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Review

Greening the Virtual: An Interdisciplinary Narrative Review of the Environmental Sustainability Potential of the Metaverse

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Abstract: As the Metaverse emerges as a transformative digital ecosystem, questions about its environmental footprint remain largely underexplored. This interdisciplinary narrative review examines how Metaverse technologies intersect with environmental sustainability across applied sectors including education, healthcare, tourism, e-commerce, manufacturing, and urban development. Drawing from a broad range of scholarly and industry sources, the study synthesizes current practices, projected benefits, and underlying trade-offs. While the Metaverse offers potential for dematerializing physical activities, optimizing urban infrastructure through digital twins, and reducing travel emissions via immersive experiences, it also introduces significant environmental challenges. These include energy-intensive backend infrastructure, short hardware life cycles, and the rebound effects of increased digital consumption. The review argues that the sustainability of the Metaverse is not intrinsic to its virtual nature but contingent on design choices, policy frameworks, and the broader energy systems in which it operates. By reframing virtual innovation through a sustainability lens, the study contributes to the growing discourse on responsible digital futures and calls for collaborative, cross-sectoral approaches to ensure that immersive technologies evolve in alignment with planetary boundaries.

Keywords: metaverse; environmental sustainability; digital twins; virtual education; green technology; immersive systems

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1. Introduction

As the planet grapples with escalating environmental degradation, rising global temperatures, and the depletion of natural resources, the call for sustainable alternatives has never been more urgent. Across every sector—from energy and transportation to education and urban development—there is a growing need for solutions that not only minimize ecological footprints but also promote long-term resilience [1,2]. Nevertheless, in the face of these persistent challenges, a novel and unconventional pathway has emerged: the digital realm [3,4]. More specifically, the Metaverse, often characterized as a convergence of persistent, immersive, and interconnected virtual environments, is being reimagined not just as a social or technological novelty, but as a potential ally in the pursuit of sustainability [5,6].

While the Metaverse has gained widespread visibility through applications in entertainment, gaming, and commerce, its relevance to environmental sustainability remains a relatively untapped area of scholarly inquiry [7,8]. This paper seeks to engage with that gap. The conversation around sustainability typically centers on tangible infrastructure—solar panels, electric vehicles, green buildings [9]. Rarely do we consider how intangible digital spaces might meaningfully contribute to reducing emissions, cutting waste, or reshaping human behavior toward more sustainable patterns [10,11]. And yet, if designed and deployed responsibly, the Metaverse might offer precisely such opportunities.

This narrative review is rooted in an interdisciplinary approach, drawing from fields as varied as environmental science, computer science, urban planning, digital education, and industrial ecology. It does not treat the Metaverse as a monolithic technology but rather as a socio-technical ecosystem—an evolving interface between human users, immersive content, and underlying infrastructure. This

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broader lens allows for a more comprehensive discussion that goes beyond the novelty of virtual worlds and interrogates their real-world environmental implications.

To that end, the review explores both the potential and the paradoxes of the Metaverse's role in advancing sustainability. On one hand, virtual reality meetings could replace carbon-intensive business travel [12,13]. Virtual tourism might reduce the environmental burden of mass travel on ecologically sensitive sites [14,15]. Educational institutions could lower their physical infrastructure demands through persistent virtual campuses [16,17]. Cities could experiment with digital twins to optimize energy use before physical construction begins [18,19]. These are not just conceptual speculations—they are emerging use cases already under exploration.

Yet, there is a flipside. Hosting immersive environments at scale demands vast computational power, high-speed data transfers, and the continuous operation of energy-intensive data centers [20]. Virtual reality headsets, like any other consumer electronics, come with their own lifecycle of raw material extraction, manufacturing, and eventual e-waste [21]. Blockchain-based transactions—often tied to virtual economies—are notoriously carbon-intensive [22]. In other words, the Metaverse could just as easily exacerbate environmental degradation if its growth proceeds without sustainability baked into its design.

