, a single NFT transaction produces as much CO_2 as 18 litres of diesel.

Nevertheless, many aspects of the Metaverse can also encourage sustainability and lessen global CO_2 emissions. The virtualisation of work, socialising, and shopping can decrease physical travel and lessen global waste, while immersive experiences can help laypersons understand the impact of climate change (Lo and Tsai, 2022). The Metaverse is expected to tremendously impact social and economic systems, changing economic infrastructure, industries, employment, and social structures globally (De Giovanni, 2023). With the looming impact of various environmental and social challenges, it is crucial to consider the ecological impact of the Metaverse and how to maximise its potential for advancing global environmental and social sustainability and the United Nations sustainable development goals (SDGs) (Umar, 2022).

Some emergent studies have examined the Metaverse and sustainability from the perspective of energy (Zhao et al., 2023), transport (Deveci et al., 2022), travel (Go and Kang, 2023), and digital transformation (De Giovanni, 2023). The problem is that because the development of the Metaverse is still in its early stages, research is scarce on the Metaverse, environmental sustainability, and climate change as Metaverse technologies evolve, and existing research lacks proposed solutions to the environmental problems the Metaverse poses (Jauhiainen et al., 2023; Kshetri and Dwivedi, 2023).

This integrative literature review aims to better understand how Metaverse technologies can impact environmental sustainability and climate change. The findings of this study will answer crucial questions about the Metaverse's impact on the environment and climate change and offer actionable solutions to combat the potential negative environmental consequences of this rapidly emerging technology. This integrative literature review is significant in promoting positive social change and advancing professional practice in the Metaverse that is in line with the SDGs. Since the Metaverse will likely become a crucial disruptor to our current economy and society, it is vital to consider its role in meeting SDG targets by 2030. In-depth research on the Metaverse's impact on environmental sustainability that proposes solutions has yet to be conducted.

This integrative literature review is framed by the following research question: *What are the impacts of the Metaverse digital ecosystem on global environmental sustainability and climate change?*

2 Conceptual framework

Despite the growing wealth of research and publications on the Metaverse, there is a dearth of literature discussing issues of the Metaverse and sustainability (Jauhiainen et al., 2023). Metaverse applications and their complex nature are relatively new topics in the scholarly literature and do not allow the emergence of a reference model for grounding empirical study on their impact on climate change and the environment. Given this limitation in the theoretical literature, this integrative literature review study is grounded in Kontogianni and Anthopoulos's (2024) concept of the Metaverse as a digital ecosystem.

3 The Metaverse as a digital ecosystem

Ecosystems have been defined as "aggregations of organisms engaging in mutual interactions, denoted as complex networks of interdependent resources" [Kontogianni and Anthopoulos, (2024), p.4]. A digital ecosystem is a diverse system where interdependence is demonstrated across stakeholders, infrastructures, resources, and institutions. The Metaverse is seen as the next generation of the digital ecosystem of the Web 2.0 internet (Yang et al., 2024).

Kontogianni and Anthopoulos (2024) additionally see the Metaverse as a business ecosystem, demonstrating the characteristics of an economic community with a network of interrelated individuals and organisations, including producers, consumers, and competitors. This economic community can include the use of Metaverse applications by organisations and entrepreneurial ventures (Halkias et al., 2023b). Other scholars see the Metaverse as a meta-ecosystem hosting other, smaller ecosystems in the form of platforms. These platforms are organisational fields that are united through shared technology standards and core technologies, all supporting the process of value co-creation (Schöbel and Leimeister, 2023).

In the digital ecosystem of the Metaverse, various actors collaborate, socialise, and conduct business processes (Kontogianni and Anthopoulos, 2024). This ecosystem is rapidly emerging and dynamic, changing as the hardware and software technologies associated with it advance. Kontogianni and Anthopoulos (2024) divide this ecosystem into various categories:

a centralised and decentralised Metaverse gateways

b NFT and PFT collections

c social and meeting hubs

d general economy for crypto wallets and access and marketplaces

e music and entertainment

f avatar and interoperability

g digital fashion and identity

h user interface and immersion

i visualisation and digital twin

j development and infrastructure

k cloud, scalability and storage, connectivity

l decentralised infrastructure

m artificial intelligence

n marketing.

The sustainability of the Metaverse as a digital ecosystem is an area of growing debate and discussion (Kontogianni and Anthopoulos, 2024). Although the Metaverse can reduce physical mobility and transportation and thus the energy consumption associated with such activities, the tremendous amounts of electricity needed to power Metaverse hardware and software imply a significant increase in carbon emissions. Kontogianni and Anthopoulos (2024) recommend that design and technological specifications must be adapted in order to ensure that the digital Metaverse ecosystem is socially, economically, and environmentally sustainable.

4 Materials and methods

The integrative literature review method allows researchers to combine and summarise knowledge from empirical studies, theoretical writings, and industry reports to create an in-depth understanding of a specific theme or topic (Torraco, 2016). This method allows the researcher to investigate a particular issue, the factors that contribute to this issue, and how the issue evolves. Research topics constantly change and develop, prompting practitioners, researchers, and policymakers to explore these new developments (Webster and Watson, 2002). These new developments can be explored through studies of behaviours, events, and reasons behind changes in a topic, enhancing different stakeholders' understanding of what will likely change and stay constant (Boote and Beile, 2005). Literature reviews can also draw parameters for future conceptual frameworks (Halkias and Neubert, 2020).

The inclusion criteria for this study included:

a peer-reviewed scholarly papers, conference papers, industry reports, and news articles

b related to the central research question

c published after the year 2018.

The data collection and analysis took place over six months, from October 2022 to April 2023. This primary data collection period was preceded by a three-month preliminary collection period. We developed a comprehensive search strategy of the representative literature for this integrative literature review using keywords and key phrases such as *Metaverse and sustainability*, *Metaverse and climate change*, *Metaverse energy use*, *Metaverse and SDGs*, and *Metaverse and pollution*.

Google Scholar and institutional library databases were used to collect sources for this study. Although Google Scholar has been questioned regarding whether its information is accurate (Serenko, 2015), the search engine provides recent citation numbers and includes grey literature such as reports and conference papers. The documents selected for this study included Metaverse, VR, AR, sustainability, climate change, pollution, energy, and SDGs.

In selecting documents for this integrative literature review, we decided against including the criterion of methodological quality. Our aim was not to investigate the validity of other authors' claims; relatively few empirical studies have been conducted on this topic, given its newly emerging nature. Instead, our focus is to gain a greater understanding of the topic of the Metaverse and sustainability in order to generate relevant recommendations and actionable solutions for future practice and research.

During the data analysis phase, we performed a thematic analysis of selected literature to build an understanding of the negative and positive impacts of Metaverse technologies on global environmental sustainability and how the negative impacts can be mitigated. After synthesising key arguments and themes from the literature, we organised our findings according to several thematic clusters to shed light on information or knowledge omitted, hidden, or taken for granted in the existing literature. We follow with implications and recommendations for practice and future research, as well as conclusions on the results of our study.

