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Critical University Studies and the Defense of the Public University: Neoliberalism, Knowledge Socialism and Science as a Global Public Good

Michael A. Peters*

ABSTRACT. This paper proposes an argument for the defence of the public university in discussion of the field of Critical University Studies by examining the assault on the notion of the public and the public sphere by neoliberal policies. It elaborates an argument concerning the critique of neoliberalism and puts forward the idea of science as a global public good in the name of 'knowledge socialism' (as opposed to knowledge capitalism, or the knowledge economy). In particular it champions open science as a necessary public platform for the open science digital university and draws the interconnections between the idea of 'knowledge socialism' and open science as a global public good.

Keywords: critical university studies; defense of public university; neoliberalism; knowledge socialism; global public goods

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1. Introduction: The Assault on 'the Public'

The parameters of the discourse of Critical University Studies was largely formulated in relation to the abrupt shift away from the liberal model of the public good university to a neoliberal privatized user-pays model that took place rapidly during the 1980s in the core states of the Anglophone neoliberal world (US, UK, Australia, Canada, NZ) in the years following the elections of Margaret Thatcher and Ronald Reagan who came to power in 1979 and 1980 respectively. This massive shift in policy, discourse and ideology, driven largely by second generation Chicago school economics and rational choice theory, targeted 'big government' and the welfare state on both economic and moral grounds arguing for greater individual self-reliance. It was an ideology that sought to repeal all forms of social provision and collectivism including welfare redistribution to focus on the logic of individualism of market fundamentalism based on the rehabilitation of *homo economicus*. During the 1980s the university had become the new star-ship in the policy fleet for governments around the world, as a key driver of the knowledge economy. Universities were refitted as an entrepreneurial and commercialized cultures to seek links with industry and business in venture and private-public partnerships (Olssen & Peters, 2005). The older liberal emphasis on a professional collegial culture of open intellectual enquiry and debate was replaced with institutional performativity based on global measured outputs, strategic planning, performance indicators, and quality assurance measures and academic audits. Hazelkorn (2017: 10) argued 'globalization has privileged increasing concentrations of wealth and led to an intensification of hierarchical differentiation and social stratification of higher education.' The transformation of universities into multinational and transnational corporations with the growth of consortia have created global knowledge production networks aided by trade agencies and policies of GATS for the pursuit of the World Class University that sidesteps the public good in the service of social democracy in favour of a neoliberal privatized model as a centre of innovation and entrepreneurial activity.

The early origins of neoliberalism can be traced to the Colloque Walter Lippman (est. 1934) and the Mount Pelerin Society (est. 1947) established by Hayek:

> Essentially, it became known as a set of related public policies that was aimed at deregulating capital markets, embracing 'free trade' globalization, and privatization policies responsible for state assets sale, and the commercialization and corporatization of government departments with the overall aim of paring back the state and increasing individual responsibility. These were the *public policies* developed by conservative and right-wing governments' intent on limiting the powers of the state, attacking 'big government' and repealing social welfare provisions. The 'Washington Consensus'

was a term developed by John Williamson in 1989 to describe the policies of Washington, DC based institutions such as the World Bank, the International Monetary Fund, and the US Treasury in ten points, including: fiscal policy discipline; redirection of public spending away from subsidies to user-pays; tax reform; market interest rates; competitive exchange rates; trade liberalization; privatization of state assets; deregulation; and securing property rights (Williamson, 2017). This was neoliberalism as a *development model* in relation to perceived problems of Latin American economies as a basis for loans (Peters, 2021a).

Among the spectacular results was to create an enormous student debt burden. On the basis of the argument that higher education was a private rather than a public good, US student loans became a trillion-dollar business with steadily increasing tuition fees. At the school level under 'user-pays' students and parents became consumers and early childhood education became a fully privatised sector with some relief for paid parent leave.

2. Financialization of Higher Education, International Education and Rise of China

The global financial crisis and consequent educational restructuring (Peters, et al., 2015) was driven by the worldwide integration and globalization of finance, an aspect of 'financialization' that coincided with the rise of market-oriented neoliberalism promoting free trade and privatization strategies. New Internet-based technologies have reinforced financial market integration, creating a fragile, globally integrated financial ecosystem that now poses new systemic risks and contagion effects characterized by excessive borrowing and ballooning debt, massive asset bubbles, a huge shadow banking system, and financial innovation leading to collateralized debt obligation and securitization. Public education has been at the core of neoliberal privatization strategies and financialization with the trillion-dollar blowout of student loans. Education, once considered a national and global public good tied to the creation of knowledge and the basis of a just and democratic society, has undergone a profound transformation and financial restructuring based on the growth of finance capitalism and financialization, as well as the financialization of higher education and its consequences.

At the same time, at least during the immediate pre-COVID-19 years the international student market led to the growth of export education within core neoliberal states with an estimated value of US $196 billion predicted to reach US$433 by the end of the decade.[1] International education is a massive global market of over 5.5 million students studying abroad with Anglophone neoliberal countries alone enrolling nearly 3 million international students per year and predicted to swell to more than eight million by 2030. Since WWII

international education has been up until most recently a Western undertaking that first followed the philosophy and aspirations of liberal internationalism and neoliberalism. International education is also a product of globalization developed through international schooling and university collaborations, consortia and partnerships. In the 1980s international higher education became an 'export industry' under neoliberal policies that reflected the dominance of Anglophone countries (US, UK, Australia, Canada, NZ) which accounted for more than 50% of all foreign students, with nearly 50% from China and India combined. The globalization of international education also has led to the international schools movement, the internationalization of the curriculum and the development of global regimes of accreditation and quality assurance. Most recently, international education has fostered the development of franchises, overseas campuses and regional hubs, with transnational research collaborations contributing to the global science economy.

Over the last five years IE has been challenged by four major changes: 1. The election of Donald Trump as the 45th US president in 2017 accompanied the global rise of the far-right that together have questioned the assumptions of liberal internationalism; 2. The rise of China and the integration of the Asian market has created new a regional hub based on very different conception of internationalism such as the Belt & Road Initiative (BRI); 3. Rising geopolitical tensions between China and the west, with China increasingly pursuing policies of decoupling and national self-reliance; 4. COVID-19 has disrupted international education especially the flow of international students. Today Asian student diaspora are leading international education demand with China, the market leader for the last two decades, as the largest source market with over 1 million international students, followed by India (0.5 million), the fastest growing source market growing at 8.5% pa, and Bangladesh, Vietnam and Indonesia. This growth in the Asian market is a result of 'demographic trends, rising affordability and household incomes, poor quality of local education provision, improved accessibility of international education, premium salaries commanded by foreign graduates, and a greater desire to emigrate to Anglophone countries,'[2] although there have been significant geopolitical disruption particularly in China–Australian relations under the Morrison administration that look set to disrupt the $40 AUS billion market in 2021–22. The key destination markets are still those of the Anglophone countries – the U.K., the U.S., Australia, Canada and New Zealand, although China and India are fast becoming a regional hub for Asian and BRI students.

This brief history constitutes the immediate background of the forces and pressures that have led to the decline of the public university, mostly as a result of wider neoliberal and structural adjustment policies that have gone through a number of different stages or phases and affected the entire world.

3. Habermas and the Public Sphere

It is not surprising the Critical University Studies discourse grew up around the critique of neoliberalism and the defence of the public good with key themes of privatisation, student debt, academic labour and zero-hour contracts. This critical discourse grew out of the Left's broad adoption of the word 'critical' to denote Critical Legal Studies, Critical Race Theory, and Critical Pedagogy that themselves owed their origins to Critical Theory of the Frankfurt School best articulated in relation to the notion of the public by Habermas' (1962, Eng. 1989) classic *The Structural Transformation of the Public Sphere*. Habermas argues that the bourgeois public sphere was constituted when private individuals came together to debate the general rules governing commodity exchange and social labor: "The *publicum* developed into the public, the *subjectum* into the [reasoning] subject, the receiver of regulations from above into the ruling authorities' adversary" (p. 26). It was deeply tied to a liberal jurisprudence and legal constructivism concerning liberal values, especially freedom of speech and freedom to learn, teach and research.[3]

Habermas demonstrated that the notion of the 'public' emerged historically in modern Europe that is associated with the growth of liberal jurisprudence and constitutional rights developed by a range of philosophers including Locke, Rousseau, and Kant. Second, it is also associated with 'public intellectuals' whose role is to protect freedoms, and with notions of the 'public interest', the 'public good' (considered to be both *non-excludable* and *non-rivalrous*), and 'public opinion', a 'weak' epistemological determination of public judgement. Third, the modern history of 'the public' is indissociably linked with the rise and complexity of public discourse, public education, the growth of science, and the proliferation of public media, all designed to educate citizens and inform public debate. The meaning of 'the public' and what constitutes 'the public good' is an historical product open to changes in the landscape of public media. Public institutions and the laws governing them, have been also subject to political capture. Neoliberalism in the last fifty years has been directed against 'big' government wanting to downsize the public sector, and privatize education. Central to this policy debate has been arguments about the 'public-private' distinction and whether education should be regarded as a public good, as it was in the heyday of the welfare state (Peters, 2022a).

Habermas' idealized conception came under attack by those critics who pointed out that particular historical examples only existed through the systematic occlusion of others (e.g., Fraser, 1990, 2007). Habermas (1983) responded by jettisoning the ideal speech community to talk of 'discourse ethics' as a vehicle for the exploration of links between moral consciousness and communicative action. He thought that a new moral system could be derived from the rules of argumentation alone. His mature position led to the theory of communicative action where communicative rationality is seen

as the rational potential built into everyday speech. Habermas' theory becomes the basis for his deliberative theory of democracy and others following him attempted to show how the idealized model of practical discourse connected with real institutional contexts (Bohman & Rehr, 2017). His mature discourse theory has strong implications for international modes of deliberation, especially cosmopolitan political theory where the global political order is considered to be based on a democratic form of life and the ideology of human rights – a substantive conception of cosmopolitan democracy.

4. The Discourse of Critical University Studies and the Notion of Public Good

As Calhoun (1992) and others have pointed out Habermas has helped us to understand 'the history, foundations and internal processes of public discourse' and 'inform[ed] democratic theory…, self-reflection of literary and other cultural critics, …new approaches in ethics and jurisprudence, and empirical studies in sociology, history and communications' (p. vii). Higher education was seen as the institution with a critical and transformative role protection of the public good as well as the conditions and practices for intellectual freedom within shifted landscape of public media. Calhoun (2006) argued that critical theorists needed to understand the conditions of their own work because the 'deep transformation' of universities was a reflection of wider economic and political forces leading to privatization of public institutions, intensification of social inequalities and changed conditions of access to knowledge. He suggested four basic questions concerning the meaning of the *public* university: '(1) where does its money come from? (2) who governs? (3) who benefits? and (4) how is knowledge produced and circulated?'

The summary answers to these questions seriously call the notion of public university into question as national funding regimes increasingly ease the State out of social provision allowing universities able to charge and increase tuition fees, with greater emphasis on the bonanza international fee-paying students, and the commercialization of research. There are many studies that address the second question in one word – 'managerialism' – with the side-ways shift of academics and the business domination of university councils. Who benefits? is an interesting question because out of increased revenue streams HE policies could afford targeted assistance in the face of what used to be free tertiary education. The production of knowledge and its circulation has become very focused on strategic technology innovations.

The Palgrave Critical University Studies Series, (ed. John Smyth) with some 19 books, 'to foster, encourage, and publish scholarship' concerning the 'direction of reforms' was to explore: 'the deleterious effects on academic work, the impact on student learning, the distortion of academic leadership and institutional politics, and the perversion of institutional politics' by

focusing on universities under 'disaster capitalism', 'compassionate campuses', the reclaiming of the university as a public good, resisting neoliberalism, academic freedom, the public intellectual and the citizen scholar, academic labour and unemployment, managerialism and the assessment of research. Critical University Studies itself had strongly emerged with Slaughter and Leslie's (1997) *Academic Capitalism: Politics, Policies, and the Entrepreneurial University* and William Jeffrey's (2012) attempt to frame the moment.

It is important to rework the concept of the public good as a social or collective good, normally provided through public taxation and characterized in economics as *non-excludable* and *non-rivalrous*, meaning in essence that use by one person does not delete use by others. These are also the characteristics of digital knowledge goods, sometimes referred to in terms of *expansibility* or non-depletion of use, that implies the normal scarcity conditions for commodities does not apply. Knowledge is the ideal public good: knowledge is non-rivalrous as the stock of knowledge is not depleted by use; it is also barely excludable being very difficult to exclude users. Knowledge also is not transparent, like education in general, it requires some experience and skill to know whether it is worthwhile or suited and relevant to a particular purpose. Knowledge at the ideation stage operates expansively to defy the law of scarcity. Knowledge in its digital information form approximates pure thought (Peters, 2009a).

It is part of the reason that the term 'digital public goods' recently has come into use to explain the nature of symbolic economy, public knowledge goods, and processes of peer production. In a knowledge economy, knowledge (or information) can be shared through pdf at little or no additional cost. The economic idea originated with Paul Samuelson in the 1950s in a mathematical formalism. Free and open source software fits the criteria of pure public goods. In terms of these criteria it is easy to see why science and education have been regarded as public goods, as much as infrastructure, public health, national defence, public TV and the environment. Academic publishing is based on an artificial notion of intellectual property that creates a pay wall on the basis of copyright. The main argument for public goods is that they create positive externalities and the provision of public goods is also often associated with market failure such that the sovereign or commonwealth, as Adam Smith argued, needed to fund those public institutions or 'public works' necessary for the functioning of society beyond the resources of private individuals. Mancur Olson was to investigate the private provision of public goods, and indicated that private/public entities can provide public goods, raising the ethical question of who should pay. Neoliberalism was successful because it modelled all behaviour on the assumptions of *homo economicus* of rationality, individuality and self-interest. Yet as Anderson (1993: 159) remarks:

> Some goods can be secured only through a form of democratic provision that is nonexclusive, principle – and need – regarding, and regulated primarily through voice. To attempt to provide these goods through market mechanisms is to undermine our capacity to value and realize ourselves as fraternal democratic citizens. (cited in Reiss, 2021)

While primary and secondary education traditionally are seen as fitting into this category neoliberals make the case that university education does not and they contested the welfare and democracy benefits and argued that tertiary education is largely a private good, an argument accepted as public higher education entered into the massification stage and was typically regarded as unsustainable government spending. This debate needs to be redrawn in the digital age and the discourse of the public university needs to re-examine the concept in recent economics literature since Samuelson's (1954) early welfare formulation, especially in relation to knowledge goods, the primacy of ideas and the economics of abundance (Peters, 2009b).

Working with Ron Barnett from the London Institute I coedited two companion volumes called *The Idea of the University* (Peters & Barnett, 2018; Barnett & Peters, 2018) that was basically a defense of the liberal concept of the university based on the concept of academic freedom and its erosion under neoliberalism: the first volume presents readings from the major texts on the idea of the university over the last two hundred years that go back to Kant and Newman; the second examines ideas of the university that frame its national and global perspective, and offers new thinking in rejuvenating the public university. In my contribution – 'Renewing the Idea of the University: The Cosmopolitan and Postcolonial Projects' (Peters, 2018) – I argued these were the most promising lines of renewal for the public university. I had become more aware of the extent to which universities had functioned during the colonial era to aid the process of extraction of wealth, create a ruling elite to 'administer' and subdue local inhabitants. Historically, the notion of the public and publicly funded universities served as a regulative ideal in the era of postwar welfare capitalism but its ambitions were rarely achieved in practice and quickly broke down during the pressures of massification of higher education in the 1980s and after.

5. Neoliberal Knowledge Capitalism and the Digital Economy

If I can pause to reflect on events in a personal way. As a secondary schoolteacher in the 1970s I went back to university to complete a PhD on the concept of rationality in Wittgenstein (Peters, 2022b). I had been the local branch organizer of the teacher union (PPTA) in a couple of schools, and after completing my PhD in 1984 and taking a job as an associate professor at the University of Auckland in the mid-1990s I became Academic Vice

President of NZ Association of University Teachers. I was deeply involved in debates with NZ Treasury and the policies of the Fourth Labor Government of the brand of NZ neoliberalism, a form of Thatcherism speeded up and taken to its absurd conclusion. In those days I argued that beginning in the 1980s 'a distinctive strand of neoliberalism emerged as the dominant paradigm of public policy in the West' based on the Chicago school 'citizens were redefined as individual consumers of newly competitive public services' commodifying 'welfare rights'. The public sector itself underwent considerable 'downsizing' as governments pursued an agenda of commercialisation, corporatisation and incremental privatisation of public services where the principles of 'new public management that emulated private sector styles, was delegated rather than genuinely devolved, while executive power became concentrated even more at the centre' (Peters, 2012a: 135). In this period and after I wrote a number of books and articles on neoliberalism that highlighted a debate within liberalism (neoliberalism) about the public good, trying to maintain the goals and values of the public university based on second wave democratization and increasing access especially to minority groups.

It quickly became apparent that neoliberalism was itself interrupted by the digital revolution sometimes call 'cognitive capitalism' (Peters & Bulut, 2011) that strengthened the relationship between neoliberalism and digital capitalism, leading to digital governance of the university through a performativity matrix of rankings, online delivery of teaching (MOOCs) and globalization of HE. The financialization of higher education took place efficiently until the global financial crisis. A second generation of CUS scholars began to question the proprietorial consequences of the new digital technologies and the form of an emerging platform capitalism that had captured the university to scaled-up university partnerships and consortia.

6. Critical Theory of Technology: 'Technoscience, Rationality and the University'

In my own case, influenced by a Nietzschean reading of Marx and a Wittgenstein/Foucault line of inquiry I turned to critical theory of technology (Heidegger, Marcuse, Feenberg) and Foucault's 'power/knowledge' and 'biopower' to investigate themes such as 'Technoscience, Rationality and the University' (Peters, 1989). This was my first attempt to explore Lyotard's hypothesis that 'the status of knowledge is altered as societies enter the post-industrial age and cultures enter the postmodern age', a situation where the legitimation of science as emancipatory had fallen away, and knowledge and power had been revealed to be two sides of the same coin. I pursued the argument over the years concerning the technoscientific rationality of the university through Wittgenstein's influence on historicist philosophy of

science (Toulmin, Kuhn, Feyerabend) and Lyotard's critique of capitalist technoscience (Peters, 2020a).

In Lyotard there was an analysis of the significance of a semiotic understanding of technology as a language based on a deep code that brings informatics into line with synthetic biology, together with an understanding of the effects of the transformation of knowledge on public power and civil institutions. In my PhD (completed 1984; 2000b) I had argued that the loss of faith in science as *the* paradigm of rationality concerned to provide universal standards of rationality valid for all actual and possible claims to knowledge had forced a re-evaluation of the Enlightenment and western culture. This view of western science as the paradigm of rationality had not recognized Habermas' human interests of knowledge nor Foucault's 'power/knowledge'. In terms of political economy, it had not recognized the extent to which science had become part of 'the industrial-military complex' (Eisenhower's phase) or the 'academia-industrial-military complex' funded by several trillion of dollars worldwide (the US miliary budget alone was almost $750 billion in 2022); or indeed, the pharma-medical-industrial complex, or, increasingly, the digital-platform-financial (fintech) complex driven by algorithmic rationality. In terms of the top-100 US Government defence contractors some $665 billion was awarded in 2020. The privatisation of science has been a creeping silent phenomenon often leading to epistemic corruption. There was a strong shift 'in the U.S. innovation system towards the patentability and commercialization of the basic-research happened during the early 1980s' (Cozzi & Galli, 2021: 179).

Later I followed up this argument with a critical discussion of 'Technopolitics and the future of the university' (Peters, 2020b) that focused on forms of technological convergence, what I called 'Deep Convergence, Platform Ontologies, and Cognitive Efficiency' in my public lecture for *Thesis Eleven* where I outlined the 'new paradigm' of the US National Science Foundation that consists in a deep and progressive convergence of 'nano-bio-info-cogno' (NBIC) technologies integrated at the nano-level. This convergence recommends the application of 'cogno' technologies – the least mature – funded through cognitive neuroscience that focuses on cognitive efficiency to harness a 'bio-informationalism' of a re-programmed body.

My program was influenced by an account of 'cognitive capitalism' under the influence of Gilles Deleuze and Felix Guattari's *Capitalism and Schizophrenia*, Michel Foucault's work on the birth of biopower and Michael Hardt and Antonio Negri's *Empire and Multitude*, as well as the Italian Autonomist Marxist movement that had its origins in the Italian *operaismo* (workerism) of the 1960s. The theory of cognitive capitalism – sometimes referred to as 'third capitalism,' after mercantilism and industrial capitalism – became for me an increasingly significant theory, given its focus on the socio-economic changes caused by Internet and Web 2.0 technologies that have transformed

the mode of production and the nature of digital labor (Peters & Bulut, 2011). My argument questioned the neoliberal discourse of the knowledge economy with its human capital arguments. Cognitive capitalism provided an alternative left theorization that recognized the development of financialization and fintech in a way that clearly signalled a contemporary form of *knowledge capitalism* leaving open the prospects of common-based peer production of knowledge and what I call open knowledge production (OKP).

Poststructuralism, Marxism, and Neoliberalism: Between Theory and Politics (Peters, 2001) was inspired by Lyotard's analysis of the performativity crisis in universities and Foucault's lectures on neoliberalism. I argued poststructuralism is not a form of anti-Marxism but rather French poststructuralist philosophers view themselves in some kind of relationship Marx and the legacy of Marx: either they have been Marxist or still viewed themselves as Marxist, as Deleuze and Guattari did. These philosophers invented new ways of reading and writing Marx, beginning with Louis Althusser, and provide resources for critically engaging with neoliberalism as an ideology that is committed to the revitalization of *homo economicus* and neoclassical economics. Following Hardt and Negri I tried to develop a 'postcolonial biopolitics in the empire of capital' by identifying some the main lines of Foucauldian inquiry: 'the postcolonial', exemplified by Edward Said; 'the biopolitical', exemplified by Giorgio Agamben; and 'the empire of capital', exemplified by Michael Hardt and Antonio Negri. This work led to studies of subjectivities and 'technologies of the self' examining 'prudential rationality', technological unemployment, and a conjunction of Marx and Foucault.

7. Postcolonialism, Globalization and the Multiplicity of the Public Sphere

In regard to third generation Critical University Studies – CUS – it immediately seems that the postcolonial perspective problematizes the notion of public and public good, especially as a historical feature of European society or American public choice economics. One thing is that it is no longer possible to talk innocently in terms of the old discourse of CUS as the notion of 'public' has undergone huge transformation. We are no longer modelling European or American bourgeoisie as the notion has undergone a number of significant changes: It has become 1. globalized; 2. transnationalized; 3. diversified; 4. indigenized; and 4. digital. So we must problematize 'public' and also admit the possibility of 'global publics' in digital social and indigenous formations.

The defence of the public is still very western liberal notion tied to the critique of neoliberalism essentially western (Greek, Roman origins) or taking a distinctive form with modern English and American liberalism. As Tully remarks (2012: 1) 'One of the most spectacular events of our time is the emergence and proliferation of a multiplicity of public spheres and the cor-

relative multiple uses or senses of the vocabulary of public spheres around the world'. But one is force to ask: How well does it capture China and 'the Asian Century'? Or non-liberal societies like Russia? Even India, Indonesia or the Pacific? It is clear that non-liberal societies have public universities. Indeed, well before the medieval tradition that dates back to 1066 with University of Bologna (or Oxbridge or the modern German university under Humboldt) there were well established ancient centres of learning dating back thousands of years including the University of al-Qarawiyyin, first established as a mosque in 857–859, and Nalanda, a Buddhist monastic university that operated during 427 to 1197 CE, only to be re-established recently. To be sure there is something special about the modern university originating in Europe to reach a global form in the post-war period, but it is not the case that the broad notion of the liberal definition and tradition of the public continues to have uniform universal applications.

Within Europe and the core neoliberal Anglophone countries neoliberalism's attack on notion of 'the public' warrants a broadly democratic socialist response not necessarily to restore the welfare state but as a *Time for Socialism* (Piketty, 2021) that details a different kind of globalization centered around the growth of inequality, French reforms, the democratization of Europe and the fall of the US idol. Piketty outlines the long march toward equality and a participatory socialism with the social state as a vehicle for equal rights. He puts the case in education: at the beginning of the 20th century public spending was less than 0.5% of national income which gave rise to elitist systems. Over the course of the 20th century spending increased to 5–6% in the 1980s and 1990s, allowing for huge educational expansion which led to greater equality and prosperity. Conversely, the era of neoliberalism has seen cuts and stagnation in spending with correlative growth of inequalities, and the growth of the power and domination of the private sector (see pages 9–12ff). In the same spirit I coined and developed the concept and theory of *knowledge socialism* to explain the the rise of peer production through digitally enabled forms of collegiality, collaboration, and collective intelligence (Peters et al., 2020c).[4]

8. Openness, Public Good Science and the Digital University

I have argued that in the 'era of digital reason' *openness* becomes a fundamental core of the global digital public domain. With other colleagues I have argued for a vision of the digital university based on radical openness, creative labour, and the co-production of symbolic goods (Peters & Jandric, 2018). In a similar vein I have advanced arguments concerning open education, open science, and the open university 2.0 to reflect the practices and possibilities of an open intellectual commons based on a cluster of concepts including relationships between learning, creative col(labor)ation, and knowl-

edge cultures, digital reading, digital self, digital being, radical openness, creative labour, and the co-production of symbolic goods. I put the case for 'The concept of radical openness and the new logic of the public' (Peters, 2013), the philosophy of open learning (Deimann & Peters, 2016), 'Openness and the intellectual commons' (Peters, 2014), 'Open Education and Education for Openness' (Peters, 2017a) and *The Virtues of Openness: Education, Science and Scholarship in the Digital Age* (Peters & Roberts, 2012: 3) which sought to understand 'The movement toward greater openness represents a change of philosophy, ethos, and government and a set of interrelated and complex changes that transform markets altering the modes of production and consumption, ushering in a new era based on the values of openness: an ethic of sharing and peer-to-peer collaboration enabled through new architectures of participation.' In one sense I was trying to articulate a philosophy of openness which substituted for the public in a new kind of global space of science and scholarship.

