Another Brick in the Wall: A Systematic Mapping Study Toward Defining Metaverse Engineering Through Socio-Technical Issues

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Nowadays, virtual worlds are evolving into immersive **metaverses**, i.e., collective, shared virtual spaces that arise from the convergence of virtual reality (VR), augmented reality (AR), the internet, and additional digital technologies. These environments allow users to interact through avatars. While research has explored the technologies and social dynamics of the metaverse, two key limitations remain. First, there is no systematic overview of the expertise required to build metaverses and the key publication venues. Second, the socio-technical issues have not been fully synthesized or made instrumental for developing holistic design approaches that address both social and technical constraints. A deeper investigation is needed to guide future research, highlight challenges, and foster collaboration across disciplines. In this paper, we propose a systematic mapping study that addresses the limitations identified. From an initial pool of 2,323 sources, we identify 63 primary resources to (1) characterize the research community around metaverse and (2) elicit, synthesize, and categorize 19 social and 18 technical issues affecting the development of an effective metaverse. Based on our results, we contextualize the catalog of issues with respect to the current body of knowledge, providing insights and a research roadmap that transforms issues into actionable challenges in the scope of a novel, unified research asset coined **"metaverse engineering"**, i.e., the multidisciplinary discipline to identify processes and instruments to design socio-technical metaverses.

CCS Concepts: • **General and reference** → **Surveys and overviews**.

Additional Key Words and Phrases: Metaverse; Metaverse Engineering; Socio-Technical Analysis; Systematic Mapping Studies.

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1 INTRODUCTION

The concept of *"metaverse"* has generated significant interest as a frontier in internet evolution [39], merging technologies like virtual reality (VR), augmented reality (AR), and digital computing [41]. Within this shared virtual space, users engage in activities such as socializing, gaming, working, and learning, blurring the lines between the physical and digital worlds [17, 21, 31, 49, 64]. As a potential internet evolution, the metaverse opens new possibilities for communication, collaboration, and entertainment [16, 22]. Major tech companies are heavily investing in this space. For instance, Meta

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(formerly Facebook) rebranded to emphasize its focus on the metaverse, while companies like Nvidia, Microsoft, Apple, and Sony have collectively invested over $18 billion to further their ambitions in this emerging field [13].

Unfortunately, such technological advances do not come for free. The metaverse has been shown to impact mental and psychological well-being, as spending more time in virtual environments may reduce face-to-face interactions, negatively affecting mental health and relationships [5, 43, 57]. Its immersive nature could blur the lines between reality and virtuality, leading to addiction, isolation, and detachment from real-world experiences [45]. In addition, the metaverse may exacerbate socioeconomic disparities, as access may be restricted to those who can afford the necessary technology, further widening gaps in education, employment, and social connections [9, 63, 68].

To deal with these critical challenges to the widespread diffusion of the metaverse, we argue for the definition of a brand new discipline: **"metaverse engineering"**. We envision this discipline as *inherently multidisciplinary*, drawing upon expertise in virtual reality, artificial intelligence, human-computer interaction, and software engineering. Its goal is to create innovative processes and tools that balance the social and technical requirements of the metaverse, promoting fairness, equity, and sustainability. This paper provides the first step toward metaverse engineering, formalizing its **multi-disciplinary** and **socio-technical** nature. We first give an overview of the *current status of metaverse research*, identifying key expertise areas and publication venues. Then, we define a comprehensive catalog of *socio-technical issues* impacting metaverse development. These issues require collaboration across disciplines to ensure both social and technical aspects are adequately addressed. To meet these objectives, we conducted a systematic mapping study following established guidelines [29], synthesizing the current knowledge base.

The rationale behind using this research method stems from the current state of the body of knowledge. Research has advanced in areas such as (1) immersive concerns [19, 36, 48, 55], (2) virtual environments [36, 71], and (3) the mental and psychological impact of the metaverse [4, 8, 10, 12]. However, these diverse insights have not yet been fully synthesized or applied to create an integrated research community or practical tools to address fundamental design challenges. By characterizing the **research community** and defining key **socio-technical issues**, this paper aims to foster collaboration and serve as a resource for researchers in advancing metaverse engineering.

More specifically, our systematic mapping study identifies 63 primary resources from an initial pool of 2,323. The key findings show that the subject of the metaverse has been explored from multiple perspectives, touching areas related to computer vision, artificial intelligence, human-computer interaction, and software engineering. Furthermore, our work catalogs 19 social and 18 technical issues. Based on these results, we finally outline a research roadmap to metaverse engineering, describing how the identified issues might be addressed and the multidisciplinary efforts required. To sum up, this paper provides (1) a systematic overview of metaverse research, identifying key areas and publication venues to raise community awareness and foster interdisciplinary collaboration; (2) a taxonomy of socio-technical issues that can guide future research and inform practical implementation for the metaverse; (3) the introduction of the concept of "metaverse engineering" as a conceptual research asset that may integrate diverse expertise to address socio-technical issues in metaverse development; (4) a research roadmap outlining multidisciplinary effort and steps to tackle socio-technical challenges: (5) an online appendix [18] providing access to the material analyzed, supporting reproducibility, transparency, and collaboration within the research community.

2 BACKGROUND AND RELATED WORK

In these sections, we first outline the fundamental concepts and characteristics that define the metaverse and its associated technologies. We then examine how the academic community has explored and critiqued these elements, discussing how our work advances the state of the art.

2.1 Background

The term *"metaverse"* was first coined in 1992 by Neal Stephenson's science fiction entitled *Snow Crash*. The metaverse is described as a digital environment that bridges virtual and physical realities. Individuals interact with this environment through *avatar*, i.e., virtual representations of themselves, allowing them to engage with digital spaces as their alter-egos. These avatars provide a way for users to be distinguishable and interact with others within the virtual world.

Over time, the concept of the metaverse has evolved with the advancement of technology. Various definitions of the metaverse have emerged across different domains [1, 54]. It is generally considered a three-dimensional online environment where users, through their avatars, can interact with each other without the physical limitations of the real world [1, 54]. This three-dimensional environment incorporates key elements such as *realism*, *ubiquity*, *scalability*, and *interoperability* — all of which contribute to its immersive and engaging nature. *Realism* involves using sensory stimuli to create immersive and emotionally engaging virtual experiences. *Ubiquity* ensures access to the metaverse from various devices, anywhere. *Scalability* refers to supporting many users at once without performance loss. *Interoperability* enables different virtual environments to share assets and allow smooth transitions.

According to the *Metaverse Roadmap Overview*,[1], the metaverse can be described along four dimensions: the *virtual world*, enabling multi-user interaction in hybrid physical-digital spaces; the *mirror world*, offering geospatially mapped digital replicas of the real world; *life logging*, which captures and stores data on users and their environments; and *augmented reality*, which enriches physical spaces with digitally overlaid information. The goal of the metaverse is to deliver truly immersive experiences that depend on both *immersion* and *presence* [20]. Immersion measures how effectively the system can make users feel as though they are in a virtual environment separate from the physical world [14, 61]. Presence, instead, refers to the psychological sensation of actually "being" in the virtual environment [59]. Technologies like Head-Mounted Displays (HMDs) play a critical role in enhancing immersion and presence by providing users with the ability to feel physically present within the virtual world [46]. Companies like Meta (with MetaQuest Pro[2]), Microsoft (with HoloLens[3]), and Apple (with Vision Pro[4]) have developed advanced HMDs that further push the boundaries of metaverse interaction by integrating hand-based and motion input systems.

The software architecture of the metaverse leverages Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) to enhance avatar realism, optimize network performance (e.g., via 5G/6G), and support dynamic, scalable environments [5]. Beyond technical optimization, AI and the metaverse also play a transformative role in reshaping digital knowledge ecosystems. For example, the evolution from Library 1.0 to Library 5.0 illustrates how AI, IoT, and immersive technologies are reconfiguring the ways information is organized, accessed, and experienced [42]. In fact, a combination of these technologies allows the metaverse to adapt and scale, accommodating the needs of many users and the large amounts of data generated. Moreover, managing the massive amounts of data in the metaverse necessitates secure systems [17, 73]. In this regard, Blockchain technology is a suitable candidate for handling and maintaining control over sensitive data in the metaverse [17].

2.2 Related Work

Several studies have explored the properties, characteristics, and effects of the metaverse on users, offering insights that help position our work within the broader scholarly discourse.

[1] https://www.w3.org/2008/WebVideo/Annotations/wiki/images/1/19/MetaverseRoadmapOverview.pdf
[2] https://www.meta.com/it/quest/quest-pro/
[3] https://www.microsoft.com/it-it/hololens/buy
[4] https://www.apple.com/apple-vision-pro/

Green et al. [24] investigated how the metaverse is portrayed across academic and media narratives. While scholars predominantly emphasized human interaction and the need for conceptual clarity, media discussions focused instead on its economic implications, particularly in relation to cryptocurrencies and virtual payments. In a complementary effort, Almoqbel et al. [2] conducted a systematic literature review that categorized metaverse-related research into four key dimensions: *Content Creation*, *Users and Roles*, *Activity*, and *Technical Specification*. Their work underscored the lack of definitional alignment and the challenges this poses in addressing socio-technical concerns in a coherent and structured way. Building on these theoretical foundations, our work aims to overcome the dispersion observed in prior studies by proposing a holistic socio-technical taxonomy for the metaverse. In doing so, we offer a unified perspective that connects technical specifications, user needs, and societal implications.

Beyond the conceptual framing, other researchers have investigated the metaverse in relation to practical limitations that emerged during the COVID-19 pandemic. Platforms such as Teams and Zoom [37, 58] became essential tools for remote work, yet they significantly reduced embodied presence and interpersonal connection [8, 10]. The metaverse has been proposed as a possible solution to these limitations, offering immersive experiences that can mitigate the social and psychological downsides of digital isolation [39]. However, recent studies also emphasize the challenges users face when interacting with virtual environments. For example, findings from Kim et al. [28] suggest that without careful attention to usability and a concrete design of the virtual spaces, the metaverse risks reproducing or even exacerbating the very limitations it aims to overcome.

Great progress has been made in the metaverse, particularly in terms of its social and psychological aspects. Bruce et al. [4] consulted 250 experts—psychologists, neurologists, and technologists—to assess the potential mental health implications of the metaverse. While 60% of the respondents saw it as a valuable alternative to 2D applications in work and education, they also expressed concerns regarding reduced in-person interaction, overdependence on virtual environments, and the risks associated with enabling technologies such as AI, Blockchain, and IoT [32, 67], particularly in terms of privacy, misuse, and harassment [4].

Accessibility and inclusion have also emerged as critical areas of concern. Zhang et al. [71], through user interviews, identified significant barriers faced by individuals with disabilities in social VR environments, particularly in terms of avatar representation and customization. Building on this, Pellas et al. [48], Dincelli et al. [19], and Lopez et al. [36] illustrated how immersive environments are reshaping education and professional training, especially in STEM fields. These authors highlighted the importance of ensuring accessible and inclusive design to guarantee seamless interaction across diverse user groups [19, 36, 48, 71]. About inclusive design, Radanliev et al. [51–53] have gone beyond, further emphasizing and proposing both normative and empirical frameworks to address accessibility for users and content creators with disabilities [53]. In addition, they explored key risks linked to financial systems [52] and cybersecurity vulnerabilities [51], underscoring the need for robust governance mechanisms in virtual environments.

While these contributions offer valuable insights into specific aspects of metaverse development—ranging from socialization and education to inclusivity and regulatory challenges—they often remain focused on individual components. In contrast, our work adopts a comprehensive socio-technical perspective, aiming to construct a unified taxonomy that serves as an engineering-oriented roadmap for developing inclusive, sustainable, and secure metaverse systems.

Specifically, our research advances the state of the art in two significant ways. First, unlike many prior studies, we adopt a rigorous systematic review protocol [29], minimizing bias in resource selection and ensuring the robustness and breadth of the analysis. Second, while existing literature has highlighted thematic areas such as interaction or technology, few works have examined how these aspects converge across different disciplines or how they can inform practical engineering strategies for the metaverse. Our study addresses these gaps by characterizing the research community, identifying socio-technical challenges, and proposing concrete directions for cross-disciplinary collaboration.