5 Results

5.1 Energy consumption

The servers that power the Metaverse are projected to consume significant energy (Boston et al., 2022) as the Metaverse is already evolving into a highly detailed, interactive, and immersive digital ecosystem. This environment needs to be powered by servers, and the high requirements of the Metaverse will require powerful servers running 24/7 (Xiang, 2022). The devices needed to access the Metaverse, such as VR headsets, will consume energy. The energy use of data centres globally is already a significant environmental concern, and the energy needs of the Metaverse could exacerbate this issue (Morini Bianzino, 2022).

The Metaverse is expected to be a data-intensive environment, requiring high-speed, low-latency communication between users and servers (Stoll et al., 2022). According to estimates, data centres already account for at least 1% of global electricity use, which could increase as the Metaverse expands (International Energy Agency, 2023). These centres require significant upgrades to their speed, bandwidth, and computing power to accommodate higher data traffic and the computing needs of users who will spend more time online (Stoll et al., 2022). Intel predicts that a thousand-fold increase in computing power will be required to power the Metaverse (Koduri, 2021). All this data processing will result in significant CO_2 emissions.

The devices that users need to access the Metaverse also require a significant amount of energy consumption. These devices include the VR/AR headsets that provide the most immersive experiences and the computers, game consoles, and other devices that might be used to access the Metaverse (Kshetri and Dwivedi, 2023). These devices could require high-performance components to render complex 3D environments, like high-end graphics cards, which consume more energy than typical computing tasks. More energy will be consumed in these hardware's production and disposal processes (Aria et al., 2023).

Blockchain technology, which remains a critical component of the Metaverse infrastructure, further increases this energy consumption (Huang et al., 2022). Some blockchain technologies, like Bitcoin, consume significant energy due to their reliance on computationally intensive processes like mining (Moniruzzaman et al., 2022). Blockchain technologies are powered by AI, which requires high amounts of energy to be trained and run. GPT-3, for example, emitted 552 MTs of CO_2 and used 1,287 megawatts of energy during training (Wiggers, 2022).

In order to mitigate the high levels of energy consumed by the Metaverse and its associated technologies, the ongoing evolution and design of the Metaverse will have to consider energy-saving designs and renewable energy sources. Efforts are already being made to improve the energy efficiency of data centres, particularly their server management, cooling systems, and server utilisation rates (Vasques et al., 2019). Servers are being implemented with energy-saving functions, such as reducing power consumption during low utilisation and power distribution units that monitor power usage (Long et al., 2022). Emerging tools such as deduplication software allow organisations to reduce the amount of data they store – and thus the number of servers needed – by 95% (Energy Star, n.d.a). Blockchain technologies can also take up more energy-efficient mechanisms such as proof-of-authority or proof-of-stake rather than proof-of-work systems, which are more energy-intensive (Stoll et al., 2022). Renewable energy sources hold great potential for Metaverse technologies. Data centres are starting to drive the demand for renewable energy worldwide; Amazon and Microsoft, for example, were the two largest corporate buyers of renewable energy through specialised contracts (Flanagan, 2023).

The Metaverse also poses opportunities to improve global energy efficiency via digital twins. Digital twins are already being used to model energy-use scenarios for organisations, which are then used to reduce energy consumption in the physical twin (Zhao et al., 2023). For example, the NVIDIA Omniverse allows companies to re-create physical spaces and buildings in the Metaverse for architects to test out various energy-use scenarios, such as increasing the energy efficiency of air conditioning or determining the energy use of solar panels versus traditional heating (Chen, 2022). Microsoft is one of the pioneering companies in using digital twins, cutting energy consumption in one Coca-Cola bottling factory by over 9% (King, 2022). Several countries, such as Shanghai and Singapore, are already working on digital twins of entire cities to monitor energy consumption and interact with their physical twins to reduce waste and electricity consumption (Sprinzen, 2022).

5.2 E-waste

Aside from the electricity and software needs of the Metaverse, a new range of hardware is required to access the digital ecosystem of the Metaverse (Palak et al., 2023). These hardware include VR/AR headsets and simulation peripherals like throttle controls and joysticks. Other devices needed to access VR/AR platforms include wristbands, cyber shoes, glasses, and tactile gloves (Kshetri and Dwivedi, 2023). The production of this new range of products, which will be produced in the thousands to accommodate the growing range of Metaverse users, also means that these thousands of new products will also be disposed of and become e-waste (electronic waste) (Jauhiainen et al., 2023).

E-waste is already growing worldwide, with data from the United Nations indicating that global e-waste is expected to exceed 74 million metric tons by 2030 (De Giovanni and Folgiero, 2023). Less than one-fifth of global e-waste is appropriately documented and recycled (De Giovanni and Folgiero, 2023). E-waste poses significant environmental threats – technological devices are not biodegradable and contain many hazardous materials and toxins, which accumulate in the air, soil, and water (Aria et al., 2023). The energy required to manufacture new products, rather than produce them from recycled materials, contributes to greenhouse gas emissions – the processes required to manufacture one tonne of laptops result in 10 tonnes of carbon dioxide emissions (Geneva Environment Network, 2023). Recycling of e-waste remains low globally for various reasons, among them that many electronic devices still contain non-recyclable components (Liu et al., 2023).

Mitigating the impact of Metaverse e-waste will require an intentionally circular approach to product design, regulation, and waste management. Metaverse devices must be designed with longevity in mind (Aria et al., 2023). For example, modular design can be implemented into Metaverse devices, so when upgrades are needed, consumers should be able to buy replacements for specific parts of the device, such as new sensors or a new display, rather than having to buy an entirely new product (Braud et al., 2022). Some current devices already incorporate these features, such as the HP Reverb G2 Omnicept Edition, a VR headset with removal sensors (HP, n.d). Graphics cards can also be designed to be removed, upgraded, or recycled at the end of their lifespan. Devices can also be designed with recycled materials like plastic, metals, and glass. A crucial part of ensuring the sustainability of Metaverse devices will involve organisations implementing effective e-waste management programs. Organisations should offer consumers take-back programs for old devices, repair services, and recycling programs that allow old devices to be recycled rather than wasted (Partida, 2022).

Finally, consumers will need to be educated to understand the impact of e-waste and the importance of recycling their old Metaverse devices. Non-profits and advocacy groups can create communication campaigns through social media and virtual Metaverse worlds with messages tailored to specific consumers most likely to engage with the Metaverse. Metaverse hardware companies can also inform consumers about recycling their devices by including fliers in product packaging or sending targeted communications to their customers (Dwivedi et al., 2022).

5.3 Rare earth metals and conflict minerals

There are 17 elements classified as rare earth metals, such as scandium, dysprosium, neodymium, and yttrium. These elements are classified as ‘rare’ because they are rarely found in large enough amounts to be economically extracted, despite being abundant in the earth’s crust (Nayar, 2021). These are used in various technologies, such as hard drives, electric vehicle motors, and hybrid car batteries (Federation of German Industries, n.d.). Currently, four elements are classified as conflict minerals: tin, tungsten, tantalum, and gold (European Commission, n.d.). These minerals are so named because their mining and extraction often involve human rights abuses, corruption, and armed conflicts. The extraction of these metals also has significant environmental impacts (Federation of German Industries, n.d.).