The Digital University: A Dialogue and Manifesto (Peters & Jandric, 2018) was one such attempt to critically discuss 'The University in the Epoch of Digital Reason', 'Collective Intelligence and the Co-creation of Social Goods' and 'Digital Teaching, Digital Learning and Digital Science'. Defining 'the epoch of digital reason' we indicated that digital computers operating by manipulating on/off signals to implement logic functions over time, changed the means to generate on/off signals from the early mechanical devices to transistors, integrated circuits and beyond. These 'improvements' brought about faster and smaller components that have transformed computers into everyday devices. While the means of on/off signals are constantly changing, the original logic remains based in the binary system of ones and zeros which conforms to a set of rules invented by George Boole in 1850, where three operations (AND, OR, and NOT) can perform all logic functions. However, Boole's system had remained largely unused and unacknowledged, until Claude Shannon applied Boolean algebra to the design of logic circuits using electromechanical relays. Really I was trying to give a potted history of the internet age by emphasizing the development of modern algebra with its postmodern developments in the circuits of 'fast knowledge' of 'cybernetic capitalism' manifested in the emergence of educational web science, digital archives in the cloud and the political economy of information democracy.

In this book I also began to examine more closely the prospects of anchoring this conception in a vision of knowledge socialism to coedit a collection with that title with the subtitle 'The Rise of Peer Production: Collegiality, Collaboration, and Collective Intelligence' (Peters et al., 2020). In the introductory chapter 'Towards a Theory of Knowledge Socialism: Cognitive Capitalism and the Fourth Knowledge Revolution' I sketched a conception arguing:

> The fourth wave automation of knowledge and research developed quickly with the growth of 'platform capitalism', the rise of algorithmic-based knowledge capitalism and the rise of global search engines, big publishing and the metrics industries. Cognitive capitalism offers an alternative and opposing account of knowledge economy, and the notion of 'creative labour' provides an interesting alternative description to 'human capital'. In this connection, I explore the wider philosophy and political economy of openness and 'open knowledge production' with a strong emphasis on 'radical openness' and new forms of 'co(labor)ation'. In the era of 5G networks, there are still opportunities for full public knowledge, learning and publishing platforms that are, if not owned or subsidised by the State, at least strongly regulated in the interests of public good science, although it is not clear how long this will remain the case.

I indicated that 'Knowledge economy' is often referred to as deep structural transformation of the economy caused by a technological revolution altering the production and transmission of knowledge (and information), leading to a shift to knowledge-intensive activities. I liked to play up the connection with Marx and provide a post-Marxist reading that refers to Alain Touraine, Jean-Francois Lyotard and Foucault rather than a reading of Chicago School economics of human capital, Tulloch and Buchanan' public choice theory, and Romer's endogenous growth theory. I also tried to provide contested interpretations and genealogies of the knowledge economy that substitute the concept of creative labour for human capital.[5] The notion of 'digital socialism' (Peters, 2020c) did not seem so far-fetched. The conception of knowledge socialism came to me when I established the new journal when I was at the University of Glasgow. *Policy Futures in Education* (PFIE, Sage) with the following policy statement:

> Why policy futures in education? The shift of gravity in politics and public policy has moved beyond the post-war welfare state settlement with its institutionalised compromise between the demands of capital and labour. Neoliberalism, with an emphasis on privatisation of public assets and services, has dominated Anglo-American politics over the last 20 years and continues to exert a strong influence on Third Way politics and policies. Globalisation, underwritten by developments in telecommunications and information technologies and the ideology of 'free trade' agreements, has continued apace, promoting a form of world economic integration. There has been a progressive automation of the tertiary sector and a shift to service-oriented industries, which has accompanied the rise of the 'knowledge economy'….
>
> All of these factors and trends, in their complex interaction, have increased the significance of education both as one of the leading

services of the future and as one of the few governmental means through which issues of social inclusion, social cohesion, national culture and identity, and citizenship can be addressed. https://journals.sagepub.com/description/pfe

9. Bioinformational Capitalism and Biodigitalism

That time seems an era long passed. I founded PFIE in 2004 and later moved to the University of Illinois (Urbana-Champaign) in 2005, University of Waikato (NZ) in 2011, and Beijing Normal University in 2018. At these universities I taught courses on political economy of higher education with a focus on a problematization of the discourse of the 'knowledge economy'. In 2012 I authored the paper 'Bioinformational capitalism' (Peters, 2012) which was an attempt to build on the literatures on 'biocapitalism' and 'informationalism' (or 'informational capitalism') to develop the concept of 'bioinformational capitalism' in order to articulate an emergent form of capitalism that is self-renewing in the sense that it can change and renew the material basis for life and capital as well as program itself. I explained that the term develops aspects of the new biology to informatics to create new organic forms of computing and self-reproducing memory that in turn has become the basis of bioinformatics to provide a brief account of bioinformatics before brokering and discussing the term 'bioinformational capitalism' as a near-future of the neoliberal knowledge economy. My position has always begun from a critique of neoliberal capitalism as a perversion of the public university, and yet the discourse based on the public and the public I felt was in urgent need of repair so that it could include non-liberal societies and universities.

Openness as a philosophical concept seemed well place as a substitute. Open science designates a form of science based on open-source models that utilizes principles of open access, open archiving and open publishing to better encourage scientific and scholarly communication. The term also increasingly also refers to modes of governance and more democratized engagement and control of science by scientists and other users and stakeholders including citizen science. Data-intensive science focuses on 'technologies of openness' that promote not only more effective forms of scientific communication but also increasingly the deep sharing of large databases (linked data) and cloud computing. In this sense openness is also code word for peer review, horizontal flat structures of learned societies, and perhaps most importantly the ethics of science. By virtue of their professional status and membership of scientific communities, scientists are bound to openly share their work and to make public research methods and data or results. On this basis then, scientists should be open to criticism and to participate in the review of scientific work.

My most recent relevant investigations have centred on biodigitalism and postdigitalism working closely in different combinations with Petar Jandric, Tina Besley, Wang Chengbing, Liz Jackson, Marek Tesar, and Peter McLaren, and many others, including the critical philosophy of the postdigital (Peters & Besley, 2018) drawing on recent work on cybernetics, complexity theory, quantum computing, artificial intelligence, deep learning, and algorithmic capitalism. We argued that we have 'arrived into the age of algorithmic capitalism, and its current phase, 'biologization of digital reason' is a distinct phenomenon that is at an early emergent form that springs from the application of digital reason to biology and the biologization of digital processes' (p. 29). We elaborate the emerging configuration and techno-scientific convergence of new systems biology and digital technologies at the nano level – in an evolutionary context to speculate, on the basis of the latest research, future possibilities (Peters et al., 2022). This convergence is now the context for the quantum revolution and supercomputing that has become a race between China and the West in achieving exascale computing, quantum information science and a platform for zettaFLOPS-based data-intensive science and bioinformational engineering focused on the NSF SemiSynBio-III program that 'seeks to further explore and exploit synergies between synthetic biology and semiconductor technology' (Peters, 2022c). This speaks to the techno-rational view of the university where ultimately technoscience in its enveloping form of AI with an embedded algorithmic rationality takes over 'data-intensive' science obliterating the cultural context.

10. The Philosophy of the Open Science University

Commons-based peer production is a system of text production that is emerging in the digitally networked environment presages a digital system of global science and scientific publishing. In my shorthand the philosophy of openness might be summarized by the following cluster of characteristics:

1. *Openness to 'experience'*: this might be given a Baconian, inductive and empiricist reading with an accent on the pragmatics of the experiment.
2. *Openness to criticism*: an extension and naturalization of the Kantian account of Reason given in the first critique which provided the tools for rational self-critique.
3. *Openness to interpretation*: historically connected to self-expression, freedom of expression, rights to free speech and the other academic freedoms on which the university is built.
4. *Openness to the Other*: an ethical stance that in the present techno-political era can be construed in terms of institutionalized peer

production, free sharing of knowledge and collaboration to create the intellectual commons.

5. *Open science communications technologies*: this historically contingent feature, itself an episode in the history of modern science, refers to the development of open-source and open-access models of science based on the logic of distributed knowledge systems and an ethic of sharing, peer review, cooperation and collaboration.
6. *Openness = freedom*: this specifically links to items 3 and 5 above, and relates to use, reuse and modification of data and information, as the basis for creativity (the Creative Commons argument) and innovation.
7. *Open science governance*: I would like to give this feature a radical Republican interpretation (after Polyani's [1962] 'the republic of science') based on peer review extended to all levels of the professoriate and also to users, including the public. (Peters, 2009a)

There is room for addressing the postcolonial critique of knowledge in both the 'Openness to the Other' that is not simply to other scientists but to other cultures. Institutionalised science has not been receptive to indigenous knowledge systems and is only now beginning to recognize the legitimacy of non-Western science or knowledge systems. The second feature 'Open science governance' speaks to how science is organized and for what purposes. In particular, open science is most often addressed to the public good and to global problems currently facing the world. It is a means for addressing the administration of science as a political and organizational issue that captures the question of responsibility and questions 'science in the service of empire', a Baconian conception that needs to address a wider commonwealth. The original conception was aimed at presenting a public view of open science as a technologically-enabled kind of science that embraced a knowledge commons in the service of humanity as a whole rather than science conducted in and for the private sector for profit. In this sense, the concept of open science sits well and fosters the various forms of citizen science, including community and school-based science aimed at the public good. As we explained:

> The emerging political economy of global science is a significant factor influencing development of national systems of innovation, and economic, social and cultural development, with the rise of multinational actors and a new mix of corporate, private/public and community involvement. In contemporary science, policy regimes outputs often take the form of patents, unpublished consultancy, 'grey literature' or are covered by legal arrangement and 'lawyer-client confidentiality'. As a result, there are expressed concerns about the fate of scientific publishing. The term global science reflects an extension of the 'old' liberal (as opposed to the market-

> driven neo-liberal) ideology of 'universal free knowledge' based on exchange and peer review that developed with the emergence of the modern research university in the nineteenth century. The open science economy is an alternative growing sector of the global knowledge economy utilizing open source models and its multiple applications in distributed knowledge and learning systems that encourage innovation-smart processes based on the radical non-propertarian sharing of content (Peters & Besley, 2019; see also 2021b).

Yet these forms of open science while challenging mainstream practices of science through citizen science initiatives that maximise user engagement do not address the question of power directly in the way that the postcolonial critique of science does by introducing an historical perspective to demonstrate the effects of spurious and pseudoscience especially in relation to the question of race. Open science needs to explicitly address the postcolonial critique of knowledge and knowledge systems through the recognition of the significance of context, 'the local', and an understanding of the ways that the science systems has introduced distortions and unfairness in terms of funding, access and distribution. One of the major claims that emerge from the postcolonial critique is that way in which academic scholarship is always implicated in politics – what Foucault calls 'power/knowledge' – despite the ideology of objectivism, detachment and autonomy. 'Power/Knowledge' signifies that power is constituted through accepted forms of knowledge, scientific understanding and 'truth'. The postcolonial critique highlights this clearly in relation to the colonial science system aimed at the extraction of wealth, the denigration of indigenous knowledge, and the way neocolonial relations are sustained through capitalist technoscience.

This is one of the reason that I accepted an invitation to speak at the ACUSAFRICA network event to advance Critical University Studies where 'Underpinning our work is the endeavour to find 'other' ways to study universities that are capable of thinking plural forms of emancipatory higher education imaginations and futures'[6] and to demonstrate solidarity.

This conception is robust enough to capture some of the essential features of the discourse of the public while focusing on a healthy concept of global open science, that is not locked behind a pay-wall. It is inclusive of liberal and non-liberal societies. Open science is strongly supported in China and Russia. Revising this conception today I would probably frame it through a critique of the World Class University (Hazelkorn, 2011) as we argue in *The World Class University: A Contested Concept* (Rider et al., 2021):

> The connection between the handful of Big Publishers who control the bulk of academic publications (Springer, Taylor and Francis, Elsevier, Wiley-Blackwell, Sage), universities that control academic labor and ranking agencies constitutes an algorithmic form of

> governance through a template for academic innovation and development. After nearly a half century of neoliberalism, the regulation of university life through New Public Management technocratic measures such as performance indicators now serves as the benchmark for a global system of knowledge that encompasses some 20,000 universities and other HE institutions worldwide (Peters, 2017b).

We complained that 'the concept of the WCU in a global competitive model of the knowledge economy promoted by The World Bank (Salmi, 2002; 2009) … [focusing on] a small number of elite universities, creating a greater hierarchical reputational differentiation… often separating teaching and research universities to link resource allocation to institutional profiling or other classification tools informed by rankings; by contrast, the social democratic model attempts to balance excellence and equity, with an emphasis on horizontal differentiation and a "good quality" university system based on the integration of teaching and research (Hazelkorn, 2015).' My own chapter cowritten with Tina Besley was entitled 'Contesting the Neoliberal Discourse of the World Class University: 'Digital Socialism', Openness and Academic Publishing', available for free download, really spells out an argument that change in political economy of academic publishing can be observed through Open Access, cOAlition S, and 'Plan S' (mandated in 2020) established by national research funding organisations in Europe with the support of the European Commission and the European Research Council (ERC); and we suggested

> The social democratic alternative to neoliberalism and the WCU is a form of the sharing academic economy known as 'knowledge socialism'. Universities need to share knowledge in the search for effective responses to pressing world problems of fragile global ecologies and the growing significance of technological unemployment. This is a model that proceeds from a very different set of economic and moral assumptions than the neoliberal knowledge economy and the WCU.

11. Knowledge Socialism and Open Science as a Global Public Good

The idea of openness of knowledge socialism has a clear materiality and mandate for sharing knowledge, information and resources among scientists (and global publics), to distribute it freely, to make access also free online and to be sensitive to the multiplicity of global publics for the fair representation of science across all nations, genders, peoples based on historical redress and outreach, and a healthy suspicion of private science in the service of multinationals, or state suppression of the free flow of science and scientific publications.[7] UNESCO adopted the Recommendation on Open Science

23 November 2021, 'that Member States collaborate in bilateral, regional, multilateral and global initiatives for the advancement of open science' with the aim of:

> (i) promoting a common understanding of open science, associated benefits and challenges, as well as diverse paths to open science;
> (ii) developing an enabling policy environment for open science;
> (iii) investing in open science infrastructures and services;
> (iv) investing in human resources, training, education, digital literacy and capacity building for open science;
> (v) fostering a culture of open science and aligning incentives for open science;
> (vi) promoting innovative approaches for open science at different stages of the scientific process;
> (vii) promoting international and multi-stakeholder cooperation in the context of open science and with view to reducing digital, technological and knowledge gaps.
> https://unesdoc.unesco.org/ark:/48223/pf0000379949.locale=en

Clearly, if it is possible to build an argument and develop a set of practices based on science as a global public good then it is also possible to establish a vision for the university based on it. I have consistently argued that openness is a complex code word for an alternative mode of scientific production that refers to open source, open access, open archives, open publishing, open education and open science. In this sense it refers to open models of scientific and scholarly communication and distribution with the potential to address the North-South inequalities and power imbalances and the prospect of creating virtuous public science economy based on open innovation, especially in clear cases of global public goods necessary for the survival of humanity in related areas of global health and environmental sustainability.

This model of open science constitutes a radical non-propertarian social alternative to traditional methods of text production, distribution, access and dissemination. It is also clear that this alternative model of social exchange that co-exists and sits alongside the neoliberal ecosystem of intellectual property under which creativity, innovation and the free exchange of ideas are badly compromised (Peters, 2009c; 2010). One innovation has been collective writing projects that are open expressions of a new form of writing an academic article, now an established genre with over 100 articles within the last few years (Jandric et al., 2022). If I am permitted a word here concerning a postmarxist experiment in collective writing as an aspect of knowledge socialism that enables a critical philosophy of education and pedagogy, focused on the article as a collection of 500-word essays arranged and sequenced in the elaboration of the theme.

Radical openness and its links to the development of scientific communication, is one of the means for the reinvention of the public good and the constitution of the global knowledge commons. The open knowledge economy offers a way of reclaiming knowledge as a global public good and of viewing openness as an essential aspect of an emerging global knowledge commons that fosters open science and open education (Peters, 2013).

The International Science Council (ISC) recently committed itself to a vision of science as a global public good based on the value of knowledge:

> Knowledge has been amongst the most powerful of public goods. It has been the inspiration, stimulus, and agent upon which most human material, social and personal progress has been built. Access to knowledge, and to the education systems that seek to increase the stock of knowledge of individuals, and thereby, in aggregate, of society, are recognised as human rights (Bouton, 2021).

Yet as the position paper argues, science as a formalized system of peer review develops claims to knowledge based on argument and evidence that is open to criticism and reality testing and the results are communicated to the public for the improvement of the human condition – the essence of an incontrovertible argument for the public university and the milieu of public intellectuals. A fundamental commitment to openness by the public university can be defined in terms of the protection and development of knowledge as a global public good connected to a basic set of human rights that includes not only fostering open science and education but also traditional social democratic values promoting universal access, fair distribution, academic freedom and the free exchange of ideas.

I would agree with the UN Global Science Commons statement that 'Publicly funded science should be Open Science', that 'Open Science is an accelerator of the Sustainable Development Goals (SDGs)' and the recommended 'roadmap' to a science commons, guided by 'inclusiveness and respect for diversity', equitable practice, shared benefits, and opportunities for participation, at the same time it is necessary in setting up global open science that it carefully examines the structural imbalances in the emerging global science system, the histories of colonial science systems, and post-colonial new formations designed to promote emancipation in the service of the public university.

NOTES

1. https://thepienews.com/news/holoniq-intl-market-ed-data/
2. https://www.lek.com/insights/global-student-mobility-trends-2021-and-beyond
3. This section draws on Peters (2022), "Global Public Sphere or Fragmentary, Ever-Diminishing Publics?" (Editorial), *On_Education*, forthcoming.

4. The postcolonial and its significance for 'decolonizing the university' I leave to engaged scholars on the ground – for example, *Decolonising Knowledge and Knowers; Struggles for University Transformation in South Africa* (eds. Hlatshwayo et al.; incl. Fataar, 2022); Keet's (2021) 'Africanising/decolonising ourselves' and the African interpretation of critical university studies; and 'Epistemic decolonisation' from the students' perspective (Motata, 2021).

5. The book was very strongly received by Des Hewitt (2021) reviewing for *Social Epistemology*.

6. https://www.acusafrica.com/post/news-acusafrica-colloquium-2022-reflexive-solidarities-in-techno-rational-times

7. See The UN Open Science Conference 2021 and the creation of a 'Global Science Commons' (moderated by Professor Jean-Claude Guédon, https://research.un.org/conferences/OpenScienceOutcome. Also see UNESCO's Open Science portal at https://www.unesco.org/en/natural-sciences/open-science

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Metaverse and Digital Twin Technologies, Machine Learning and Image Processing Computational Algorithms, and Geospatial Analytics and Simulation Modeling Tools in Interactive Virtual and Extended Reality Environments

Jakub Horak[1] and Raluca-Ștefania Balica[2]

ABSTRACT. We draw on a substantial body of theoretical and empirical research on metaverse and digital twin technologies, machine learning and image processing computational algorithms, and geospatial analytics and simulation modeling tools. In this research, prior findings were cumulated indicating that simulation modeling and computational intelligence tools, sentiment analytics, and metaverse assets and services enable interactive virtual and extended reality environments. We carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout April 2023, with search terms including "interactive virtual and extended reality environments" + "metaverse and digital twin technologies," "machine learning and image processing computational algorithms," and "geospatial analytics and simulation modeling tools." As we analyzed research published in 2022 and 2023, only 188 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, we decided on 34, chiefly empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Distiller SR, ROBIS, and SRDR.

Keywords: metaverse; digital twin technologies; machine learning; image processing computational algorithms; geospatial analytics; simulation modeling tools; interactive virtual and extended reality environments

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1. Introduction

Spatial computing devices, real-time remote assistance and control, and empathetic computing and immersive visualization systems shape extended reality environments. The purpose of our systematic review is to examine the recently published literature on interactive virtual and extended reality environments and integrate the insights it configures on metaverse and digital twin technologies, machine learning and image processing computational algorithms, and geospatial analytics and simulation modeling tools. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that simulation modeling and computational intelligence tools, sentiment analytics, and metaverse assets and services (Barbu et al., 2021; Lyons and Lăzăroiu, 2020; Nica et al., 2023; Peters et al., 2023) enable interactive virtual and extended reality environments. The actuality and novelty of this study are articulated by addressing biometric authentication and immersive visualization systems, machine learning and image processing computational algorithms, and 3D virtual space networking and ambient intelligence tools (Lăzăroiu and Rogalska, 2023; Nica et al., 2019; Vătămănescu et al., 2022), that is an emerging topic involving much interest. Our research problem is whether behavior modeling and spatial computing technologies, digital twin simulation and image processing tools, and data stream clustering and predictive maintenance algorithms (Andronie et al., 2021; Krizanova et al., 2019; Lewkowich, 2022; Nica, 2017) configure 3D immersive environments.

In this review, prior findings have been cumulated indicating that extended reality environments develop on 3D digital twin techniques, geospatial analytics and simulation modeling tools (Nagy et al., 2023; Popescu et al., 2020; Vinerean et al., 2022), and biometric and behavioral data. The identified gaps advance voice recognition software, geolocation data mining and tracking, and blockchain-based digital asset management and brain-inspired cognitive systems. Our main objective is to indicate that signal processing and distributed intelligence tools, haptic and biometric sensor technologies, and visual object tracking and path planning algorithms (Andronie et al., 2023; Kovacova et al., 2022; Nagy and Lăzăroiu, 2022) assist immersive interconnected virtual worlds.

2. Theoretical Overview of the Main Concepts

Empathetic computing and artificial neural network-based decision support systems, cloud computing machines, and voice and gesture recognition tools are pivotal in the virtual environment of the metaverse. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), machine learning and image processing computational algorithms,

geospatial analytics and simulation modeling tools, and visual localization and mapping devices in interactive virtual and extended reality environments (section 4), metaverse and digital twin technologies, empathetic computing and artificial neural network-based decision support systems, and operational modeling and geospatial mapping tools in hyper-immersive simulated environments (section 5), digital twin simulation and image processing tools, semantic-based cognitive and machine intelligence technologies, and visual object tracking and path planning algorithms in the virtual environment of the metaverse (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

We carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout April 2023, with search terms including "interactive virtual and extended reality environments" + "metaverse and digital twin technologies," "machine learning and image processing computational algorithms," and "geospatial analytics and simulation modeling tools." As we analyzed research published in 2022 and 2023, only 188 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, we decided on 34, chiefly empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Distiller SR, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
interactive virtual and extended reality environments + metaverse and digital twin technologies	64	12
interactive virtual and extended reality environments + machine learning and image processing computational algorithms	63	11
interactive virtual and extended reality environments + geospatial analytics and simulation modeling tools	61	11
Type of paper		
Original research	154	23
Review	23	11
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.