In this regard, building on Almoqbel et al. [2] and extending their framework, we systematically mapped 2,323 research articles to trace how the metaverse intersects with technical, social, and organizational concerns. The resulting classification not only highlights key socio-technical issues but also translates them into actionable research challenges, contributing to the development of a shared foundation for future metaverse engineering efforts.

3 RESEARCH METHOD

The *goal* of the study was to elicit the socio-technical issues to face when engineering a metaverse, with the *purpose* of letting emerge a set of social and technical properties that would be worth considering to make a metaverse more fair, equitable, and economically sustainable. The *perspective* is that of researchers and tool vendors. The former are interested in gathering insights into the key socio-technical aspects that affect the engineering of a metaverse and that may represent the next research avenues to pursue. The latter are interested in identifying the features whose inclusion in the existing metaverse would make the user's experience more comfortable and safe. To reach the objective of our study, we conducted a Systematic Mapping Study (SMS) [29, 50, 65], that is, a rigorous research method aiming at collecting and synthesizing the existing body of knowledge available in the scientific literature with respect to the matter of interest, i.e., the socio-technical issues when engineering a metaverse in our case. To conduct our SMS, we followed the guidelines by Kitchenham et al. [29].

3.1 Search Strategy

Defining a search strategy is crucial for an SMS, as it ensures the completeness and accuracy of collected articles. It should include relevant keywords and descriptors, along with a careful selection of databases.

3.1.1 Research Goals and Questions. Our research questions ofstem from the metaverse's aim to blend physical reality with virtual reality, where physical reality comprises the tangible world governed by natural laws, and virtual reality offers an immersive, multi-dimensional experience beyond human senses [69]. This characteristic facilitates global connectivity through avatars, representing users in virtual environments. Consideration of avatars' appearance, surroundings, and interactions is crucial, as extensive research underscores their significant impact on individuals' sense of presence in virtual spaces [6, 7, 35]. Presence, once defined as the sensation of being in a virtual environment, now extends to "telepresence", reflecting the degree of connection individuals feel to virtual environments compared to physical ones [62]. Technology plays a pivotal role in creating presence, with the interface of the virtual world seamlessly integrating with engaging interactions, transforming it from a technological construct into a social entity [35]. Despite its potential, the metaverse faces multifaceted issues encompassing social and technical aspects, including issues related to cognition, emotion, and behavior [60]. Furthermore, its use of advanced technologies such as digital twins, blockchain, and Artificial Intelligence (AI) [34], alongside various interaction methods like VR, AR, and MR with different devices [72], further complicates its development and implementation.

Based on these considerations, our goal was to identify, synthesize, and categorize the key challenges impacting the development of the metaverse while also outlining an engineering framework. Specifically, we formulated three central research questions that guide our investigation.

Our first research question (**RQ**$_1$) represented a *preliminary*, *demographic* analysis into the research community around the metaverse. The goal of this analysis is twofold. On the one hand, it could provide an overview of the researchers involved and the connections among them, which are instrumental elements to characterize the multi-disciplinary nature of metaverse engineering. On the other hand, it could analyze the publication landscape, identify venues where metaverse research is being disseminated, such as journals and conferences, and help researchers identify relevant outlets for their work. Following these arguments, we therefore asked:

> ***RQ$_1$****: What is the current status of metaverse research in terms of* ***researchers involved*** *and* ***publication venues****?*

As a second step of our study, we aimed to identify the social issues arising when developing metaverses. The ultimate goal was to catalog the health, safety, and psychological aspects that metaverse researchers and tool vendors should consider when developing a metaverse. More particularly, we asked:

> ***RQ$_2$****: What are the current* ***social issues*** *to consider when building a metaverse?*

Our last research question (**RQ**$_3$) aimed at identifying the technical aspects concerned with the development of the metaverse. Even though the technology is evolving rapidly, it is crucial to determine which technologies—e.g., artificial intelligence, cloud computing, blockchain—can be used for the metaverse and what potential risks they may pose to users. As such, we formulated the following research question:

> ***RQ$_3$****: What are the current* ***technical issues*** *to consider when building a metaverse?*

3.1.2 Identify Search Terms. To define relevant search terms, we considered a variety of synonyms used in the literature for the metaverse. This step was crucial, especially in an emerging field like this one.

We proceeded by first drafting an initial set of synonyms for each of the key terms of our study:

- **Metaverse**: ("*metaverse*" OR "*virtual world*" OR "*cyberworld*" OR "*digital universe*" OR "*augmented reality*" OR "*multiverse*" OR "*alternate reality*" OR "*immersive environment*" OR "*virtual reality*" OR "*mixed reality*")
- **Issue**: ("*issue*" OR "*problems*" OR "*difficulty*" OR "*debate*" OR "*incident*" OR "*obstacles*" OR "*challenge*" OR "*strife*" OR "*opposition*" OR "*resistance*")
- **Social**: ("*social presence*" OR "*human interaction*" OR "*interaction*" OR "*communication*" OR "*collaboration*" OR "*cooperation*" OR "*engagement*" OR "*interpersonal aspect*" OR "*relational context*")
- **Technical**: ("*technological*" OR "*architecture*" OR "*engineering*" OR "*design*")

We experimented with a search string composed of the terms above. However, this yielded around 15,000 results, which was impractical to analyze manually. To improve precision, we adopted an alternative approach, selecting only the most relevant keywords. We employed the Delphi method [15], a structured process for synthesizing expert opinions. In general, the Delphi method involves two specific roles: *domain experts* and a *facilitator*. In our study, the domain experts were responsible for selecting relevant terms for the mapping study. At the same time, the facilitator collected feedback from the experts and determined whether consensus had been reached or if additional rounds were needed. The first two authors acted as domain experts, as they have expertise in software engineering and specific experience in the metaverse domain, with low to medium years of seniority. The third author, although with limited experience in the metaverse, has many years of expertise in software engineering and research methods, and was therefore assigned the role of facilitator, managing the overall process and ensuring methodological consistency and rigor. At the end of each cycle, the facilitator aimed to reach consensus. In this regard, we relied on the work of Lilja et al. [33] and Okoli and Pawlowski [44], who highlight that the Delphi method does not define a fixed consensus threshold; instead, agreement levels typically range from 51% to 80%, depending on the study's objectives. In our case, the first round did not reach the minimum level of agreement, so a second round was conducted. During the second round, a satisfactory level of consensus was reached. We considered this result, supported by external references, a valid indicator of consensus. After the Delphi cycles, some terms were removed because they were redundant or not distinct enough within the context of the metaverse and its social and technical challenges. For example, words like "obstacles" or "difficulty" were considered synonyms of concepts already represented in the final list, such as "issues" or "challenges". To validate the final set of keywords, we consulted four senior faculty members, each with over 20 years of experience in at least one of the following domains: virtual reality, human-computer interaction, artificial intelligence, and software engineering. They reviewed the identified terms and suggested no additional ones, confirming the soundness and completeness of the keywords generated by the Delphi method. For ethical purposes, it is important to remark that we submitted and received approval from the ethical board of our university. The final list of terms used was:

- **Metaverse**: ("*metaverse*" OR "*multiverse*" OR "*cyberworld*")
- **Issues**: ("*issue*" OR "*challenge*")
- **Social**: ("*social presence*" OR "*relational context*" OR "*communication*" OR "*collaboration*")
- **Technical**: ("*technological*" OR "*architecture*" OR "*engineering*" OR "*design*" OR "*develop*")

As a last step, we aggregated the terms above using logical operators, defining our final search query:

> ***Query***: *(("metaverse" OR "multiverse" OR "cyberworld") AND ("issue*" OR "challenge*") AND ("social presence" OR "communication" OR "collaboration" OR "relation context") AND ("technological" OR "architecture" OR "engineer*" OR "design" OR "develop"))*

3.1.3 Resources to be Searched. We selected the *ACM Digital Library*,[5] *Scopus*,[6] *IEEE Xplore*,[7] *Web of Science*,[8] and *Springer Link*[9] as our search databases, focusing on computer science. We limited the search to this field for three reasons: computer science intersects with disciplines like psychology and sociology, it covers areas where technology and social science converge (e.g., human-computer interaction), and broadening the scope would have made the review impractical. Our goal was to catalog socio-technical issues relevant to *metaverse engineering*, which can be addressed using computer science methodologies.

3.2 Article Selection Process

Figure 1 overviews the steps conducted during the systematic process, highlighting how the number of primary studies evolved while executing the selection process.

3.2.1 Inclusion and Exclusion Criteria. The first step of the article selection process involved defining the inclusion and exclusion criteria to obtain useful papers that would answer the research questions.

Exclusion criteria: Primary studies that met the following criteria were *excluded* and discarded from the subsequent data extraction and analysis phases: (1) Articles that were not peer-reviewed; (2) Article that were not written in English; (3) Poster articles or similar; (4) Articles that were not available for free; (5) Articles that were not published

[5]https://dl.acm.org
[6]https://www.scopus.com/search/form.uri?display=basic#basic
[7]https://ieeexplore.ieee.org/Xplore/dynhome.jsp?tag=1
[8]https://www.webofscience.com/wos/woscc/basic-search
[9]https://link.springer.com

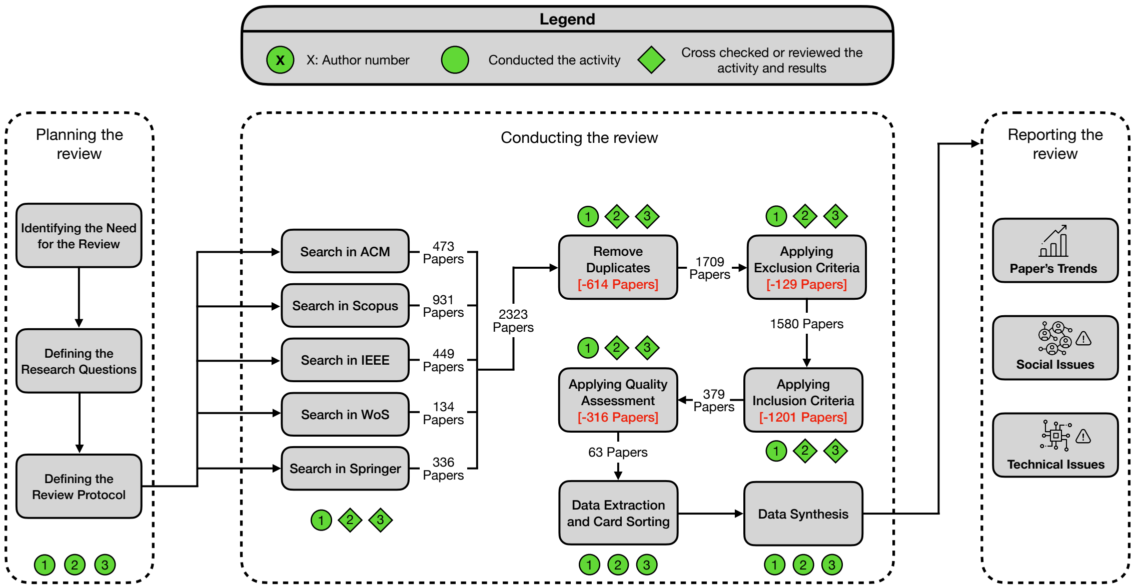


Fig. 1. Research Overview of the Steps Conducted

between 1992 and 2024. Such a temporal criterion was established to gather all relevant papers published after the inception of the term "metaverse", which was indeed in 1992.

Inclusion Criteria: Primary studies that met the following criteria were *included* and used in the subsequent data extraction and analysis phases: ❶ Articles reporting about *socially relevant issues* in the context of metaverse; ❷ Articles reporting about *technically relevant issues* in the context of metaverse.

3.2.2 Quality Assessment. In addition to exclusion and inclusion criteria, we implemented a quality assessment procedure to ensure the selected studies were reliable and suitable.

For quantitative analysis, we used bibliometric filtering to exclude low-quality resources. We applied the *CORE Rank*[10] for conferences and the *Scimago Journal Rank*[11] (SJR) for journals, ensuring high-impact studies were selected.

For qualitative analysis, we followed the *ACM/SIGSOFT Empirical Standards*[12], acknowledging that venue metrics alone do not guarantee quality. We introduced additional criteria to assess each article's rigor, allowing for the inclusion of papers from lower-ranked venues if they met our qualitative standards.