To guide this exploration, the review is framed around three central research questions:

1. What environmental benefits might be realized through the use of Metaverse technologies in domains such as education, tourism, industry, and urban planning?
2. What environmental risks and trade-offs are associated with the technological infrastructure required to support the Metaverse?
3. How can interdisciplinary strategies—spanning technology design, policy, ethics, and sustainability science—be harnessed to ensure that the Metaverse evolves in alignment with global environmental goals?

This review does not claim to offer definitive answers, but it does aim to surface the questions that must be asked if the Metaverse is to become more than just a digital playground for the affluent or a marketing buzzword for the tech industry. If the Metaverse is to have a seat at the sustainability table, it must be scrutinized with the same rigor we apply to physical systems. That means evaluating its full lifecycle impact, ensuring equitable access, building ethical frameworks, and above all, recognizing that virtual is not necessarily clean—unless it is intentionally made to be so.

By weaving together insights from multiple disciplines and synthesizing emerging literature, this review aspires to contribute to a growing discourse on sustainable digital transformation. It encourages scholars, designers, policymakers, and educators to think differently—not just about how we live, work, and learn in the digital age, but about how the tools we build for the virtual world might help safeguard the one we physically inhabit.

2. Materials and Methods

This study employs a narrative review methodology to examine the environmental sustainability potential of Metaverse technologies across various domains. A narrative review is particularly appropriate when the goal is to synthesize existing knowledge across diverse and evolving fields, enabling a critical and contextualized understanding of complex phenomena [23,24]. Given the interdisciplinary nature of the research topic—spanning computer science, environmental studies, urban planning, education, and sustainability science—this approach allows for conceptual integration rather than statistical aggregation, which is typical of systematic reviews or meta-analyses.

2.1. Review Design and Scope

The review was designed to address the following guiding research questions:

- What environmental benefits might be realized through the use of Metaverse technologies in domains such as education, tourism, industry, and urban planning?

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- What environmental risks and trade-offs are associated with the technological infrastructure required to support the Metaverse?
- How can interdisciplinary strategies—spanning technology design, policy, ethics, and sustainability science—be harnessed to ensure that the Metaverse evolves in alignment with global environmental goals?

These questions were developed to guide the identification, selection, and synthesis of relevant literature and to ensure alignment with the overarching objective of assessing both the opportunities and limitations of the Metaverse in contributing to sustainability.

2.2. Sources of Information

A comprehensive literature search was conducted across several academic databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar, between January and April 2025. The search strategy included combinations of the following keywords and Boolean operators:

- "Metaverse" AND "sustainability"
- "virtual reality" AND "environmental impact"
- "digital twins" AND "smart cities"
- "immersive learning" AND "climate education"
- "blockchain" AND "energy consumption"
- "carbon footprint" AND "virtual environments"

Inclusion criteria prioritized peer-reviewed journal articles, conference papers, institutional reports, and high-impact white papers published between 2015 and 2025, with an emphasis on literature published in English. Grey literature from credible organizations (e.g., UNEP, World Economic Forum, IEEE, and OECD) was also considered to capture emerging insights not yet fully covered in academic publications.

2.3. Selection and Screening Process

The selection process followed three stages:

- Initial Screening: Titles and abstracts were screened to assess relevance to the core themes of Metaverse technology and sustainability.
- Full-Text Review: Selected articles were then reviewed in full to evaluate their methodological quality, contextual relevance, and interdisciplinary contribution.
- Thematic Mapping: Studies were organized according to thematic categories such as energy efficiency, virtual tourism, smart city simulations, digital education, e-waste, and sustainability frameworks.

This thematic mapping helped build the structure for analysis and ensured comprehensive coverage of both benefits and drawbacks of Metaverse deployment.

2.4. Data Synthesis and Interdisciplinary Integration

Rather than applying quantitative meta-analysis techniques, the review employed qualitative thematic synthesis, consistent with narrative review protocols [25,26]. Insights were organized around two major dimensions:

- Environmental Opportunities (e.g., carbon reduction through dematerialization, energy-efficient virtual design, etc.)
- Environmental Risks (e.g., data center energy use, VR hardware e-waste, and blockchain-related emissions)

Special attention was paid to how different disciplines approach sustainability through the lens of digital technology. For example, insights from urban planning literature on digital twins were triangulated with computer science studies on simulation efficiency, and environmental policy frameworks were examined alongside software engineering best practices for green computing.