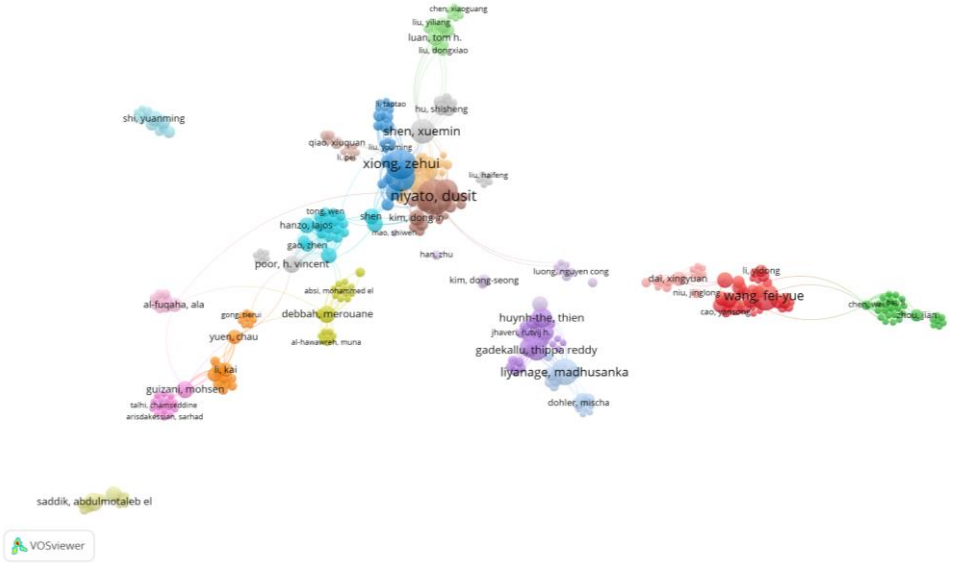

Figure 1 Co-authorship

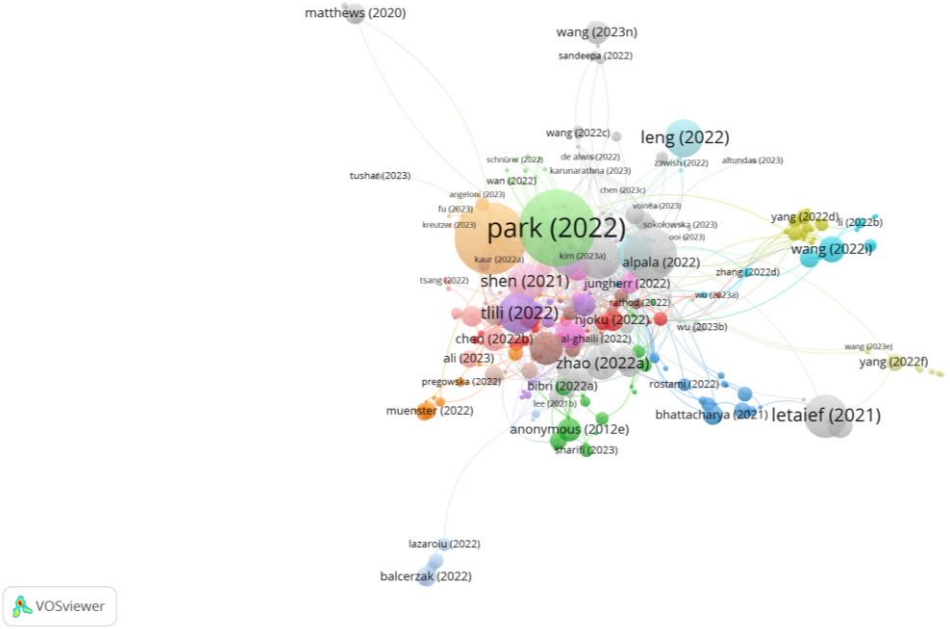

Figure 2 Citation

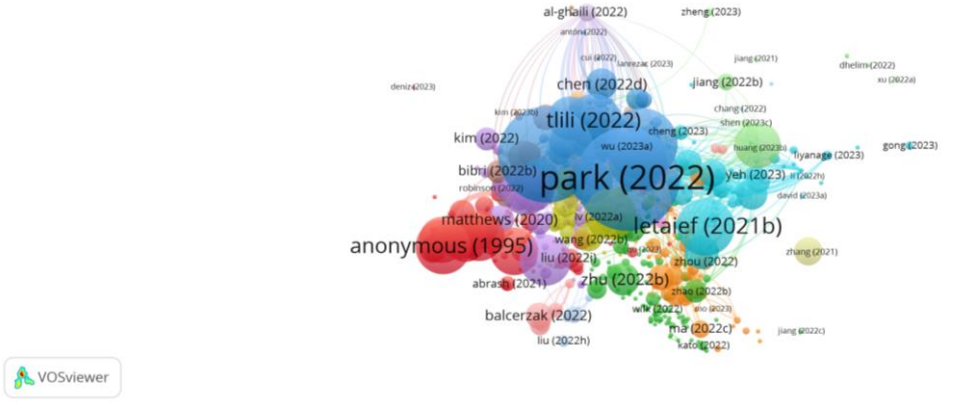

Figure 3 Bibliographic coupling

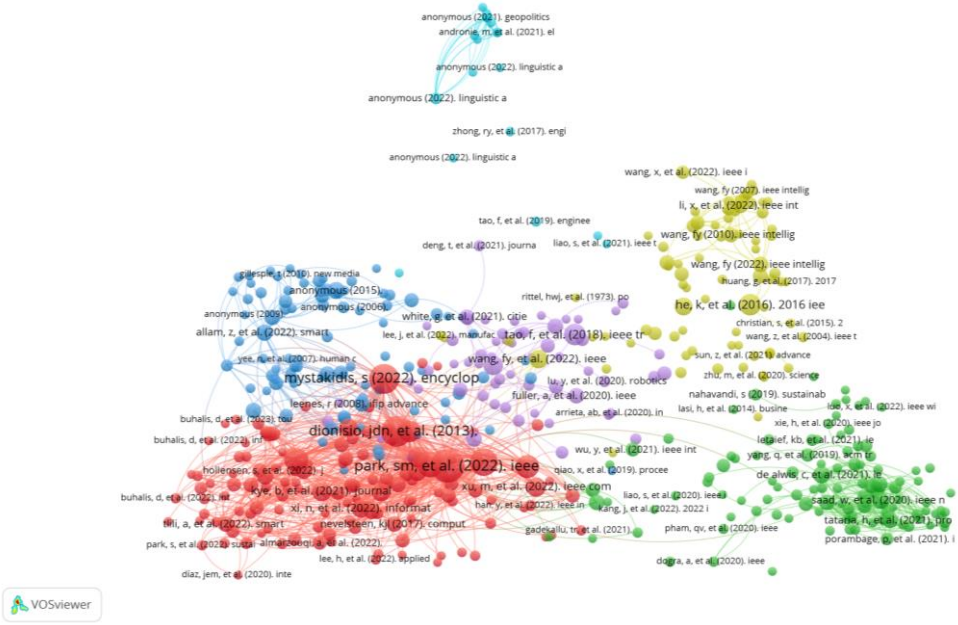

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Biometric authentication and immersive visualization systems, machine learning and image processing computational algorithms, and 3D virtual space networking and ambient intelligence tools configure simulated 3D virtual reality environments.	Cao, 2022; Valaskova et al., 2022a; Wang et al., 2022; Zheng and Yuan, 2023
Web3-powered metaverse worlds integrate wearable Internet of Things and spatial computing devices, multisensor fusion and 3D immersive virtual reality technologies, and visual perception and conversational artificial intelligence algorithms.	Barnes, 2022; Kliestik et al., 2022; Lv et al., 2022; Xu et al., 2023
Interoperable extended reality environments require emotion detection and spatial computing algorithms, computer graphics-based photorealistic imagery, and cloud-based cognitive and virtual modeling technologies.	Dwivedi et al., 2023; Hollensen et al., 2023; Vidal-Tomás, 2023
Digitally-networked mediated spaces in shared virtual environments necessitate metaverse and digital twin technologies, 3D image processing and deep learning computer vision algorithms, and photorealistic synthetic imagery.	Han et al., 2022; Kral et al., 2022**;** Machova et al., 2022; Zvarikova et al., 2022
Operational modeling and geospatial mapping tools, biometric and behavioral data, and image-based visual computing and machine intelligence technologies further hyper-immersive simulated environments.	Gauttier et al., 2022; Han et al., 2023a; McStay, 2022; Valaskova et al., 2022b
Behavioral simulation and predictive geospatial modeling tools, 3D computer vision and digital twin technologies, and sensor and actuator devices are instrumental in intelligent simulation and extended reality environments.	Han et al., 2023b; Newell, 2022; Van Huynh et al., 2022; Yoo et al., 2023
Voice recognition software, geolocation data mining and tracking, and blockchain-based digital asset management and brain-inspired cognitive systems assist a fully connected metaverse.	Egliston and Carter, 2022; Polas et al., 2022; Zarantonello and Schmitt, 2023
Semantic-based cognitive and machine intelligence technologies, computer vision and multi-sensor fusion systems, and image recognition and digital twin modeling tools articulate interconnected digital spaces and the metaverse decentralized infrastructure.	Du et al., 2023; Nagendran et al., 2022; Shi et al., 2023; Zvarikova et al., 2023
Realistic 3D digital twins, predictive maintenance and situational awareness algorithms, and geolocation data mining and tracking optimize intelligent connectivity infrastructures in the virtual environment of the metaverse.	Hawkins, 2022; Rostami and Maier, 2022; Weking et al., 2023; Zallio and Clarkson, 2022

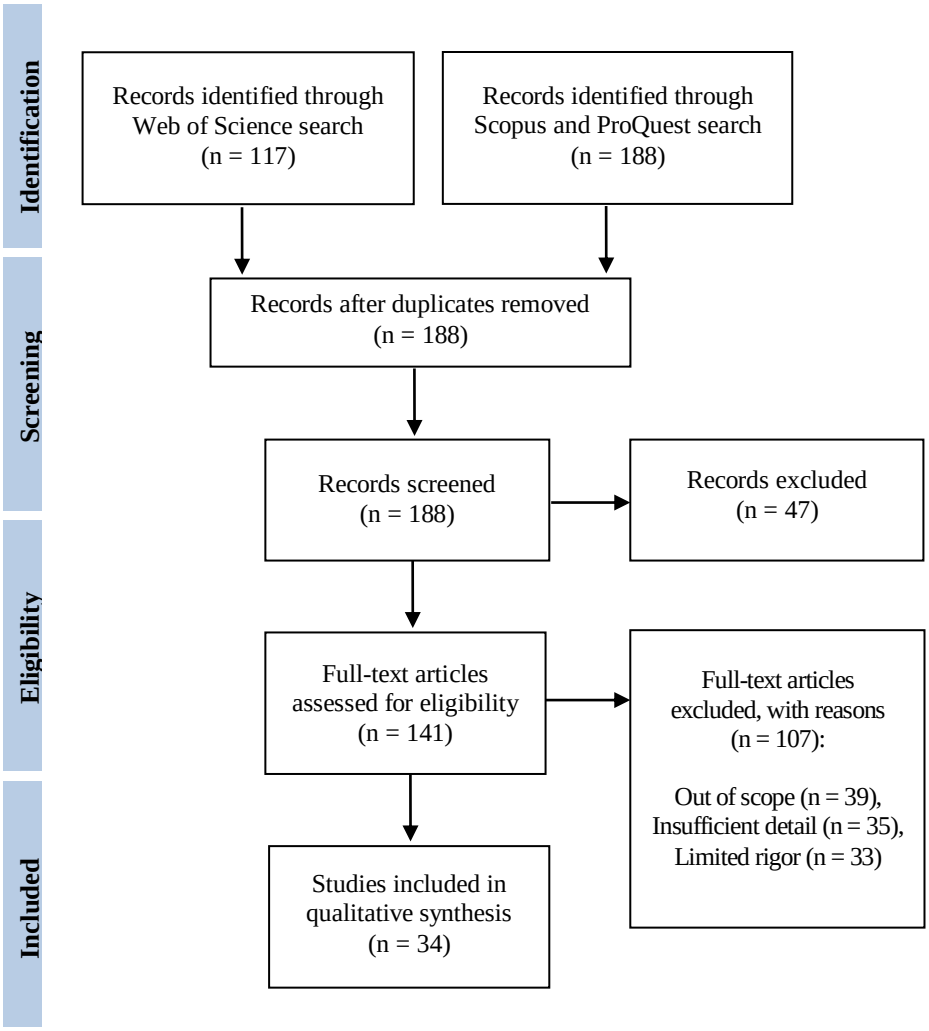

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

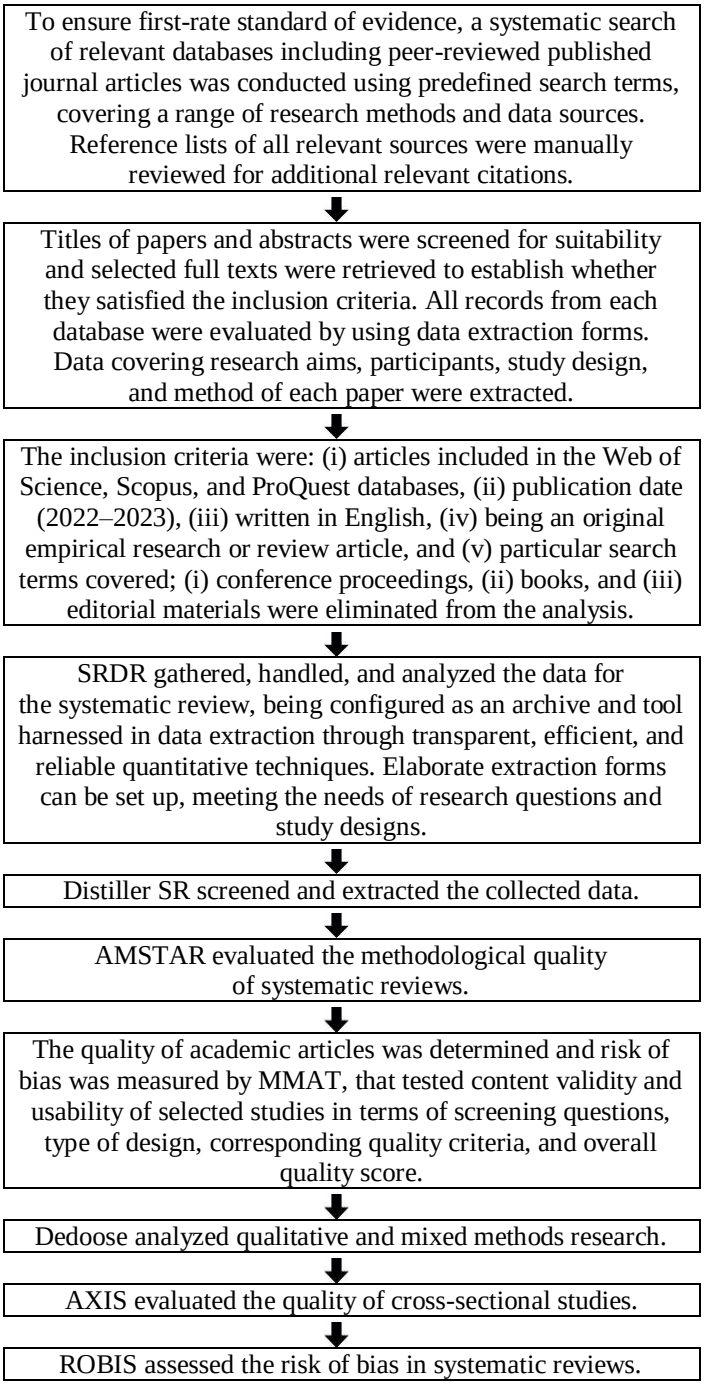

Figure 6 Screening and quality assessment tools

4. Machine Learning and Image Processing Computational Algorithms, Geospatial Analytics and Simulation Modeling Tools, and Visual Localization and Mapping Devices in Interactive Virtual and Extended Reality Environments

Biometric authentication and immersive visualization systems, machine learning and image processing computational algorithms, and 3D virtual space networking and ambient intelligence tools (Cao, 2022; Valaskova et al., 2022a; Wang et al., 2022; Zheng and Yuan, 2023) configure simulated 3D virtual reality environments. Extended reality environments develop on 3D digital twin techniques, geospatial analytics and simulation modeling tools, and biometric and behavioral data.

Web3-powered metaverse worlds (Barnes, 2022; Kliestik et al., 2022; Lv et al., 2022; Xu et al., 2023) integrate wearable Internet of Things and spatial computing devices, multisensor fusion and 3D immersive virtual reality technologies, and visual perception and conversational artificial intelligence algorithms. Simulation modeling and computational intelligence tools, sentiment analytics, and metaverse assets and services enable interactive virtual and extended reality environments.

Interoperable extended reality environments (Dwivedi et al., 2023; Hollensen et al., 2023; Vidal-Tomás, 2023) require emotion detection and spatial computing algorithms, computer graphics-based photorealistic imagery, and cloud-based cognitive and virtual modeling technologies. 3D immersive virtual experiences can be achieved by use of visual localization and mapping devices, extended reality and 3D digital twin modeling technologies, and sensor data fusion. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Biometric authentication and immersive visualization systems, machine learning and image processing computational algorithms, and 3D virtual space networking and ambient intelligence tools configure simulated 3D virtual reality environments.	Cao, 2022; Valaskova et al., 2022a; Wang et al., 2022; Zheng and Yuan, 2023
Web3-powered metaverse worlds integrate wearable Internet of Things and spatial computing devices, multisensor fusion and 3D immersive virtual reality technologies, and visual perception and conversational artificial intelligence algorithms.	Barnes, 2022; Kliestik et al., 2022; Lv et al., 2022; Xu et al., 2023
Interoperable extended reality environments require emotion detection and spatial computing algorithms, computer graphics-based photorealistic imagery, and cloud-based cognitive and virtual modeling technologies.	Dwivedi et al., 2023; Hollensen et al., 2023; Vidal-Tomás, 2023

5. Metaverse and Digital Twin Technologies, Empathetic Computing and Artificial Neural Network-based Decision Support Systems, and Operational Modeling and Geospatial Mapping Tools in Hyper-Immersive Simulated Environments

Digitally-networked mediated spaces in shared virtual environments (Han et al., 2022; Kral et al., 2022**;** Machova et al., 2022; Zvarikova et al., 2022) necessitate metaverse and digital twin technologies, 3D image processing and deep learning computer vision algorithms, and photorealistic synthetic imagery. Metaverse virtual services, visual perception and multi-sensory stimulation algorithms, and spatial and mobile edge computing technologies articulate immersive and interactive virtual environments.

Operational modeling and geospatial mapping tools, biometric and behavioral data, and image-based visual computing and machine intelligence technologies (Gauttier et al., 2022; Han et al., 2023a; McStay, 2022; Valaskova et al., 2022b) further hyper-immersive simulated environments. Empathetic computing and artificial neural network-based decision support systems, cloud computing machines, and voice and gesture recognition tools are pivotal in the virtual environment of the metaverse.

Behavioral simulation and predictive geospatial modeling tools, 3D computer vision and digital twin technologies, and sensor and actuator devices (Han et al., 2023b; Newell, 2022; Van Huynh et al., 2022; Yoo et al., 2023) are instrumental in intelligent simulation and extended reality environments. Spatial computing devices, real-time remote assistance and control, and empathetic computing and immersive visualization systems shape extended reality environments. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Digitally-networked mediated spaces in shared virtual environments necessitate metaverse and digital twin technologies, 3D image processing and deep learning computer vision algorithms, and photorealistic synthetic imagery.	Han et al., 2022; Kral et al., 2022**;** Machova et al., 2022; Zvarikova et al., 2022
Operational modeling and geospatial mapping tools, biometric and behavioral data, and image-based visual computing and machine intelligence technologies further hyper-immersive simulated environments.	Gauttier et al., 2022; Han et al., 2023a; McStay, 2022; Valaskova et al., 2022b
Behavioral simulation and predictive geospatial modeling tools, 3D computer vision and digital twin technologies, and sensor and actuator devices are instrumental in intelligent simulation and extended reality environments.	Han et al., 2023b; Newell, 2022; Van Huynh et al., 2022; Yoo et al., 2023

6. Digital Twin Simulation and Image Processing Tools, Semantic-based Cognitive and Machine Intelligence Technologies, and Visual Object Tracking and Path Planning Algorithms in the Virtual Environment of the Metaverse

Voice recognition software, geolocation data mining and tracking, and blockchain-based digital asset management and brain-inspired cognitive systems (Egliston and Carter, 2022; Polas et al., 2022; Zarantonello and Schmitt, 2023) assist a fully connected metaverse. Behavior modeling and spatial computing technologies, digital twin simulation and image processing tools, and data stream clustering and predictive maintenance algorithms configure 3D immersive environments.

Semantic-based cognitive and machine intelligence technologies, computer vision and multi-sensor fusion systems, and image recognition and digital twin modeling tools (Du et al., 2023; Nagendran et al., 2022; Shi et al., 2023; Zvarikova et al., 2023) articulate interconnected digital spaces and the metaverse decentralized infrastructure. Metaverse engagement and experiences can be attained through swarm computing and spatial cognition algorithms, immersive decentralized networking and virtual navigation tools, and 3D modeling and simulation technologies.

Realistic 3D digital twins, predictive maintenance and situational awareness algorithms, and geolocation data mining and tracking (Hawkins, 2022; Rostami and Maier, 2022; Weking et al., 2023; Zallio and Clarkson, 2022) optimize intelligent connectivity infrastructures in the virtual environment of the metaverse. Signal processing and distributed intelligence tools, haptic and biometric sensor technologies, and visual object tracking and path planning algorithms assist immersive interconnected virtual worlds. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Voice recognition software, geolocation data mining and tracking, and blockchain-based digital asset management and brain-inspired cognitive systems assist a fully connected metaverse.	Egliston and Carter, 2022; Polas et al., 2022; Zarantonello and Schmitt, 2023
Semantic-based cognitive and machine intelligence technologies, computer vision and multi-sensor fusion systems, and image recognition and digital twin modeling tools articulate interconnected digital spaces and the metaverse decentralized infrastructure.	Du et al., 2023; Nagendran et al., 2022; Shi et al., 2023; Zvarikova et al., 2023
Realistic 3D digital twins, predictive maintenance and situational awareness algorithms, and geolocation data mining and tracking optimize intelligent connectivity infrastructures in the virtual environment of the metaverse.	Hawkins, 2022; Rostami and Maier, 2022; Weking et al., 2023; Zallio and Clarkson, 2022

7. Discussion

We integrate our systematic review throughout research indicating how metaverse engagement and experiences can be attained through swarm computing and spatial cognition algorithms, immersive decentralized networking and virtual navigation tools, and 3D modeling and simulation technologies. Our research complements recent analyses clarifying how 3D immersive virtual experiences can be achieved by use of visual localization and mapping devices, extended reality and 3D digital twin modeling technologies, and sensor data fusion. We elucidate, by cumulative evidence, previous research demonstrating how behavior modeling and spatial computing technologies, digital twin simulation and image processing tools, and data stream clustering and predictive maintenance algorithms configure 3D immersive environments.

8. Synopsis of the Main Research Outcomes

Empathetic computing and artificial neural network-based decision support systems, cloud computing machines, and voice and gesture recognition tools are pivotal in the virtual environment of the metaverse. Simulation modeling and computational intelligence tools, sentiment analytics, and metaverse assets and services enable interactive virtual and extended reality environments. Signal processing and distributed intelligence tools, haptic and biometric sensor technologies, and visual object tracking and path planning algorithms assist immersive interconnected virtual worlds.

9. Conclusions

Relevant research has investigated whether extended reality environments develop on 3D digital twin techniques, geospatial analytics and simulation modeling tools, and biometric and behavioral data. This systematic literature review presents the published peer-reviewed sources covering how spatial computing devices, real-time remote assistance and control, and empathetic computing and immersive visualization systems shape extended reality environments. The research outcomes drawn from the above analyses indicate that metaverse virtual services, visual perception and multi-sensory stimulation algorithms, and spatial and mobile edge computing technologies articulate immersive and interactive virtual environments.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on metaverse and digital twin technologies, machine learning and

image processing computational algorithms, and geospatial analytics and simulation modeling tools in interactive virtual and extended reality environments may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of operational modeling and geospatial mapping tools, biometric and behavioral data, and image-based visual computing and machine intelligence technologies.

Subsequent analyses should develop on metaverse and digital twin technologies, 3D image processing and deep learning computer vision algorithms, and photorealistic synthetic imagery. Future research should thus investigate realistic 3D digital twins, predictive maintenance and situational awareness algorithms, and geolocation data mining and tracking. Attention should be directed to behavioral simulation and predictive geospatial modeling tools, 3D computer vision and digital twin technologies, and sensor and actuator devices.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
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Brain-inspired Artificial Intelligence and Machine Learning-based Navigation Algorithms, Spatial Data Visualization and Digital Twin Modeling tools, and Emotion Detection and Recognition Technologies in the Decentralized and Interconnected Metaverse

Sofia Bratu*

ABSTRACT. Despite the relevance of synthetic biometric data, human digital twin and haptic object recognition systems, and real-time 3D rendering and visual immersion technologies, only limited research has been conducted on this topic. In this article, I cumulate previous research findings indicating that interactional and contextual data, digital twin and tactile sensing technologies, and behavioral predictive and geospatial big data analytics configure the decentralized and interconnected metaverse. Throughout May 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "the decentralized and interconnected metaverse" + "brain-inspired artificial intelligence and machine learning-based navigation algorithms," "spatial data visualization and digital twin modeling tools," and "emotion detection and recognition technologies." As I inspected research published between 2022 and 2023, only 179 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 30, generally empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, Distiller SR, and MMAT.

Keywords: brain-inspired artificial intelligence; machine learning; navigation algorithms; spatial data visualization; digital twin modeling tools; emotion detection and recognition technologies; decentralized and interconnected metaverse

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1. Introduction

The virtual environment of the metaverse necessitates artificial intelligence-based image recognition and affective computing technologies, spatial data visualization and digital twin modeling tools, and wearable haptic garments. The purpose of my systematic review is to examine the recently published literature on the decentralized and interconnected metaverse and integrate the insights it configures on brain-inspired artificial intelligence and machine learning-based navigation algorithms, spatial data visualization and digital twin modeling tools, and emotion detection and recognition technologies. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that synthetic biometric data, human digital twin and haptic object recognition systems, and real-time 3D rendering and visual immersion technologies (Andronie et al., 2023a; Lăzăroiu et al., 2017; Milward et al., 2019) enable the virtual economy of the metaverse. The actuality and novelty of this study are articulated by addressing virtual reality-based and Internet of Things sensor data analytics, digital twin modeling tools, and multi-sensor fusion and explainable artificial intelligence-based decision support systems (Andronie et al., 2023b; Gennadyevna Leshkevich and Vladimirovna Kataeva, 2023; Lăzăroiu et al., 2020), that is an emerging topic involving much interest. My research problem is whether mobile sensors and actuators, geospatial mapping and behavioral simulation tools, and affective modeling and sensor path planning algorithms (Andronie et al., 2021; Fernando and Lăzăroiu, 2023; Nica, 2019) further immersive decentralized 3D digital worlds.

In this review, prior findings have been cumulated indicating that interactional and contextual data, digital twin and tactile sensing technologies, and behavioral predictive and geospatial big data analytics (Gura et al., 2023; Lăzăroiu et al., 2022; Trettin et al., 2019) configure the decentralized and interconnected metaverse. The identified gaps advance immersive and extended reality technologies, geospatial big data visualization and multimodal sensing systems (Balcerzak et al., 2022; Kovacova et al., 2022a; Valaskova et al., 2022), and spatio-temporal fusion and machine learning-based recognition algorithms. My main objective is to indicate that Internet of Things-based sensing and human digital twin systems, big geospatial data and real-time predictive analytics (Dabija et al., 2022; Kliestik et al., 2020; Scott et al., 2020), and virtual modeling and geospatial mapping technologies (Dabija et al., 2018; Lewkowich, 2022; Pop et al., 2021; Popescu, 2018) shape photorealistic synthetic environments.