After this filtering process, we assessed the suitability of the resulting papers using the following questions: [1] Does the paper clearly and exhaustively describe the method used to conduct the research?; [2] Does the paper discuss or describe possible limitations or threats to validity?; [3] Does the paper clearly define what the aim of the research is?.

The checklist evaluated the clarity and comprehensiveness of the primary studies, focusing on research methods, limitations, and objectives to ensure the selected studies were suitable for our research. To minimize ambiguity in linguistic nuances [38], we applied Zadeh's fuzzy logic [70], assigning values from 0 to 1 to capture varying levels of completeness in each study. Specifically, the questions of the checklist were evaluated based on a specific range: '*Yes*'

[10] http://portal.core.edu.au/conf-ranks/
[11] https://www.scimagojr.com
[12] https://acmsigsoft.github.io/EmpiricalStandards/docs/?standard=SystematicReviews

Table 1. Search results for each data source

Data Source	Query Execution	Without Duplicates	Exclusion Criteria	Inclusion Criteria	Quality Assessment
ACM Digital Library	473	364	339	64	11
Scopus	931	530	471	107	23
IEEE Xplore	449	425	408	154	13
Web Of Science	134	85	68	17	2
Springer Link	336	305	294	37	14
Total	**2323**	**1709**	**1580**	**379**	**63**

with the maximum score of 1, '*Mostly*' with a range between $(0.7 - 0.9)$, '*Partially*' with a range $(0.4 - 0.6)$, '*Rarely*' with a range between $(0.1 - 0.3)$, and '*No*' with the lowest score of 0. Finally, we combined the scores for each quality criterion, and all articles with a final score between 1.7 and 3 were included in our analysis.

3.2.3 Search Process Overview. Table 1 summarizes how the number of primary studies evolved as a consequence of the various selection steps performed.

- **Query execution**: We executed the search string against the five databases, identifying a total of 2,323 articles. Afterward, we removed duplicate papers, i.e., those identified when running the search string against multiple databases. The first and second columns of Table 1 show the transition from the obtained set of papers to the set without considering duplicates.
- **Exclusion Criteria**: We applied the exclusion criteria to the articles retrieved from the query results. All the papers not satisfying at least one of the exclusion criteria from (1) to (5) shown in Section 3.2.1 were discarded. This step led to the exclusion of 129 papers out of the initial 2,323: 20 were excluded when applying exclusion criterion (2), 20 as a consequence of exclusion criterion (3), 82 because of exclusion criterion (4), and 7 after applying exclusion criterion (5). The remaining 1,580 primary studies were considered for the next stage.
- **Inclusion Criteria**: By reading title, keywords, and abstract, the inclusion criteria were verified on the set of 1,5890 primary studies according to the checklist from ❶ and ❷. In borderline cases, the conclusion section was also assessed. As a result of this stage, 379 papers were considered for further assessment, while 1,201 primary studies were discarded.
- **Quality Assessment**: Each of the 379 papers was assessed in terms of publication venue and verified according to the checklist developed from [1] to [3] in Section 3.2.2. A final number of 63 papers were deemed eligible to address the research questions of the study.

The execution was mainly curated by the first author of the paper. All the phases were, however, monitored and verified by the other authors through weekly meetings.

3.3 Data Extraction and Analysis

Upon completion of the selection process, the 63 primary studies were read throughout in order to extract and analyze relevant data that might have addressed our research questions.

3.3.1 Data Extraction. For the data extraction process, we followed the guidelines proposed by Kitchenham et al. [29], which recommend systematically organizing information from the collected studies. Accordingly, we recorded each paper's title and assigned a unique identifier to it. We then extracted specific data items relevant to answering RQ_1, RQ_2, and RQ_3. For $\mathbf{RQ}_1$, we collected metadata, including the year of publication, author list, publication venue, ranking, and the source from which the paper was retrieved. For $\mathbf{RQ}_2$, we extracted social issues, while for $\mathbf{RQ}_3$, we focused on technical issues. This structured approach facilitated a consistent data representation and supported an efficient analysis. All the authors were primarily responsible for data extraction. Additionally, each author reviewed the results obtained by the others. In case of disagreement, they organized and participated in joint meetings to resolve the issues.

3.3.2 Data Analysis. To address our **RQ**s, we analyzed the data extracted in the previous step. Specifically, we computed descriptive statistics to address $\mathbf{RQ}_1$, focusing on the items of the data extraction form related to the metadata. In Section 4, we present charts, tables, and statistics that illustrate the distribution of these metadata elements across the primary studies. As for $\mathbf{RQ}_2$ and $\mathbf{RQ}_3$, we had to elicit, synthesize, and catalog the socio-technical issues discussed within the primary studies. To this end, we employed an *open card sorting* method [40], a commonly used qualitative research technique that facilitates the creation of mental models and the development of taxonomies from qualitative data. Such a technique has been employed in previous similar research aimed at eliciting properties from data [11, 25, 47].

The method involved all the authors of this paper (one Ph.D. Student and two Senior Researchers, respectively, with over 10 and 20 years of experience), who undertook this process to organize the social and technical issues that emerge in the metaverse. Specifically, we engaged in three iterative sessions, which are described below.

Iteration 1: An initial set of 32 papers was selected. Two of the authors — from now on called *inspectors* — analyzed each of them independently. Their task was to review the content of each article and annotate the main issue(s) described, as well as whether these issues pertained to technical or social concerns. The inspectors were left free to manually annotate the identified issues or report them in a file. Once the inspectors had completed their individual assessments of the 32 papers, they scheduled a physical meeting to discuss the outcomes produced so far. For each paper, the inspectors compared their own judgments on the issues identified in an attempt to find a consensus on (i) the procedure employed to perform the elicitation task and (ii) the types and labels to assign to the identified issues. During the meeting, the third author of the article acted as the *external evaluator*, providing feedback on the choices made by the inspectors, suggesting possible improvements on how the elicitation task was performed, and resolving possible disagreements between the inspectors. The meeting lasted around two hours. The inspectors could first refine their elicitation procedure by exchanging information on how to standardize the operations performed. More importantly, the inspectors obtained a *full agreement* on the issues identified in the 32 papers considered; most of the discussion revolved around the best labels to assign to the issues. The inspectors concluded the first iteration with a provisional taxonomy of the social and technical issues.

Iteration 2: The initial 32 papers were reviewed and re-classified by the inspectors according to the decisions taken at the previous iteration. In addition, the inspectors repeated the elicitation task on the remaining 31 papers; however, this time they classified the issues identified using the provisional taxonomy that had been generated as an output of the previous iteration. The purpose of this phase was twofold. First, to assess the reliability of the provisional taxonomy, they could use it as a starting point to classify new issues and determine whether existing categories should be merged or redefined. Second, to identify new categories that did not previously emerge. At the end of the task, the inspectors held another physical meeting of approximately two hours, with the involvement of the external evaluator. The inspectors individually summarized the operations performed to assess their consistency with respect to the feedback received in the first iteration. Then, they discussed the types and categories of issues identified. During the discussion, they agreed to introduce a new category concerned with technical issues, while leaving the social ones unchanged. The output of this iteration was a final taxonomy of social and technical issues.

Iteration 3: In the final stage, the two inspectors performed a double-check of the operations performed. More specifically, they went through each of the 63 papers previously considered, verifying the consistency of the classifications reported. The inspectors agreed that, in case of inconsistencies, a new round of discussion should have been opened. Nonetheless, they did not identify inconsistencies.

Additional Validation: While the third iteration confirmed the consistency of the classification process, an additional validation step was conducted to further ensure the reliability of the final taxonomy. Specifically, the third author — who had previously served as an external evaluator — independently reviewed all 63 papers and performed a comprehensive annotation of the issues, using the taxonomy defined in previous iterations. In total, 311 issues were identified across the 63 papers, of which 140 were categorized as social and 171 as technical issues. This step confirmed the exhaustiveness of the taxonomy, as no new categories were added. However, seven minor cases of misalignment between the third evaluator and the previous classification emerged. These disagreements were discussed by the first two evaluators until consensus was reached. To quantify the overall inter-rated agreements of the categorization process, we computed Krippendorff's α [30], obtaining a value of 0.89, which indicates almost perfect agreement.

After these iterations, the taxonomy of social and technical issues was confirmed as final, and the card sorting process was concluded. The taxonomy of social and technical issues represents the main outcome of the study. It is organized as a hierarchical taxonomy composed of three layers. In Section 4, we firstly address $\mathbf{RQ}_1$, then we address $\mathbf{RQ}_2$, and $\mathbf{RQ}_3$ by discussing the specific issues identified by the card sorting method.

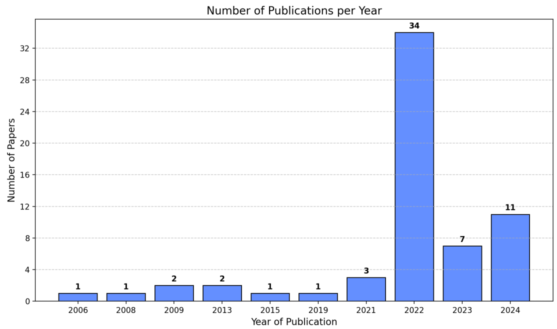
4 ANALYSIS OF THE RESULTS

In the following section, we describe the results achieved for each research question.

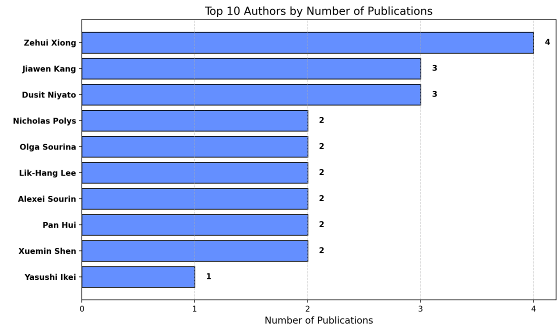
4.1 RQ_1: What is the Current Status of Metaverse Research in Terms of Researchers Involved and Publication Venues?

This section outlines the state of metaverse research, highlighting trends, methods, and progress across fields.

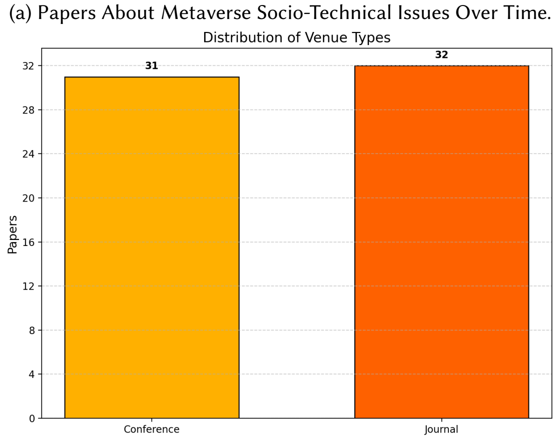
4.1.1 Evolution of the Discipline Over Time. While the term metaverse first appeared in 1992, the technology at the time was insufficient to support the concept. Over the years, with the rise of virtual reality, the metaverse has gained traction and become an increasingly relevant topic of interest. Figure 2a illustrates the publication trends regarding the metaverse, which can be divided into three key clusters. The first cluster spans from 2006 to 2009, during which an initial exploration of the social and technical issues associated with the metaverse took place. At this stage, the technology was not yet well established; it was still viewed as more of a theoretical concept rather than a practical solution. The second cluster, covering the years from 2013 to 2015, reflects a similar focus on the issues surrounding the metaverse. Although interest persisted, the technology had not yet developed to a point where it could be considered feasible for widespread use. In contrast, the third cluster, which spans from 2019 to 2024, exhibits a notable increase in interest from the scientific community. This growth can be attributed to several factors. First, there was a significant advancement in virtual reality technologies, including the commercial availability of early HTC headsets. Second, the COVID-19 pandemic created new challenges that highlighted the need for virtual interactions. Finally, Mark Zuckerberg's announcement in late 2021 about rebranding Facebook to Meta generated considerable excitement and investment in the metaverse. Overall, this progression indicates a shift from initial curiosity to robust and ongoing exploration of the metaverse's potential.