Electronic devices require a certain amount of rare earth metals and conflict minerals (Dang et al., 2021). The increased demand for Metaverse hardware devices as this digital ecosystem grows will equal an increased demand for these resources. This growing demand can potentially exacerbate the environmental and social destruction caused by these resources' mining, extraction, and disposal (Jauhiainen et al., 2023). The environmental impact of mining, extracting, and processing these resources is mainly destructive (Oladipo et al., 2023). Large areas of land are cleared to make way for mining operations, which leads to soil erosion, deforestation, and the destruction of biodiversity and ecosystems, especially in the case of open pit mining. Processing and extracting these minerals also significantly pollute the atmosphere, soil, and water sources, which are contaminated by toxic chemicals, gases, and particulates (Jouini et al., 2022). Additionally, these elements are often extracted from ores containing radioactive uranium and thorium, which results in significant radioactive waste. The mining process is also fueled by vast amounts of fossil fuels, which emit greenhouse gases and contribute to atmospheric warming (Dang et al., 2021).

Furthermore, this practice involves severe human rights abuses, such as forced labour and highly hazardous working conditions without protection for labourers (United States Government Accountability Office, 2022). In order to mitigate the adverse effects of the growing demand for rare earth metals and conflict minerals that the Metaverse will bring, organisations must ensure supply chain transparency. Companies that make Metaverse hardware will have to comply with existing regulations for tech companies to report their use of conflict minerals, such as the Consumer Protection Act of 2010 and the Dodd-Frank Wall Street Reform in the US (Global Witness, 2017), and the Conflict Minerals Regulation in the EU, which ensures that EU importers of tin, tungsten, tantalum, and gold meet international responsible sourcing standards (European Commission, n.d.). Efforts are also being made to recycle and reuse rare earth metals and conflict minerals used in hardware devices (Jyothi et al., 2020). Extracting these metals from used hardware devices is also less costly and energy-efficient than extracting raw materials (Balaram, 2019).

Another area in which research is underway is the substitution of rare earth metals and conflict minerals in electronics with alternative materials. Efforts are already being made to test electronics made with alternative materials, such as using iron or magnesium instead of rare earth metals in particular kinds of magnets used in hard drives and electric vehicle motors (Irving, 2019; McMahan, 2019). Aluminum is being tested to replace tantalum in capacitors, while graphene, metal mesh, and carbon nanotubes are being tested to replace indium in solar cells and touch screens (Kim et al., 2015).

5.4 Changes in physical travel

One area in which experts have made significantly optimistic predictions about the impact of the digital ecosystem of the Metaverse is the area of physical travel and commuting (Anshari et al., 2022). Roughly 25% of global carbon emissions come from transport, with 75% of transport emissions coming from buses, cars, motorcycles, and trucks (Timperley, 2020). The Metaverse can potentially decrease carbon emissions from transport by reducing the need for physical travel and commuting. Metaverse platforms are already being used to replicate certain features of in-person work and entertainment in the years following the COVID-19 pandemic (Esposito, 2023; Jauhiainen et al., 2023).

If these features become an integrated feature of existing workplaces and social events, such as through virtual meetings, virtual workspaces, and virtual social events, such as concerts, physical travel and the emissions associated with it can be drastically reduced (Kshetri and Dwivedi, 2023). Experts predict that other transport activities, such as pilot training, can be done through Metaverse (Kshetri and Dwivedi, 2023). Metaverse hardware is also becoming more interconnected with other digital devices, reducing the need for workers to travel between workplace and home to access specific files or other digital objects – the Oculus Quest headset, for example, allows users to access files and documents from their personal computer (Allam et al., 2022).

At the time of writing, Metaverse platforms are already being used to offer virtual alternatives to in-person workplaces (Entsminger et al., 2022). Metaverse meeting platform gather.town is a popular choice for virtual work arrangements; in early 2021, the platform already had 4 million users (Seal, 2021). Organisations such as RippleMatch use the platform to mimic real-life collaboration and teamwork. Organisations such as NASA and PwC have been testing Meta's virtual workspace platform, Horizon Workrooms (Link, 2023). In 2021, Korean real estate technology company Zigbang created its own Metaverse work platform, Metapolis, and removed its physical headquarters (Choi, 2022). Metaverse work platforms can also offer new business opportunities to organisations; Zigbang only uses part of the Metapolis platform and leases the rest to other organisations (Choi, 2022). Metaverse platforms are also growing in education, from K-12 institutions to universities to reskilling and upskilling programs (Diaz and Halkias, 2021; Diaz et al., 2022; Halkias et al., 2020, 2023a).

Excessive use of Metaverse platforms, however, may negatively affect users' physical health. Physical activity such as walking or riding bicycles is crucial for maintaining physical health and fitness. If increased use of Metaverse platforms reduces time spent walking and exercising, more people worldwide will live a sedentary lifestyle, negatively impacting their physical health (Donatiello and Marfia, 2022). Virtual gyms, however, are rising to combat this issue (Allam et al., 2022). Nevertheless, the rise of virtual work may negatively impact workers' mental health and well-being (Harkiolakis, 2022; Harkiolakis and Komodromos, 2023).

Finally, requiring access to Metaverse platforms and hardware in order to complete work and social activities risks exacerbating global digital divides. Users will need to be able to afford to pay for Metaverse hardware, such as VR headsets and haptic touch devices, and any potential subscription models for Metaverse platforms, and will need a robust and reliable internet connection to access these platforms (Corpuz, 2023). These requirements can significantly disadvantage users in developing economies and those in developed economies who lack financial security or high incomes. These users will be excluded from work and social events in which Metaverse participation is required, thus increasing already-existing digital and social divides (Soriani and Bonafede, 2023). Older adults and disabled populations can also potentially be excluded from the Metaverse and, thus, from the social and economic opportunities it offers (Allam et al., 2022).

5.5 Encouraging sustainable behaviours

Encouraging citizens worldwide to adopt more sustainable behaviours has recently been a rising social and business trend (De Giovanni, 2023; Mendelsohn, 2021). Consumers are increasingly pushed to recycle and minimise their waste output and energy consumption (Allam et al., 2022). Businesses, meanwhile, are offering more sustainable options for products and services than ever before, such as products made from recycled materials and energy-conserving modes on electronics (Kshetri and Dwivedi, 2023). These trends represent a global push toward the circular economy in business and society (Esposito et al., 2018a, 2018b; Goyal et al., 2018).

Experts predict that the digital ecosystem of the Metaverse can be used to encourage sustainable behaviours further. The infrastructure of the Metaverse already incorporates sustainable activities through the processes of virtualisation (the process of constructing a virtual form of a physical process or activity) and dematerialisation (the reduction in the amount of materials needed to service economic functions in society) (Casciani et al., 2022). As previously explored, the Metaverse is already accelerating the virtualisation of work, socialising, entertainment, and transport (Allam et al., 2022).