2. Theoretical Overview of the Main Concepts

The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), virtual modeling and geospatial mapping technol-

ogies, multi-sensor fusion and explainable artificial intelligence-based decision support systems, and objection recognition and sensor path planning algorithms in the decentralized and interconnected metaverse (section 4), Internet of Things-based decision support and bio-inspired artificial vision systems, machine perception and affective computing technologies, and spatial data visualization and digital twin modeling tools in immersive multisensory virtual spaces (section 5), brain-inspired artificial intelligence and machine learning-based navigation algorithms, operational modeling and digital twin simulation tools, and emotion detection and recognition technologies in a fully connected metaverse (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout May 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "the decentralized and interconnected metaverse" + "brain-inspired artificial intelligence and machine learning-based navigation algorithms," "spatial data visualization and digital twin modeling tools," and "emotion detection and recognition technologies." As I inspected research published between 2022 and 2023, only 179 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 30, generally empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, Distiller SR, and MMAT (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
the decentralized and interconnected metaverse + brain-inspired artificial intelligence and machine learning-based navigation algorithms	61	11
the decentralized and interconnected metaverse + spatial data visualization and digital twin modeling tools	59	10
the decentralized and interconnected metaverse + emotion detection and recognition technologies	59	9
Type of paper		
Original research	146	19
Review	23	11
Conference proceedings	8	0
Book	1	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

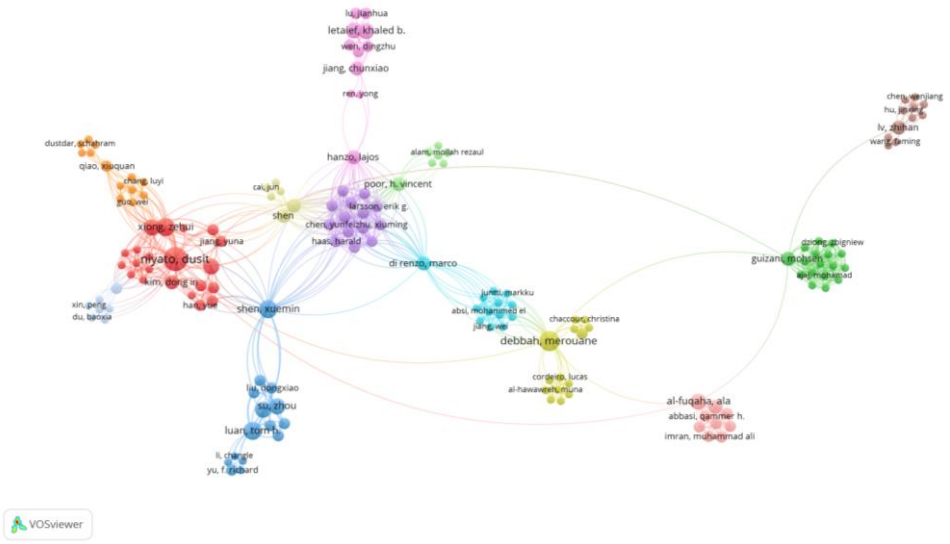

Figure 1 Co-authorship

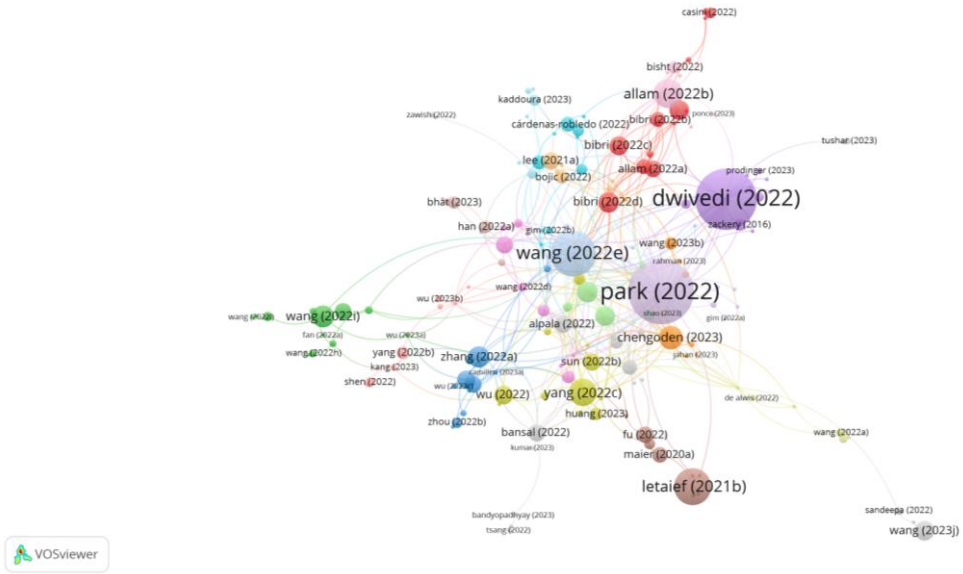

Figure 2 Citation

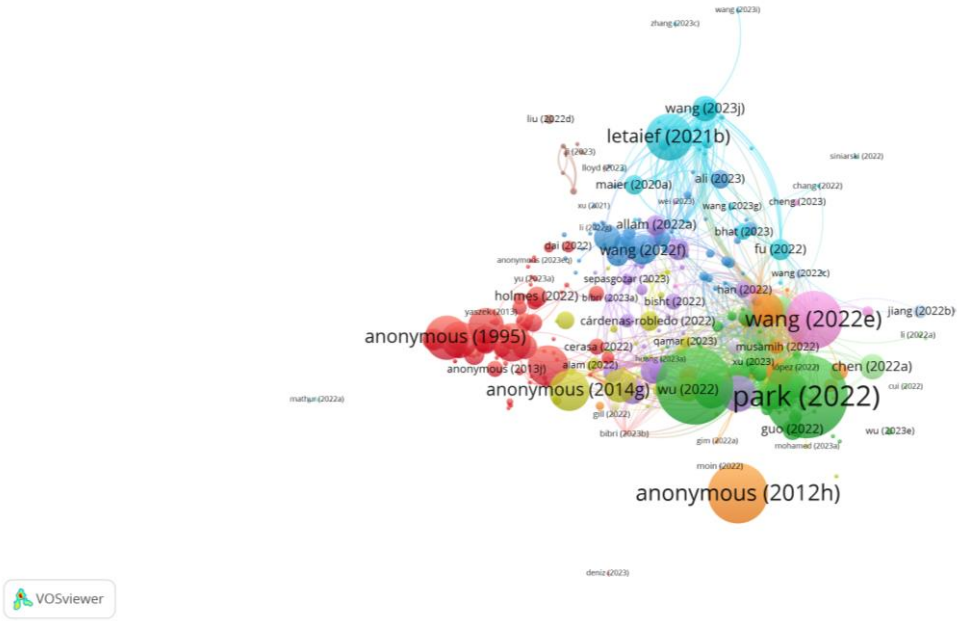

Figure 3 Bibliographic coupling

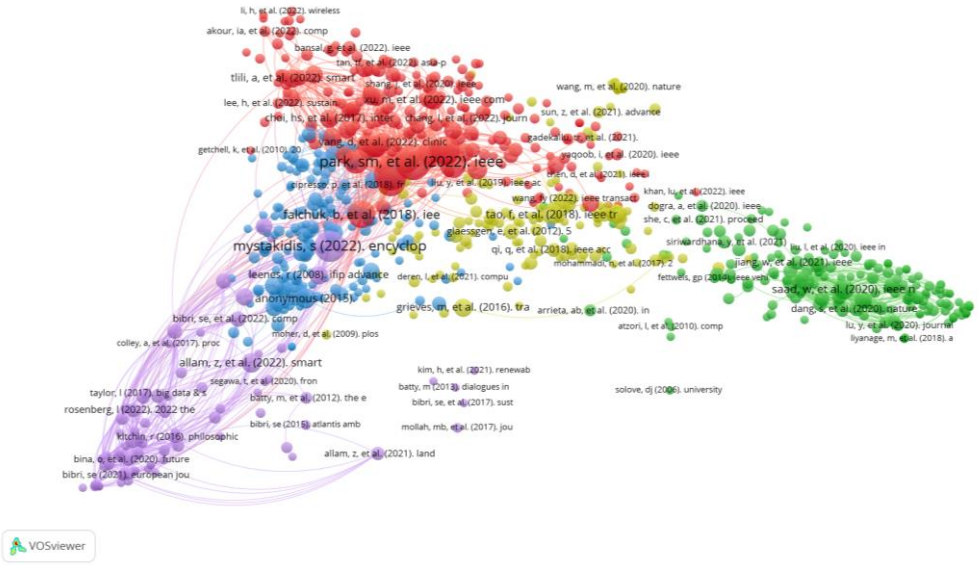

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Automated perception and geospatial big data visualization systems, behavioral predictive and sentiment analytics, and ontology-based semantic and eye-tracking technologies configure the decentralized and interconnected metaverse.	Grupac and Lăzăroiu, 2022; He et al., 2023; Zhao et al., 2022
Synthetic digitally-mediated environments develop on virtual reality-based and Internet of Things sensor data analytics, digital twin modeling tools, and multi-sensor fusion and explainable artificial intelligence-based decision support systems.	Duncan, 2022; Golf-Papez et al., 2022; Kovacova et al., 2022b; Popp and Cuțitoi, 2022
Immersive virtual experiences can be achieved through objection recognition and sensor path planning algorithms, intelligent sensing and deep learning-based generative networks, and neuromorphic image processing and motion capture systems in extended reality environments.	Geambazi et al., 2022; Kozinets, 2023; Lv et al., 2022; Venugopal et al., 2023
3D immersive environments integrate user behavior data mining, performance capture and cognitive modeling technologies, and brain-inspired artificial intelligence and data stream clustering algorithms.	Daneshfar and Jamshidi, 2023; Gordon, 2022; Kovacova et al., 2022b; Mourtzis et al., 2022
Immersive multisensory virtual spaces require machine perception and affective computing technologies, location intelligence data, and Internet of Things-based decision support and bio-inspired artificial vision systems.	Ahn et al., 2023; Hennig-Thurau et al., 2022; Ramadan, 2023
Virtual reality-based immersive experiences can be attained by use of immersive geospatial data visualization and spatial computing technologies, 3D path planning and computer vision algorithms, and data modeling and geospatial intelligence tools.	Bordegoni and Ferrise, 2023; McStay, 2023; Smart, 2022
Immersive and extended reality technologies, geospatial big data visualization and multimodal sensing systems, and spatio-temporal fusion and machine learning-based recognition algorithms are pivotal in decentralized 3D virtual spaces.	Kwok and Tang, 2023; Rydell, 2022; Zhang et al., 2023
Immersive virtual experiences can be attained through monitoring and sensing technologies, human digital twin and bio-inspired artificial vision systems, and autonomous visual object detection and distributed intelligence tools.	Oláh and Nica, 2022; Park and Kim, 2023; Zainab et al., 2022
Immersive metaverse experiences can be achieved by use of virtual machine interoperability, emotion detection and recognition technologies, and digital twin modeling and synthetic data tools in a fully connected metaverse.	Carey, 2022; Queiroz et al., 2023; Zhu et al., 2023

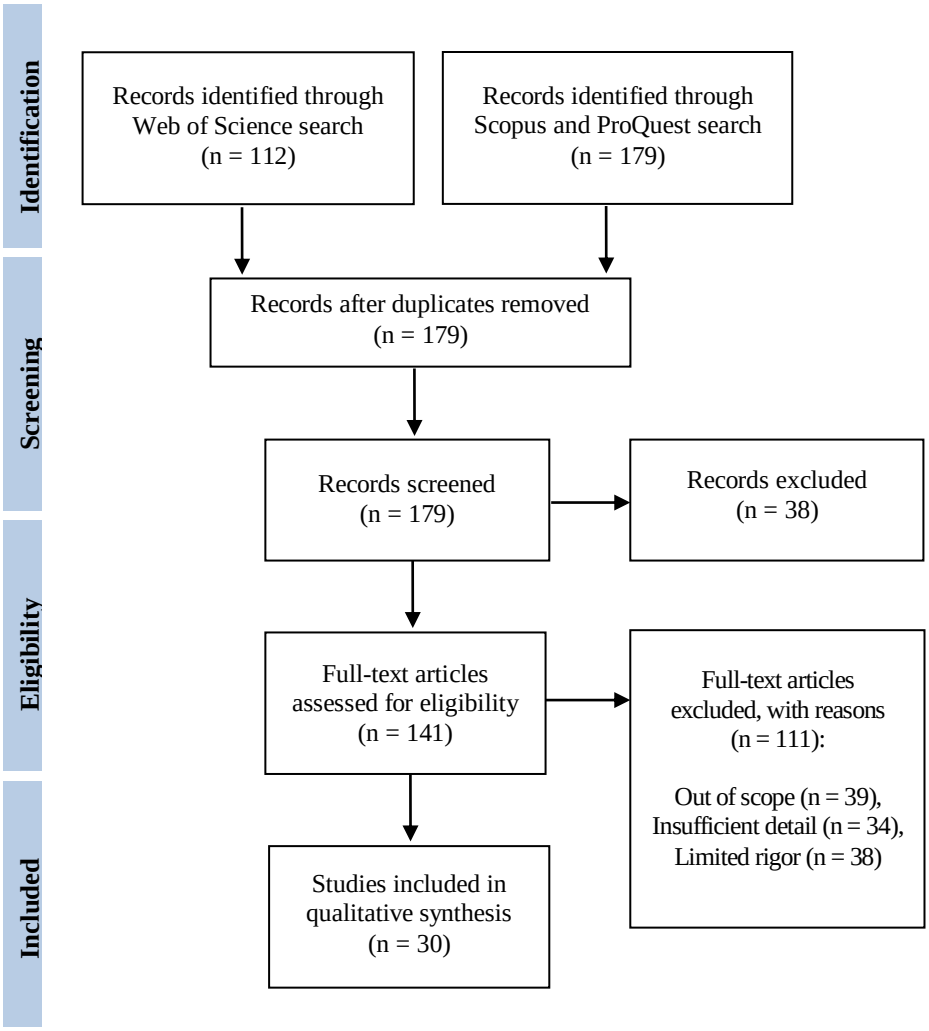

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

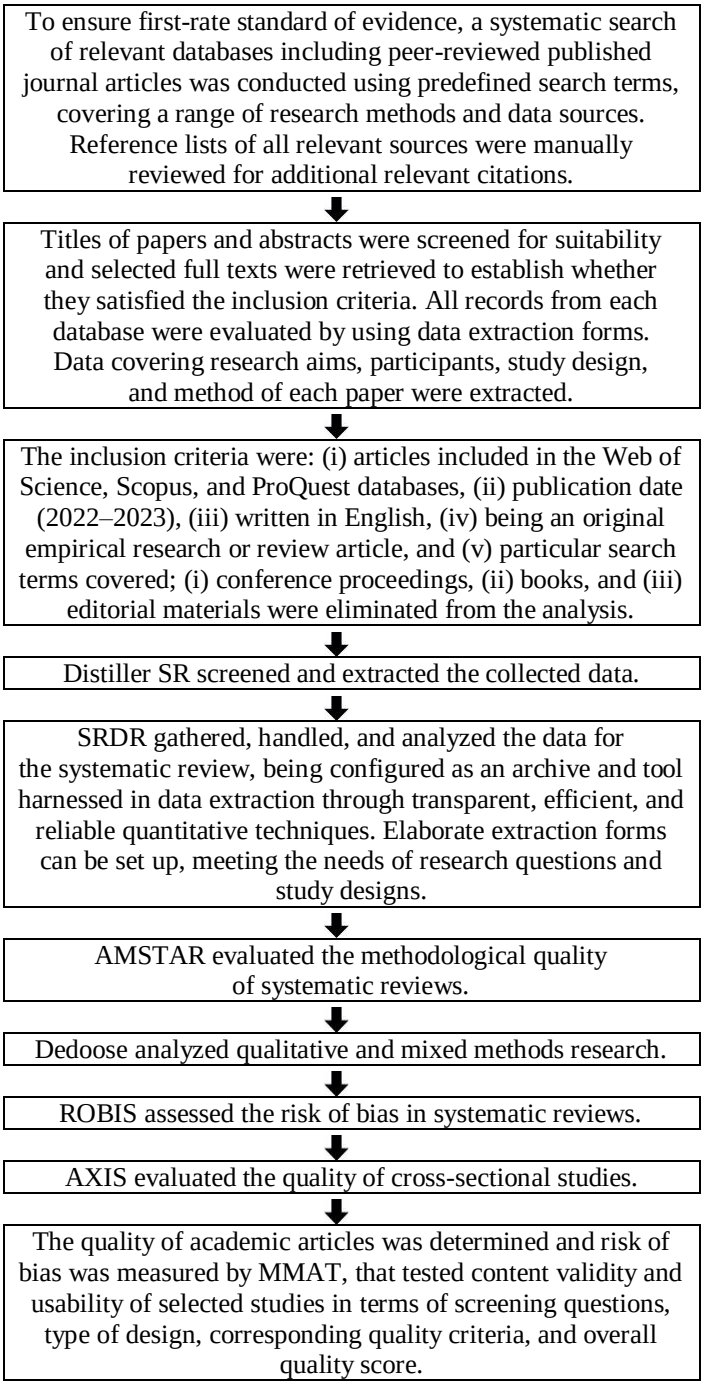

Figure 6 Screening and quality assessment tools

4. Virtual Modeling and Geospatial Mapping Technologies, Multi-Sensor Fusion and Explainable Artificial Intelligence-based Decision Support Systems, and Objection Recognition and Sensor Path Planning Algorithms in the Decentralized and Interconnected Metaverse

Automated perception and geospatial big data visualization systems, behavioral predictive and sentiment analytics, and ontology-based semantic and eye-tracking technologies (Grupac and Lăzăroiu, 2022; He et al., 2023; Zhao et al., 2022) configure the decentralized and interconnected metaverse. Internet of Things-based sensing and human digital twin systems, big geospatial data and real-time predictive analytics, and virtual modeling and geospatial mapping technologies shape photorealistic synthetic environments.

Synthetic digitally-mediated environments (Duncan, 2022; Golf-Papez et al., 2022; Kovacova et al., 2022a; Popp and Cuțitoi, 2022) develop on virtual reality-based and Internet of Things sensor data analytics, digital twin modeling tools, and multi-sensor fusion and explainable artificial intelligence-based decision support systems. Synthetic biometric data, human digital twin and haptic object recognition systems, and real-time 3D rendering and visual immersion technologies enable the virtual economy of the metaverse.

Immersive virtual experiences can be achieved through objection recognition and sensor path planning algorithms, intelligent sensing and deep learning-based generative networks, and neuromorphic image processing and motion capture systems (Geambazi et al., 2022; Kozinets, 2023; Lv et al., 2022; Venugopal et al., 2023) in extended reality environments. Sensorial and cognitive technologies, predictive modeling and virtual mapping algorithms, and photorealistic synthetic images and data optimize the virtual environment of the metaverse. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Automated perception and geospatial big data visualization systems, behavioral predictive and sentiment analytics, and ontology-based semantic and eye-tracking technologies configure the decentralized and interconnected metaverse.	Grupac and Lăzăroiu, 2022; He et al., 2023; Zhao et al., 2022
Synthetic digitally-mediated environments develop on virtual reality-based and Internet of Things sensor data analytics, digital twin modeling tools, and multi-sensor fusion and explainable artificial intelligence-based decision support systems.	Duncan, 2022; Golf-Papez et al., 2022; Kovacova et al., 2022b; Popp and Cuțitoi, 2022
Immersive virtual experiences can be achieved through objection recognition and sensor path planning algorithms, intelligent sensing and deep learning-based generative networks, and neuromorphic image processing and motion capture systems in extended reality environments.	Geambazi et al., 2022; Kozinets, 2023; Lv et al., 2022; Venugopal et al., 2023

5. Internet of Things-based Decision Support and Bio-inspired Artificial Vision Systems, Machine Perception and Affective Computing Technologies, and Spatial Data Visualization and Digital Twin Modeling Tools in Immersive Multisensory Virtual Spaces

3D immersive environments (Daneshfar and Jamshidi, 2023; Gordon, 2022; Kovacova et al., 2022b; Mourtzis et al., 2022) integrate user behavior data mining, performance capture and cognitive modeling technologies, and brain-inspired artificial intelligence and data stream clustering algorithms. Deep reinforcement learning and 3D modeling tools, voice recognition software, and cognitive artificial intelligence and spatial data mining algorithms articulate 3D immersive environments.

Immersive multisensory virtual spaces (Ahn et al., 2023; Hennig-Thurau et al., 2022; Ramadan, 2023) require machine perception and affective computing technologies, location intelligence data, and Internet of Things-based decision support and bio-inspired artificial vision systems. Mobile sensors and actuators, geospatial mapping and behavioral simulation tools, and affective modeling and sensor path planning algorithms further immersive decentralized 3D digital worlds.

Virtual reality-based immersive experiences can be attained by use of immersive geospatial data visualization and spatial computing technologies, 3D path planning and computer vision algorithms, and data modeling and geospatial intelligence tools (Bordegoni and Ferrise, 2023; McStay, 2023; Smart, 2022) in immersive multisensory virtual spaces. The virtual environment of the metaverse necessitates artificial intelligence-based image recognition and affective computing technologies, spatial data visualization and digital twin modeling tools, and wearable haptic garments. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

3D immersive environments integrate user behavior data mining, performance capture and cognitive modeling technologies, and brain-inspired artificial intelligence and data stream clustering algorithms.	Daneshfar and Jamshidi, 2023; Gordon, 2022; Kovacova et al., 2022c; Mourtzis et al., 2022
Immersive multisensory virtual spaces require machine perception and affective computing technologies, location intelligence data, and Internet of Things-based decision support and bio-inspired artificial vision systems.	Ahn et al., 2023; Hennig-Thurau et al., 2022; Ramadan, 2023
Virtual reality-based immersive experiences can be attained by use of immersive geospatial data visualization and spatial computing technologies, 3D path planning and computer vision algorithms, and data modeling and geospatial intelligence tools in immersive multisensory virtual spaces.	Bordegoni and Ferrise, 2023; McStay, 2023; Smart, 2022

6. Brain-inspired Artificial Intelligence and Machine Learning-based Navigation Algorithms, Operational Modeling and Digital Twin Simulation Tools, and Emotion Detection and Recognition Technologies in a Fully Connected Metaverse

Immersive and extended reality technologies, geospatial big data visualization and multimodal sensing systems, and spatio-temporal fusion and machine learning-based recognition algorithms (Kwok and Tang, 2023; Rydell, 2022; Zhang et al., 2023) are pivotal in decentralized 3D virtual spaces. Real-time predictive and mobile location analytics, brain-inspired artificial intelligence and machine learning-based navigation algorithms, and multi-sensor fusion and perception systems assist extended reality environments.

Immersive virtual experiences can be attained through monitoring and sensing technologies, human digital twin and bio-inspired artificial vision systems, and autonomous visual object detection and distributed intelligence tools (Oláh and Nica, 2022; Park and Kim, 2023; Zainab et al., 2022) in shared virtual environments. Photorealistic synthetic imagery, operational modeling and digital twin simulation tools, and visual immersion and remote sensing technologies are instrumental in real-time immersive 3D worlds.

Immersive metaverse experiences can be achieved by use of virtual machine interoperability, emotion detection and recognition technologies, and digital twin modeling and synthetic data tools (Carey, 2022; Queiroz et al., 2023; Zhu et al., 2023) in a fully connected metaverse. Interactional and contextual data, digital twin and tactile sensing technologies, and behavioral predictive and geospatial big data analytics configure the decentralized and interconnected metaverse. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive and extended reality technologies, geospatial big data visualization and multimodal sensing systems, and spatio-temporal fusion and machine learning-based recognition algorithms are pivotal in decentralized 3D virtual spaces.	Kwok and Tang, 2023; Rydell, 2022; Zhang et al., 2023
Immersive virtual experiences can be attained through monitoring and sensing technologies, human digital twin and bio-inspired artificial vision systems, and autonomous visual object detection and distributed intelligence tools in shared virtual environments.	Oláh and Nica, 2022; Park and Kim, 2023; Zainab et al., 2022
Immersive metaverse experiences can be achieved by use of virtual machine interoperability, emotion detection and recognition technologies, and digital twin modeling and synthetic data tools in a fully connected metaverse.	Carey, 2022; Queiroz et al., 2023; Zhu et al., 2023

7. Discussion

I integrate my systematic review throughout research indicating how mobile sensors and actuators, geospatial mapping and behavioral simulation tools, and affective modeling and sensor path planning algorithms further immersive decentralized 3D digital worlds. My research complements recent analyses clarifying how real-time predictive and mobile location analytics, brain-inspired artificial intelligence and machine learning-based navigation algorithms, and multi-sensor fusion and perception systems assist extended reality environments. I elucidate, by cumulative evidence, previous research demonstrating how the virtual environment of the metaverse necessitate artificial intelligence-based image recognition and affective computing technologies, spatial data visualization and digital twin modeling tools, and wearable haptic garments.

8. Synopsis of the Main Research Outcomes

Sensorial and cognitive technologies, predictive modeling and virtual mapping algorithms, and photorealistic synthetic images and data optimize the virtual environment of the metaverse. Synthetic biometric data, human digital twin and haptic object recognition systems, and real-time 3D rendering and visual immersion technologies enable the virtual economy of the metaverse. Internet of Things-based sensing and human digital twin systems, big geospatial data and real-time predictive analytics, and virtual modeling and geospatial mapping technologies shape photorealistic synthetic environments.

9. Conclusions

Relevant research has investigated whether photorealistic synthetic imagery, operational modeling and digital twin simulation tools, and visual immersion and remote sensing technologies are instrumental in real-time immersive 3D worlds. This systematic literature review presents the published peer-reviewed sources covering how Interactional and contextual data, digital twin and tactile sensing technologies, and behavioral predictive and geospatial big data analytics configure the decentralized and interconnected metaverse. The research outcomes drawn from the above analyses indicate that deep reinforcement learning and 3D modeling tools, voice recognition software, and cognitive artificial intelligence and spatial data mining algorithms articulate 3D immersive environments.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant

sources on brain-inspired artificial intelligence and machine learning-based navigation algorithms, spatial data visualization and digital twin modeling tools, and emotion detection and recognition technologies in the decentralized and interconnected metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of machine perception and affective computing technologies, location intelligence data, and Internet of Things-based decision support and bio-inspired artificial vision systems.

Subsequent analyses should develop on automated perception and geospatial big data visualization systems, behavioral predictive and sentiment analytics, and ontology-based semantic and eye-tracking technologies. Future research should thus investigate user behavior data mining, performance capture and cognitive modeling technologies, and brain-inspired artificial intelligence and data stream clustering algorithms. Attention should be directed to immersive geospatial data visualization and spatial computing technologies, 3D path planning and computer vision algorithms, and data modeling and geospatial intelligence tools.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

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The author confirms being the sole contributor of this work and approved it for publication. The author takes full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
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Metaverse Decentralized Governance and Networked Immersive Virtual Reality Systems, Machine Learning-based Image Recognition and Predictive Modeling Tools, and Cognitive Automation and Multisensor Fusion Technologies in Digital Hyper-Realistic Worlds

Diana Atkinson*

ABSTRACT. Based on an in-depth survey of the literature, the purpose of the paper is to explore wearable augmented and virtual reality devices, behavior pattern clustering, and metaverse economic and multimodal sensing systems. In this research, previous findings were cumulated showing that intelligent data processing and artificial intelligence-powered prediction tools, picture-making neural networks, and image detection and deep learning-based predictive algorithms configure decentralized 3D digital worlds. Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "digital hyper-realistic worlds" + "metaverse decentralized governance and networked immersive virtual reality systems," "machine learning-based image recognition and predictive modeling tools," and "cognitive automation and multisensor fusion technologies." As research published in 2022 and 2023 was inspected, only 176 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, I selected 31 mainly empirical sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR.

Keywords: metaverse decentralized governance; networked immersive virtual reality systems; machine learning; image recognition; predictive modeling tools; cognitive automation; multisensor fusion technologies; digital hyper-realistic worlds

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1. Introduction

3D virtual immersive environments necessitate artificial vision and cognitive computing systems, immersive geospatial data visualization and digital contact tracing technologies, and real-time event analytics. The purpose of my systematic review is to examine the recently published literature on digital hyper-realistic worlds and integrate the insights it configures on metaverse decentralized governance and networked immersive virtual reality systems, machine learning-based image recognition and predictive modeling tools, and cognitive automation and multisensor fusion technologies. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that virtual personas and identities, augmented reality and spatial computing technologies, and predictive maintenance and data-driven artificial intelligence algorithms (Nagy and Lăzăroiu, 2022; Valaskova et al., 2022; Vătămănescu et al., 2020) are pivotal in immersive interconnected virtual worlds. The actuality and novelty of this study are articulated by addressing wearable augmented and virtual reality devices, behavior pattern clustering, and metaverse economic and multimodal sensing systems (Lăzăroiu and Rogalska, 2023; Nagy et al., 2023; Vinerean et al., 2022), that is an emerging topic involving much interest. My research problem is whether intelligent data processing and artificial intelligence-powered prediction tools, picture-making neural networks, and image detection and deep learning-based predictive algorithms (Andronie et al., 2021a; Nica et al., 2023; Novak et al., 2022) configure decentralized 3D digital worlds.