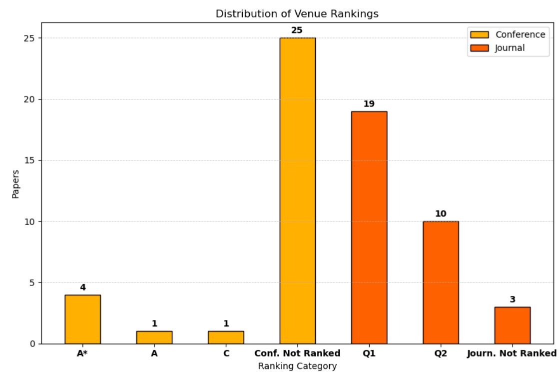
(a) Papers About Metaverse Socio-Technical Issues Over Time.



(b) Top-10 Authors with Socio-Technical Issues Publication



(c) Distribution Conference vs. Journals



(d) Rank Distribution for Conferences and Journals

Fig. 2. Some statistics about identified studies.

4.1.2 Authors and Research Communities. With a total of 266 authors, a diverse range of contributors explores this emerging technology. Among them, some authors distinguish themselves with a significantly higher number of publications; therefore, in Figure 2b, we report the top 10 authors based on their contributions to metaverse-related socio-technical issues. Notably, *Zehui Xiong* has the largest number of publications, with 4, followed by *Jiawen Kang* and *Dusit Niyato*, each with 3 publications. *Nicholas Polys*, *Olga Sourina*, *Lik-Hang Lee*, *Alexei Sourin*, *Pan Hui*, and *Xuemin Shen* each have 2 publications, while the remaining authors, such as *Yasushi Ikei*, have contributed with one.

Although the metaverse is a relatively new topic, it attracts diverse research communities. Our analysis reveals that this broad interest stems from both its technological novelty and the potential for various fields to contribute actively.

The most engaged communities include *Human-Computer Interaction* and *Virtual Reality*, which are expected areas given the complexities of interaction in virtual environments. Following these are communities focused on *Software Security* and *Cloud Computing*, working to ensure the metaverse's safety through encryption algorithms, even in a hypothetical cloud-based metaverse. Lastly, communities such as *Artificial Intelligence*, *IoT*, *Health*, and *Computer Science Education* also play crucial roles in this diverse research landscape.

However, it is notable that the software engineering community is not yet represented in the publications related to the metaverse. This absence highlights a critical gap in the research, as software engineering principles are essential for connecting all the research communities and developing robust and scalable metaverse applications, leading to the establishment of metaverse engineering. By doing so, we aim to raise greater awareness of the various aspects that the metaverse may encompass, and how to design and implement multidisciplinary solutions within this innovative space.

4.1.3 Venue and Rank. Figure 2c illustrates the distribution of the 63 studies included in our analysis: 31 were published at conferences, while 32 were published in journals. This distribution indicates that the communities interested in the metaverse publish in both formats, with a slight preference for journals over conferences. Although the difference is minor, the trend suggests growing interest and a likely rise in publications.

Even more interesting is the rank distribution of the various conferences and journals. The results shown in Figure 2d indicate that, in addition to favoring journals over other publication types, researchers tend to prioritize top journals ranked as Q1, with 19 papers, and Q2 with 10 papers, according to the SJR indicator. Among the Q1 journals are multidisciplinary titles such as the *International Journal of Human Computer Studies* and *ACM Computing Surveys*, while Q2 includes journals like *Virtual Reality* and *Transactions on Emerging Telecommunications Technologies*. It is worth noting that only three of them are not ranked, indicating they are likely new emerging journals.

On the conference side, four publications took place at A* conferences such as the *CHI Conference on Human Factors in Computing Systems*, while only one was at an A-level conference, the *ACM Internet Measurement Conference*, and one at a C-level conference. A key finding is that 25 publications were presented at non-ranked conferences, indicating that many metaverse studies are submitted to venues not yet recognized by the CORE indicator. A key point is that only one conference, the *International Conference on Intelligent Metaverse Technologies & Applications* (iMETA), is dedicated to the metaverse, highlighting a gap in venues for metaverse research. Given its complexity and interdisciplinary nature, there is a need for more conferences and journals focused on this topic. Such venues would increase visibility, foster community building, and address emerging challenges related to interaction, immersion, and socio-technical issues.

4.2 RQ_2: What are the Current Social Issues in the Metaverse?

Our goal was to highlight the most critical social issues that the metaverse needs to address. The findings, shown in Figure 3, categorize these issues into five key areas: *Interaction and Engagement*, *Accessibility and Inclusivity*, *Privacy and Security*, *Social Norms and Ethics*, and *Mental Health and Well-Being*. Each of these key areas includes multiple categories, which in turn may contain several subcategories.

4.2.1 Interaction and Engagement. The first category concerns interaction and engagement, covering interface usability, virtual interaction quality, and methods to sustain user immersion.

Avatar Representation and Perception. The representation and perception of avatars significantly influence interaction and engagement in virtual environments, affecting issues such as gender identity, privacy, mental health, and addiction. Ensuring equal access to avatar representation and customization in every aspect, such as gender and voice customization, can promote inclusivity, foster a more engaged community, and help reduce social disparities [A1, A2, A4, A5, A21]. However, this opportunity can also encourage cultural appropriation, a phenomenon where elements of one group's culture are adopted by another in a disrespectful or unauthorized manner, leading to insensitivity and racism, with negative consequences for interaction and engagement [A6–A8]. Additionally, the discrepancy between one's real identity and the idealized identity of avatars can cause psychological stress, exacerbating issues related to mental health and addiction [A9]. For this reason, there is a need for balancing the anonymity that avatar customization could provide with the accountability of the person behind the avatar [A10]. Indeed, the enhancement

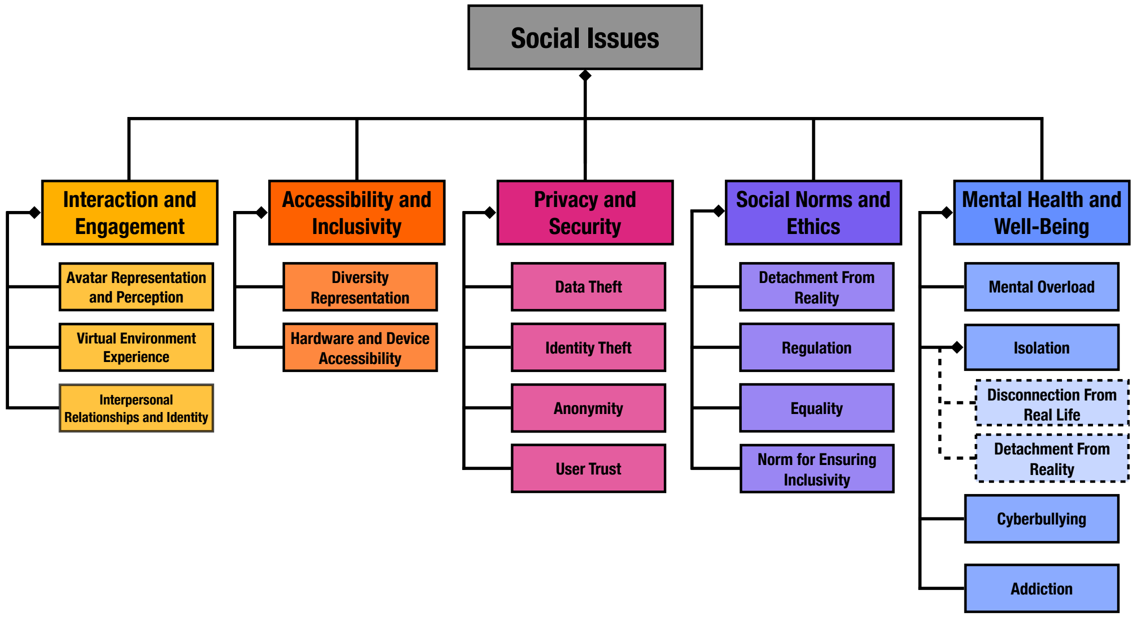


Fig. 3. Social Issues Taxonomy for the Metaverse – Each social issue is represented using the *IBM Palette Library* for color blindness, with different opacity levels indicating the membership of sublevels within their parent categories. Multiple memberships within the same category are also represented using dashed lines.

of avatar quality is one of the most critical issues that must be addressed for social interaction [A11], but without causing confusion between real and virtual identities [A12].

Virtual Environment Experience. One of the critical aspects to consider is presence and immersion, meaning the extent to which a user feels present and immersed in the virtual environment [A13]. Currently, virtual environments suffer from a significant problem: the lack of a unified metaverse. This leads to the existence of numerous virtual environments [A1], each with a specific purpose but developed with low immersivity [A14] and without promoting social interaction and conversation [A15]. A critical consideration is connecting multiple virtual environments, creating smooth transitions between them, and ensuring each virtual environment incorporates inclusive design aspects, considering gender-sensitive design elements — e.g., public spaces, virtual buildings, or safe zones where users can report harassment to find support [A16]. Additionally, a high level of satisfaction in using graphical interfaces is necessary [A17]. Among the various virtual environments, many are related to education. Still, they lack educational approaches that maximize interaction dynamics, leading to low engagement compared to current 2D tool strategies [A2, A14, A18].

Interpersonal Relationship and Identity. The interaction between virtual and real experiences significantly impacts interpersonal relationships and identity. Communication difficulties in virtual spaces, such as the lack of non-verbal cues, contribute to potential misunderstandings and increasing complexity between users and avatars [A19]. This highlights the need for more intuitive communication methods that mimic real-world interactions [A15], which can significantly reduce interpersonal issues related to the authenticity of interactions [A13, A16]. Additionally, excessive engagement in the metaverse can blur the line between virtual and real life, potentially compromising users' sense of personal identity [A21, A22].

4.2.2 Accessibility and Inclusivity. This category focuses on metaverse accessibility, ensuring assistive technologies, affordable hardware, and an inclusive environment for diverse user needs.

Diversity Representation. One significant social issue that demands considerable attention is the lack of diversity representation in virtual environments. To address this, it is crucial to develop strategies that promote the active involvement of users from diverse backgrounds and consider gender differences [A16]. Embracing practices that enable accurate and realistic 3D representation of individuals, both in terms of physical appearance and gender [A16, A23], is essential to achieving enhanced interaction, fostering collaboration, and strengthening social connections [A17, A24].

Hardware and Device Accessibility. Promoting digital and social inclusivity requires ensuring accessibility to hardware and devices. Inclusive hardware design incorporates tactile feedback and adjustable interfaces to promote independence and productivity for individuals with disabilities. These designs should also be continually refined and updated [A25, A26]. In addition, essential assistive technologies like screen readers and voice recognition must be both accessible and affordable for all potential applications in the metaverse [A21], eliminating barriers to professional growth and career advancement [A27].

4.2.3 Privacy and Security. This category deals with the issues of safeguarding user privacy and ensuring security within the metaverse, including data protection, secure interactions, and the prevention of unauthorized accesses.

Data Theft. Data theft poses significant social issues intertwined with misuse, deception, security concerns, privacy issues, and cyber threats. Data protection and privacy within the metaverse are crucial, as personal information is vulnerable to misuse, necessitating stringent privacy regulations [A25]. Indeed, virtual environments have already presented constant threats of harassment, financial theft, fraud, and identity theft, compromising users' privacy and security [A21, A28, A29]. The primary cause of these problems can be attributed to various factors, including the use of wearable devices [A30] and the potential for improperly customizing and manipulating personal characteristics such as voice representation [A10]. Consequently, the metaverse has significant gaps in terms of the manipulation of data within the metaverse [A26] and how this data is collected, stored, and used [A27].

Identity Theft. One of the critical areas is the security issues of wearable devices, which store sensitive personal identity data. Although failures or compromise of these devices could lead to leakage of identity information, the use of biometric authentication is an excellent alternative to reduce risks related to identity theft [A21]. However, privacy concerns related to biometric data are still significant, as the use of biometric authentication methods, while enhancing security, raises substantial privacy issues. Safeguarding biometric data from misuse is essential to maintaining users' trust and privacy in the digital realm [A28]. In addition, identity hacking threatens the security and authenticity of users' identities in the metaverse and is, therefore, a vital area of concern [A31]. Finally, intrusion of privacy and identity theft due to a false sense of security often leads to excessive sharing of personal information. This over-sharing, combined with a lack of real constraints, makes individuals vulnerable to identity theft [A32].