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2.5. Quality and Rigor

While narrative reviews are inherently flexible, care was taken to ensure transparency, depth, and methodological rigor. This included maintaining a detailed audit trail of the literature selection process, applying inclusion/exclusion criteria consistently, and engaging in peer debriefing with interdisciplinary researchers to validate thematic categorizations and interpretations.

3. Results

This review uncovered a broad range of insights into how the Metaverse may contribute to environmental sustainability across applied sectors. Rather than analyzing the technology in isolation, this section explores its potential and limitations through the lens of key societal domains: education, healthcare, tourism, e-commerce, manufacturing, and urban development. Each subsection integrates interdisciplinary literature and highlights the sector-specific environmental implications of adopting Metaverse technologies.

The analysis of publication types (Figure 1) reveals a strong dominance of journal articles, which constitute the majority of the reviewed sources with a total of 56 entries. This reflects the maturity and academic interest in the topic across peer-reviewed literature. Book chapters follow with 8 contributions, indicating interdisciplinary engagement and the inclusion of the Metaverse and sustainability topics in edited academic volumes. Conference papers are limited to just 2 entries, suggesting relatively lower representation of this topic in conference proceedings. Only 1 book was identified, pointing to a limited number of comprehensive monographs in this area. Overall, the distribution highlights that journal publications serve as the primary vehicle for disseminating scholarly insights into Metaverse applications and sustainability.

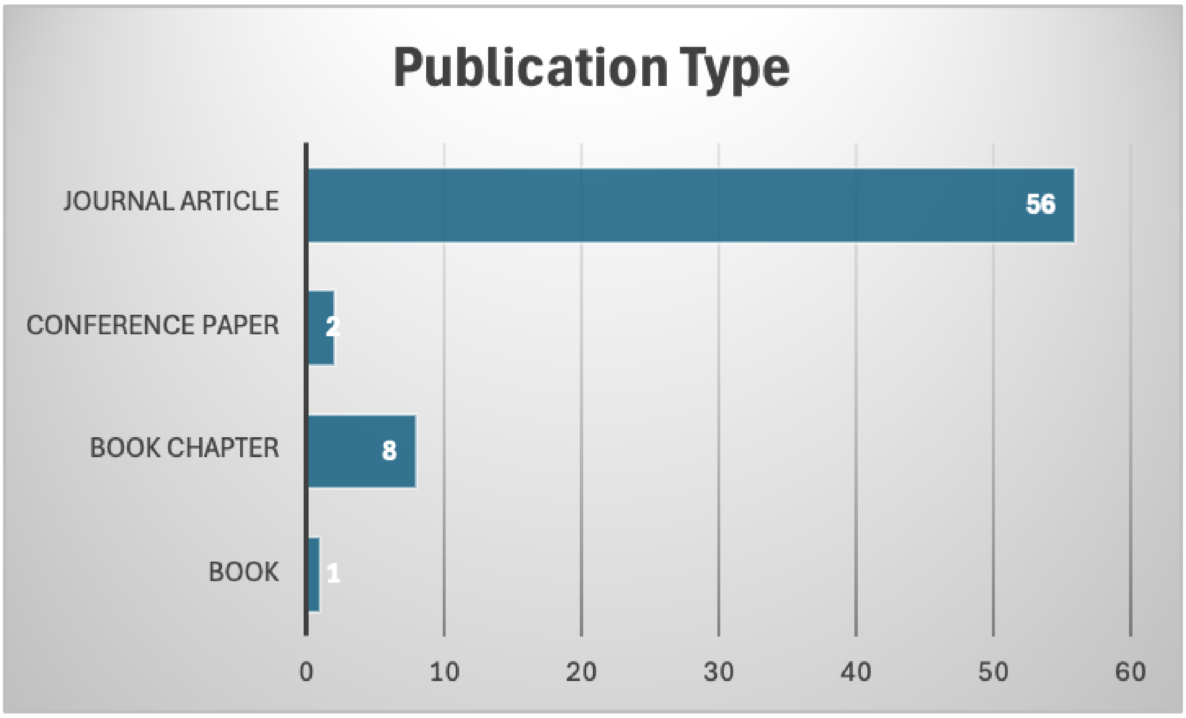

Figure 1. Reviewed Publication Types.