In this review, prior findings have been cumulated indicating that wearable haptic augmented reality and immersive visualization systems, dynamic anthropometric data, and spatio-temporal fusion and computer vision algorithms (Andronie et al., 2021b; Dabija et al., 2018; Peters et al., 2023) enable interconnected digital spaces. The identified gaps advance photorealistic synthetic images and data, metaverse decentralized governance and networked immersive virtual reality systems (Andronie et al., 2023; Lewkowich, 2022; Nica et al., 2023), and holographic telepresence and sentiment recognition technologies. My main objective is to indicate that 3D virtual avatars, interactional and contextual data, and auditory and visual immersion systems (Nica, 2018; Popescu and Ciurlău, 2019; Vătămănescu et al., 2022) optimize intelligent simulation environments and interactive digital worlds.

2. Theoretical Overview of the Main Concepts

The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), machine learning-based image recognition and predictive modeling tools, wearable haptic augmented reality and immersive

visualization systems, and cognitive automation and multisensor fusion technologies in blockchain-empowered metaverse (section 4), image recognition and edge computing technologies, virtual navigation and artificial intelligence-powered prediction tools, and photorealistic synthetic images and data in the metaverse interactive environment (section 5), metaverse decentralized governance and networked immersive virtual reality systems, intelligent data processing and artificial intelligence-powered prediction tools, and semantic communication and geospatial mapping technologies in digital hyper-realistic worlds (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "digital hyper-realistic worlds" + "metaverse decentralized governance and networked immersive virtual reality systems," "machine learning-based image recognition and predictive modeling tools," and "cognitive automation and multisensor fusion technologies." As research published in 2022 and 2023 was inspected, only 176 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, I selected 31 mainly empirical sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
digital hyper-realistic worlds + metaverse decentralized governance and networked immersive virtual reality systems	61	11
digital hyper-realistic worlds + machine learning-based image recognition and predictive modeling tools	59	10
digital hyper-realistic worlds + cognitive automation and multisensor fusion technologies	56	10
Type of paper		
Original research	142	20
Review	23	11
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

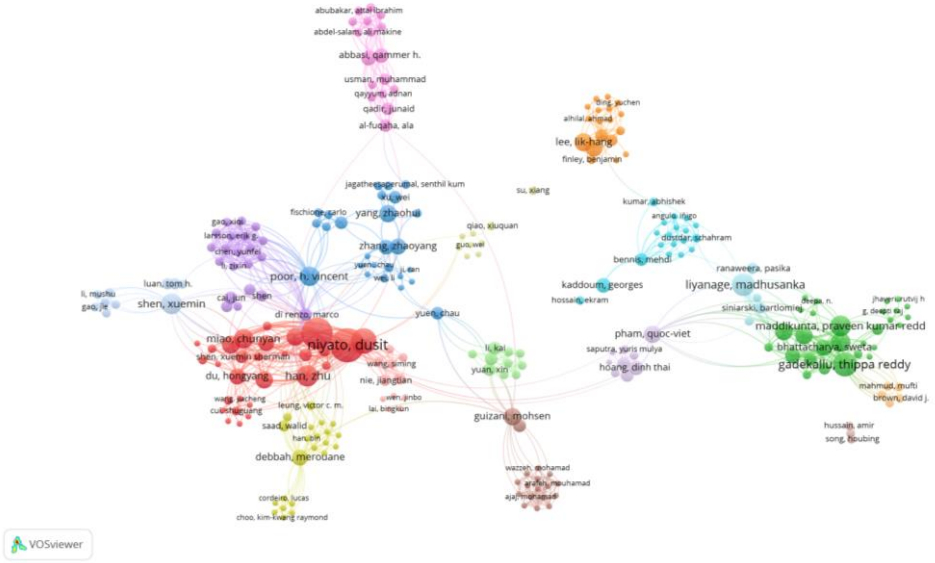

Figure 1 Co-authorship

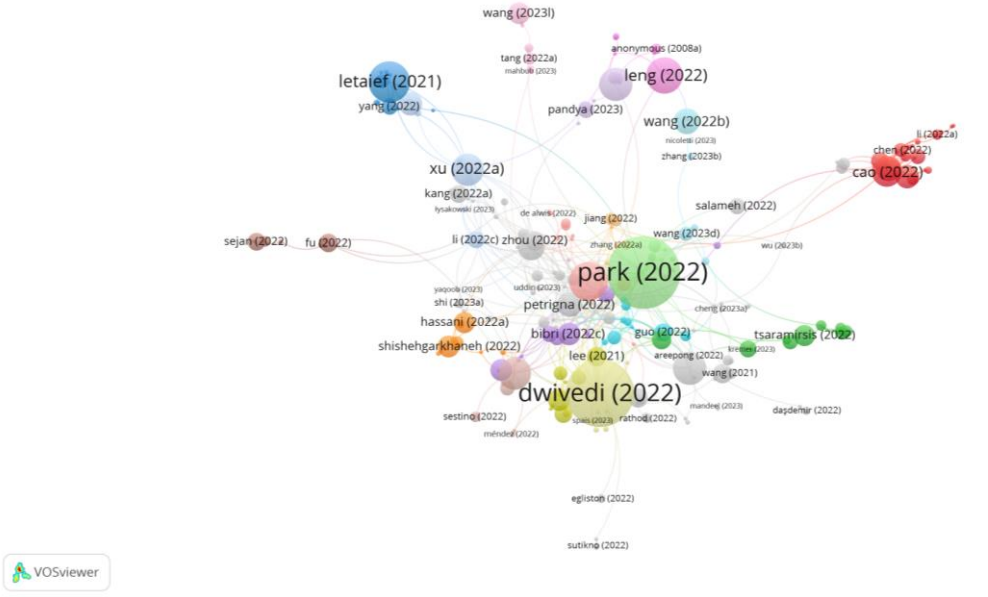

Figure 2 Citation

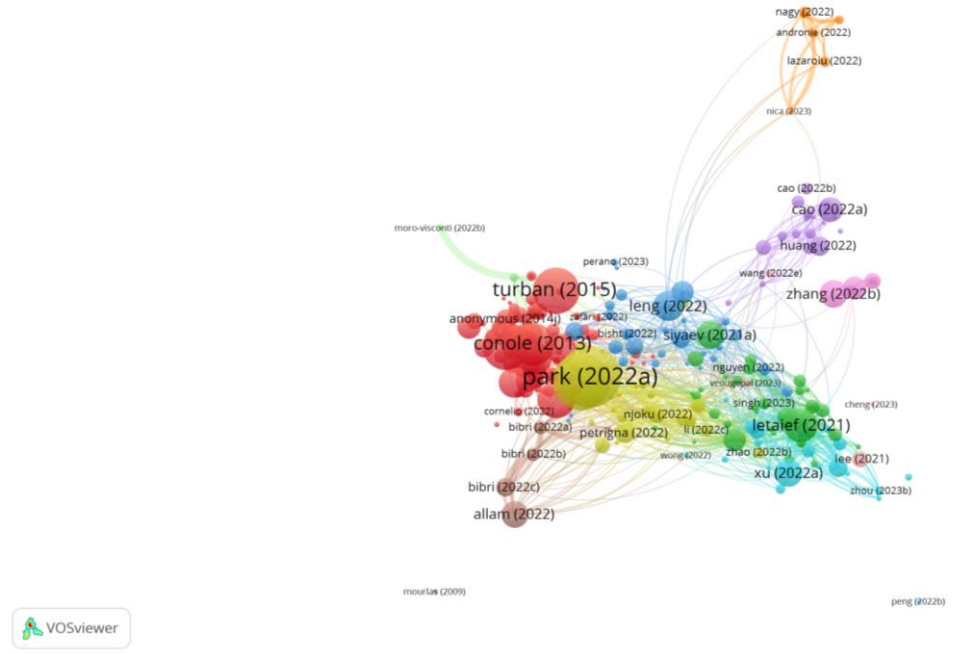

Figure 3 Bibliographic coupling

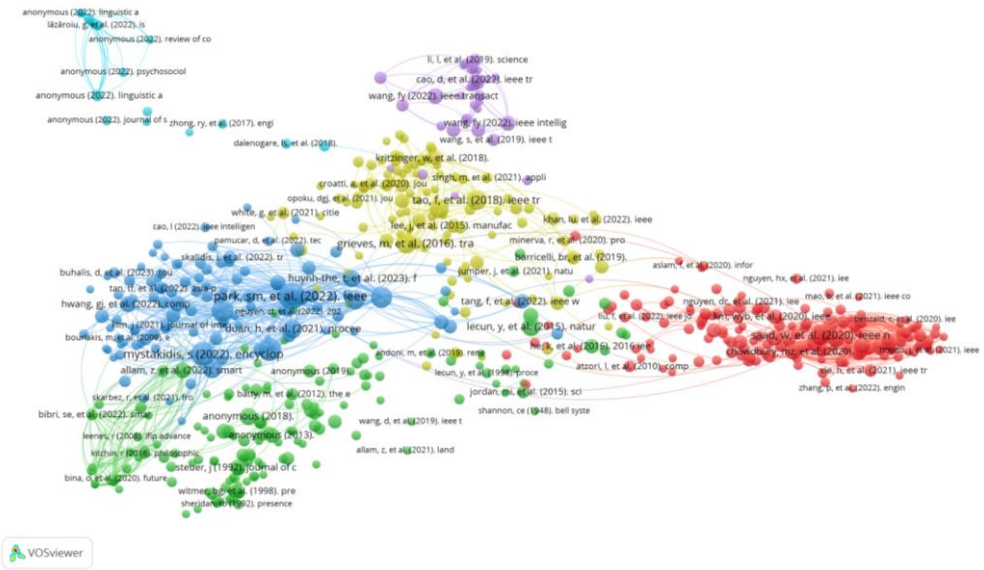

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Digital twin simulation and big data processing tools, visual cognitive and deep learning algorithms, and mobile geofencing and edge computing technologies optimize realistic virtual simulation environments.	Hancock, 2022; Perkins, 2022a; Tang et al., 2023; Watson, 2022
Immersive virtual environments and Internet of Things sensing infrastructures develop on behavior pattern clustering, dynamic routing and motion capture technologies, and big data management and machine learning-based image recognition tools.	Cheng et al., 2022; Majerová and Pera, 2022; Zhang et al., 2023
Immersive virtual reality experiences can be achieved by use of deep learning-based digital image generators, cognitive and behavioral algorithms, and spatial computing and remote sensing technologies in blockchain-empowered metaverse.	Dincelli and Yayla, 2022; Morley, 2022; Zhou et al., 2023
Blockchain-enabled economic and visual sensor systems, geospatial mapping and 4D body scanning technologies, and predictive modeling and machine vision algorithms articulate across the metaverse economy.	Dawson, 2022; Huynh-The et al., 2023a; Lv et al., 2022; Xu et al., 2023
Ambient sound recognition software, virtual navigation and artificial intelligence-powered prediction tools, and data analytics and geospatial mapping technologies further the metaverse interactive environment.	Huynh-The et al., 2023b; Meng et al., 2023; Wang et al., 2022
Immersive virtual experiences can be attained by use of blockchain token-based digital assets, photorealistic synthetic images and data, and intelligent data processing and visual perception tools in the digital asset-based virtual economy.	Ding et al., 2022; Perkins, 2022b; Shi et al., 2023; Zyda, 2022
Photorealistic synthetic images and data, metaverse decentralized governance and networked immersive virtual reality systems, and holographic telepresence and sentiment recognition technologies are instrumental in ambient intelligence environments.	Chen, 2022; Hamilton, 2022; Li et al., 2023; Zabel et al., 2023)
Immersive 3D and augmented reality experiences can be attained through spatial computing devices, distributed decision and control algorithms, and operational modeling and natural language processing tools in entertaining metaverse events.	Du et al., 2023; Faraboschi et al., 2022; Zhang et al., 2022a
Wearable augmented and virtual reality devices, behavior pattern clustering, and metaverse economic and multimodal sensing systems articulate immersive 3D virtual environments.	Panagiotakopoulos et al., 2022; Zhang et al., 2022b; Zvarikova et al., 2022

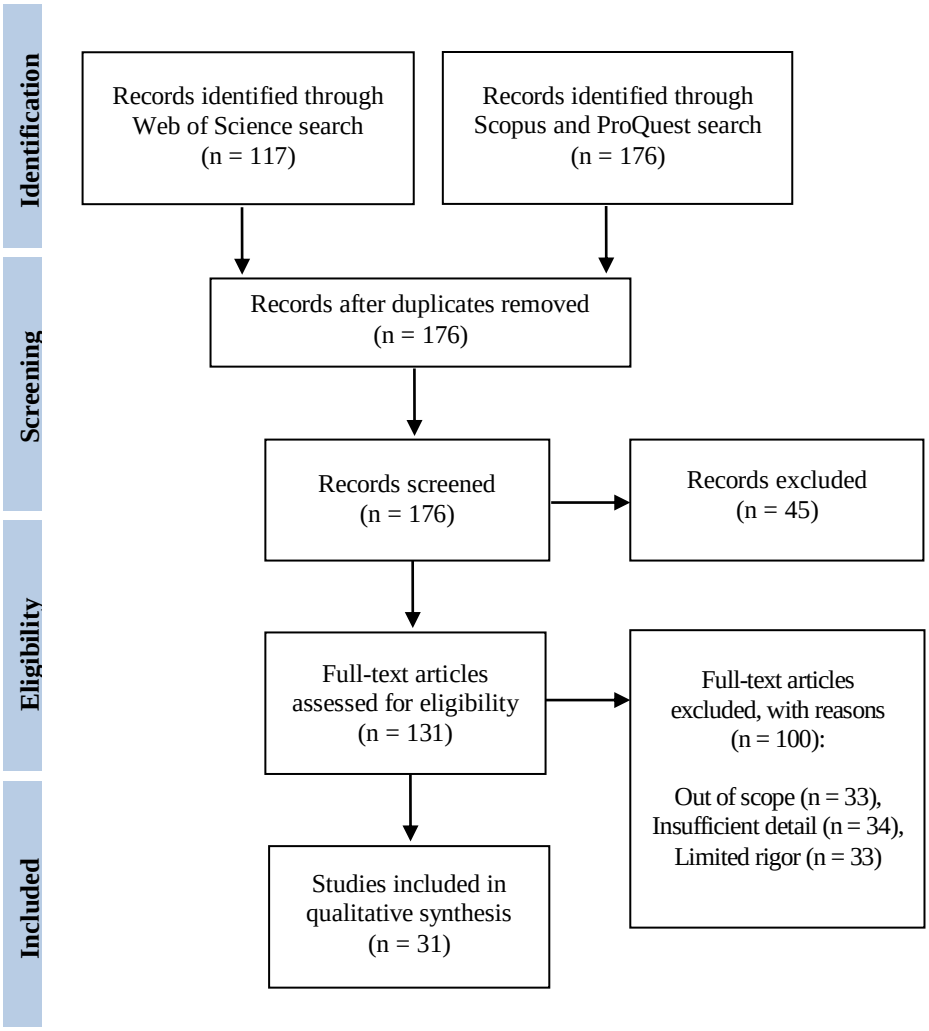

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

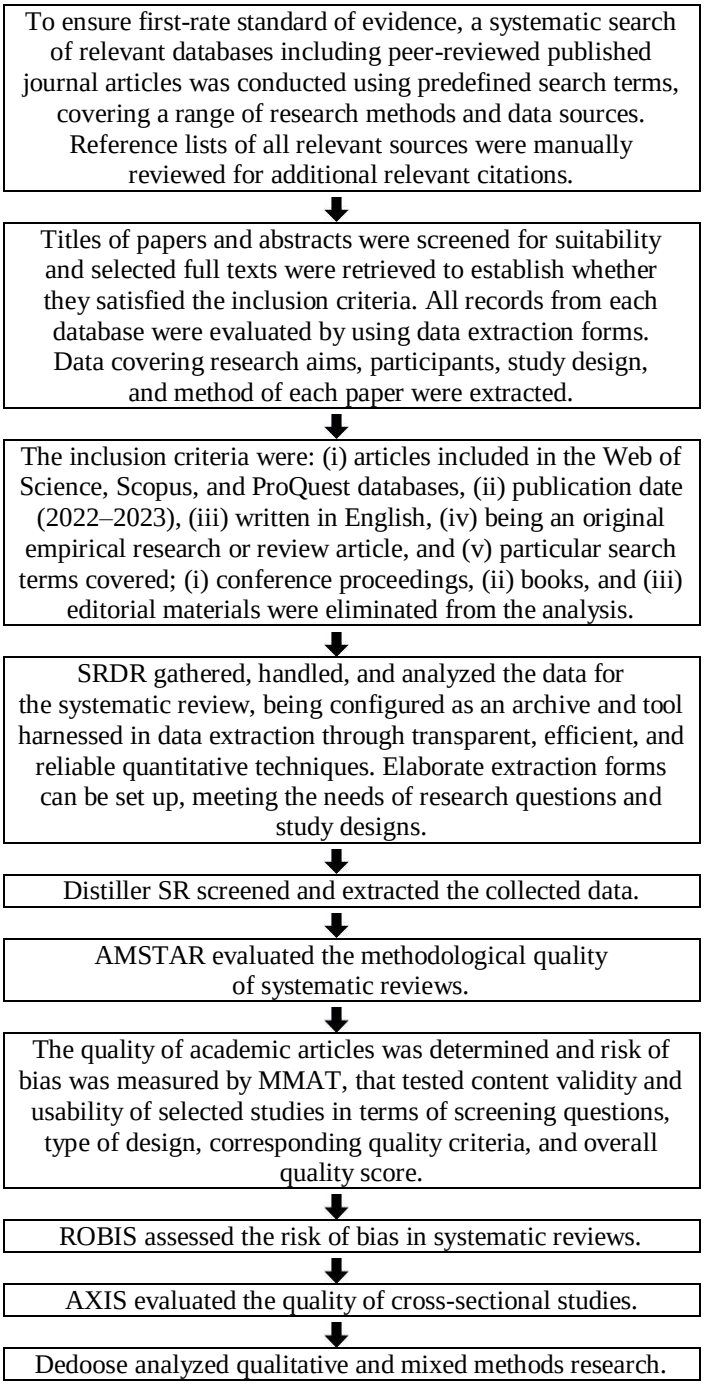

Figure 6 Screening and quality assessment tools

4. Machine Learning-based Image Recognition and Predictive Modeling Tools, Wearable Haptic Augmented Reality and Immersive Visualization Systems, and Cognitive Automation and Multisensor Fusion Technologies in Blockchain-empowered Metaverse

Digital twin simulation and big data processing tools, visual cognitive and deep learning algorithms, and mobile geofencing and edge computing technologies (Hancock, 2022; Perkins, 2022a; Tang et al., 2023; Watson, 2022) optimize realistic virtual simulation environments. Cloud and edge computing technologies, machine learning-based image recognition and predictive modeling tools, and sensory data mining techniques configure extended reality environments.

Immersive virtual environments and Internet of Things sensing infrastructures (Cheng et al., 2022; Majerová and Pera, 2022; Zhang et al., 2023) develop on behavior pattern clustering, dynamic routing and motion capture technologies, and big data management and machine learning-based image recognition tools. Wearable haptic augmented reality and immersive visualization systems, dynamic anthropometric data, and spatio-temporal fusion and computer vision algorithms enable interconnected digital spaces.

Immersive virtual reality experiences can be achieved by use of deep learning-based digital image generators, cognitive and behavioral algorithms, and spatial computing and remote sensing technologies (Dincelli and Yayla, 2022; Morley, 2022; Zhou et al., 2023) in blockchain-empowered metaverse. Synthetic reality spaces and immersive virtual worlds integrate multi-machine cooperation and geospatial analytics tools, captured image data, and cognitive automation and multisensor fusion technologies. 3D virtual avatars, interactional and contextual data, and auditory and visual immersion systems optimize intelligent simulation environments and interactive digital worlds. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Digital twin simulation and big data processing tools, visual cognitive and deep learning algorithms, and mobile geofencing and edge computing technologies optimize realistic virtual simulation environments.	Hancock, 2022; Perkins, 2022a; Tang et al., 2023; Watson, 2022
Immersive virtual environments and Internet of Things sensing infrastructures develop on behavior pattern clustering, dynamic routing and motion capture technologies, and big data management and machine learning-based image recognition tools.	Cheng et al., 2022; Majerová and Pera, 2022; Zhang et al., 2023
Immersive virtual reality experiences can be achieved by use of deep learning-based digital image generators, cognitive and behavioral algorithms, and spatial computing and remote sensing technologies in blockchain-empowered metaverse.	Dincelli and Yayla, 2022; Morley, 2022; Zhou et al., 2023

5. Image Recognition and Edge Computing Technologies, Virtual Navigation and Artificial Intelligence-powered Prediction Tools, and Photorealistic Synthetic Images and Data in the Metaverse Interactive Environment

Blockchain-enabled economic and visual sensor systems, geospatial mapping and 4D body scanning technologies, and predictive modeling and machine vision algorithms (Dawson, 2022; Huynh-The et al., 2023a; Lv et al., 2022; Xu et al., 2023) articulate across the metaverse economy. The blockchain-based virtual economy require auditory and visual immersion systems, image recognition and edge computing technologies, and metaverse digital asset management.

Ambient sound recognition software, virtual navigation and artificial intelligence-powered prediction tools, and data analytics and geospatial mapping technologies (Huynh-The et al., 2023b; Meng et al., 2023; Wang et al., 2022) further the metaverse interactive environment. 3D virtual immersive environments necessitate artificial vision and cognitive computing systems, immersive geospatial data visualization and digital contact tracing technologies, and real-time event analytics.

Immersive virtual experiences can be attained by use of blockchain token-based digital assets, photorealistic synthetic images and data, and intelligent data processing and visual perception tools (Ding et al., 2022; Perkins, 2022b; Shi et al., 2023; Zyda, 2022) in the digital asset-based virtual economy. Virtual personas and identities, augmented reality and spatial computing technologies, and predictive maintenance and data-driven artificial intelligence algorithms are pivotal in immersive interconnected virtual worlds. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Blockchain-enabled economic and visual sensor systems, geospatial mapping and 4D body scanning technologies, and predictive modeling and machine vision algorithms articulate across the metaverse economy.	Dawson, 2022; Huynh-The et al., 2023a; Lv et al., 2022; Xu et al., 2023
Ambient sound recognition software, virtual navigation and artificial intelligence-powered prediction tools, and data analytics and geospatial mapping technologies further the metaverse interactive environment.	Huynh-The et al., 2023b; Meng et al., 2023; Wang et al., 2022
Immersive virtual experiences can be attained by use of blockchain token-based digital assets, photorealistic synthetic images and data, and intelligent data processing and visual perception tools in the digital asset-based virtual economy.	Ding et al., 2022; Perkins, 2022b; Shi et al., 2023; Zyda, 2022

6. Metaverse Decentralized Governance and Networked Immersive Virtual Reality Systems, Intelligent Data Processing and Artificial Intelligence-powered Prediction Tools, and Semantic Communication and Geospatial Mapping Technologies in Digital Hyper-Realistic Worlds

Photorealistic synthetic images and data, metaverse decentralized governance and networked immersive virtual reality systems, and holographic telepresence and sentiment recognition technologies (Chen, 2022; Hamilton, 2022; Li et al., 2023; Zabel et al., 2023) are instrumental in ambient intelligence environments. Internet of Things-connected machines, virtual immersive and spatial computing technologies, and smart environment modeling and image recognition tools assist the blockchain-based virtual economy.

Immersive 3D and augmented reality experiences can be attained through spatial computing devices, distributed decision and control algorithms, and operational modeling and natural language processing tools (Du et al., 2023; Faraboschi et al., 2022; Zhang et al., 2022a) in entertaining metaverse events. Intelligent data processing and artificial intelligence-powered prediction tools, picture-making neural networks, and image detection and deep learning-based predictive algorithms configure decentralized 3D digital worlds.

Wearable augmented and virtual reality devices, behavior pattern clustering, and metaverse economic and multimodal sensing systems (Panagiotakopoulos et al., 2022; Zhang et al., 2022b; Zvarikova et al., 2022) articulate immersive 3D virtual environments. 3D modeling and data mining tools, semantic communication and geospatial mapping technologies, and text mining and analytics shape digital hyper-realistic worlds and blockchain-based metaverse platforms. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Photorealistic synthetic images and data, metaverse decentralized governance and networked immersive virtual reality systems, and holographic telepresence and sentiment recognition technologies are instrumental in ambient intelligence environments.	Chen, 2022; Hamilton, 2022; Li et al., 2023; Zabel et al., 2023)
Immersive 3D and augmented reality experiences can be attained through spatial computing devices, distributed decision and control algorithms, and operational modeling and natural language processing tools in entertaining metaverse events.	Du et al., 2023; Faraboschi et al., 2022; Zhang et al., 2022a
Wearable augmented and virtual reality devices, behavior pattern clustering, and metaverse economic and multimodal sensing systems articulate immersive 3D virtual environments.	Panagiotakopoulos et al., 2022; Zhang et al., 2022b; Zvarikova et al., 2022

7. Discussion

I integrate my systematic review throughout research indicating how synthetic reality spaces and immersive virtual worlds integrate multi-machine cooperation and geospatial analytics tools, captured image data, and cognitive automation and multisensor fusion technologies. My research complements recent analyses clarifying how intelligent data processing and artificial intelligence-powered prediction tools, picture-making neural networks, and image detection and deep learning-based predictive algorithms configure decentralized 3D digital worlds. I elucidate, by cumulative evidence, previous research demonstrating how 3D modeling and data mining tools, semantic communication and geospatial mapping technologies, and text mining and analytics shape digital hyper-realistic worlds and blockchain-based metaverse platforms.

8. Synopsis of the Main Research Outcomes

Cloud and edge computing technologies, machine learning-based image recognition and predictive modeling tools, and sensory data mining techniques configure extended reality environments. The blockchain-based virtual economy require auditory and visual immersion systems, image recognition and edge computing technologies, and metaverse digital asset management. 3D virtual avatars, interactional and contextual data, and auditory and visual immersion systems optimize intelligent simulation environments and interactive digital worlds.