The Metaverse is currently enabling the rise of virtual consumption, where users in Metaverse environments can purchase, sell, and trade virtual clothing, art, household goods, and real estate (De Giovanni, 2023; Kreutzer and Klose, 2023). Many virtual items exist as NFTs, which allows them to be minted on a blockchain with their ownership and authenticity recorded and certified (Zhang et al., 2023). As the Metaverse grows and people spend more time in virtual environments, the growth in consumption of virtual items may result in a decreased consumption of physical items and, thus, a decrease in greenhouse gas emissions and global waste (Jauhiainen et al., 2023). The increasing implementation of the Metaverse in business operations will follow previous trends of the growing digitalisation of businesses, which has long had implications for sustainability (Goyal et al., 2019).

Beyond virtual consumption, the Metaverse can enable other activities and processes that encourage sustainable behaviours. Metaverse platforms and technologies can host immersive experiences that educate users on climate change and environmental conservation (Kreutzer and Klose, 2023; Lo and Tsai, 2022). Traditional interventions and campaigns to promote sustainable behaviours, such as distributing brochures, have been found to have a limited effect on behaviour change and learning (Queiroz et al., 2023). So far, immersive climate change education experiments have been met with positive results (Spiegel and Wang, 2024).

However, it is essential to note that sustainability initiatives in the Metaverse are not without certain caveats (Nelson et al., 2020). These initiatives require energy consumption, contributing to CO_2 emissions (Zhang et al., 2023). These initiatives must also be carefully and effectively designed to engage their target audience since poorly designed initiatives will likely not yield positive effects (Aria et al., 2023). Effective design of such initiatives will thus require in-depth research and piloting and adequate funding. Such initiatives must also be accessible and equitable according to each initiative's goals (Barrera and Shah, 2023).

5.6 Critique of the extant literature to identify the future of practice and research

Although the scholarly research literature on the Metaverse as a digital ecosystem has grown significantly in the past two years, there are still notable limitations in the literature. Firstly, the Metaverse remains a nascent field of study and technological development. Although VR and AR technologies and platforms have existed for years, the Metaverse is still under development and has not yet been wholly integrated into mainstream social and work environments (Jauhiainen et al., 2023). As such, the field is still in flux as technologies rapidly advance and more stakeholders become involved in developing and defining what the Metaverse will be. As such, there is still a lack of general agreement on the definition of the Metaverse, its components, and its evolution as a digital ecosystem, and much research on the impact of the Metaverse on the environment and climate change is as yet speculative (Lee, 2021).

Additionally, technological innovations advance rapidly today, while scholarly literature and research often take two or more years from conception to final publication. As such, there is a lag between what has been published in scholarly research and what occurs daily as technology and innovations advance (Christie et al., 2021). As such, much of the most recent assertions and predictions about the Metaverse come from industry reports, scientific journalism, pre-prints, and conference proceedings; although this grey literature is considered reliable, it sometimes lacks the methodological rigor of peer-reviewed scholarly work.

Additionally, existing research on the Metaverse, whether from academia or industries, tends to be affected by cultural and regional biases and commercial interests. Big tech companies are still mainly defining how the Metaverse is being developed in alignment with the pursuit of profitability and scalability, which has traditionally been at odds with environmental and social sustainability (Pellegrino et al., 2023). Existing industry research, even while addressing issues of sustainability in the Metaverse, is thus still potentially influenced by competing interests and drives.

Furthermore, scholars and research institutions in developed economies have done much of the existing research on the Metaverse and sustainability (Ignatyev et al., 2023). Due to several factors impacting developing nations, including a lack of strong internet connectivity, an inability to afford advanced technology products, and a more significant pollution burden, the mass uptake of Metaverse technologies in the developed nations may have adverse social and environmental implications for developing ones and may even deepen existing social and economic divides in the former (Abalansa et al., 2021; Corpuz, 2023; Soriani and Bonafede, 2023).

6 Implications for practice

The results of this integrative literature review have implications for practitioners at every stage of the complex digital ecosystem that facilitates the development of the Metaverse. Practitioners in technology companies that produce Metaverse hardware need to consider their products' production, energy use, and lifecycle. Metaverse hardware must be designed with energy-saving modes and modular parts that can be replaced and reused (Braud et al., 2022). Companies that produce Metaverse hardware should also invest in testing, developing, and using alternatives to rare earth metals in their devices whenever possible (Balaram, 2019). Such companies should also facilitate the recycling and refurbishment of Metaverse hardware, as has been successfully piloted and implemented for other categories of digital devices (Liu et al., 2023).

Practitioners in companies that produce the software, platforms, and core components of the Metaverse, such as NFTS, should also invest in energy efficiency. Several steps can be taken to reduce the high energy consumption of these components, such as using energy-efficient data centres and server farms or those that use renewable energy; centralising resources to reduce the need for multiple copies of data and other assets; using storage optimisation and data deduplication techniques; minimising network traffic by using data compression (Energy Star, n.d.b). Practitioners involved in Metaverse software and platforms can also promote green design principles in the virtual world by creating virtual solar panels and wind turbines and incentivising virtual 'green' initiatives.

7 Recommendations for future research

Although scholarly research on the Metaverse as a digital ecosystem is growing, there remains a lag in such research due to the time it takes for peer review and publication, as is often the case in many areas of study (Christie et al., 2021). As such, scholars should continue researching the impact of the Metaverse on the environment and consider publishing early results on pre-print platforms and via rapid-response publishing. Nascent research should also consider how the mass uptake of Metaverse devices and software may exacerbate or alleviate the conditions that enable climate-change-induced natural disasters, such as mass wildfires and flooding (Funk, 2021). The mass uptake of these devices should also be considered about other effects of climate change since research predicts that climate change will increase crop failure, at least in the United States, and alter tropical cyclone characteristics (Bakkensen and Mendelsohn, 2019; Kim and Mendelsohn, 2023).

Additionally, due to the developing status of the Metaverse, the majority of research on this topic about sustainability and climate change involves future projections and conjectures (Stoll et al., 2022). As such, more research needs to be conducted to measure the actual effect of Metaverse hardware and software on the environment (Fredericks et al., in press). Such efforts can include measuring the energy consumption of a VR headset compared to a standard laptop or experimentally testing the effectiveness of green energy sources in powering a Metaverse device or platform compared to fossil fuels.

There is also a growing number of experimental interventions and scholarly analyses of real-world cases of implementing the Metaverse in social and work spheres. Early experimental interventions must be replicated to ensure validity (Hui et al., 2023). This replication is especially crucial for interventions that promote sustainability, such as conservation and recycling campaigns in VR programs. Further replication can ensure the effectiveness of these interventions, which may encourage their uptake in private and public forums. Analyses of real-world cases should also take a comparative approach and scrutinise different cases in comparison with each other while also taking a critical viewpoint to understand the limitations of each case in terms of its unique cultural environment (Choi, 2022).