Anonymity. Anonymity is one of the issues that most stem from our days and the misuse of platforms such as Instagram, Facebook, and others. As a social problem, anonymity has several significant consequences that affect individuals and the community. A primary concern is the erosion of personal accountability, where individuals, protected by the cloak of anonymity, may enact behaviors that they would otherwise avoid if their identity were known. This lack of accountability can lead to an increase in cases of cyberbullying and online harassment as perpetrators feel encouraged by their perceived invisibility [A33]. Anonymity can foster misinformation by obscuring sources and complicating verification [A12].

User Trust. User trust is vital for social dynamics, impacting critical areas such as safety, privacy, control, and communication. The foundation of trust lies in ensuring the safeguarding of user information and interactions [A28]. This is closely intertwined with upholding privacy, as users anticipate their data to be handled securely and transparently [A15]. Furthermore, the perception of control is paramount; users should feel empowered to control their data and the content they engage with [A34]. Clear and honest communication facilitates the alignment of user expectations with actual experiences and strengthens trust [A21].

4.2.4 Social Norms and Ethics. This category concerns establishing social norms and ethics in the metaverse to ensure respectful, safe, and inclusive interactions.

Detachment From Reality. The metaverse presents a range of social and ethical issues related to social norms. The lack of adequate control and regulation creates a fertile ground for abusive behaviors and illegal activities, such as privacy violations and cyberbullying [A21]. Social norms that regulate human behavior in the real world are not easily applicable in the metaverse, causing users a sense of anarchy and insecurity [A33]. Furthermore, how individuals represent themselves in the metaverse can lead to issues of identity and authenticity, creating dissonance between virtual and real identities [A35]. Finally, constant immersion in the metaverse can have adverse effects on users' mental and social health, leading to isolation, addiction, and alienation from reality [A22]. Therefore, developing clear rules and regulations to address these issues and ensure a safe and inclusive virtual environment is crucial.

Regulation. The metaverse introduces numerous regulatory issues that remain unresolved. Effective governance mechanisms are needed to address virtual crimes and AI ethics, while robust community management practices are essential for maintaining a safe and respectful virtual space [A36, A37]. As such, legal and ethical complexities arise in regulating virtual economies, with particular attention needed for content moderation, censorship, and misinformation [A26, A31]. Avoiding spreading false information is a significant concern in less controlled environments, highlighting the importance of digital citizenship education and ethical guidelines [A33]. By emphasizing the importance of these measures, the audience will feel a sense of responsibility and commitment to maintaining a safe virtual space. Understanding the impact of virtual assets and digital identities on the digital economy, along with establishing fair digital currency systems, is crucial for seamless transactions and positive community in the metaverse [A38, A39].

Equality. The equality theme in the metaverse presents several significant issues that require attention to ensure a fair and inclusive virtual environment. Economic and political constraints play a critical role in the development and accessibility of the metaverse. These constraints can limit its growth and hinder the equitable distribution of benefits, making it crucial to navigate these factors carefully [A28]. Additionally, understanding the impact of virtual currency and incentivized activities on user behavior is vital. By developing economic models that encourage positive participation, the metaverse can foster an inclusive environment that supports diverse social dynamics [A37]. Moreover, ethical and moral challenges arise from the diverse ideologies and worldviews present in the metaverse, which can lead to potential conflicts. Establishing a well-organized metaverse with clear rules and ecosystems is essential to managing these challenges effectively and promoting equality [A12].

Norm for Ensuring Inclusivity. Respecting cultural differences, fostering gender inclusivity, and ensuring accessibility for all individuals, regardless of physical or mental abilities, are essential guidelines for promoting equity and acceptance within diverse social settings. Emphasizing these aspects can reduce social disparities and foster environments where everyone feels valued and included. Implementing such practices enables organizations and communities to build a more just and cohesive society, reflecting core principles of human rights and dignity [A16, A19, A27].

4.2.5 Mental Health and Well-Being. This category focuses on the issues related to the mental health and well-being, including managing screen time, preventing addiction, and supporting users facing negative psychological effects.

Mental Overload. The immersive nature of the metaverse can lead to an overwhelming amount of information, causing users to experience increased stress and cognitive strain. Navigating complex virtual environments and managing virtual and physical responsibilities can violate personal space and privacy, significantly impacting user experiences and well-being. Furthermore, the constructed realities within the metaverse may reinforce or exacerbate existing cognitive biases, further complicating users' mental processing and decision-making abilities [A24, A33].

Isolation. The rise of virtual interactions may affect traditional socializing, potentially increasing isolation [A27, A40]. The balance between virtual and real social connections is essential to mitigate feelings of loneliness and psychological distress [A41]. A clear example comes from the COVID-19 pandemic, in which distance learning and virtual engagements exacerbated isolation among individuals, contributing to anxiety and reduced community engagement [A18]. As shown in Figure 3, this category can be split into two subcategories, i.e., *Disconnection from Real Life* and *Detachment From Reality*. Although the two sub-categories seem to have the same meaning, disconnection is typically associated with problems where users neglect or isolate themselves from real-world responsibilities and interactions [A41, A42]. This issue often occurs during the transition between virtual and real environments, where users prioritize their digital lives over real interactions [A43], leading to a devaluation of real-world experiences [A44]. Unfortunately, disconnection can lead to detachments, making it harder to differentiate between the physical and digital worlds [A42], especially with prolonged interactions with NPCs—mimicking real-life identities [A9]—which can cause confusion and disorientation [A33].

Cyberbullying. It is a growing concern, reflecting aggressive and intentional acts carried out through virtual platforms. This form of bullying often overlaps with traditional bullying but is potentially exacerbated by the anonymity provided online [A32, A45]. Cyberbullying in the metaverse involves persistent harassment, which can have severe psychological effects on victims due to the immersive and pervasive nature of virtual environments [A32]. The issue is compounded by the ethical dilemmas posed by AI-driven content and interactions, which can sometimes unintentionally contribute to the spread of harmful behavior [A36]. Addressing cyberbullying requires a comprehensive approach that includes technological, ethical, and social interventions to create safer virtual spaces.

Addiction. The rise of the metaverse has also raised significant concerns about addiction. This immersive environment can lead to excessive use, causing users to neglect real-world responsibilities and experience social isolation and mental health issues [A28, A46]. The appeal of the metaverse often exacerbates feelings of loneliness and anxiety as some users become more comfortable in the virtual world, which in turn hinders their real-life social skills and relationships [A41]. Based on this, virtual environment companies can exploit users' addictive behaviors through transactions and the sale of virtual goods, potentially leading to financial strain for those who cannot control their spending [A33]. Addressing these interconnected issues requires a comprehensive approach, including responsible design practices by developers, mental health support for users, and public awareness campaigns to mitigate the negative impacts on individuals and society [A12].

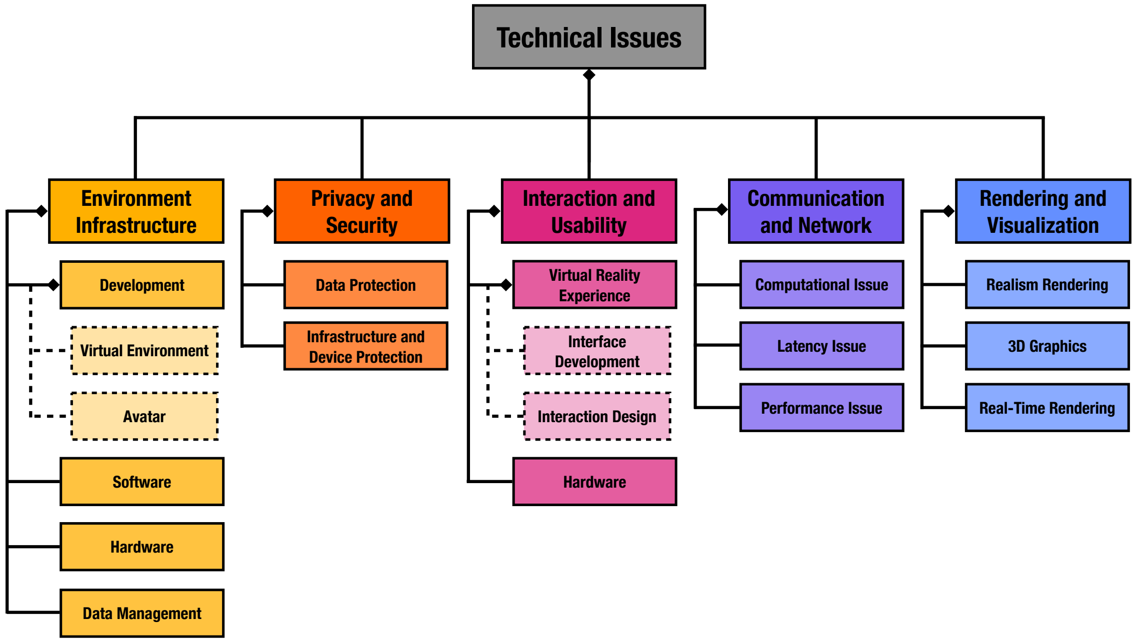


Fig. 4. Technical Issues Taxonomy for the Metaverse – Each technical issue is represented using the *IBM Palette Library* for color blindness, with different opacity levels indicating the membership of sublevels within their parent categories. Multiple memberships within the same category are also represented using dashed lines.

4.3 RQ_3: What are the Current Technical Issues in Metaverse?

In RQ_3, our goal was to highlight the most critical technical issues that the metaverse needs to address. The findings, shown in Figure 4, categorize these issues into five key areas: *Environment Infrastructure*, *Privacy and Security*, *Interaction and Usability*, *Communication and Network*, and *Rendering and Visualization*. Each of these key areas includes multiple categories, which in turn may contain several subcategories. While these subcategories may appear to address similar topics, they are intended to highlight different dimensions and nuances within the broader category. As a result, these subcategories provide valuable insights into where research and the scientific community should focus their efforts to enhance the overall category. The following sections describe the specific categories identified in our work.

4.3.1 Environment Infrastructure. This category addresses the issues related to the infrastructure of the metaverse, including the need for robust and scalable hardware and software, efficient data storage and processing, and ensuring stable and high-speed connectivity to support seamless user experiences.

Development. The development of the metaverse involves addressing several key issues, each of which underscores the need for advanced technologies. Generally, advanced voice synthesis is required for accurate attribute recognition and real-time speech generation [A10], CNNs with anti-aliasing for biometric recognition [A28], and dual exposure fusion algorithms to improve low-light image quality [A28]. These technologies are not just desirable, but essential for the evolution of the metaverse. Robust system architectures and load balancing are also essential [A37], as well as software compatibility and standardization [A26] and managing digital object manipulation complexity [A16]. Advanced algorithms and realistic mobility models are needed for dynamic areas of interest [A37]. Deep learning and data analytics enhance user interactions [A17], while interoperability ensures seamless experiences [A47]. Efficient navigation systems are crucial for functionality [A15, A48]. In education, the metaverse needs engaging content, AI-driven virtual instructors, and standardized protocols for cybercampuses [A14]. It also benefits from pedagogical integration for language learning [A43] and real-time environment modifications to boost engagement [A16]. However, as shown in Figure 4, the metaverse has developmental issues from the perspective of its representative elements, i.e., *Virtual Environment* and *Avatar*. On the one hand, avatar development needs accurate facial recognition and animation technologies to achieve realistic expressions [A9, A49]. Realistic avatars demand natural facial expressions and mouth movements, but integrating real-world data into the metaverse involves advanced processing [A19, A50]. Customization for non-gender identities is limited and often depends on third-party tools, including advanced voice modulation [A23]. Avatar creation tools must adapt to various online contexts and personality nuances [A44]. Additionally, creating visually and motion-accurate avatars is complex, with high-fidelity tracking being resource-intensive [A6], particularly for full-body tracking, which results in a lack of diversity in body types and gestures [A23]. NPCs need enhanced artificial intelligence to interact realistically [A43]. On the other hand, the virtual environment development also presented issues that needed to be addressed. Achieving a high level of immersion requires advanced VR technologies, sophisticated graphics, and user-friendly interfaces [A22]. The precise manipulation of 3D objects involves using hand gestures in a more dynamic way to select and edit vertices with pressing, pointing, and gripping actions that are sometimes hindered by sensor inaccuracies and require careful consideration to ensure smooth user experiences [A51]. Addressing issues such as color distortions and unrealistic textures in virtual environments and human body characteristics is also essential to achieving greater degrees of photo realism and immersion [A52].