9. Conclusions

Relevant research has investigated whether Internet of Things-connected machines, virtual immersive and spatial computing technologies, and smart environment modeling and image recognition tools assist the blockchain-based virtual economy. This systematic literature review presents the published peer-reviewed sources covering how virtual personas and identities, augmented reality and spatial computing technologies, and predictive maintenance and data-driven artificial intelligence algorithms are pivotal in immersive interconnected virtual worlds. The research outcomes drawn from the above analyses indicate that wearable haptic augmented reality and immersive visualization systems, dynamic anthropometric data, and spatio-temporal fusion and computer vision algorithms enable interconnected digital spaces.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant

sources on metaverse decentralized governance and networked immersive virtual reality systems, machine learning-based image recognition and predictive modeling tools, and cognitive automation and multisensor fusion technologies in digital hyper-realistic worlds may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of digital twin simulation and big data processing tools, visual cognitive and deep learning algorithms, and mobile geofencing and edge computing technologies.

Subsequent analyses should develop on ambient sound recognition software, virtual navigation and artificial intelligence-powered prediction tools, and data analytics and geospatial mapping technologies. Future research should thus investigate blockchain-enabled economic and visual sensor systems, geospatial mapping and 4D body scanning technologies, and predictive modeling and machine vision algorithms. Attention should be directed to immersive 3D and augmented reality experiences can be attained through spatial computing devices, distributed decision and control algorithms, and operational modeling and natural language processing tools.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
The author confirms being the sole contributor of this work and approved it for publication. The author takes full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
The editors declare no conflict of interest in the review and publication decision regarding this article.

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Synthetic Data and Image Processing Tools, Immersive 3D and Digital Contact Tracing Technologies, and Cognitive Artificial Intelligence and Spatial Computing Algorithms in the Metaverse Interactive Environment

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ABSTRACT. The aim of this systematic review is to synthesize and analyze virtual modeling and simulation tools, computer vision and data fusion algorithms, and metaverse assets and services. In this research, prior findings were cumulated indicating that spatial computing and immersive 3D technologies, big geospatial data analytics, and virtual navigation and data acquisition tools optimize interactive virtual environments. We carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout May 2023, with search terms including "the metaverse interactive environment" + "synthetic data and image processing tools," "immersive 3D and digital contact tracing technologies," and "cognitive artificial intelligence and spatial computing algorithms." As we analyzed research published in 2022 and 2023, only 177 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, we decided on 30, chiefly empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Distiller SR, ROBIS, and SRDR.

Keywords: synthetic data; image processing tools; immersive 3D; digital contact tracing technologies; cognitive artificial intelligence; spatial computing algorithms; metaverse interactive environment

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1. Introduction

Immersive digital worlds necessitate spatio-temporal fusion and machine learning algorithms, smart sensor devices, and synthetic data generation and collaborative localization techniques. The purpose of our systematic review is to examine the recently published literature on the metaverse interactive environment and integrate the insights it configures on synthetic data and image processing tools, immersive 3D and digital contact tracing technologies, and cognitive artificial intelligence and spatial computing algorithms. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that 3D immersive content, ambient intelligence and deep reinforcement learning tools, and virtual environmental and location sensors (Andronie et al., 2021; Fernando and Lăzăroiu, 2023; Lewkowich, 2022) are instrumental in extended reality environments. The actuality and novelty of this study are articulated by addressing virtual modeling and simulation tools, computer vision and data fusion algorithms, and metaverse assets and services (Balcerzak et al., 2022; Lăzăroiu and Rogalska, 2023; Snake-Beings et al., 2023), that is an emerging topic involving much interest. Our research problem is whether spatial computing and immersive 3D technologies, big geospatial data analytics, and virtual navigation and data acquisition tools (Andronie et al., 2023a; Lăzăroiu et al., 2022a; Nica et al., 2019) optimize interactive virtual environments.

In this review, prior findings have been cumulated indicating that extended reality environments require cognitive artificial intelligence and eye-tracking technologies (Andronie et al., 2023b; Krizanova et al., 2019; Lăzăroiu et al., 2022b), metaverse assets and services, and simulation modeling and image processing tools. The identified gaps advance digital twin data modeling and visualization (Barbu et al., 2021; Lăzăroiu, 2018; Milward et al., 2019; Popescu et al., 2020), synthetic data and image processing tools, and convolutional neural and interoperable virtual networks. Our main objective is to indicate that modal synthetic data fusion, immersive 3D and digital contact tracing technologies, and Internet of digital twins (Novak et al., 2022; Pelau et al., 2021; Popescu and Ciurlău, 2019; Trettin et al., 2019) are pivotal in blockchain-based virtual worlds.

2. Theoretical Overview of the Main Concepts

Automated speech recognition and virtual navigation tools, metaverse engagement metrics, and environment mapping and spatio-temporal fusion algorithms articulate 3D digital environments. The metaverse interactive environment integrates event modeling and forecasting tools, cognitive artificial intelligence and eye-tracking technologies, and sensor data fusion.

The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), cognitive artificial intelligence and spatial computing algorithms, synthetic data and image processing tools, and immersive 3D and digital contact tracing technologies in the metaverse interactive environment (section 4), spatial computing and simulation modeling algorithms, movement and behavior tracking tools, and convolutional neural and interconnected sensor networks in the virtual economy of the metaverse (section 5), digital twin simulation and spatial data visualization tools, cloud-edge computing and autonomous cognitive systems, and deep learning and visual perception algorithms in extended reality environments (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

We carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout May 2023, with search terms including "the metaverse interactive environment" + "synthetic data and image processing tools," "immersive 3D and digital contact tracing technologies," and "cognitive artificial intelligence and spatial computing algorithms." As we analyzed research published in 2022 and 2023, only 177 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/ unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, we decided on 30, chiefly empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Distiller SR, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
the metaverse interactive environment + synthetic data and image processing tools	60	11
the metaverse interactive environment + immersive 3D and digital contact tracing technologies	59	10
the metaverse interactive environment + cognitive artificial intelligence and spatial computing algorithms	58	9
Type of paper		
Original research	149	22
Review	18	8
Conference proceedings	9	0
Book	0	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.

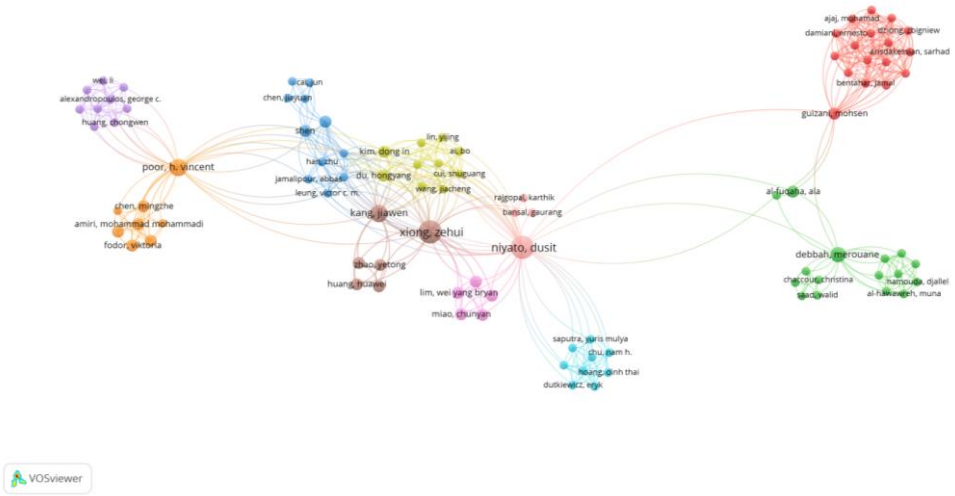

Figure 1 Co-authorship

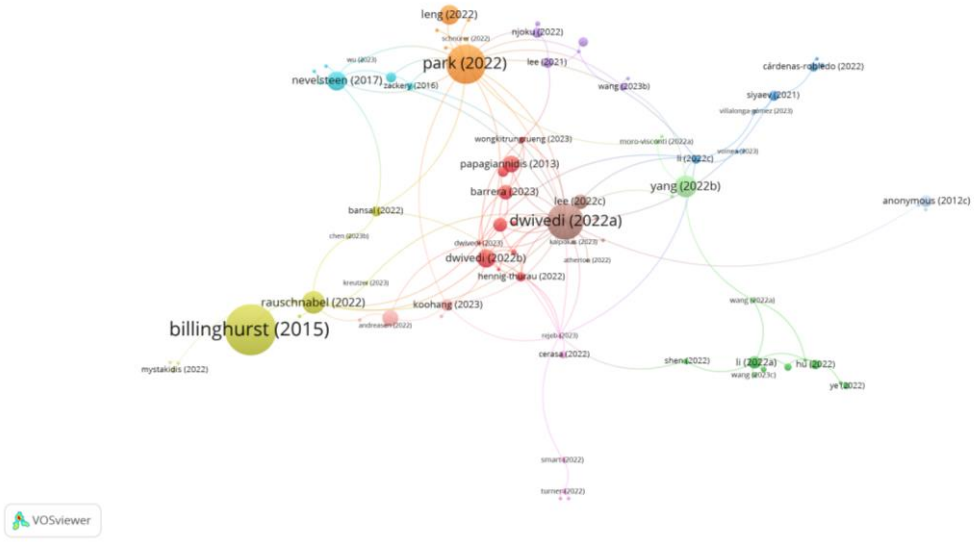

Figure 2 Citation

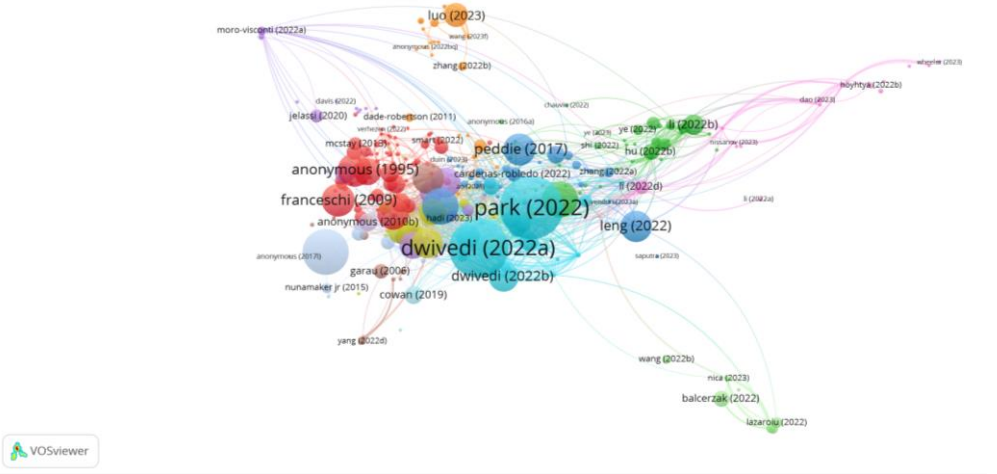

Figure 3 Bibliographic coupling

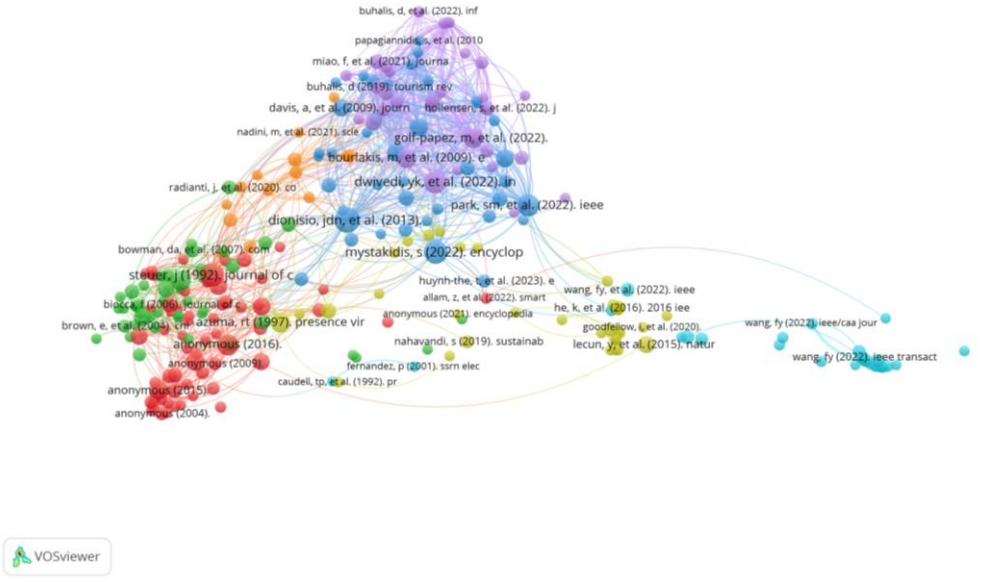

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Cognitive artificial intelligence and spatial computing algorithms, monitoring and sensing technologies, and digital twin modeling and deep reinforcement learning tools articulate the metaverse interactive environment.	Bojic, 2022; Ersoy and Gürfidan, 2023; Hamilton, 2022; Xu et al., 2023
Immersive decentralized 3D digital worlds require virtual twin modeling and geospatial mapping tools, 3D object detection and tracking algorithms, and edge computing and tactile sensing technologies.	Hollensen et al., 2023; McStay, 2022; Zauskova et al., 2022
Immersive metaverse experiences can be achieved by use of digital twin data modeling and visualization, synthetic data and image processing tools, and convolutional neural and interoperable virtual networks in real-time simulation environments.	Braud et al., 2022; Han et al., 2022; Shen, 2022
Blockchain-based metaverse platforms and virtual worlds develop on synthetic data interoperability, autonomous cognitive and location-aware networked systems, and spatial computing and simulation modeling algorithms.	Aloqaily et al., 2022; Han et al., 2023; Kovacova et al., 2022
Convolutional neural and interconnected sensor networks, image recognition and visual perception algorithms, and movement and behavior tracking tools further the virtual economy of the metaverse.	Hancock, 2022a; Newell, 2022; Oh et al., 2023; Van Huynh et al., 2022
Virtual modeling and simulation tools, computer vision and data fusion algorithms, and metaverse assets and services shape immersive digital worlds and shared virtual environments.	Egliston and Carter, 2022; Perkins, 2022; Rostami and Maier, 2022
Immersive 3D virtual environments necessitate collaborative data analysis and virtual navigation tools, deep learning-based ambient sound processing, and cloud-edge computing and autonomous cognitive systems.	Huang et al., 2023; Mourtzis et al., 2022; Vidal-Tomás, 2023
Immersive metaverse experiences can be attained through deep learning and visual perception algorithms, digital twin simulation and spatial data visualization tools, and edge intelligence and cognitive enhancement technologies in extended reality environments.	Cao, 2022; Hancock, 2022b; Ramadan, 2023; Wu et al., 2023
Cognitive enhancement and cloud computing technologies, digital twin-based virtual sensors, and physics-based modeling and simulation tools optimize immersive 3D worlds.	Du et al., 2023; Polas et al., 2022; Wongkitrungrueng and Suprawan, 2023

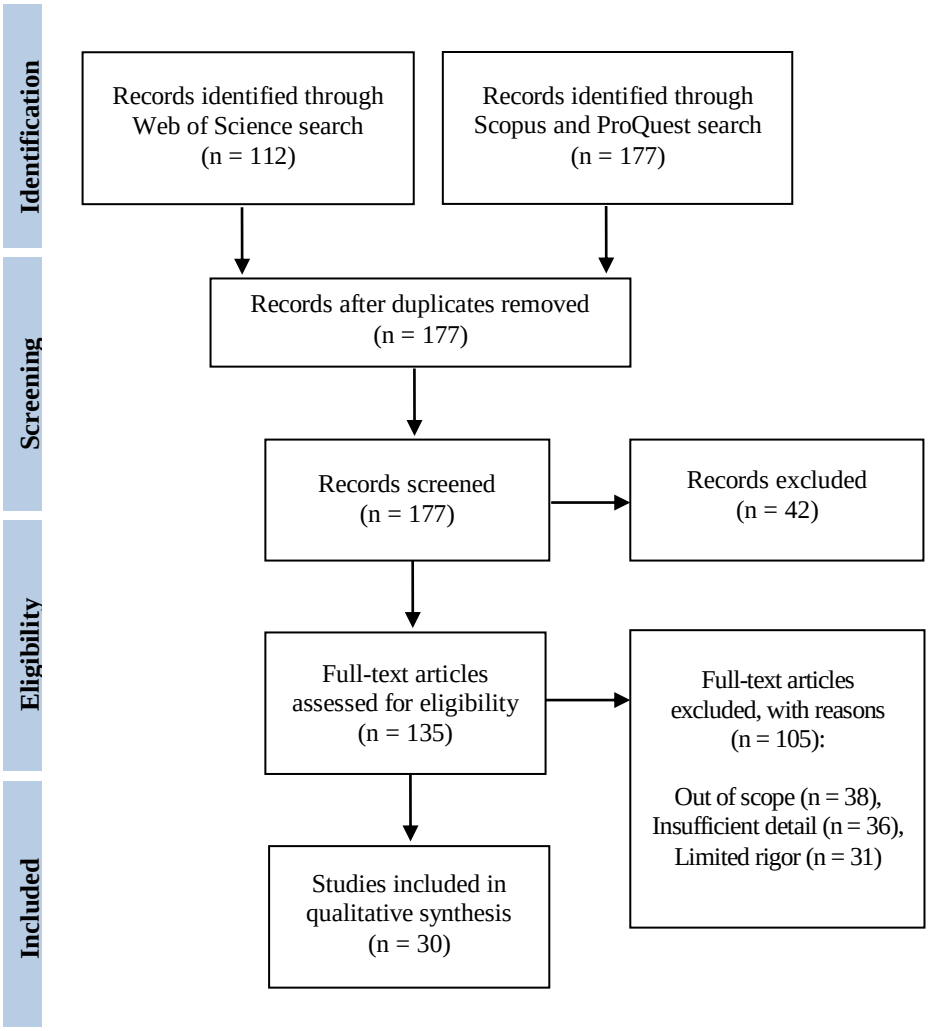

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

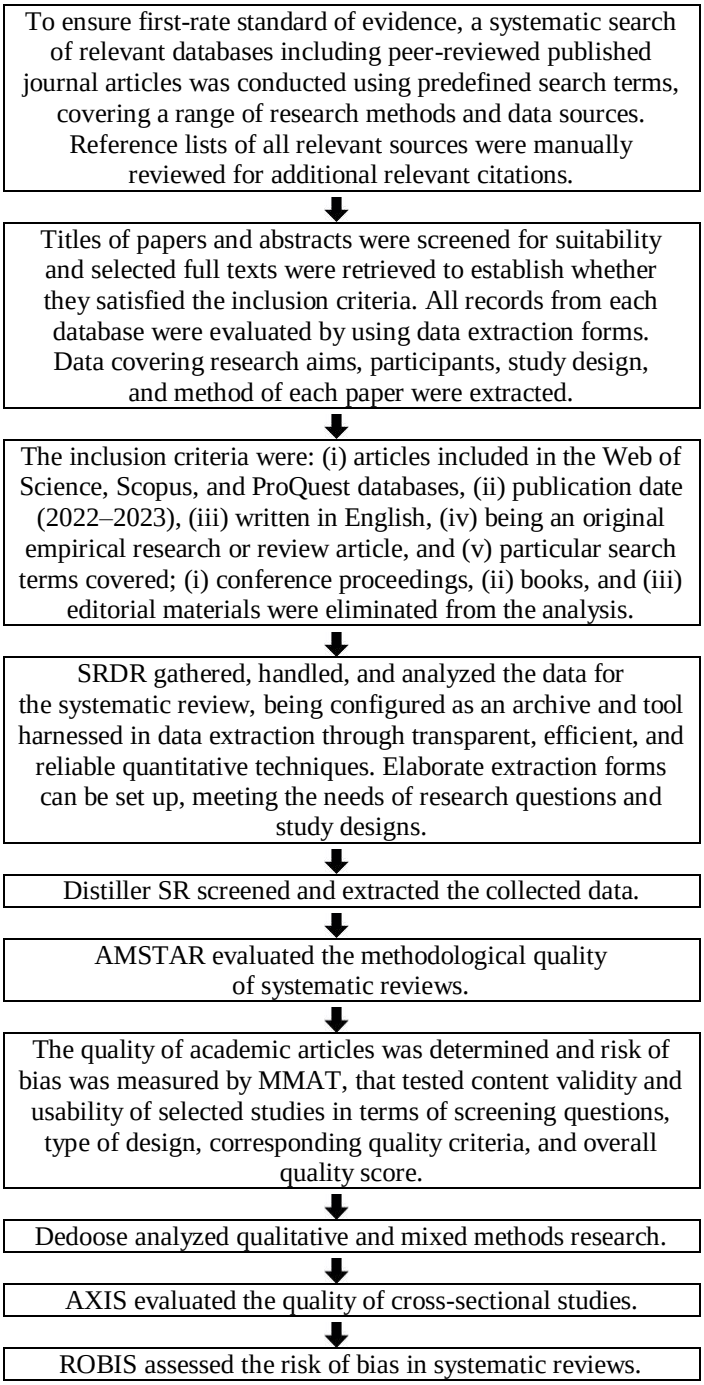

Figure 6 Screening and quality assessment tools

4. Cognitive Artificial Intelligence and Spatial Computing Algorithms, Synthetic Data and Image Processing Tools, and Immersive 3D and Digital Contact Tracing Technologies in the Metaverse Interactive Environment

Cognitive artificial intelligence and spatial computing algorithms, monitoring and sensing technologies, and digital twin modeling and deep reinforcement learning tools (Bojic, 2022; Ersoy and Gürfidan, 2023; Hamilton, 2022; Xu et al., 2023) articulate the metaverse interactive environment. 3D immersive content, ambient intelligence and deep reinforcement learning tools, and virtual environmental and location sensors are instrumental in extended reality environments.

Immersive decentralized 3D digital worlds (Hollensen et al., 2023; McStay, 2022; Zauskova et al., 2022) require virtual twin modeling and geospatial mapping tools, 3D object detection and tracking algorithms, and edge computing and tactile sensing technologies. Deep learning and machine vision algorithms, computer graphics-based photorealistic imagery, and metaverse engagement metrics enable extended reality environments and interconnected digital realms.

Immersive metaverse experiences can be achieved by use of digital twin data modeling and visualization, synthetic data and image processing tools, and convolutional neural and interoperable virtual networks (Braud et al., 2022; Han et al., 2022; Shen, 2022) in real-time simulation environments. Modal synthetic data fusion, immersive 3D and digital contact tracing technologies, and Internet of digital twins are pivotal in blockchain-based virtual worlds. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Cognitive artificial intelligence and spatial computing algorithms, monitoring and sensing technologies, and digital twin modeling and deep reinforcement learning tools articulate the metaverse interactive environment.	Bojic, 2022; Ersoy and Gürfidan, 2023; Hamilton, 2022; Xu et al., 2023
Immersive decentralized 3D digital worlds require virtual twin modeling and geospatial mapping tools, 3D object detection and tracking algorithms, and edge computing and tactile sensing technologies.	Hollensen et al., 2023; McStay, 2022; Zauskova et al., 2022
Immersive metaverse experiences can be achieved by use of digital twin data modeling and visualization, synthetic data and image processing tools, and convolutional neural and interoperable virtual networks in real-time simulation environments.	Braud et al., 2022; Han et al., 2022; Shen, 2022

5. Spatial Computing and Simulation Modeling Algorithms, Movement and Behavior Tracking Tools, and Convolutional Neural and Interconnected Sensor Networks in the Virtual Economy of the Metaverse

Blockchain-based metaverse platforms and virtual worlds (Aloqaily et al., 2022; Han et al., 2023; Kovacova et al., 2022) develop on synthetic data interoperability, autonomous cognitive and location-aware networked systems, and spatial computing and simulation modeling algorithms. Sensing and computing technologies, digital twin modeling and simulation tools, and artificial intelligence-powered search capabilities configure extended reality environments.

Convolutional neural and interconnected sensor networks, image recognition and visual perception algorithms, and movement and behavior tracking tools (Hancock, 2022a; Newell, 2022; Oh et al., 2023; Van Huynh et al., 2022) further the virtual economy of the metaverse. Automated speech recognition and virtual navigation tools, metaverse engagement metrics, and environment mapping and spatio-temporal fusion algorithms articulate 3D digital environments.

Virtual modeling and simulation tools, computer vision and data fusion algorithms, and metaverse assets and services (Egliston and Carter, 2022; Perkins, 2022; Rostami and Maier, 2022) shape immersive digital worlds and shared virtual environments. Spatial computing and immersive 3D technologies, big geospatial data analytics, and virtual navigation and data acquisition tools optimize interactive virtual environments. Immersive digital worlds necessitate spatio-temporal fusion and machine learning algorithms, smart sensor devices, and synthetic data generation and collaborative localization techniques. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Blockchain-based metaverse platforms and virtual worlds develop on synthetic data interoperability, autonomous cognitive and location-aware networked systems, and spatial computing and simulation modeling algorithms.	Aloqaily et al., 2022; Han et al., 2023; Kovacova et al., 2022
Convolutional neural and interconnected sensor networks, image recognition and visual perception algorithms, and movement and behavior tracking tools further the virtual economy of the metaverse.	Hancock, 2022a; Newell, 2022; Oh et al., 2023; Van Huynh et al., 2022
Virtual modeling and simulation tools, computer vision and data fusion algorithms, and metaverse assets and services shape immersive digital worlds and shared virtual environments.	Egliston and Carter, 2022; Perkins, 2022; Rostami and Maier, 2022

6. Digital Twin Simulation and Spatial Data Visualization Tools, Cloud-edge Computing and Autonomous Cognitive Systems, and Deep Learning and Visual Perception Algorithms in Extended Reality Environments

Immersive 3D virtual environments (Huang et al., 2023; Mourtzis et al., 2022; Vidal-Tomás, 2023) necessitate collaborative data analysis and virtual navigation tools, deep learning-based ambient sound processing, and cloud-edge computing and autonomous cognitive systems. User identification and eye-tracking technologies, synthetic data and virtual twin modeling tools, and sentiment and user journey analytics assist immersive digital worlds.

Immersive metaverse experiences can be attained through deep learning and visual perception algorithms, digital twin simulation and spatial data visualization tools, and edge intelligence and cognitive enhancement technologies (Cao, 2022; Hancock, 2022b; Ramadan, 2023; Wu et al., 2023) in extended reality environments. Sensor data fusion, cyber-physical cognitive and biometric authentication systems, and natural language processing and data mining tools configure blockchain-based metaverse platforms.