8 Conclusions

The collective, virtual shared space of the Metaverse digital ecosystem has been growing exponentially over the past two years, an innovative progression that has triggered many discussions and predictions regarding its environmental impact, particularly its effects on sustainability and climate change. Our study has aimed to critically examine these effects, shedding light on environmental and climatic consequences stemming from the integration of the Metaverse into converging digital ecosystems. This integrative literature review revealed five critical areas of environmental sustainability upon which the mass uptake of Metaverse technologies will have a significant impact: energy consumption, e-waste, rare earth metals and conflict minerals, changes in physical travel, and encouraging sustainable behaviours. Each area will likely experience a complex mix of positive and negative effects. Stakeholders from across different areas of scholarship and practice will need to work together to find practical, effective, agile solutions to ensure that the Metaverse becomes a tool that promotes sustainability and maximises positive environmental and social impacts for generations to come.

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References

Abalansa, S., El Mahrad, B., Icely, J. and Newton, A. (2021) 'Electronic waste, an environmental problem exported to developing countries: the GOOD, the BAD and the UGLY', *Sustainability*, Vol. 13, No. 9, Article 5302, https://doi.org/10.3390/su13095302.

Allam, Z., Sharifi, A., Bibri, S.E., Jones, D.S. and Krogstie, J. (2022) 'The Metaverse as a virtual form of smart cities: opportunities and challenges for environmental, economic, and social sustainability in urban futures', *Smart Cities*, Vol. 5, No. 3, pp.771–801, https://doi.org/10.3390/smartcities503004.

Anshari, M., Syafrudin, M., Fitriyani, N.L. and Razzaq, A. (2022) 'Ethical responsibility and sustainability (ERS) development in a Metaverse business model', *Sustainability*, Vol. 14, No. 23, Article 15805, https://doi.org/10.3390/su142315805.

Aria, R., Archer, N., Khanlari, M. and Shah, B. (2023) 'Influential factors in the design and development of a sustainable Web3/Metaverse and its applications', *Future Internet*, Vol. 15, No. 4, Article 131, https://doi.org/10.3390/fi15040131.

Bakkensen, L.A. and Mendelsohn, R.O. (2019) 'Global tropical cyclone damages and fatalities under climate change: an updated assessment', in Collins, J.M. and Walsh, K. (Eds.): *Hurricane Risk*, pp.179–197, Springer Cham, https://doi.org/10.1007/978-3-030-02402-4_9.

Balaram, V. (2019) 'Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact', *Geoscience Frontiers*, Vol. 10, No. 4, pp.1285–1303, https://doi.org/10.1016/j.gsf.2018.12.005.

Barrera, K.G. and Shah, D. (2023) 'Marketing in the Metaverse: conceptual understanding, framework, and research agenda', *Journal of Business Research*, Vol. 155, Article 113420, https://doi.org/10.1016/j.jbusres.2022.113420.

Boote, D.N. and Beile, P. (2005) 'Scholars before researchers: on the centrality of the dissertation literature review in research preparation', *Educational Researcher*, Vol. 34, No. 6, pp.3–15, https://doi.org/10.3102/0013189X034006003.

Boston, O., Stier, J., Adams, W. and Myles, T. (2022) *Why it's Important to Make the Metaverse an Enabler of Sustainability*, Ernst & Young Global [online] https://assets.ey.com/content/dam/ey-sites/ey-com/en_us/topics/workforce/ey-why-its-important-to-make-the-Metaverse-an-enabler-of-sustainability.pdf (accessed 1 June 2023).

Braud, T., Lee, L.H., Alhilal, A., Fernández, C.B. and Hui, P. (2022) 'DiOS – an extended reality operating system for the Metaverse', *IEEE MultiMedia*, Vol. 30, No. 2, pp.70–80, https://doi.org/10.1109/MMUL.2022.3211351.

Casciani, D., Chkanikova, O. and Pal, R. (2022) 'Exploring the nature of digital transformation in the fashion industry: opportunities for supply chains, business models, and sustainability-oriented innovations', *Sustainability: Science, Practice and Policy*, Vol. 18, No. 1, pp.773–795, https://doi.org/10.1080/15487733.2022.2125640.

Chen, A. (2022) 'How "GREEN" is the METAVERSE? The two sides of the environmental impact of the Metaverse', *Medium*, 16 January [online] https://medium.com/geekculture/how-green-is-the-Metaverse-the-two-sides-of-the-environmental-impact-of-the-Metaverse-6a35913fd329 (accessed 1 June 2023).

Choi, H.Y. (2022) 'Working in the Metaverse: does telework in a Metaverse office have the potential to reduce population pressure in megacities? Evidence from young adults in Seoul, South Korea', *Sustainability*, Vol. 14, No. 6, Article 3629, https://doi.org/10.3390/su14063629.

Christie, A.P., White, T.B., Martin, P.A., Petrovan, S.O., Bladon, A.J., Bowkett, A.E., Littlewood, N.A., Mupepele, A-C., Rocha, R., Sainsbury, K.A., Smith, R.K., Taylor, N.G. and Sutherland, W.J. (2021) 'Reducing publication delay to improve the efficiency and impact of conservation science', *PeerJ*, Vol. 9, Article e12245 [online] https://peerj.com/articles/12245/ (accessed 1 June 2023).

Corpuz, J.C.G. (2023) 'Metaverse phenomenon and its impact on public health', *Journal of Public Health*, Vol. 45, No. 4, epp.838–e839, https://doi.org/10.1093/pubmed/fdad119.

Dang, D.H., Thompson, K.A., Ma, L., Nguyen, H.Q., Luu, S.T., Duong, M.T.N. and Kernaghan, A. (2021) 'Toward the circular economy of rare earth elements: a review of abundance, extraction, applications, and environmental impacts', *Archives of Environmental Contamination and Toxicology*, Vol. 81, No. 4, pp.521–530, https://doi.org/10.1007/s00244-021-00867-7.

De Giovanni, P. (2023) 'Sustainability of the Metaverse: a transition to Industry 5.0', *Sustainability*, 15 (7), Article 6079, https://doi.org/10.3390/su15076079.

De Giovanni, P. and Folgiero, P. (2023) *Strategies for the Circular Economy: Circular Districts and Networks*, Taylor & Francis, New York.

Deveci, M., Mishra, A.R., Gokasar, I., Rani, P., Pamucar, D. and Özcan, E. (2022) 'A decision support system for assessing and prioritizing sustainable urban transportation in Metaverse', *IEEE Transactions on Fuzzy Systems*, Vol. 31, No. 2, pp.475–484, https://doi.org/10.1109/TFUZZ.2022.3190613.

Diaz, J. and Halkias, D. (2021) 'Reskilling and upskilling 4IR leaders in business schools through an innovative executive education ecosystem: an integrative literature review', *Social Science Research Network*, http://dx.doi.org/10.2139/ssrn.3897059.

Diaz, J., Halkias, D. and Thurman, P.W. (2022) *The Innovative Management Education Ecosystem: Reskilling and Upskilling the Future Workforce*, Taylor & Francis, New York.

Donatiello, L. and Marfia, G. (2022) 'Proposing the RecursiVerse overlay application for the Metaverse', *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp.844–845, Institute of Electrical and Electronics Engineers, https://doi.org/10.1109/VRW55335.2022.00273.