Software. The development and maintenance of software infrastructure within the metaverse environment present several critical issues. The lack of standardized protocols and frameworks complicates the integration of various platforms, hindering seamless interaction and affecting user experience and asset sharing [A13, A33]. Additionally, integration with existing educational tools and ensuring compatibility with a wide range of devices, particularly mobile technologies, is crucial for accessibility [A14]. Ensuring interoperability across AR/MR technologies remains a significant issue [A27], and blockchain integration for managing virtual content and handling high transaction volumes is essential [A25, A39, A53]. These issues collectively lead to significant consequences, including the digital divide, where unequal access to technology reinforces social inequalities [A35]. Innovative technologies integrating AI and blockchain bring both opportunities and issues [A41], highlighting the need for sophisticated technology to create immersive experiences [A52]. Addressing these software-related issues is vital for fostering a unified and accessible metaverse ecosystem, ensuring security and sustainability [A12, A22].

Hardware. The development and immersive experience of the metaverse, especially for educational purposes, are significantly constrained by current hardware capabilities and infrastructure limitations. The technical infrastructure needed to support cybercampuses requires substantial investment in hardware, cost considerations, and advanced sensor technology to achieve the desired level of interactivity and immersive experiences [A28]. Integrating head-mounted displays with hand tracking for VR and ensuring compatibility with mobile platforms for AR users is critical for synchronizing actions and interactions in real-time across different user environments [A17]. Additionally, in metaverse educational classes, there is a need for high-quality one-way cameras to capture full classroom settings, but the high cost associated with professional-grade equipment presents a barrier [A18]. The substantial development costs and infrastructural challenges in supporting the data-intensive nature of the metaverse further complicate the deployment of these advanced technologies [A34]. Consequently, the hardware requirements, including processing power, battery life, and display technologies, need significant advancements to meet the demands of the metaverse [A31, A46]. High device costs also limit widespread adoption and accessibility, adding to the complexity of building an inclusive and comprehensive metaverse infrastructure [A12].

Data Management. In the metaverse, effective data management is a crucial technical issue involving many technologies, including Artificial Intelligence, Blockchain, and Cloud Computing. Addressing issues such as processing efficiency and managing large volumes of data is critical. Seamless experiences and real-time interactions depend on robust data processing capabilities [A25]. Artificial Intelligence faces difficulties in delivering personalized experiences and conducting emotional analysis due to the need to manage and process vast amounts of data while also considering ethical implications [A34]. These data management challenges are further complicated by the requirement for secure storage solutions, real-time data processing, and data integration from various sources [A26, A33].

4.3.2 Privacy and Security. This category focuses on the technical issues related to protecting user data and ensuring secure interactions within the metaverse.

Data Protection. The dynamic nature of the metaverse should allow users to access multiple virtual worlds through a single platform. While this concept seems like science fiction, it is actually quite similar to how we understand the internet. Managing vast data depends on the virtual world being accessed [A31]. This data can be divided into two main categories: (1) *personal data* related to the physical person and (2) *personal data* related to the virtual person, which may or may not derive from the physical person. The first category includes information such as name, surname, and banking details; the second includes data related to the virtual person, such as avatar representation, including voice customization ensuring the user's physical gender and other characteristics with which the user identifies [A10, A28] virtual assets such as customized 3D virtual scene or objects. Therefore, it is crucial to implement security techniques that focus on the privacy of virtual users, from authentication to the use of virtual components [A12, A41, A54], preventing unauthorized access or misuse of user/avatar data within the metaverse [A36, A55].

Infrastructure and Device Protection. Ensuring the security of the metaverse involves multiple critical aspects, focusing on building robust privacy systems and protecting devices. Firstly, wearable devices, which are expected to be primary access points for the metaverse, require secure key management and user authentication methods that are efficient and do not heavily tax their limited computational resources [A36]. Secondly, network security is crucial for safeguarding data transmission and preventing unauthorized access. This requires comprehensive measures such as encryption and advanced firewalls to protect the vast network infrastructure [A36]. Lastly, maintaining system integrity and stability is essential for user trust. This includes protecting against intellectual property theft and mitigating denial of service attacks through robust defense mechanisms [A32]. Addressing these areas collectively ensures a secure and seamless metaverse experience.

4.3.3 Interaction and Usability. This category focuses on the issues related to enhancing user interaction and usability within the metaverse, including intuitive interface design, seamless navigation, and user-friendly experiences that cater to diverse user preferences and abilities.

Virtual Reality Experience. It is crucial to allocate significant attention to the interaction design phase to create a seamless virtual reality experience in the metaverse. Indeed, as shown in Figure 4, this category can be split in *Interface Development*, and *Interaction Design* to have a unique experience that facilitate user interaction with the environment and with other users. Real-time interaction capabilities are crucial to prevent interruptions to ensure interactions that foster emotional engagement, providing a seamless user experience and a sense of control within the virtual environment [A13, A33]. Moreover, balancing realism and usability adds another layer of complexity, as it is essential to create a realistic virtual environment while maintaining ease of navigation for effective interactions through head-mounted display [A43]. For this reason, addressing VR motion sickness by optimizing rotational movements and angular velocities is paramount for ensuring user comfort and usability [A16].

Then, creating intuitive and user-friendly interfaces across different platforms is essential for seamless user experiences. Managing immersive virtual environments with realistic details is crucial for achieving more immersiveness [A13, A27, A51]. To enhance user interaction, systems must enable users to engage with digital content effectively, encouraging interaction and evoking emotions through well-integrated design elements [A15, A43, A56]. Furthermore, these interfaces must be accessible and cohesive, seamlessly integrating multiple functionalities to provide a comprehensive and user-friendly experience [A16].

Hardware. The metaverse is significantly dependent and related to hardware, which impacts user interaction and usability. Issues with device dependence and limitations hinder the overall experience. Current head-mounted displays (HMDs) suffer from problems such as poor display quality, limited field of view, and user discomfort, which restrict accessibility and versatility [A27]. Moreover, integrating multisensory inputs, combining visual, auditory, tactile, and potentially olfactory stimuli, poses a considerable challenge in creating cohesive and immersive experiences [A13]. The implementation of haptic interaction further complicates usability in virtual environments. Developing software capable of interacting with virtual objects through touch and managing high refresh rates for effective haptic feedback is critical for enhancing user experience [A57]. Additionally, ensuring high-quality visual and interactive experiences is essential for the effectiveness of immersive systems, as the type of camera used—i.e., professional vs. non-professional—significantly affects the overall quality of experiences such as tele-education [A18]. Lastly, sensitivity profiles need to be implemented to adjust interaction parameters to counteract adverse effects caused by head movements and sensor limitations, thereby enhancing hand gestures' stability and accuracy [A51].

4.3.4 Communication and Network. These issues concern metaverse communication infrastructure, requiring reliable connectivity, high bandwidth, and low latency for real-time interactions.

Computational Issue. The computational issues within the metaverse are extensive and diverse. Creating high-quality 3D environments and integrating AI necessitates significant computational resources and advanced hardware [A25, A35]. Using deep learning for dynamic interactions introduces additional complexity, requiring advanced computational capabilities to ensure seamless user experiences [A18, A39]. Robust infrastructure and networking solutions are critical to accommodate the metaverse's high connectivity and data transfer requirements[A25, A58]. Furthermore, integrating various communication methods —i.e., voice, text, gesture—and the wide spectrum of resources needed underscores the technical limitations involved [A30, A43, A59]. Lastly, addressing the intricacies of human image synthesis, particularly in disentangling pose and appearance, is crucial for crafting realistic and immersive virtual experiences [A52].

Latency Issue. Latency is a critical issue in the metaverse, significantly impacting the user experience and the effectiveness of XR (Extended Reality) applications [A6, A18, A21, A26, A57, A60]. Real-time XR streaming must handle device inputs efficiently to ensure a smooth and immersive user experience, which is essential for the effectiveness of XR applications and for achieving the high frame rates necessary for real-time interactions and immersive experiences [A61]. Low latency is crucial to prevent delays that could disrupt interactions and cause discomfort, such as dizziness, due to delayed data transmission, necessitating extremely low latency to ensure a high-quality user experience [A21, A61]. High-end end-to-end latency, particularly on web-based platforms, highlights the need for improved server-processing techniques and receiver-side optimizations to enhance the overall performance and reduce lag in the metaverse [A11]. Ensuring low latency and addressing these technical issues are crucial to support the growing demand for high-quality, real-time virtual experiences in shared virtual spaces.

Performance Issue. Performance issues in the metaverse are a significant concern, as highlighted by various studies [A11, A36–A38]. Ensuring scalability and consistent performance across dynamic user-generated content and variable user behavior is crucial. Linear increases in throughput, as more users join, can lead to scalability issues and increased on-device resource utilization. Maintaining network security is also essential to prevent threats and attacks on the vast network infrastructure supporting the metaverse. Integrating emerging technologies like blockchain and AI further complicates performance considerations, necessitating efficient handling of high transaction volumes. Addressing these issues requires optimizing infrastructure, implementing advanced software solutions, and ensuring network security to provide users with a seamless and immersive experience.

4.3.5 Rendering and Visualization. These issues involve metaverse rendering and visualization, requiring high-quality graphics, real-time rendering, and immersive visuals to boost engagement.

Realism Rendering. Realism rendering involves the process of creating virtual objects and avatars that closely resemble and behave like their real-world counterparts. This task can be critical due to the variability of environmental conditions, such as different lighting scenarios and indoor versus outdoor settings [A27]. Additionally, avatars need to accurately represent physical and demographic characteristics, including skin tones, facial and emotional expressions, and body shapes [A44]. Seamless integration of virtual objects with real environments is crucial for creating unique metaverse experiences [A16, A57]. Accurate textures, shadows, and physical properties are vital for immersion but are complex to implement, affecting the overall metaverse experience.

3D Graphic. Despite significant advancements in 3D graphics and computer vision, the metaverse and its graphical rendering still pose significant issues that could potentially impact the overall user experience and engagement quality. As a result, the metaverse is particularly prone to technical issues, such as glitches when creating and rendering complex virtual environments or objects with intricate details [A60, A62, A63]. Additionally, there are instances of lag and slower rendering times, which are directly related to the communication and network issues discussed earlier.

Real-Time Rendering. This subcategory, together with the two above-mentioned, enhances the infrastructure to support seamless interactions among multiple users without lag or technical glitches. This involves addressing the complexity of rendering dynamic multi-user activities and interactions in these environments to ensure smooth and efficient performance [A15]. Additionally, focusing on the technical aspects of real-time rendering and overall fidelity helps reduce discrepancies between visual perception and physical motion, significantly reducing motion sickness [A16]. Furthermore, improving the rendering capabilities ensures that real-time collaborative modifications and synchronous visualization in shared virtual spaces are executed effectively [A57].

5 DISCUSSION, IMPLICATIONS, AND FUTURE STEPS

As a first output of our study, the results allow to extend the theoretical metaverse classification proposed by Almoqbel et al. [2], enriching it with additional insights from our SMS. This is illustrated in Figure 5 and would serve as the

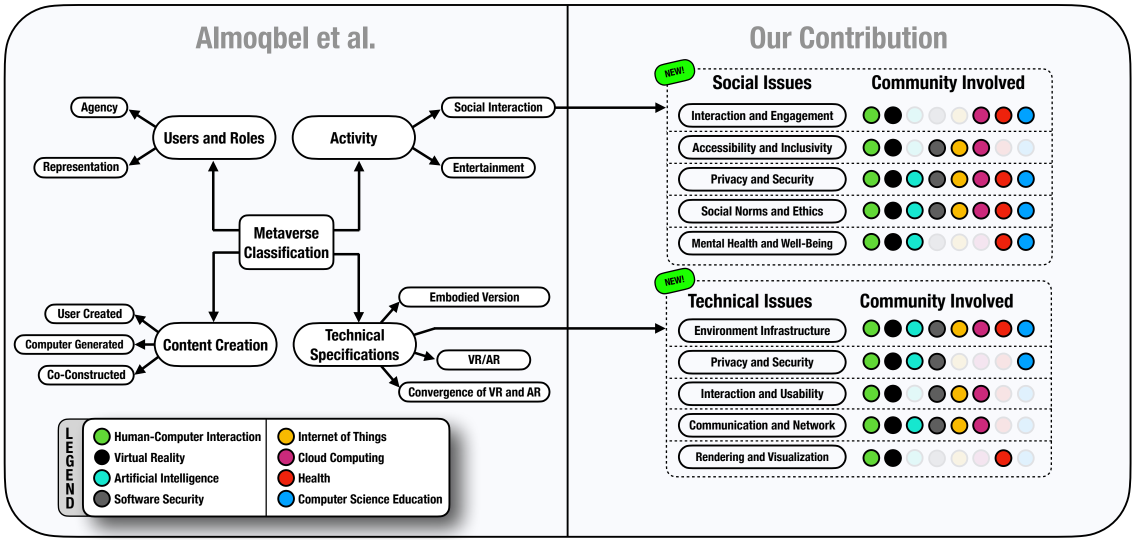


Fig. 5. How our contribution with Social and Technical Issues advances the metaverse classification proposed by Almoqbel et al. [2]

foundation for the definition of metaverse engineering, offering a theoretical framework for understanding the metaverse from different perspectives and connecting them to the specific research communities in the field.