Cognitive enhancement and cloud computing technologies, digital twin-based virtual sensors, and physics-based modeling and simulation tools (Du et al., 2023; Polas et al., 2022; Wongkitrungrueng and Suprawan, 2023) optimize immersive 3D worlds. The metaverse interactive environment integrates event modeling and forecasting tools, cognitive artificial intelligence and eye-tracking technologies, and sensor data fusion. Extended reality environments require cognitive artificial intelligence and eye-tracking technologies, metaverse assets and services, and simulation modeling and image processing tools. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive 3D virtual environments necessitate collaborative data analysis and virtual navigation tools, deep learning-based ambient sound processing, and cloud-edge computing and autonomous cognitive systems.	Huang et al., 2023; Mourtzis et al., 2022; Vidal-Tomás, 2023
Immersive metaverse experiences can be attained through deep learning and visual perception algorithms, digital twin simulation and spatial data visualization tools, and edge intelligence and cognitive enhancement technologies in extended reality environments.	Cao, 2022; Hancock, 2022b; Ramadan, 2023; Wu et al., 2023
Cognitive enhancement and cloud computing technologies, digital twin-based virtual sensors, and physics-based modeling and simulation tools optimize immersive 3D worlds.	Du et al., 2023; Polas et al., 2022; Wongkitrungrueng and Suprawan, 2023

7. Discussion

We integrate our systematic review throughout research indicating how modal synthetic data fusion, immersive 3D and digital contact tracing technologies, and Internet of digital twins are pivotal in blockchain-based virtual worlds. Our research complements recent analyses clarifying how sensing and computing technologies, digital twin modeling and simulation tools, and artificial intelligence-powered search capabilities configure extended reality environments. We elucidate, by cumulative evidence, previous research demonstrating how immersive digital worlds necessitate spatio-temporal fusion and machine learning algorithms, smart sensor devices, and synthetic data generation and collaborative localization techniques.

8. Synopsis of the Main Research Outcomes

3D immersive content, ambient intelligence and deep reinforcement learning tools, and virtual environmental and location sensors are instrumental in extended reality environments. Sensor data fusion, cyber-physical cognitive and biometric authentication systems, and natural language processing and data mining tools configure blockchain-based metaverse platforms. Deep learning and machine vision algorithms, computer graphics-based photo-realistic imagery, and metaverse engagement metrics enable extended reality environments and interconnected digital realms. The metaverse interactive environment integrates event modeling and forecasting tools, cognitive artificial intelligence and eye-tracking technologies, and sensor data fusion.

9. Conclusions

Relevant research has investigated whether extended reality environments require cognitive artificial intelligence and eye-tracking technologies, meta-verse assets and services, and simulation modeling and image processing tools. This systematic literature review presents the published peer-reviewed sources covering how user identification and eye-tracking technologies, synthetic data and virtual twin modeling tools, and sentiment and user journey analytics assist immersive digital worlds. The research outcomes drawn from the above analyses indicate that spatial computing and immersive 3D technologies, big geospatial data analytics, and virtual navigation and data acquisition tools optimize interactive virtual environments.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant

sources on synthetic data and image processing tools, immersive 3D and digital contact tracing technologies, and cognitive artificial intelligence and spatial computing algorithms in the metaverse interactive environment may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of deep learning and visual perception algorithms, digital twin simulation and spatial data visualization tools, and edge intelligence and cognitive enhancement technologies.

Subsequent analyses should develop on convolutional neural and interconnected sensor networks, image recognition and visual perception algorithms, and movement and behavior tracking tools. Future research should thus investigate Cognitive artificial intelligence and spatial computing algorithms, monitoring and sensing technologies, and digital twin modeling and deep reinforcement learning tools. Attention should be directed to synthetic data interoperability, autonomous cognitive and location-aware networked systems, and spatial computing and simulation modeling algorithms.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Context Awareness and Deep Learning Algorithms, Immersive Visualization and Autonomous Cognitive Systems, and Natural Language Processing and Digital Twin Modeling Tools in the Blockchain-based Metaverse

Michael Barker*

ABSTRACT. The objective of this paper is to systematically review geospatial mapping and 3D virtual space networking tools, visual object tracking and deep learning algorithms, and cloud computing and cognitive artificial intelligence technologies. The findings and analyses highlight that extended reality environments require sensor fusion and 3D path planning algorithms, synthetic biometric data, and ontology-based semantic and 3D immersive virtual reality technologies. Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "the blockchain-based metaverse" + "context awareness and deep learning algorithms," "immersive visualization and autonomous cognitive systems," and "natural language processing and digital twin modeling tools." As research published in 2022 and 2023 was inspected, only 181 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, I selected 30 mainly empirical sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR.

Keywords: context awareness; deep learning algorithms; immersive visualization; autonomous cognitive systems; natural language processing; digital twin modeling tools; blockchain-based metaverse

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1. Introduction

Machine learning-based image recognition and real-time data tracking tools, sensing and computing technologies, and empathetic computing and extended cognitive systems further extended reality environments. The purpose of my systematic review is to examine the recently published literature on the blockchain-based metaverse and integrate the insights it configures on context awareness and deep learning algorithms, immersive visualization and autonomous cognitive systems, and natural language processing and digital twin modeling tools. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that hyper-realistic immersive 3D simulations, affective and perceptual technologies, and natural language processing and digital twin modeling tools (Fernando and Lăzăroiu, 2023; Nica, 2019; Popescu, 2018) shape the virtual environment of the metaverse. The actuality and novelty of this study are articulated by addressing geospatial mapping and 3D virtual space networking tools, visual object tracking and deep learning algorithms, and cloud computing and cognitive artificial intelligence technologies (Andronie et al., 2023; Nagy et al., 2023; Valaskova et al., 2022a), that is an emerging topic involving much interest. My research problem is whether data visualization and deep reinforcement learning tools, 3D immersive content, and user identification and cognitive automation technologies (Andronie et al., 2021a; Gura et al., 2023; Vătămănescu et al., 2020) articulate digital hyper-realistic worlds.

In this review, prior findings have been cumulated indicating that automated speech recognition and real-time visual analytics systems, sensory data mining techniques, and visual attention modeling and data acquisition tools (Andronie et al., 2021b; Nica, 2017; Zhuravleva et al., 2019) enable interoperable extended reality environments. The identified gaps advance spatial data visualization and simulation modeling tools (Andronie et al., 2021c; Lăzăroiu, 2018; Pop et al., 2021), geolocation data mining and tracking, and context awareness and deep learning algorithms. My main objective is to indicate that extended reality environments require sensor fusion and 3D path planning algorithms (Dabija et al., 2022; Lewkowich, 2022; Nica et al., 2023), synthetic biometric data, and ontology-based semantic and 3D immersive virtual reality technologies.

2. Theoretical Overview of the Main Concepts

The metaverse interactive environment necessitates convolutional neural and wireless sensor networks, 3D modeling and simulation technologies, and big data computing and socially-extended cognition systems. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), spatial data visualization and simulation modeling tools, big data com-

puting and socially-extended cognition systems, and context awareness and deep learning algorithms in the metaverse interactive environment (section 4), spatio-temporal fusion and computer vision algorithms, immersive visualization and autonomous cognitive systems, machine learning-based image recognition and real-time data tracking tools, and in the blockchain-based metaverse (section 5), natural language processing and digital twin modeling tools, cognitive enhancement and deep learning-based sensing technologies, and situational awareness and computer vision algorithms in the virtual environment of the metaverse (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "the blockchain-based metaverse" + "context awareness and deep learning algorithms," "immersive visualization and autonomous cognitive systems," and "natural language processing and digital twin modeling tools." As research published in 2022 and 2023 was inspected, only 181 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, I selected 30 mainly empirical sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
the blockchain-based metaverse + context awareness and deep learning algorithms	62	11
the blockchain-based metaverse + immersive visualization and autonomous cognitive systems	60	10
the blockchain-based metaverse + natural language processing and digital twin modeling tools	59	9
Type of paper		
Original research	152	22
Review	18	8
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

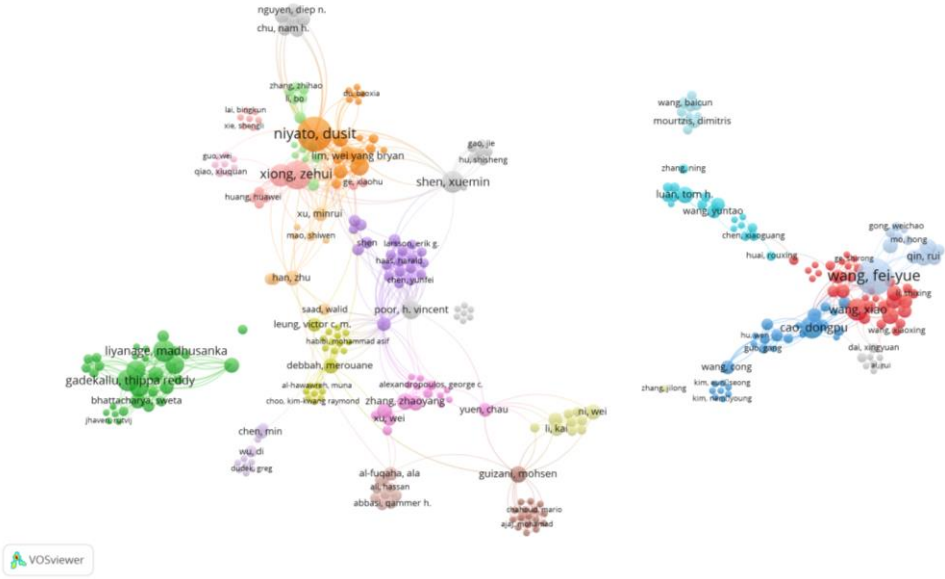

Figure 1 Co-authorship

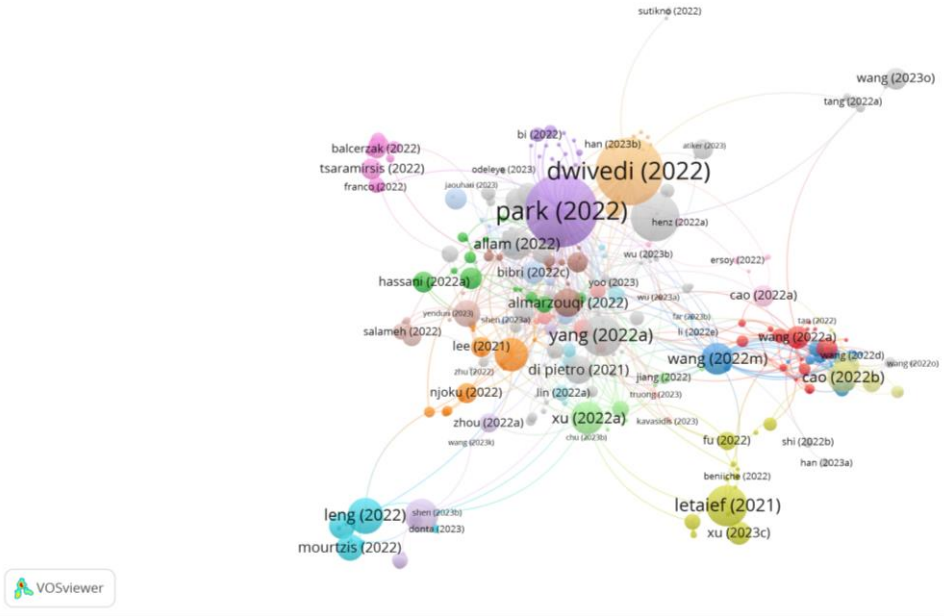

Figure 2 Citation

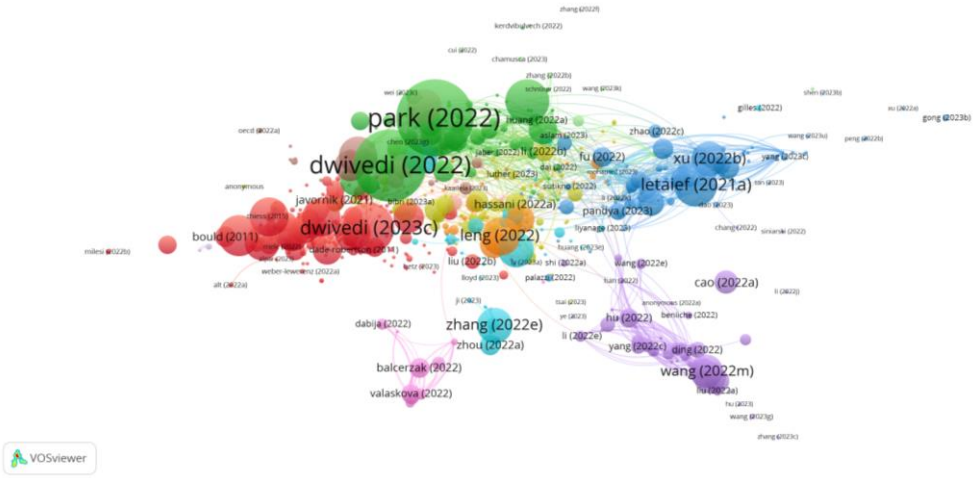

Figure 3 Bibliographic coupling

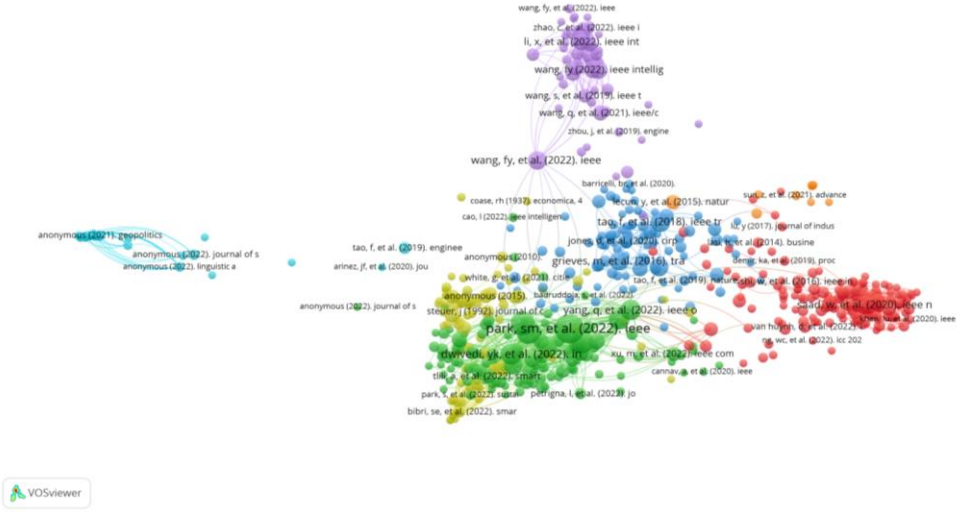

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

The blockchain-based metaverse require artificial intelligence-powered search capabilities, automated speech recognition and virtual twin modeling tools, and edge computing and data fusion technologies.	Dwivedi et al., 2023; Nagendran et al., 2022; Zheng and Yuan, 2023
Extended reality environments develop on spatial data visualization and simulation modeling tools, geolocation data mining and tracking, and context awareness and deep learning algorithms.	Adams, 2022; Hennig-Thurau et al., 2022; Zhang et al., 2022
Artificial intelligence-powered search capabilities, digital twin and user identification technologies, and real-time data tracking and virtual navigation tools shape intelligent connectivity infrastructures in extended reality environments.	Barnes, 2022; Gauttier et al., 2022; Li et al., 2023; Zabel et al., 2023
Modeling and forecasting tools, cognitive computing and immersive visualization systems, and spatio-temporal fusion and computer vision algorithms configure immersive digital worlds and Internet of Things sensing infrastructures.	Hawkins, 2022; Lv et al., 2022; Njoku et al., 2023; Zainab et al., 2022
Geospatial mapping and 3D virtual space networking tools, visual object tracking and deep learning algorithms, and cloud computing and cognitive artificial intelligence technologies are instrumental in the metaverse interactive environment.	Balica, 2022; Dolata and Schwabe, 2023; Zhang et al., 2023
Geospatial mapping and synthetic data tools, machine vision and deep learning algorithms, and cognitive artificial intelligence and cloud computing technologies optimize immersive decentralized 3D digital worlds.	Corpodean et al., 2022; Kwok and Tang, 2023; Queiroz et al., 2023; Zhao et al., 2022
Extended reality environments integrate spatial cognition and computer vision algorithms, immersive visualization and automated speech recognition systems, and ambient intelligence and 3D virtual space networking tools.	Shi et al., 2023; Valaskova et al., 2022b; Zhu et al., 2023
Synthetic user experiences can be attained through user journey and sentiment analytics, monitoring and sensing technologies, and image recognition and machine learning algorithms across extended reality environments.	Hadi et al., 2023; Zallio and Clarkson, 2022; Zvarikova et al., 2023
3D immersive spaces and experiences can be achieved by use of cognitive enhancement and deep learning-based sensing technologies, 3D modeling and geospatial mapping tools, and machine vision and situational awareness algorithms in interactive digital worlds.	Faraboschi et al., 2022; Wang et al., 2022; Zhou et al., 2023

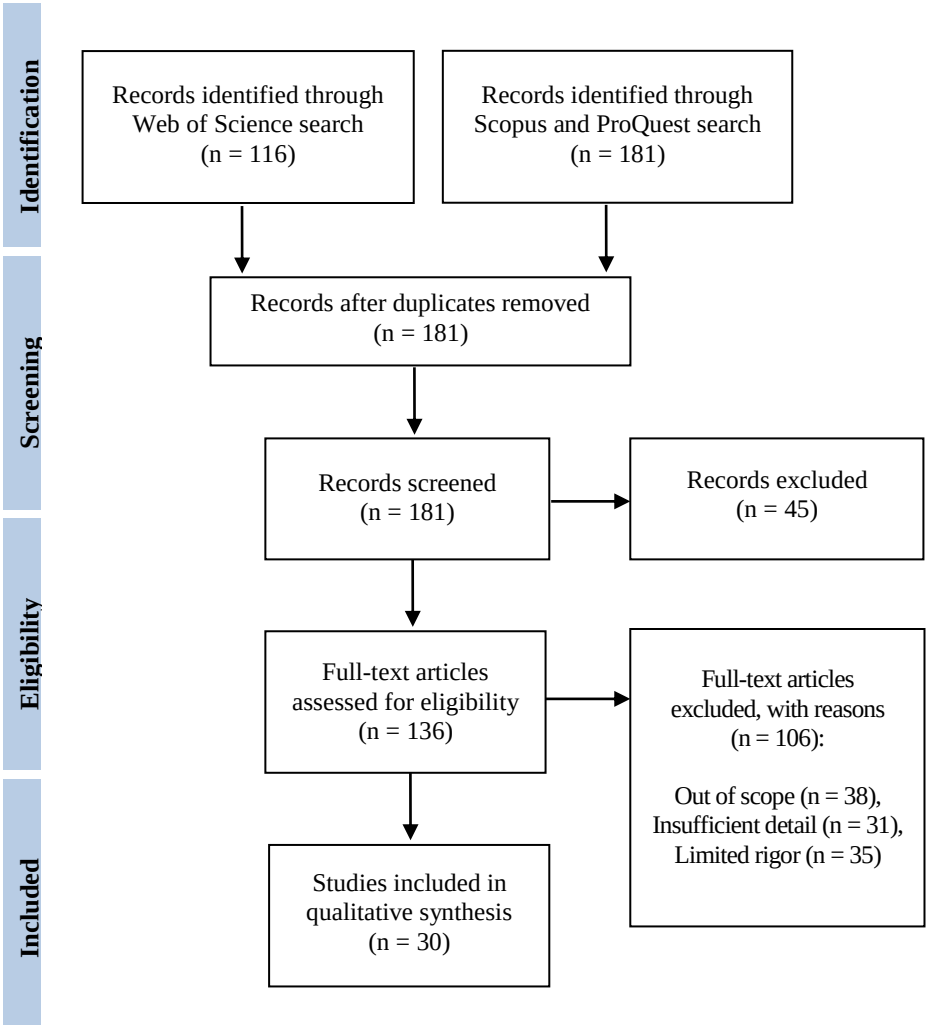

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

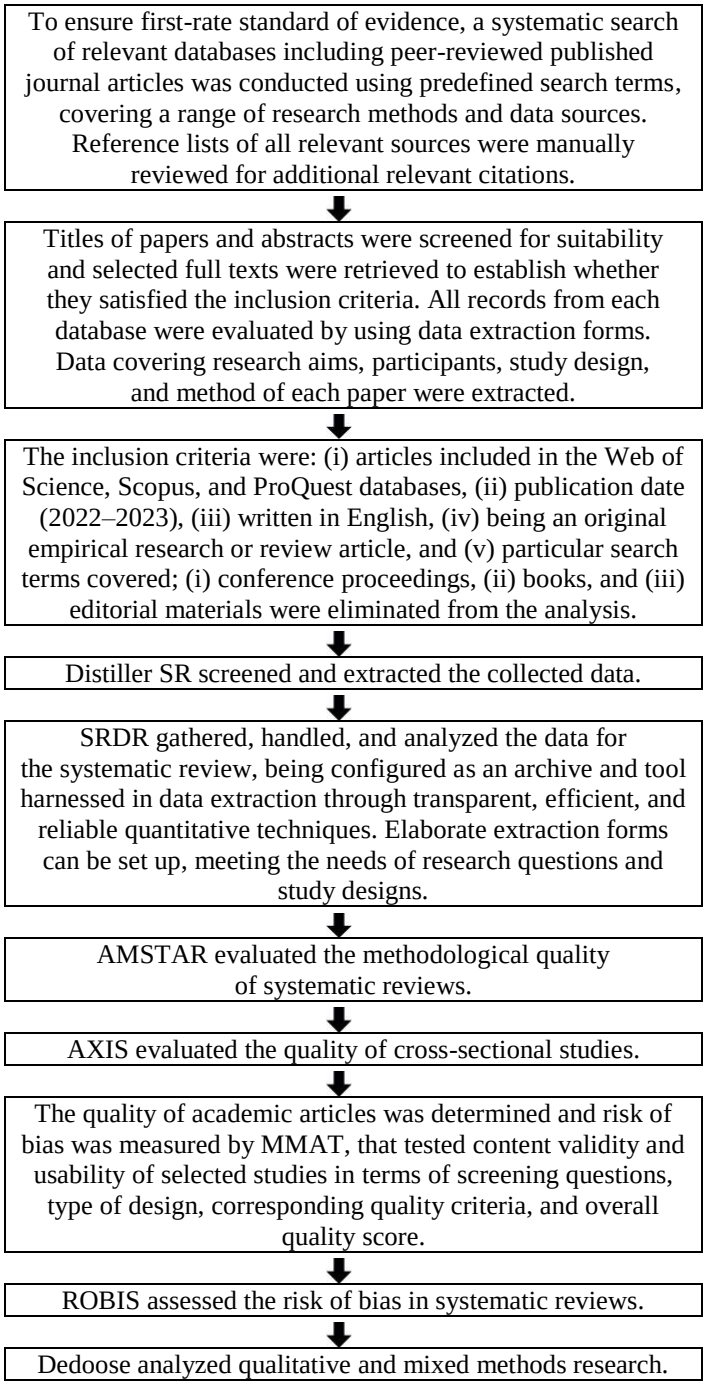

Figure 6 Screening and quality assessment tools

4. Spatial Data Visualization and Simulation Modeling Tools, Big Data Computing and Socially-Extended Cognition Systems, and Context Awareness and Deep Learning Algorithms in the Metaverse Interactive Environment

The blockchain-based metaverse (Dwivedi et al., 2023; Nagendran et al., 2022; Zheng and Yuan, 2023) require artificial intelligence-powered search capabilities, automated speech recognition and virtual twin modeling tools, and edge computing and data fusion technologies. Data visualization and deep reinforcement learning tools, 3D immersive content, and user identification and cognitive automation technologies articulate digital hyper-realistic worlds.

Extended reality environments (Adams, 2022; Hennig-Thurau et al., 2022; Zhang et al., 2022) develop on spatial data visualization and simulation modeling tools, geolocation data mining and tracking, and context awareness and deep learning algorithms. Deep learning-based ambient sound processing, monitoring and sensing technologies, and computer vision and image recognition algorithms enable immersive 3D virtual environments.

Artificial intelligence-powered search capabilities, digital twin and user identification technologies, and real-time data tracking and virtual navigation tools (Barnes, 2022; Gauttier et al., 2022; Li et al., 2023; Zabel et al., 2023) shape intelligent connectivity infrastructures in extended reality environments. The metaverse interactive environment necessitates convolutional neural and wireless sensor networks, 3D modeling and simulation technologies, and big data computing and socially-extended cognition systems. Extended reality environments require sensor fusion and 3D path planning algorithms, synthetic biometric data, and ontology-based semantic and 3D immersive virtual reality technologies. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

The blockchain-based metaverse require artificial intelligence-powered search capabilities, automated speech recognition and virtual twin modeling tools, and edge computing and data fusion technologies.	Dwivedi et al., 2023; Nagendran et al., 2022; Zheng and Yuan, 2023
Extended reality environments develop on spatial data visualization and simulation modeling tools, geolocation data mining and tracking, and context awareness and deep learning algorithms.	Adams, 2022; Hennig-Thurau et al., 2022; Zhang et al., 2022
Artificial intelligence-powered search capabilities, digital twin and user identification technologies, and real-time data tracking and virtual navigation tools shape intelligent connectivity infrastructures in extended reality environments.	Barnes, 2022; Gauttier et al., 2022; Li et al., 2023; Zabel et al., 2023

5. Spatio-Temporal Fusion and Computer Vision Algorithms, Immersive Visualization and Autonomous Cognitive Systems, Machine Learning-based Image Recognition and Real-Time Data Tracking Tools, and in the Blockchain-based Metaverse

Modeling and forecasting tools, cognitive computing and immersive visualization systems, and spatio-temporal fusion and computer vision algorithms (Hawkins, 2022; Lv et al., 2022; Njoku et al., 2023; Zainab et al., 2022) configure immersive digital worlds and Internet of Things sensing infrastructures. Deep learning-based ambient sound processing, immersive visualization and autonomous cognitive systems, and 3D holographic avatars configure the blockchain-based metaverse.

Geospatial mapping and 3D virtual space networking tools, visual object tracking and deep learning algorithms, and cloud computing and cognitive artificial intelligence technologies (Balica, 2022; Dolata and Schwabe, 2023; Zhang et al., 2023) are instrumental in the metaverse interactive environment. Machine learning-based image recognition and real-time data tracking tools, sensing and computing technologies, and empathetic computing and extended cognitive systems further extended reality environments.