As evidenced by publishing trends (see Table 1), interest in the Metaverse's environmental effects has grown steadily and recently, quite significantly. Only a small number of studies from 1997, 2004, and 2015 made significant contributions prior to 2020. Although they established the framework, these early works did not amount to a thorough academic discussion. That changed dramatically starting around 2021. Its increasing popularity is demonstrated by the 25 studies that had been published on the topic by 2024. The momentum resulted in 18 more publications in 2025. This quick development

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shows that the relationship between digital innovation and environmental responsibility is becoming more and more important to researchers. As the Metaverse continues to develop from idea to reality, more people are participating in the conversation by asking questions about the environmental effects of virtual worlds and the potential for creation in them.

Table 1. Distribution of Reviewed Publications by Year.

Year	Number of Reviewed Publications
1997	1
2004	1
2005	1
2012	1
2015	2
2016	1
2017	1
2018	1
2021	3
2022	7
2023	5
2024	25
2025	18

Moreover, Table 2 presents the results of the thematic analysis conducted on the reviewed literature, highlighting how Metaverse technologies can contribute to sustainability across various disciplines. The following sections will delve further into each of these fields, examining in greater depth the environmental implications of integrating the Metaverse within their specific contexts.

Table 2. Disciplinary Themes and Sustainability Enhancements via Metaverse Adoption.

Discipline	Sustainability Enhancement via Metaverse
Education	Reduces campus infrastructure usage, commuting emissions, and paper consumption through immersive virtual classrooms. Enables virtual environmental education to foster ecological awareness.
Healthcare	Decreases patient and staff travel emissions, reduces use of disposable training materials, and limits energy consumption through remote diagnostics and virtual training.
Tourism	Minimizes air and ground travel, alleviates pressure on ecologically sensitive destinations, and reduces emissions by offering immersive virtual alternatives to physical tourism.
E-Commerce and Retail	Dematerializes product interactions by enabling virtual try-ons and digital goods, potentially reducing material waste and energy used in supply chains—contingent on energy-efficient infrastructure.
Manufacturing and Industry	Lowers prototyping waste and manufacturing errors via digital twins and simulations, helping optimize energy use and resource planning before physical production.
Urban Development	Supports energy-efficient city planning using digital twins to simulate urban infrastructure, reducing trial-and-error material use and supporting low-carbon decision-making.

3.1. Education: Towards Low-Impact, Immersive Learning Ecosystems

The educational sector emerges as a key arena where the Metaverse is being piloted to create fully immersive virtual classrooms [27,28]. In terms of sustainability, the implications are twofold. First, shifting instruction to persistent virtual environments can reduce the physical demands of campus-based infrastructure, such as lighting, cooling, paper consumption, and student commuting [29]. Studies estimate that online learning can lead to more than 30% reduction in per-student carbon emissions when compared to traditional modes, especially in higher education settings where students often travel long distances [30,31].

Second, immersive learning offers novel opportunities for environmental education itself. Virtual experiences allow learners to observe the melting of glaciers, simulate the impact of urban pollution, or visualize biodiversity loss from a first-person perspective [32]. These experiences may cultivate ecological empathy, especially among students with limited access to field-based education. However, hardware requirements and bandwidth demands could counterbalance environmental gains if devices are not designed with lifecycle sustainability in mind [33].

3.2. Healthcare: Remote Diagnostics and Resource Reduction

In healthcare, the Metaverse enables virtual diagnostics, surgical planning, and therapeutic interventions within immersive digital environments [34]. From a sustainability perspective, virtual consultations and simulated medical training reduce the need for inter-hospital transport, printed materials, and in-person facility use [35]. For example, training medical professionals via VR-based procedures has been shown to significantly cut down on plastic anatomical models, disposable instruments, and energy-intensive lab usage [36–38].

Furthermore, the reduction in patient travel for routine consultations can meaningfully lower healthcare-related transportation emissions [39,40]. That said, sustainability gains vary significantly based on health system infrastructure and digital literacy.