Dwivedi, Y.K., Hughes, L., Baabdullah, A.M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M.M., Dennehy, D., Metri, B., Buhalis, D., Cheung, C.M.K., Conboy, K., Doyle, R., Dubey, R., Dutot, V., Felix, R., Goyal, D.P., Gustafsson, A., Hinsch, C., Jebabli, I., … Wamba, S.F. (2022) 'Metaverse beyond the hype: multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy', *International Journal of Information Management*, Vol. 66, Article 102542, https://doi.org/10.1016/j.ijinfomgt.2022.102542.

Energy Star (n.d.a) *Implement Efficient Data Storage Measures* [online] https://www.energystar.gov/products/implement_efficient_data_storage_measure (accessed 1 June 2023).

Energy Star. (n.d.b) *16 More Ways To Cut Energy Waste in the Data Center* [online] https://www.energystar.gov/products/16_more_ways_cut_energy_waste_data_center (accessed 1 June 2023).

Entsminger, J., Esposito, M. and Tse, T. (2022) 'Who will establish Metaverse ethics?', *Project Syndicate*, 17 August [online] https://www.project-syndicate.org/commentary/who-establishes-Metaverse-ethics-by-josh-entsminger-et-al-2022-08?barrier=accesspaylog (accessed 1 June 2023).

Esposito, M. (2023) 'The five forces that help us understand Globalization 2.0', *HULT Blogs* [online] https://www.hult.edu/blog/the-five-forces-that-help-us-understand-globalization-2-0/ (accessed 1 June 2023).

Esposito, M., Halkias, D., Tse, T. and Harkiolakis, T. (2023) 'Environmental and climate impacts of the Metaverse', *SSRN Electronic Journal*, http://dx.doi.org/10.2139/ssrn.4616695.

Esposito, M., Tse, T. and Soufani, K. (2018a) 'The circular economy: an opportunity for renewal, growth, and stability', *Thunderbird International Business Review*, Vol. 60, No. 5, pp.725–728, https://doi.org/10.1002/tie.21912.

Esposito, M., Tse, T. and Soufani, K. (2018b) 'Introducing a circular economy: new thinking with new managerial and policy implications', *California Management Review*, Vol. 60, No. 3, pp.5–19, https://doi.org/10.1177/0008125618764691.

European Commission (n.d.) *Conflict Minerals Regulation: The Regulation Explained* [online] https://policy.trade.ec.europa.eu/development-and-sustainability/conflict-minerals-regulation/regulation-explained_en (accessed 31 August 2023).

Federation of German Industries (n.d.) *Raw Materials Extraction in Conflict Regions* [online] https://english.bdi.eu/topics/global-issues/conflict-minerals (accessed 31 August 2023).

Flanagan, C. (2023) 'How data centers are driving the renewable energy transition', *Forbes*, 13 March [online] https://www.forbes.com/sites/siemens-smart-infrastructure/2023/03/13/how-data-centers-are-driving-the-renewable-energy-transition/ (accessed 1 June 2023).

Fredericks, J., Davis, H., Parker, C., Tomitsch, M., Caldwell, G., Foth, M. and Crosby, A. (in press) 'Designing smart over a distance for sustainable communities: reflecting on AI, the Metaverse, and the role of HCI for addressing the sustainable development goals', *OzCHI'23: Proceedings of the 35th Australian Conference on Human-Computer Interaction*, Association for Computing Machinery [online] http://hdl.handle.net/10453/179663 (accessed 1 June 2023).

Funk, C.C. (2021) *Drought, Flood, Fire: How Climate Change Contributes to Catastrophes*, Cambridge University Press, Cambridge.

Geneva Environment Network (2023) *The Growing Environmental Risks of E-waste*, 16 January [online] https://www.genevaenvironmentnetwork.org/resources/updates/the-growing-environmental-risks-of-e-waste/ (accessed 1 June 2023).

Global Witness (2017) *US Conflict Minerals Law*, 15 November [online] https://www.globalwitness.org/en/campaigns/conflict-minerals/dodd-frank-act-section-1502/ (accessed 1 June 2023).

Go, H. and Kang, M. (2023) 'Metaverse tourism for sustainable tourism development: tourism agenda 2030', *Tourism Review*, Vol. 78, No. 2, pp.381–394, https://doi.org/10.1108/TR-02-2022-0102.

Goyal, S., Esposito, M. and Kapoor, A. (2018) 'Circular economy business models in developing economies: lessons from India on reduce, recycle, and reuse paradigms', *Thunderbird International Business Review*, Vol. 60, No. 5, pp.729–740, https://doi.org/10.1002/tie.21883.

Goyal, S., Sergi, B.S. and Esposito, M. (2019) 'Literature review of emerging trends and future directions of e-commerce in global business landscape', *World Review of Entrepreneurship, Management and Sustainable Development*, Vol. 15, Nos. 1–2, pp.226–255, https://doi.org/10.1504/WREMSD.2019.098454.

Halkias, D. and Neubert, M. (2020) 'Extension of theory in leadership and management studies using the multiple-case study design', *International Leadership Journal*, Vol. 12, No. 2, pp.48–73, http://dx.doi.org/10.2139/ssrn.3586256.

Halkias, D., Diaz, J. and Esposito, M. (2023a) 'The business school meets the Metaverse: expanding the upskilling experience', *Global Focus: The EFMD Business Magazine*, 5 June, Vol. 17, No. 2, pp.16–21 [online] https://www.globalfocusmagazine.com/the-business-school-meets-the-Metaverse-expanding-the-upskilling-experience/ (accessed 1 June 2023).

Halkias, D., Esposito, M., Harkiolakis, T., Diaz, J. and Ikpogu, N.M. (2023b) 'Digital entrepreneurship and disruptive innovation in the Greek maritime industry: the case of harbor lab', in Ramadani, V., Kjosev, S. and Sergi, B.S. (Eds.): *Entrepreneurship Development in the Balkans: Perspective from Diverse Contexts*, Emerald Publishing Limited, Leeds.

Halkias, D., Neubert, M., Thurman, P.W., Adendorff, C. and Abadir, S. (2020) *The Innovative Business School: Mentoring Today's Leaders for Tomorrow's Global Challenges*, Routledge, Abingdon.

Harkiolakis, T. (2022) 'Health and well-being for knowledge workers in the post-pandemic world: an integrative literature review', *Social Science Research Network*, http://dx.doi.org/10.2139/ssrn.4121605.

Harkiolakis, T. and Komodromos, M. (2023) 'Supporting knowledge workers' health and well-being in the post-lockdown era', *Administrative Sciences*, Vol. 13, No. 2, Article 49, https://doi.org/10.3390/admsci13020049.

HP (n.d.). *HP Omnicept & HP Reverb G2 Omnicept Edition* [online] https://www.hp.com/us-en/vr/reverb-g2-vr-headset-omnicept-edition.html (accessed 31 August 2023).

Huang, H., Zeng, X., Zhao, L., Qiu, C., Wu, H. and Fan, L. (2022) 'Fusion of building information modeling and blockchain for Metaverse: a survey', *IEEE Open Journal of the Computer Society*, Vol. 3, pp.195–207, https://doi.org/10.1109/OJCS.2022.3206494.