In particular, the left side depicts the aspects outlined in the related work section, specifically the elements pertaining to the definition of the metaverse provided by Almoqbel et al. [2], such as "*Activity*", and "*Technical Specification*" elements. Instead, the enhancement on the right side represents our contribution, namely the connection between the *Activity* and *Technical Specification* categories and the taxonomies presented in the results section. Our research has uncovered that the metaverse presents interconnected socio-technical issues. For instance, from a social perspective, particularly in the "*Interaction and Engagement*" category, we have emphasized the significance of avatar representation and perception in virtual interactions and environments and how these aspects impact social factors such as gender identity, privacy, mental health, and addiction. Concurrently, from the technical perspective, specifically in terms of "*Environment Infrastructure*," where we have highlighted the necessity for advanced facial recognition and animation technologies to capture natural expressions, including the potential for customization to support non-binary identities, both in physical appearance and voice. Thus social and technical issues are deeply interconnected. Addressing technical challenges — such as enhancing facial recognition — can lead to more realistic avatars, better support for gender identity representation, and, ultimately, improved social well-being.

However, the process is not straightforward. Despite improvements, the absence of regulations and norms of behavior, described as "*Social Norms and Ethics*" issues, could give rise to abuse and illegal activities such as cyberbullying, resulting in psychological problems in the physical and virtual world. It is therefore essential to address both technical and social aspects in a balanced way, ensuring that technical advancements contribute positively to social outcomes without creating unintended drawbacks. Achieving this balance requires the involvement of diverse expertise from multiple scientific communities, each bringing valuable perspectives. However, identifying the specific skills needed to effectively manage this interplay remains a complex challenge. To navigate this, we have partially drawn on the findings from **RQ**$_1$, focusing on the research communities that have previously engaged with similar issues, thereby helping to identify which communities should be involved in managing the socio-technical relationship.

5.1 Toward a Unified Metaverse Framework

The metaverse remains a topic that present opportunities across a wide range of fields, including business, healthcare, and entertainment. However, most of the current research and application focus on educational environments, that enhance learning experiences [A12, A18, A32, A34] [39]. These experiences can range from virtual classrooms and interactive labs to historical field trips, providing immersive learning opportunities that go beyond traditional methods.

Despite this opportunities, the current definition and understanding of the metaverse still lack essential improvements in its characteristics, particularly regarding the *interoperability*. As a result of this limitation, the metaverse still resembles isolated virtual reality applications and has not yet become the comprehensive digital environment envisioned by many; consequently, it still lacks the characteristics of a unified platform that integrates diverse contexts and functionalities. This fragmentation may explain the continued skepticism among researchers and practitioners.

To move beyond basic VR, the metaverse must address the interoperability issues, evolving into the next iteration of the Internet. Several studies cited in the taxonomy of technical issues have identified the interoperability issue as a critical concern. They emphasize that today's metaverse consists of separate, non-communicating virtual environments, which limits both user experience and overall development. Addressing these interoperability issues is essential to enable seamless transitions across virtual instances, allowing different applications, domains, and communities to converge. As shown in the previous section, both technical and social challenges affect multiple contexts and must be adapted accordingly. When viewed not as obstacles but as drivers of innovation, these challenges can guide the creation of a unified metaverse—open, collaborative, and inclusive. In this regard, remarkable advancements were made by Havele et al. [A63], who provide a framework for realizing interoperability for a unified metaverse. They trace the evolution of virtual worlds, highlighting both advancements and the ongoing challenges that hinder the development of a cohesive virtual ecosystem. The authors emphasize the importance of interoperability, advocating for the adoption of the *Extensible 3D (X3D) standard*, which supports interactive 3D content across different platforms. By integrating with web standards such as HTML5 and WebGL, X3D enables seamless transitions between virtual worlds, ensuring users can move seamlessly across environments without losing their identity or data. They also argue that, with current technology and open standards, a unified metaverse is both feasible and near.

However, X3D is not the only framework proposed in the literature. Other initiatives, such as glTF (GL Transmission Format), aim to provide a lightweight and efficient format for transmitting 3D models, widely used in real-time rendering applications and web-based environments. glTF is often referred to as the "JPEG of 3D" due to its focus on fast loading and runtime performance, making it suitable for immersive applications. Moreover, standards like OpenXR and WebXR have emerged to ensure cross-device compatibility for input and interaction, enabling a unified runtime interface across VR/AR headsets. It is worth noting that these are not the only unique frameworks studied in the literature; therefore, more systematic studies are needed to report the pros and cons of the interoperability framework.

Despite this opportunity, the unified metaverse requires software advancements from various perspectives. It must adopt and adapt the same core principles of software engineering: "*the establishment and the use of sound engineering principles to obtain economically developed software that is reliable and works efficiently on real machines*"[56].

The unified concept of the metaverse that we envision incorporates the key features outlined by Havele [A63] as well as the foundational principles of software engineering [56].

Each metaverse instance—whether developed for education, entertainment, healthcare, or business—must be engineered to address domain-specific socio-technical challenges through dedicated research and development. A concrete example of this engineering effort involves utilizing blockchain technologies to securely manage and store data within each metaverse context. These independently developed instances can then be integrated into a broader interoperable ecosystem, such as the one enabled by the X3D framework.

In this vision, interoperability is not just a technical feature but a foundational design goal: by adopting a shared structure like X3D, individual metaverse instances can communicate and exchange data while preserving user identity and experience continuity. For example, users could seamlessly transition between different metaverse environments—such as from a healthcare metaverse to an educational one—without losing access to their personal data or virtual identity. This is made possible through the use of dedicated blockchains in each context, combined with a unifying blockchain infrastructure that governs data consistency, identity persistence, and avatar representation across the entire metaverse ecosystem [A53]. Such an approach allows users to register once within the unified metaverse, create a core identity and personal avatar, and then either maintain or adapt these representations based on the specific needs of each domain, all while ensuring legal, ethical, and security standards are upheld.

5.2 The Starting Point for Metaverse Engineering

The Unified Metaverse Framework discussed above must integrate key theoretical foundations to support the development of Metaverse Engineering as a novel and rigorous research field. Based on our empirical findings and the identified entanglement between technical and social issues, it is essential to position this emerging discipline in relation to existing paradigms such as *Socio-Technical Systems Theory* (STST) [3], *Actor-Network Theory* (ANT) [27], and *Human-Centered Computing* (HCC) [26]. Each of these frameworks provides a complementary lens to understand the multifaceted nature of metaverse systems. STST emphasizes the co-constitution of technical infrastructures and social practices, offering valuable guidance for the design of collaborative and organizationally embedded virtual environments [3]. ANT, in contrast, draws attention to the heterogeneous networks of human and non-human actors—such as avatars, algorithms, interfaces, and spatial rules—whose interactions shape both the experience and the behavior within metaverse ecosystems [27]. Finally, HCC places the needs, values, and abilities of users at the center of the design process, promoting accessibility, ethical awareness, and value-sensitive design—dimensions that align closely with several of the socio-technical concerns uncovered in our mapping study [26]. However, our intent is not to treat STST, ANT, or HCC as sufficient paradigms in themselves, but rather to build upon their strengths to establish Metaverse Engineering as a dedicated design- and problem-solving-oriented discipline. In our vision, a new research domain, called ***Metaverse Engineering*** actively synthesizes these theoretical contributions to tackle the unique challenges posed by immersive, entangled, and evolving systems. Drawing on the language of ANT, we consider each research community as a socio-technical actor, guided by both human-centered values and technological innovation.

In addition to these theoretical foundations, Metaverse Engineering draws on established applied domains such as *Software Engineering*, *Human-Computer Interaction*, and *Digital Experience Design*. However, it goes beyond merely integrating their methods or goals. More particularly, Human-Computer Interaction provides foundational knowledge in interface design, embodiment, and usability, but Metaverse Engineering requires going beyond traditional screen-based interactions to address presence, avatar-mediated communication, and the affective and ethical dimensions of persistent identity in virtual spaces. Similarly, while Software Engineering offers methods for requirements elicitation, architecture, and testing, these need to be rethought for systems that are co-produced by user communities, evolve in real-time, and implicate social norms, fairness, and governance. Digital Experience Design contributes to an understanding of immersion, engagement, and aesthetics, yet these are only a part of the broader value-sensitive and inclusive design challenges at stake in metaverse environments. So, we envision Metaverse Engineering as a novel engineering paradigm that synthesizes these contributions into a cohesive socio-technical perspective, capable of guiding both research and practice. Based on these conceptual and applied foundations, we provide a clear definition of Metaverse Engineering, clarifying its relationship with, and divergence from, existing research communities:

> *The **Metaverse Engineering** (ME) is an emerging interdisciplinary field concerned with the systematic requirements, design, development, and governance of immersive virtual environments. It builds upon and reorients principles from established domains such as Software Engineering, Human-Computer Interaction, Artificial Intelligence, Internet-of-Things, and related fields to address the socio-technical challenges posed by virtual, augmented, and mixed reality. ME aims to provide a unified framework for engineering metaverse systems that span several application contexts while ensuring ethical, inclusive, and sustainable user experiences.*

Such a new paradigm may even potentially evolve into a dedicated research field, inform interdisciplinary curricula, and inspire lifecycle models specifically tailored to the development and governance of immersive and socially embedded systems. In this sense, we may conceptualize ME along three complementary dimensions. First, as *an emerging research domain*, it integrates perspectives from engineering, human-computer interaction, and the social sciences to establish methods, tools, and evaluation frameworks that are attuned to the socio-technical complexities of the metaverse. Second, it has the potential to shape a *new curricular framework* that combines technical competencies with participatory design, ethics, identity management, and policy literacy, thereby equipping future professionals to navigate the distinct challenges of responsible metaverse development. Third, ME may support the definition of a *dedicated lifecycle model*, where socio-technical iteration is a core principle and values such as fairness, inclusion, and accountability are treated not as peripheral concerns but as foundational elements, integrated from requirements elicitation through to deployment and ongoing system governance, with explicit attention to macro-ethical and dual-use risks [23].

Following the ME definition, we emphasize the adaptation of software engineering principles within the metaverse. As a result, the metaverse engineering with software engineering principles leads to fundamental aspects: software engineering for the metaverse (SE4Metaverse) and the use of the metaverse for enhancing software engineering practices (Metaverse4SE). In our discussion, the primary focus is on the SE4Metaverse, which aims to use and adapt software engineering principles to create individual instances of VR worlds that can seamlessly integrate into a larger, unified metaverse. Our study can be seen as a first step toward adapting software engineering practices to the context of the metaverse, and more specifically, to the ME. The scientific method we used, i.e., a *Systematic Mapping Study*, plays a similar role to the early stages of software development: it acts like requirements elicitation. In software engineering, this means gathering needs, expectations, and constraints from stakeholders. In our case, the socio-technical issues we identified can be understood as Functional Requirements (FRs), and Non-Functional Requirements (NFRs). Depending on the context, these requirements will need to be analyzed, designed, implemented, and tested, following an engineering approach that considers both the technical side and the human side of virtual environments. FRs in ME define **what** a particular virtual world instance must accomplish. They outline the features, functions, and capabilities that the metaverse should offer users. In contrast, NFRs specify **how** the metaverse should behave, addressing key quality attributes such as performance, security, scalability, and usability, ensuring the system meets certain standards.