3.3. Tourism: Immersive Travel Without the Carbon Cost

The tourism industry, long scrutinized for its substantial carbon footprint, presents a compelling case for Metaverse-driven sustainability [41,42]. Virtual tourism—offering immersive 3D explorations of heritage sites, museums, or natural parks—can decouple travel experiences from physical mobility [43]. Several platforms are already providing virtual safaris, cultural reenactments, or historical site walkthroughs, all of which reduce air travel and over-tourism pressures on fragile ecosystems.

Environmentally, the shift from physical to virtual visits could significantly lower greenhouse gas emissions, particularly those associated with long-haul flights [44,45]. However, such gains depend on user adoption, quality of experience, and platform accessibility. Critics also caution that virtual tourism may not replace travel but instead act as an additional layer of media consumption—potentially encouraging rather than displacing real-world visits [46,47].

3.4. E-Commerce and Retail: Dematerializing Consumer Habits

The rise of virtual storefronts, avatar-based shopping, and digital goods marketplaces introduces the potential to "dematerialize" consumption [48]. Virtual fashion, for instance, allows users to dress their avatars in designer clothing that never physically exists [49]. Theoretically, this could reduce fabric waste, dye runoff, and carbon emissions from fast fashion supply chains [50].

Some brands are also integrating blockchain to authenticate and sell limited edition virtual items [51]. While this innovation may appeal to sustainability-conscious consumers, its environmental success is tied to the underlying blockchain protocol. Proof-of-work systems, still used in many NFT transactions, have been criticized for their extreme energy demands [52]. Thus, while e-commerce in the Metaverse may reduce certain types of waste, it may simultaneously introduce invisible emissions unless supported by low-energy infrastructure.

3.5. Manufacturing and Industry: Sustainable Prototyping and Virtual Twins

In manufacturing, the use of digital twins—high-fidelity virtual replicas of machines or production processes—has opened new avenues for energy-efficient product development [28,53]. Virtual simulations allow companies to test various configurations, anticipate inefficiencies, and design for modularity before physical production begins [54]. This minimizes the waste associated with traditional prototyping and reduces downtime and energy waste in factories [55,56].

Moreover, supply chains visualized in the Metaverse can support more transparent logistics, allowing managers to identify inefficient shipping routes or excessive inventory storage [57,58]. However, these systems require continuous streams of sensor data, real-time updates, and immersive visualization—all of which rely on high computational throughput and sustained power consumption [59]. Without green data centers and optimized software, the sustainability promise may be undercut by backend energy use [60].

3.6. Urban Development and Smart Cities: Simulating Low-Carbon Futures

Smart city initiatives have been among the most active adopters of Metaverse infrastructure [5,61]. Urban planners now use immersive simulations to engage citizens in environmental decision-making, model traffic flows, and experiment with zoning policies for energy-efficient development [62,63]. For instance, digital twin cities have been used to simulate flood mitigation strategies, green roof effectiveness, and solar exposure for housing developments [64,65].

These tools help reduce the trial-and-error cycle of urban development and support more evidence-based planning. Additionally, participatory Metaverse platforms enable more inclusive and democratic planning processes, potentially leading to more socially and ecologically resilient outcomes [5]. Still, their use remains concentrated in technologically advanced cities. Scaling these tools equitably across different income levels and urban densities remains a challenge.

3.7. Sustainability Impacts of Implementing the Metaverse Across Sectors

The integration of Metaverse technologies across diverse sectors—such as education, healthcare, tourism, commerce, and manufacturing—presents a multilayered set of implications for environmental sustainability. While the emerging literature points toward several promising avenues [27,28,34,41,48,53,61], these impacts remain context-dependent and often contingent on underlying infrastructural and policy variables. Based on an interdisciplinary review, the sustainability implications appear to cluster into three overlapping categories: direct ecological advantages, systemic or indirect transitions, and latent or unintended consequences.