Hui, X., Raza, S.H., Khan, S.W., Zaman, U. and Ogadimma, E.C. (2023) 'Exploring regenerative tourism using media richness theory: Emerging role of immersive journalism, Metaverse-based promotion, eco-literacy, and pro-environmental behavior', *Sustainability*, Vol. 15, No. 6, Article 5046, https://doi.org/10.3390/su15065046.

Ignatyev, A., Kurbatova, T. and Khapov, A. (2023) *Developing Metaverses and Implementing Metaverse-Enabling Technologies: Social and Humanitarian Aspects and Global Challenges (T20 Policy Brief)*, Observer Research Foundation [online] https://www.orfonline.org/research/developing-Metaverses-and-implementing-Metaverse-enabling-technologies/ (accessed 1 June 2023).

International Energy Agency (2023) *Data Centres and Data Transmission Networks*, 11 July [online] https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks (accessed 28 August 2023).

Irving, M. (2019) 'Common element combos could replace rare-Earth metals in electronics', *New Atlas*, 5 July [online] https://newatlas.com/common-elements-replace-rare-earth-metals-electronics/60447/ (accessed 1 June 2023).

Jauhiainen, J.S., Krohn, C. and Junnila, J. (2023) 'Metaverse and sustainability: systematic review of scientific publications until 2022 and beyond', *Sustainability*, Vol. 15, No. 1, Article 346, https://doi.org/10.3390/su15010346.

Jouini, M., Royer-Lavallée, A., Pabst, T., Chung, E., Kim, R., Cheong, Y.W. and Neculita, C.M. (2022) 'Sustainable production of rare earth elements from mine waste and geoethics', *Minerals*, Vol. 12, No. 7, Article 809, https://doi.org/10.3390/min12070809.

Jyothi, R.K., Thenepalli, T., Ahn, J.W., Parhi, P.K., Chung, K.W. and Lee, J.Y. (2020) 'Review of rare earth elements recovery from secondary resources for clean energy technologies: grand opportunities to create wealth from waste', *Journal of Cleaner Production*, Vol. 267, Article 122048, https://doi.org/10.1016/j.jclepro.2020.122048.

Kim, S.M. and Mendelsohn, R.O. (2023) 'Climate change to increase crop failure in US', *Environmental Research Letters*, Vol. 18, No. 1, Article 014014, https://doi.org/10.1088/1748-9326/acac41.

Kim, W., Oh, H., Kwak, Y., Park, K., Ju, B.K. and Kim, K. (2015) 'Development of a carbon nanotube-based touchscreen capable of multi-touch and multi-force sensing', *Sensors*, Vol. 15, No. 11, pp.28732–28741, https://doi.org/10.3390/s151128732.

King, J. (2022) '*Microsoft Touts Industrial Metaverse As Innovation, Sustainability Tool*, 13 October, SDxCentral [online] https://www.sdxcentral.com/articles/news/microsoft-touts-industrial-Metaverse-as-innovation-sustainability-tool/2022/10/ (accessed 1 June 2023).

Koduri, R. (2021) *Powering the Metaverse*, Intel, 14 December [online] https://www.intel.com/content/www/us/en/newsroom/opinion/powering-Metaverse.html#gs.apvqov (accessed 1 June 2023).

Kontogianni, E. and Anthopoulos, L. (2024) 'Preliminary research results on exploring the business ecosystem and the value sources of Metaverse', *Sustainability*, Vol. 16, No. 8, Article 3134, https://doi.org/10.3390/su16083134.

Kraus, S., Kumar, S., Lim, W.M., Kaur, J., Sharma, A. and Schiavone, F. (2023) 'From moon landing to Metaverse: tracing the evolution of technological forecasting and social change', *Technological Forecasting and Social Change*, Vol. 189, Article 122381, https://doi.org/10.1016/j.techfore.2023.122381.

Kreutzer, R.T. and Klose, S. (2023) *Next Stop Metaverse: A Quick Guide to Concepts, Uses, and Potential for Research and Practice*, Springer Nature, Wiesbaden.

Kshetri, N. and Dwivedi, Y.K. (2023) 'Pollution-reducing and pollution-generating effects of the Metaverse', *International Journal of Information Management*, Vol. 69, Article 102620, https://doi.org/10.1016/j.ijinfomgt.2023.102620.

Lee, J.Y. (2021) 'A study on Metaverse hype for sustainable growth', *International Journal of Advanced Smart Convergence*, Vol. 10, No. 3, pp.72–80, https://doi.org/10.7236/IJASC.2021.10.3.72.

Link, J. (2023) 'Does Meta's horizon workrooms deliver? Customers say yes… and no', *Wired*, 6 January [online] https://www.wired.co.uk/article/meta-horizon-workrooms-glitchy-company-trials (accessed 1 June 2023).

Liu, K., Tan, Q., Yu, J. and Wang, M. (2023) 'A global perspective on e-waste recycling', *Circular Economy*, Vol. 2, No. 1, Article 100028, https://doi.org/10.1016/j.cec.2023.100028.

Lo, S.C. and Tsai, H.H. (2022) 'Design of 3D virtual reality in the Metaverse for environmental conservation education based on cognitive theory', *Sensors*, Vol. 22, No. 21, Article 8329, https://doi.org/10.3390/s22218329.

Long, S., Li, Y., Huang, J., Li, Z. and Li, Y. (2022) 'A review of energy efficiency evaluation technologies in cloud data centers', *Energy and Buildings*, Vol. 260, Article 111848, https://doi.org/10.1016/j.enbuild.2022.111848.

McKinsey & Company (2022) *What is the Metaverse?*, 17 August [online] https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-the-Metaverse#/ (accessed 1 June 2023).

McMahan, S. (2019) 'New materials may reduce or replace rare-earth elements in strong permanent magnets', *EE Power*, 3 April [online] https://eepower.com/news/new-materials-may-reduce-or-replace-rare-earth-elements-in-strongest-permanent-magnets/# (accessed 1 June 2023).

Mendelsohn, R.O. (Ed.) (2021) *Climate Change Economics: Commemoration of Nobel Prize for William Nordhaus*, World Scientific Publishing, https://doi.org/10.1142/12569.

Meta (2022) *2021 Sustainability Report* [online] https://sustainability.fb.com/wp-content/uploads/2022/06/Meta-2021-Sustainability-Report.pdf (accessed 1 June 2023).

Moniruzzaman, M., Yassine, A. and Benlamri, R. (2022) 'Blockchain and Metaverse for peer-to-peer energy marketplace: research trends and open challenges', *2022 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD)*, pp.1–8, Institute of Electrical and Electronics Engineers, https://doi.org/10.1109/ICTMOD55867.2022.10041871.

Morini Bianzino, N. (2022) *How the Metaverse Could Bring Us Closer To A Sustainable Reality*, 4 September, VentureBeat [online] https://venturebeat.com/virtual/how-the-Metaverse-could-bring-us-closer-to-a-sustainable-reality/ (accessed 1 June 2023).

Nayar, J. (2021) 'Not so "green" technology: the complicated legacy of rare earth mining', *Harvard International Review*, 12 August [online] https://hir.harvard.edu/not-so-green-technology-the-complicated-legacy-of-rare-earth-mining/ (accessed 1 June 2023).