To illustrate this, we provide a non-exhaustive list of examples in the following that demonstrate how socio-technical challenges can serve as the basis for ME. Our focus is on functional requirements related to the technical category of *Environment Infrastructure*, which includes the creation of *Virtual Environments* and *Avatars*:

- **Virtual Environment FR1.** *In an educational context, students should be able to interact with virtual learning tools, manipulate virtual objects, and collaborate with peers.*
- **Virtual Environment FR2.** *The virtual environment should enable the addition or removal of digital resources, such as virtual boards or specific tools related to the subject matter.*
- **Virtual Environment FR3.** *The environment should offer accessibility features like speech-to-text and text-to-speech options, adjustable display settings, and intuitive navigation for users with disabilities.*

For avatars, FRs might include:

- **Avatar FR1.** *Avatars should feature facial recognition capabilities for an accurate representation of facial expressions, enabling users to perceive emotional cues, thus enhancing engagement and feedback.*
- **Avatar FR2.** *Users should be able to customize their avatars' facial features, body types, clothing, and accessories.*
- **Avatar FR3.** *Avatars should support flexible gender representation, allowing users to select non-binary or gender-fluid avatars, particularly in inclusive educational or social settings.*

Regarding NFRs, examples include:

- **NFR1.** *The environment should ensure secure communication, protect data, and comply with privacy regulations.*
- **NFR2.** *The environment must support various hardware (VR headsets, AR glasses, desktops) and software platforms, while integrating with educational tools like Learning Management Systems (LMS).*
- **NFR3.** *The environments should be designed with existing interoperable frameworks to ensure smooth transitions between different environments.*

However, the current lack of virtual environments specifically tailored to different fields limits the exploration of how the metaverse can be used for software engineering. Despite the potential to enhance collaboration, visualization, and simulation in software development, more research and specialized platforms are required to achieve effective integration between the metaverse and software engineering.

Further studies and experimentation will be crucial in clarifying how the metaverse can revolutionize software development practices. We envision that applying software engineering methods to metaverse development within a unified framework will lay the foundation needed to use the metaverse for advancing the software engineering field.

5.3 The Metaverse Engineering Roadmap

In this section, our goal is to leverage the findings from $\mathbf{RQ}_2$ and $\mathbf{RQ}_3$, in conjunction with the unified metaverse outline, to craft a roadmap with distinct phases for research and development in social and technical challenges. This roadmap will provide researchers with a solid foundation for letting the metaverse evolve while equipping them with the user's needs and addressing technical and social aspects and the required knowledge to build them.

5.3.1 Phase 1: Defining Social and Technical Guidelines. In this initial phase, clear social and technical guidelines will be established to shape the foundation of the metaverse. From a social perspective, there will be a strong focus on ensuring accessibility and inclusivity. This includes providing equitable representation for all users, particularly those with disabilities or from marginalized groups, and guaranteeing that the metaverse is a space where diverse identities can expand. Privacy and security protocols must also be prioritized, with measures to protect personal data, prevent identity theft, and secure the anonymity of users where necessary. Additionally, there must be a focus on mental health and well-being, with proactive measures to prevent addiction, isolation, and disconnection from real-life interactions.

On the technical side, this phase involves laying down the infrastructure to support these social priorities. Technologies that enable real-time rendering and seamless user interaction will be identified and refined. Furthermore, the network infrastructure must ensure that the platform can accommodate large numbers of users simultaneously without compromising on performance. This will involve ensuring low-latency connections, fast data processing, and a robust system architecture that can handle high user engagement in dynamic virtual environments.

5.3.2 Phase 2: Technological Implementation. In this phase, the focus will shift toward implementing the technologies that will drive interaction and engagement within the metaverse. One of the critical aspects of this is enhancing avatar representation and interaction. Sophisticated facial recognition and motion-capture technologies will be integrated to allow users to express themselves more naturally in the virtual space, making interactions feel more real and emotionally resonant. Improvements in real-time rendering will ensure that these interactions remain fluid and responsive, further enhancing the sense of immersion.

Simultaneously, security measures will be deployed to safeguard user data. Blockchain technology, for example, can decentralize the management of personal information, ensuring higher levels of data protection. Additionally, tools will be introduced to monitor for harmful behaviors, such as cyberbullying or abuse, and provide interventions where necessary. Systems to support mental well-being, including the monitoring of excessive use or signs of social isolation, will also be implemented to keep users safe and engaged in a healthy manner.

5.3.3 Phase 3: Validation and Regulation. Once the core technological infrastructure is in place, the metaverse will enter a phase of validation and regulation. Accessibility testing will be conducted to ensure that all features and functions are usable by individuals with disabilities. This will include examining how well avatar customization, user interfaces, and interaction systems cater to diverse needs. The goal here is to create a universally inclusive platform that empowers all users, regardless of physical or cognitive abilities, to participate fully. As part of the validation process, it is also crucial to test interoperability across metaverse instances. This includes verifying whether user identities, digital assets, and interaction protocols can persist and operate consistently across different platforms built on heterogeneous technologies. Interoperability validation ensures that the metaverse does not evolve as a set of isolated environments, but rather as a cohesive ecosystem capable of supporting seamless transitions and cross-domain continuity. At the same time, this phase will involve developing ethical and regulatory frameworks for the metaverse. Legal experts, sociologists, and ethicists will work together to create a system of rules and norms that govern behavior within the platform. These regulations will help maintain respectful interactions, provide safeguards against abuse, and address legal and economic complexities that may arise in virtual spaces, such as intellectual property issues and the governance of virtual economies. In addition to standard validation activities, Phase 3 should also include a systematic assessment of macro-ethical and dual-use risks [23]. While traditional validation approaches in Software Engineering and Human-Computer Interaction emphasize usability, performance, and safety, metaverse systems introduce distinctive societal challenges. These include pervasive surveillance enabled by biometric and behavioral tracking, labor exploitation within virtual economies, the manipulation of public opinion through immersive misinformation, and the potential militarization or coercive misuse of immersive platforms. These risks clearly require the adoption of regulatory frameworks and design principles that account not only for technical failure modes but also for far-reaching societal impacts. To this end, we advocate for the integration of established ethical frameworks into the validation process. For instance, the *ACM Code of Ethics*[13] and the *IEEE Ethically Aligned Design*[14] offer a foundational basis for guiding ethical decision-making in the

[13]The ACM Code of Ethics: https://www.acm.org/code-of-ethics.
[14]The IEEE Ethically Aligned Design: https://standards.ieee.org/wp-content/uploads/import/documents/other/ead_v2.pdf.

design and deployment of metaverse systems. Indeed, these frameworks emphasize principles such as accountability, non-maleficence, transparency, and the primacy of public good, providing a normative anchor for addressing both intended and unintended uses of immersive technologies. Incorporating these principles during Phase 3 ensures that ethical and dual-use concerns are not postponed to post-deployment remediation, but instead treated as first-class validation criteria integrated throughout the lifecycle of metaverse engineering.

5.3.4 Phase 4: Continuous Improvement and Maintenance. Lastly, this involves regularly reviewing and updating accessibility, inclusivity, privacy, and mental health policies based on user feedback and emerging social needs. On the technical side, infrastructure, real-time rendering, and network performance will be continually optimized to keep pace with advances and increasing user demand. Security measures, such as blockchain-based protections, will also be updated to counter new threats. Ethical and regulatory frameworks will adapt to evolving legal standards and societal expectations, while also remaining vigilant toward macro-ethical and dual-use risks such as surveillance, labor exploitation, or misuse for coercive purposes. This phase acts as a feedback loop, ensuring that improvements from Phases 1, 2, and 3 are consistently integrated, keeping the metaverse secure, inclusive, and up-to-date. In parallel, ongoing research will focus on the psychological and social impacts of the metaverse on its users. This will involve studying how users interact with the platform, identifying any new social or technical challenges that arise, and ensuring that the guidelines and systems in place can adapt to meet these emerging needs. By continuing to research and address these issues, the platform will remain responsive, safe, and engaging for its diverse user base.

6 THREATS TO VALIDITY

Threats to the validity of an SMS often stem from data extraction errors, incomplete studies due to search term or engine limits, and researcher bias in selection criteria. We identified and mitigated such threats in our study [29, 66].

Internal Validity. Internal Validity threats concerns the ability to establish cause-effect relationships without interference from external factors [66]. Our study follows the systematic method by Kitchenham et al. [29], so threats are mainly linked to the data selection process described in Section 3. To address them, we detailed the search terms, data sources, inclusion/exclusion criteria, and quality assessment to ensure replicability.

Search terms were derived from previous SLRs and primary studies. Given the metaverse's multidisciplinary nature, spanning VR, software engineering, and HCI, we employed the Delphi method to refine and validate the terminology with experts across these domains. While this process may involve some bias, the terms used were grounded in established literature, and expert input expanded but did not alter the core list.

We queried reputable databases, including the *ACM Digital Library*, *Scopus*, *IEEE Xplore*, *Web of Science*, and *Springer-Link*, ensuring comprehensive coverage. To mitigate researcher bias, each author independently applied the selection and quality criteria to ensure objectivity. Discrepancies were discussed and resolved in regular meetings.

Construct Validity. Threats associated to construct validity concerns how accurately a study measures the concept it intends to assess [66]. Although we aimed to comprehensively define metaverse engineering through social and technical issues, some nuances may have been overlooked due to the evolving and multifaceted nature of the metaverse. It means that operational definitions might risk oversimplifying complex phenomena that are essential for a complete understanding. To mitigate this, we adopted an iterative categorization process, including continuous feedback and multiple validation cycles, allowing us to refine our categories and better reflect the intricacies of the domain. Still, we encourage future studies to triangulate our results and offer complementary perspectives.

Additionally, we used a card sorting method to develop our taxonomy. While structured, this method may introduce subjectivity, as different themes might emerge if conducted by different individuals or at different times. To reduce this risk, we iteratively refined the taxonomy by merging or splitting categories when necessary, devoting significant effort to ensuring its consistency and completeness.

Conclusion Validity. Threats to conclusion validity relates to the credibility of the study's findings [66]. To ensure reliability and minimize bias during data selection and extraction, the entire research process — outlined in Figure 1 — was carefully conducted and jointly reviewed by all authors. Disagreements were promptly resolved through consensus.

To strengthen the validity of our conclusions, we followed established guidelines from Kitchenham et al. [29] and the *ACM/SIGSOFT Empirical Standards*. These standards were especially relevant during the quality assessment phase, where we applied both qualitative and quantitative criteria to select studies from reputable academic databases.

External Validity. Threats to external validity refer to the extent to which findings can be generalized beyond the study context [66]. Our study did not include non-peer-reviewed articles or paywalled sources that were not accessible through institutional or open channels. The decision to exclude inaccessible articles was a result of budget constraints, despite our attempts to obtain them through alternative avenues. We recognize that these exclusions may compromise the comprehensiveness of our review, particularly in a rapidly evolving field like the metaverse.

We relied on a subset of established databases commonly used in humanities research. While relevant, this may have excluded interdisciplinary studies—especially from psychology and sociology—that are indexed elsewhere and crucial to socio-technical issues. Our focus on high-impact venues aimed to ensure quality but may have overlooked valuable, less visible work. Finally, restricting the review to English-language publications may introduce geographical bias.

7 CONCLUSION

This paper presents a systematic mapping study that offers four main contributions. First, it provides a comprehensive overview of metaverse-related research, highlighting key thematic areas and publication venues to characterize the community and foster interdisciplinary collaboration. Second, it presents a taxonomy of 19 social and 18 technical issues relevant to shaping future research and practice. Third, it introduces a conceptual foundation for a new research field — i.e., *metaverse engineering*. Fourth, it outlines a research roadmap which, together with the proposed definition of metaverse engineering, aims to address socio-technical challenges and support the development of an interoperable metaverse. This framework integrates diverse expertise to define methodologies for designing inclusive and sustainable socio-technical metaverses. These contributions lay the groundwork for future research at the intersection of social and technical concerns. Our agenda addresses core priorities, including accessibility, privacy, ethics, psychological well-being, and infrastructure performance. Through this vision, we support the emergence of metaverse engineering as a coherent and interdisciplinary field that guides the design of effective virtual environments.

SMS – FORMAL LITERATURE

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