Direct environmental gains are most evident in the displacement of physical activities with digital equivalents. For example, virtual learning environments may reduce carbon emissions associated with commuting, classroom lighting, and campus infrastructure, particularly when institutions adopt persistent virtual campuses [29–31]. Similarly, in healthcare, applications such as telemedicine and remote diagnostics could lower emissions by minimizing patient and practitioner travel [35,39,40]. In tourism, virtual alternatives to in-person visits—especially those substituting long-haul flights—have the potential to mitigate high-emission activities, though the scalability of such alternatives is still under investigation [43–45].

Indirect benefits are more diffuse but potentially transformative. The adoption of digital twins in urban planning, industrial production, and infrastructure management facilitates anticipatory modeling, which may reduce material waste and optimize ecological outcomes [54–56]. In commercial domains, developments such as avatar-based shopping, virtual product simulations, and immersive consumer experiences may gradually shift behavioral preferences toward less materially intensive forms of consumption [49–51]. Nonetheless, these benefits are often mediated by socio-economic and cultural contexts that shape adoption trajectories and usage intensity.

Yet, the review also reveals a set of sustainability trade-offs that merit critical attention. The technological infrastructure underpinning Metaverse platforms—including data centers, extended reality (XR) hardware, and ultra-low-latency networks such as 5G and beyond—demands high energy input [59,60]. This demand becomes particularly problematic in regions where electricity is primarily generated from non-renewable sources [52]. Furthermore, environmental externalities related to hardware production, such as rare-earth mineral extraction, short device lifecycles, and insufficient e-waste recycling protocols, are often overlooked in platform-centric sustainability narratives [33].

A further concern involves rebound effects. In several scenarios, increased efficiency through virtualization does not lead to net reductions in environmental impact but instead catalyzes new patterns of digital consumption. For instance, while virtual tourism might offer an alternative to physical travel, it could also operate as a complementary activity that increases total energy expenditure by expanding the overall scope of tourism-related services [46,47]. In such cases, the environmental calculus becomes more ambiguous, underscoring the need for lifecycle assessments and regulatory frameworks that account for both direct savings and emergent forms of digital demand.

The sustainability impact of Metaverse adoption, therefore, is highly context-dependent. Its net environmental benefit hinges on several critical variables:

- The energy mix powering data centers and network infrastructure.
- The hardware lifecycle, including repairability, recyclability, and responsible disposal.
- The behavioral dynamics of users—whether Metaverse applications replace or simply add to existing activities.
- The policy frameworks that regulate, incentivize, or constrain environmentally damaging practices within virtual ecosystems.

To fully harness the sustainability potential of the Metaverse, implementation must be accompanied by intentional strategies for green platform design, renewable energy integration, ethical hardware sourcing, and regulatory oversight. Without these measures, the Metaverse could exacerbate digital inequalities and environmental degradation, rather than mitigate them.

3.8. Interdisciplinary Strategies for Responsible Metaverse Development

Across all themes, a common conclusion emerges: achieving environmental sustainability in the Metaverse is not a technological issue alone. Rather, it requires an integrative framework combining environmental ethics, policy regulation, technical innovation, and stakeholder engagement.

Green software engineering practices—such as algorithmic efficiency, load balancing, and compression—can significantly reduce energy costs. Policy instruments like digital carbon taxes or virtual sustainability certifications are being discussed as means to guide developers toward more responsible design. Moreover, transdisciplinary partnerships between urban planners, engineers, ecologists, and social scientists are seen as crucial to balance innovation with ecological limits.

Finally, the review points to a need for international governance structures that parallel those in the physical world. Just as buildings are subject to environmental assessments, immersive platforms might eventually require digital equivalents to ensure sustainable operation. Without these frameworks, the Metaverse risks becoming yet another layer of unchecked consumption—albeit a virtual one.

4. Discussion

The results of this interdisciplinary narrative review reveal a complex interplay between Metaverse technologies and environmental sustainability. Across sectors such as education, healthcare, tourism, commerce, and urban planning, the Metaverse presents both opportunities and contradictions—environmental benefits exist, but they are not evenly distributed, nor are they automatic. This section reflects on the broader meaning of these findings, offering theoretical contributions, practical guidance, policy recommendations, and avenues for future inquiry.