Nelson, K.M., Anggraini, E. and Schlüter, A. (2020) 'Virtual reality as a tool for environmental conservation and fundraising', *PloS One*, Vol. 15, No. 4, Article e0223631, https://doi.org/10.1371/journal.pone.0223631.

Oladipo, H.J., Tajudeen, Y.A., Taiwo, E.O., Muili, A.O., Yusuf, R.O., Jimoh, S.A., Oladipo, M.K., Oladunjoye, I.O., Egbewande, O.M., Sodiq, Y.I., Ahmed, A.F. and El-Sherbini, M.S. (2023) 'Global environmental health impacts of rare earth metals: insights for research and policy making in Africa', *Challenges*, Vol. 14, No. 2, Article 20, https://doi.org/10.3390/challe14020020.

Palak, S., Gulia, P., Gill, N.S. and Chatterjee, J.M. (2023) 'Metaverse and its impact on climate change', in Hassanien, A.E., Darwish, A. and Torky, M. (Eds.): *The Future of Metaverse in the Virtual Era and Physical World*, pp.211–222, Springer Cham, https://doi.org/10.1007/978-3-031-29132-6_12.

Partida, D. (2022) 'How to keep the Metaverse sustainable', *AR Insider*, 24 August [online] https://arinsider.co/2022/08/24/how-to-keep-the-Metaverse-sustainable/ (accessed 1 June 2023).

Pellegrino, A., Stasi, A. and Wang, R. (2023) 'Exploring the intersection of sustainable consumption and the Metaverse: a review of current literature and future research directions', *Heliyon*, Vol. 9, No. 9, Article E19190, https://doi.org/10.1016/j.heliyon.2023.e19190.

Queiroz, A.C., Fauville, G., Abeles, A.T., Levett, A. and Bailenson, J.N. (2023) 'The efficacy of virtual reality in climate change education increases with amount of body movement and message specificity', *Sustainability*, Vol. 15, No. 7, Article 5814, https://doi.org/10.3390/su15075814.

Schöbel, S.M. and Leimeister, J.M. (2023) 'Metaverse platform ecosystems', *Electronic Markets*, Vol. 33, No. 1, Article 12, https://doi.org/10.1007/s12525-023-00623-w.

Seal, R. (2021) 'Can virtual meeting spaces save us all from Zoom fatigue?', *The Guardian*, 8 May [online] https://www.theguardian.com/technology/2021/may/08/work-can-virtual-meeting-spaces-save-us-all-from-zoom-fatigue (accessed 1 June 2023).

Serenko, A. (2015) 'Citation classics published in knowledge management journals. Part II: studying research trends and discovering the Google Scholar effect', *Journal of Knowledge Management*, Vol. 19, No. 6, pp.1335–1355, https://doi.org/10.1108/JKM-02-2015-0086.

Soriani, A. and Bonafede, P. (2023) 'Metaverse and education: which pedagogical perspectives for the school of tomorrow?', *Journal of Inclusive Methodology and Technology in Learning and Teaching*, Vol. 3, No. 1 [online] https://inclusiveteaching.it/index.php/inclusiveteaching/article/view/54 (accessed 1 June 2023).

Spiegel, S. and Wang, H. (2024) 'Exploring climate science in the metaverse: interactive storytelling in immersive environments for deep learning and public engagement', in Coran, E. and Wang, H. (Eds.): *Storytelling to Accelerate Climate Solutions*, pp.365–378, Springer Cham, https://doi.org/10.1007/978-3-031-54790-4_17.

Sprinzen, M. (2022) 'Metaverse: Saving the world or another digital distraction?', *Forbes*, 31 March [online] https://www.forbes.com/sites/forbestechcouncil/2022/03/31/the-Metaverse-saving-the-world-or-another-digital-distraction/?sh%2011c29a3f38c8&sh=4ceef9138c8d (accessed 1 June 2023).

Stoll, C., Gallersdörfer, U. and Klaaßen, L. (2022) 'Climate impacts of the Metaverse', *Joule*, Vol. 6, No. 12, pp.2668–2673, https://doi.org/10.1016/j.joule.2022.10.013.

Timperley, J. (2020) 'How our daily travel harms the planet', *BBC*, 18 March [online] https://www.bbc.com/future/article/20200317-climate-change-cut-carbon-emissions-from-your-commute.

Torraco, R.J. (2016) 'Writing integrative literature reviews: Using the past and present to explore the future', *Human Resource Development Review*, Vol. 15, No. 4, pp.404–428, https://doi.org/10.1177/1534484316671606.

Umar, A. (2022) 'Metaverse for public welfare and the United Nations Sustainable Development Goals', *2022 International Conference on Cloud Computing, Big Data and Internet of Things (3CBIT)*, October, pp.160–165, Institute of Electrical and Electronics Engineers, https://doi.org/10.1109/3CBIT57391.2022.00040.

United States Government Accountability Office (2022) *Conflict Minerals: Overall Peace and Security in Eastern Democratic Republic of Congo Has Not Improved Since 2014* [online] https://www.gao.gov/assets/gao-22-105411.pdf (accessed 1 June 2023).

Vasques, T.L., Moura, P. and de Almeida, A. (2019) 'A review on energy efficiency and demand response with focus on small and medium data centers', *Energy Efficiency*, Vol. 12, pp.1399–1428, https://doi.org/10.1007/s12053-018-9753-2.

Webster, J. and Watson, R.T. (2002) 'Analyzing the past to prepare for the future: writing a literature review', *MIS Quarterly*, Vol. 26, No. 2, pp.xiii–xxiii [online] https://www.jstor.org/stable/4132319 (accessed 1 June 2023).

Wiggers, K.L. (2022) 'The environmental impact of the Metaverse', *VentureBeat*, 26 January [online] https://venturebeat.com/data-infrastructure/the-environmental-impact-of-the-Metaverse/ (accessed 1 June 2023).

Xiang, N. (2022) 'The Metaverse's hunger for energy must be quantified', *Nikkei Asia*, 24 March [online] https://asia.nikkei.com/Opinion/The-Metaverse-s-hunger-for-energy-must-be-quantified (accessed 1 June 2023).

Yang, L., Ni, S.T., Wang, Y., Yu, A., Lee, J.A. and Hui, P. (2024) *Interoperability of the Metaverse: A Digital Ecosystem Perspective Review*, ArXiv, https://doi.org/10.48550/arXiv.2403.05205.

Zhang, S., Lim, W.Y.B., Ng, W.C., Xiong, Z., Niyato, D., Shen, X.S. and Miao, C. (2023) 'Towards green Metaverse networking: Technologies, advancements and future directions', *IEEE Network*, https://doi.org/10.1109/MNET.130.2200510.

Zhao, N., Zhang, H., Yang, X., Yan, J. and You, F. (2023) 'Emerging information and communication technologies for smart energy systems and renewable transition', *Advances in Applied Energy*, Vol. 9, Article 100125, https://doi.org/10.1016/j.adapen.2023.100125.