4.1. Theoretical Implications

From a conceptual standpoint, the intersection of the Metaverse and sustainability challenges several assumptions within both fields. The Metaverse has often been theorized as a purely digital or post-material space. Yet, this review highlights that such spaces remain deeply rooted in material infrastructures—data centers, hardware production, and global energy grids—all of which carry environmental consequences. This calls for a rethinking of digital dualism, particularly within theories of virtualization, which often separate physical from virtual impacts. The findings here suggest a hybrid ontology: virtual environments are not abstract escapes from the physical world, but rather extensions of it, embedded in planetary systems.

At the same time, sustainability theory must contend with emerging "virtual ecologies"—networks, platforms, and behaviors that influence real-world resource flows. Concepts such as dematerialization, substitution, and circularity require new definitions when applied to digital ecosystems. For instance, virtual consumption may reduce physical goods production, but it can also create new forms of energy use that remain poorly understood in traditional life-cycle models.

This review also complicates existing models of socio-technical transitions. Much of the literature on sustainable innovation focuses on changes to infrastructure, policy, or user behavior in physical systems. The Metaverse introduces a layer of simulation, experimentation, and symbolic interaction that precedes or even displaces material change. Theorizing sustainability in this context requires integrating digital semiotics, behavioral psychology, and platform economics with more conventional ecological models.

4.2. Practical Implications

For practitioners—technologists, designers, educators, and business leaders—the review offers several actionable insights. First, sustainability must be addressed as a design problem, not a retrofit. Platforms should be built with energy efficiency, modularity, and longevity in mind. Developers of immersive technologies must move beyond speed and immersion as primary goals, integrating metrics such as energy use per interaction, device repairability, and software lifespan.

In education, institutions piloting Metaverse classrooms should evaluate not just pedagogical outcomes but also carbon accounting. Is the shift from physical to virtual delivery leading to actual reductions in campus emissions? Are virtual labs reducing consumable usage, or simply adding another digital layer to existing practices?

For businesses exploring e-commerce in the Metaverse, the review suggests caution in framing virtual goods as inherently sustainable. The sustainability of a virtual product is not only about its immateriality but also about the energy, computation, and marketing structures it rides upon. Digital greenwashing—using virtual aesthetics to suggest environmental responsibility without actual accountability—is a growing risk.

Urban planners and architects working with digital twins must also be mindful of data ethics and energy cost. While simulations can reduce waste during design phases, their continuous operation must be assessed through an ecological lens, not just a technical one.

4.3. Policy Implications

The findings point to a significant policy gap in how digital sustainability is governed. Most countries maintain regulations for energy-intensive industries, waste management, and emissions from buildings and vehicles. Yet, few have developed frameworks for assessing the environmental impact of immersive digital systems, virtual economies, or real-time data ecosystems.

To address this gap, several recommendations emerge. First, governments and international bodies should develop Digital Environmental Impact Assessments (D-EIAs) for large-scale Metaverse projects. These assessments could evaluate projected server energy consumption, e-waste generation, and social inequalities introduced by immersive access.

Second, sustainability certifications for virtual platforms—analogous to LEED for buildings or ISO standards for manufacturing—could guide industry practices. Metrics might include carbon intensity per user hour, hardware recyclability, and software optimization scores.

Third, incentives for green infrastructure must extend to data centers powering Metaverse environments. Tax reductions for renewable-powered computing, mandatory carbon disclosures for platform operators, and subsidies for circular electronics are all tools that could align the digital economy with environmental targets.

Fourth, international cooperation is essential. Given the global nature of virtual environments, sustainability cannot be governed by any one jurisdiction. Cross-border standards, led by coalitions of digital and environmental agencies, will be necessary to ensure accountability.

4.4. Future Research Directions

This review opens several promising avenues for further inquiry. First, there is a need for quantitative studies that measure the actual energy use, emissions, and waste associated with Meta-

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verse deployments. Life-cycle analyses specific to VR headsets, spatial computing platforms, and 3D rendering engines would provide critical data to support or challenge prevailing assumptions.

Second, user behavior within Metaverse environments deserves more study. Do virtual alternatives actually reduce physical consumption, or do they simply repackage it? Does exposure to immersive environmental simulations translate to long-term behavioral change?

Third, research on digital justice and environmental equity in Metaverse systems is vital. Who has access to low-energy devices, renewable-powered platforms, or carbon-neutral digital tools? How might new digital infrastructures exacerbate or mitigate global inequalities in sustainability access?

Fourth, interdisciplinary collaboration is essential. Environmental scientists, AI researchers, ethicists, urban designers, and behavioral economists must work together to build models that reflect the true complexity of digital sustainability. This includes designing common sustainability vocabularies, shared data repositories, and testbeds for low-carbon virtual systems.

Lastly, scholars should explore the symbolic and psychological dimensions of sustainability in virtual spaces. What cultural meanings do users assign to virtual nature, carbon footprints, or digital cleanliness? How might these meanings influence or distort collective action on climate change?

5. Conclusions & Research Limitations

The promise of the Metaverse has often been framed in terms of immersive experiences, digital innovation, and the reshaping of human interaction. But as this review has shown, its implications extend further—into the material systems we rely on, the energy that powers our lives, and the ways in which we engage with the environment. At a time when ecological limits are increasingly visible, it becomes essential to ask whether new technologies such as the Metaverse are part of the solution or a subtle extension of the problem.

This review does not offer a simple answer. Instead, it paints a picture that is at once hopeful and cautionary. In education, healthcare, tourism, and beyond, the potential to reduce physical waste, limit unnecessary travel, and rethink resource use is real. Yet that potential is neither automatic nor universal. Whether the Metaverse serves sustainability depends on a long chain of decisions—some technical, some behavioral, and many political.

Perhaps the most important insight here is that sustainability in virtual environments is not an abstraction. It is embedded in the electricity that powers servers, the metals used in headsets, the lifespan of devices, and the culture of consumption that often follows technological excitement. The environmental consequences of the Metaverse may be out of sight, hidden in server farms and mineral extraction sites, but they are no less real.

To think of the Metaverse as "immaterial" is misleading. It is constructed from tangible resources and sustained by global systems of energy, labor, and production. Its sustainability, then, will not be decided by developers or designers alone—but by the coordination of sectors, the choices of users, and the frameworks built by regulators.

This review aimed to bring together these threads, not to resolve them, but to offer a lens that is interdisciplinary and rooted in the lived complexity of applied sectors. It is an invitation to continue the conversation—not only about what the Metaverse can do, but what it ought to do in a world that can no longer afford to build new futures without regard for the planet that sustains them.

5.1. Research Limitations

There are, of course, limitations to what this review could achieve. First, the scope of the study was intentionally broad, and while that breadth allowed for a panoramic view across sectors, it also meant that some areas—especially those with sparse empirical data—were covered more speculatively than others. The review leans heavily on conceptual arguments and thematic patterns. It does not, and cannot, claim to offer definitive carbon calculations or lifecycle data for every domain.

Second, the literature in this space is rapidly evolving. What holds true today may shift within months as new technologies emerge or sustainability efforts are scaled. The Metaverse is not a static system—it is a moving target, shaped by innovation, adoption, and policy in real time. This review reflects a snapshot, not a final word.

Third, there is an inherent limitation in how sustainability was framed. While the focus here was on environmental sustainability, other dimensions—particularly those related to social equity, psychological wellbeing, and ethical design—deserve deeper treatment. These themes surfaced often, but they were not the primary axis of analysis. A more comprehensive approach would weave these strands together to understand how virtual spaces intersect with justice, accessibility, and inclusion.

Lastly, like any narrative review, the findings here are shaped by the selection of sources and the interpretations drawn from them. Bias is inevitable, and while efforts were made to incorporate a diverse range of disciplinary voices, some perspectives may be underrepresented—especially from regions where Metaverse adoption is limited or still emerging.

That said, these limitations do not diminish the urgency of the questions raised. On the contrary, they underline the need for more data, more cross-sector dialogue, and more critical inquiry. If the Metaverse is to evolve into a space that contributes to sustainability rather than undermines it, then the work of thinking through its implications—honestly, rigorously, and collaboratively—has only just begun.

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