Geospatial mapping and synthetic data tools, machine vision and deep learning algorithms, and cognitive artificial intelligence and cloud computing technologies (Corpodean et al., 2022; Kwok and Tang, 2023; Queiroz et al., 2023; Zhao et al., 2022) optimize immersive decentralized 3D digital worlds. Automated speech recognition and real-time visual analytics systems, sensory data mining techniques, and visual attention modeling and data acquisition tools enable interoperable extended reality environments. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Modeling and forecasting tools, cognitive computing and immersive visualization systems, and spatio-temporal fusion and computer vision algorithms configure immersive digital worlds and Internet of Things sensing infrastructures.	Hawkins, 2022; Lv et al., 2022; Njoku et al., 2023; Zainab et al., 2022
Geospatial mapping and 3D virtual space networking tools, visual object tracking and deep learning algorithms, and cloud computing and cognitive artificial intelligence technologies are instrumental in the metaverse interactive environment.	Balica, 2022; Dolata and Schwabe, 2023; Zhang et al., 2023
Geospatial mapping and synthetic data tools, machine vision and deep learning algorithms, and cognitive artificial intelligence and cloud computing technologies optimize immersive decentralized 3D digital worlds.	Corpodean et al., 2022; Kwok and Tang, 2023; Queiroz et al., 2023; Zhao et al., 2022

6. Natural Language Processing and Digital Twin Modeling Tools, Cognitive Enhancement and Deep Learning-based Sensing Technologies, and Situational Awareness and Computer Vision Algorithms in the Virtual Environment of the Metaverse

Extended reality environments (Shi et al., 2023; Valaskova et al., 2022; Zhu et al., 2023) integrate spatial cognition and computer vision algorithms, immersive visualization and automated speech recognition systems, and ambient intelligence and 3D virtual space networking tools. Sentiment and real-time predictive analytics, virtual navigation and 3D generative modeling tools, and cognitive artificial intelligence and virtual simulation algorithms assist immersive 3D worlds.

Synthetic user experiences can be attained through user journey and sentiment analytics, monitoring and sensing technologies, and image recognition and machine learning algorithms (Hadi et al., 2023; Zallio and Clarkson, 2022; Zvarikova et al., 2023) across extended reality environments. Hyper-realistic immersive 3D simulations, affective and perceptual technologies, and natural language processing and digital twin modeling tools shape the virtual environment of the metaverse.

3D immersive spaces and experiences can be achieved by use of cognitive enhancement and deep learning-based sensing technologies, 3D modeling and geospatial mapping tools, and machine vision and situational awareness algorithms (Faraboschi et al., 2022; Wang et al., 2022; Zhou et al., 2023) in interactive digital worlds. 3D immersive content, situational awareness and computer vision algorithms, and decision intelligence and modelling tools are pivotal in interactive virtual environments. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Extended reality environments integrate spatial cognition and computer vision algorithms, immersive visualization and automated speech recognition systems, and ambient intelligence and 3D virtual space networking tools.	Shi et al., 2023; Valaskova et al., 2022b; Zhu et al., 2023
Synthetic user experiences can be attained through user journey and sentiment analytics, monitoring and sensing technologies, and image recognition and machine learning algorithms across extended reality environments.	Hadi et al., 2023; Zallio and Clarkson, 2022; Zvarikova et al., 2023
3D immersive spaces and experiences can be achieved by use of cognitive enhancement and deep learning-based sensing technologies, 3D modeling and geospatial mapping tools, and machine vision and situational awareness algorithms in interactive digital worlds.	Faraboschi et al., 2022; Wang et al., 2022; Zhou et al., 2023

7. Discussion

I integrate my systematic review throughout research indicating how sentiment and real-time predictive analytics, virtual navigation and 3D generative modeling tools, and cognitive artificial intelligence and virtual simulation algorithms assist immersive 3D worlds. My research complements recent analyses clarifying how automated speech recognition and real-time visual analytics systems, sensory data mining techniques, and visual attention modeling and data acquisition tools enable interoperable extended reality environments. I elucidate, by cumulative evidence, previous research demonstrating how data visualization and deep reinforcement learning tools, 3D immersive content, and user identification and cognitive automation technologies articulate digital hyper-realistic worlds.

8. Synopsis of the Main Research Outcomes

Deep learning-based ambient sound processing, monitoring and sensing technologies, and computer vision and image recognition algorithms enable immersive 3D virtual environments. The metaverse interactive environment necessitates convolutional neural and wireless sensor networks, 3D modeling and simulation technologies, and big data computing and socially-extended cognition systems. Machine learning-based image recognition and real-time data tracking tools, sensing and computing technologies, and empathetic computing and extended cognitive systems further extended reality environments.

9. Conclusions

Relevant research has investigated whether 3D immersive content, situational awareness and computer vision algorithms, and decision intelligence and modelling tools are pivotal in interactive virtual environments. This systematic literature review presents the published peer-reviewed sources covering how hyper-realistic immersive 3D simulations, affective and perceptual technologies, and natural language processing and digital twin modeling tools shape the virtual environment of the metaverse. The research outcomes drawn from the above analyses indicate that deep learning-based ambient sound processing, immersive visualization and autonomous cognitive systems, and 3D holographic avatars configure the blockchain-based metaverse.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on context awareness and deep learning algorithms, immersive

visualization and autonomous cognitive systems, and natural language processing and digital twin modeling tools in the blockchain-based metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of modeling and forecasting tools, cognitive computing and immersive visualization systems, and spatio-temporal fusion and computer vision algorithms.

Subsequent analyses should develop on artificial intelligence-powered search capabilities, digital twin and user identification technologies, and real-time data tracking and virtual navigation tools. Future research should thus investigate spatial cognition and computer vision algorithms, immersive visualization and automated speech recognition systems, and ambient intelligence and 3D virtual space networking tools. Attention should be directed to cognitive enhancement and deep learning-based sensing technologies, 3D modeling and geospatial mapping tools, and machine vision and situational awareness algorithms.


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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

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The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Holographic Telepresence and Digital Twin Simulation Technologies, 3D Virtual Space Networking and Machine Learning-based Image Recognition Tools, and Environment Mapping and Cognitive Artificial Intelligence Algorithms in a Fully Connected Metaverse

Rebecca Sullivan*

ABSTRACT. In this article, I cumulate previous research findings indicating that deep learning-based ambient sound processing, spatial audio and edge computing technologies, and event modeling and forecasting tools configure hyper-realistic 3D worlds. I contribute to the literature on context awareness and simulation modeling algorithms, image recognition and cognitive enhancement technologies, and data visualization and virtual navigation tools by showing that the virtual environment of the metaverse integrate modeling and forecasting tools, spatio-temporal fusion and deep learning algorithms, and predictive modeling processes. Throughout May 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "a fully connected metaverse" + "holographic telepresence and digital twin simulation technologies," "3D virtual space networking and machine learning-based image recognition tools," and "environment mapping and cognitive artificial intelligence algorithms." As I inspected research published in 2022 and 2023, only 183 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 35, generally empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, ROBIS, and SRDR.

Keywords: holographic telepresence; digital twin simulation technologies; 3D virtual space networking; machine learning; image recognition tools; environment mapping; cognitive artificial intelligence algorithms; fully connected metaverse

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1. Introduction

Synthetic digitally-mediated and 3D virtual environments require smart sensor devices, 3D generative adversarial and multi-modal deep neural networks, and digital twin simulation and synthetic data tools. The purpose of my systematic review is to examine the recently published literature on a fully connected metaverse and integrate the insights it configures on holographic telepresence and digital twin simulation technologies, 3D virtual space networking and machine learning-based image recognition tools, and environment mapping and cognitive artificial intelligence algorithms. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that computer vision and spatio-temporal fusion algorithms, voice recognition software, and 3D modeling and virtual simulation tools (Andronie et al., 2021; Dabija et al., 2023; Peters et al., 2023; Vătămănescu et al., 2020) further extended reality environments. The actuality and novelty of this study are articulated by addressing context awareness and simulation modeling algorithms, image recognition and cognitive enhancement technologies, and data visualization and virtual navigation tools (Andronie et al., 2023a; Lăzăroiu et al., 2020; Pelau et al., 2021), that is an emerging topic involving much interest. My research problem is whether deep learning-based ambient sound processing, spatial audio and edge computing technologies, and event modeling and forecasting tools (Andronie et al., 2023b; Lyons and Lăzăroiu, 2020; Popescu et al., 2020) configure hyper-realistic 3D worlds.

In this review, prior findings have been cumulated indicating that the virtual environment of the metaverse integrate modeling and forecasting tools, spatio-temporal fusion and deep learning algorithms (Balcerzak et al., 2022; Valaskova et al., 2022a; Nagy and Lăzăroiu, 2022), and predictive modeling processes. The identified gaps advance cloud computing and infrastructure virtualization technologies, digital twin modeling and simulation tools (Lăzăroiu et al., 2022; Scott et al., 2020; Trettin et al., 2019), and environment mapping and cognitive artificial intelligence algorithms. My main objective is to indicate that environment perception sensors, edge artificial intelligence-based and ambient scent technologies, and 3D modeling and virtual mapping tools (Kliestik et al., 2020; Lewkowich, 2022; Popescu et al., 2019; Valaskova et al., 2022b) are pivotal in immersive 3D worlds.

2. Theoretical Overview of the Main Concepts

Big data computing and automated speech recognition systems, behavioral biometric and data fusion technologies, and cognitive digital twins enable immersive 3D virtual environments. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), computer vision and spatio-temporal fusion algorithms, virtual navigation and col-

laborative intelligence tools, and dynamic routing and extended reality technologies in a fully connected metaverse (section 4), holographic telepresence and digital twin simulation technologies, environment mapping and cognitive artificial intelligence algorithms, and 3D virtual space networking and machine learning-based image recognition tools in the blockchain-based metaverse (section 5), digital twin modeling and contextual intelligence tools, geospatial mapping and deep learning-based sensing technologies, and neuromorphic image processing and haptic object recognition systems in the metaverse interactive environment (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout May 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "a fully connected metaverse" + "holographic telepresence and digital twin simulation technologies," "3D virtual space networking and machine learning-based image recognition tools," and "environment mapping and cognitive artificial intelligence algorithms." As I inspected research published in 2022 and 2023, only 183 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 35, generally empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
a fully connected metaverse + holographic telepresence and digital twin simulation technologies	64	12
a fully connected metaverse + 3D virtual space networking and machine learning-based image recognition tools	62	12
a fully connected metaverse + environment mapping and cognitive artificial intelligence algorithms	57	11
Type of paper		
Original research	153	28
Review	18	7
Conference proceedings	9	0
Book	1	0
Editorial	2	0

Source: Processed by the author. Some topics overlap.

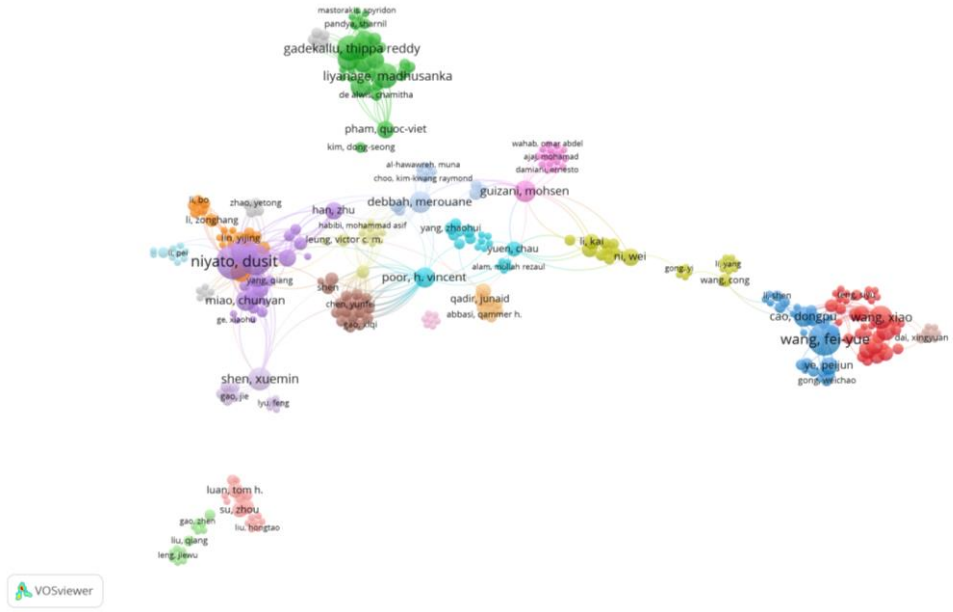

Figure 1 Co-authorship

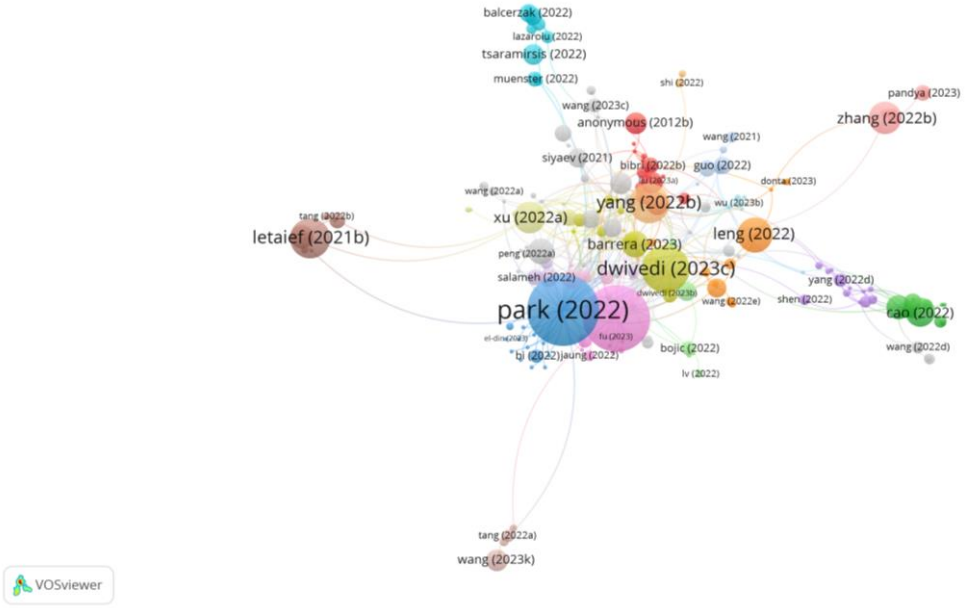

Figure 2 Citation

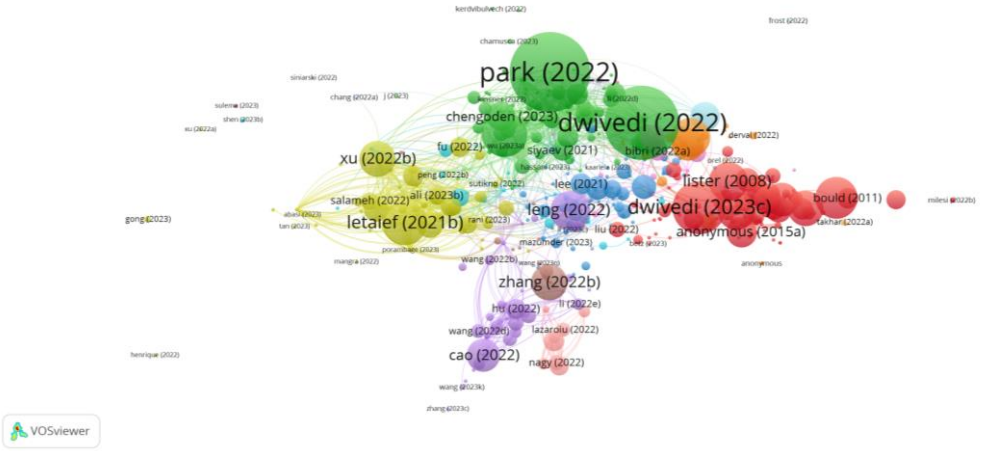

Figure 3 Bibliographic coupling

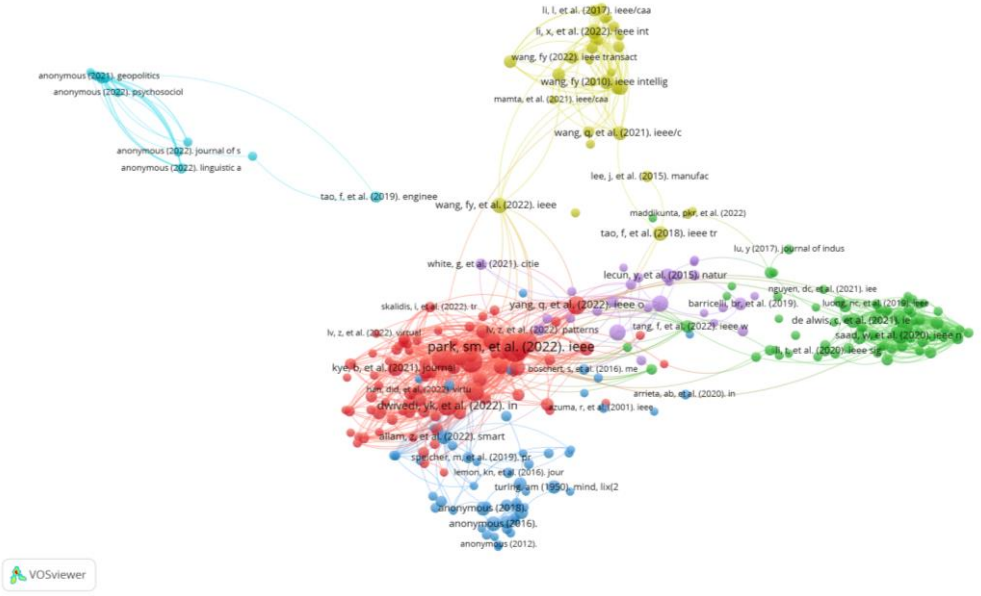

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Blockchain-based virtual worlds and extended reality environments necessitate context awareness and simulation modeling algorithms, image recognition and cognitive enhancement technologies, and data visualization and virtual navigation tools.	Bojic, 2022; Mircică, 2022; Park and Kim, 2023; Ramadan, 2023
Computer vision and deep learning algorithms, metaverse engagement metrics, and geospatial mapping and image processing tools articulate extended reality and simulated 3D modeling environments.	Barnes, 2022; Chen, 2022; Dolata and Schwabe, 2023; Zhang et al., 2023
Machine vision and spatio-temporal fusion algorithms, dynamic routing and extended reality technologies, and real-time data tracking and deep reinforcement learning tools configure a fully connected metaverse.	Ahn et al., 2023; Cheng et al., 2022; Huynh-The et al., 2023; Rowland and Newell, 2022
Spatio-temporal fusion and machine learning prediction algorithms, image recognition and cognitive computing technologies, and virtual navigation and real-time data tracking tools shape intelligent connectivity infrastructures.	Dincelli and Yayla, 2022; Han et al., 2023; Zhu et al., 2023
Holographic telepresence and digital twin simulation technologies, 3D virtual space networking and machine learning-based image recognition tools, and photorealistic synthetic images and data optimize the blockchain-based metaverse.	Ding et al., 2022; Giang Barrera and Shah, 2023; Shen, 2022; Valaskova et al., 2022c
Cloud computing and infrastructure virtualization technologies, digital twin modeling and simulation tools, and environment mapping and cognitive artificial intelligence algorithms assist collaborative 3D design environments.	Beckett, 2022; Golf-Papez et al., 2022; Li et al., 2023; Oh et al., 2023
Augmented reality environments require digital twin simulation and ambient intelligence tools, geospatial artificial intelligence and digital contact tracing technologies, and Internet of Things-based decision support systems.	Kozinets, 2023; Meng et al., 2023; Yoo et al., 2023; Zarantonello and Schmitt, 2023
Digital twin modeling and contextual intelligence tools, networked embedded sensing devices, and geospatial mapping and deep learning-based sensing technologies shape immersive photorealistic virtual spaces.	Bordegoni and Ferrise, 2023; McStay, 2023; Smart, 2022; Xu et al., 2023
Immersive interconnected virtual worlds develop on neuromorphic image processing and haptic object recognition systems, digital twin and virtual modeling technologies, and automated speech recognition and geospatial mapping tools.	Hancock, 2022; Panagiotakopoulos et al., 2022; Shi et al., 2023; Tang et al., 2023

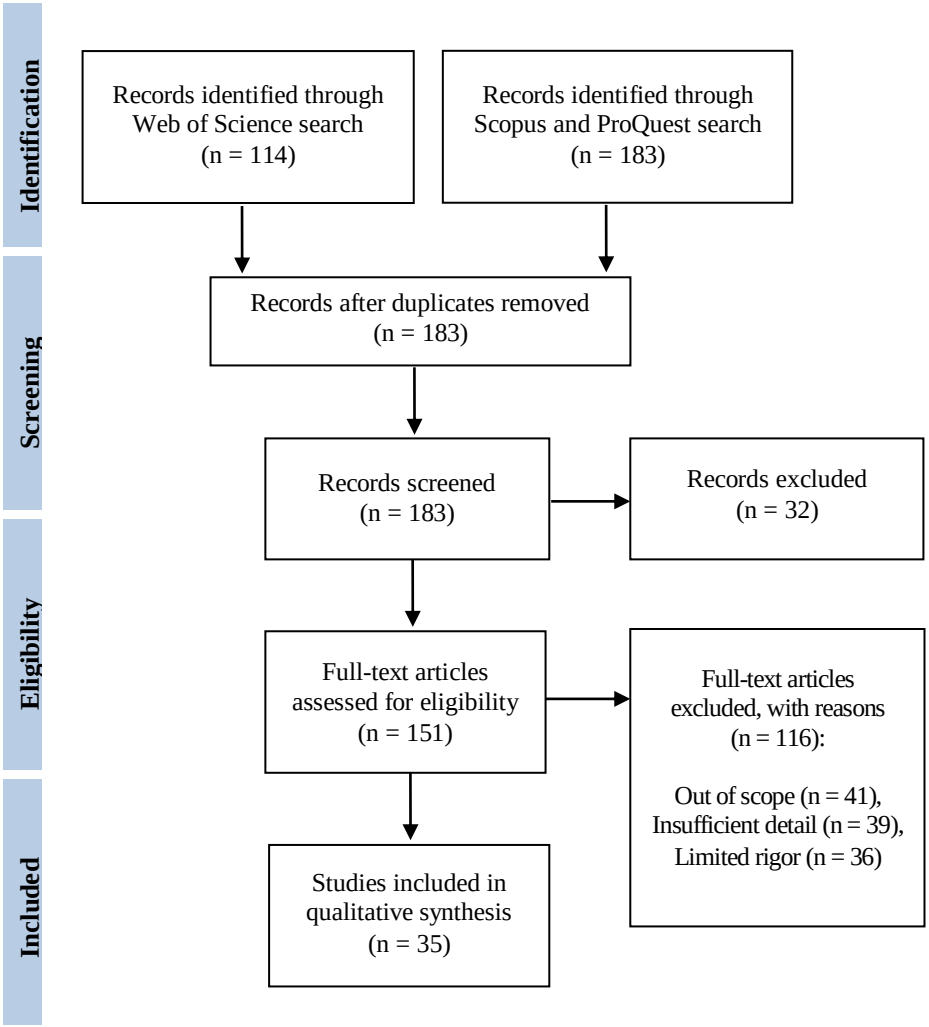

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

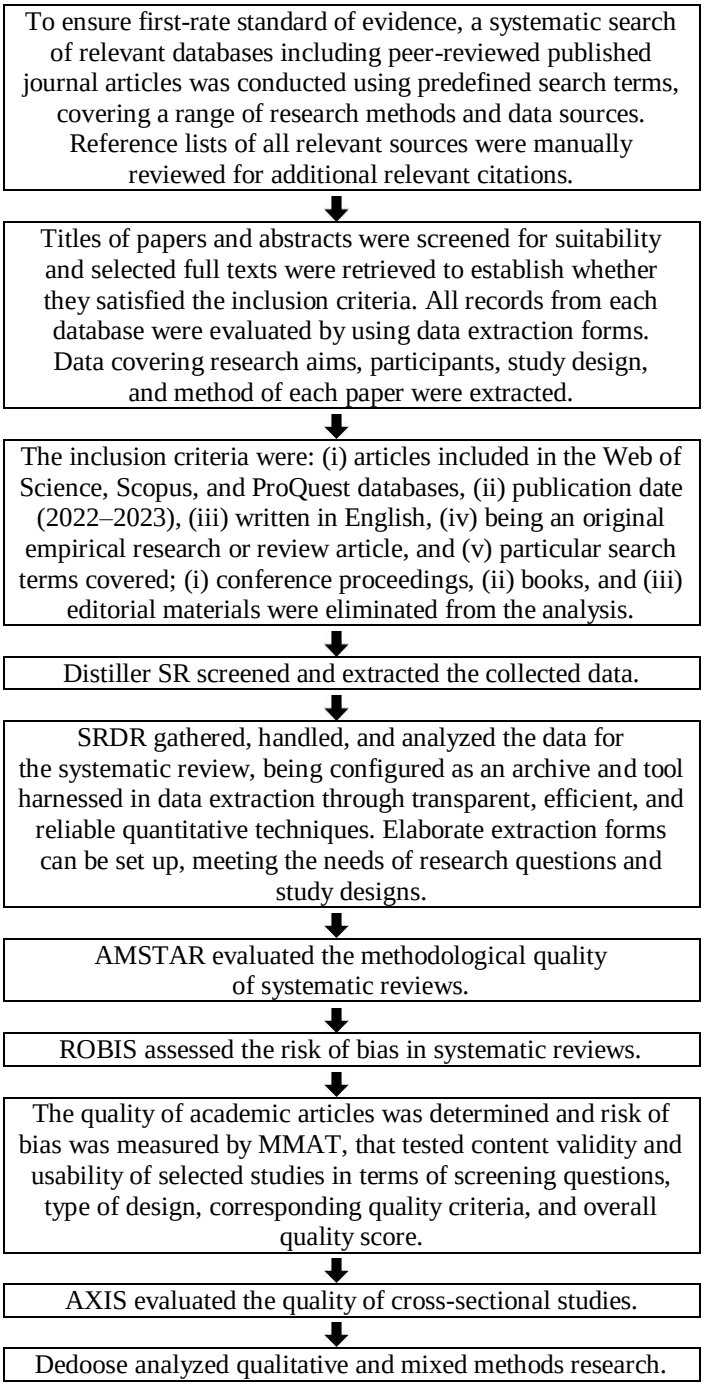

Figure 6 Screening and quality assessment tools

4. Computer Vision and Spatio-Temporal Fusion Algorithms, Virtual Navigation and Collaborative Intelligence Tools, and Dynamic Routing and Extended Reality Technologies in a Fully Connected Metaverse

Blockchain-based virtual worlds and extended reality environments (Bojic, 2022; Mircică, 2022; Park and Kim, 2023; Ramadan, 2023) necessitate context awareness and simulation modeling algorithms, image recognition and cognitive enhancement technologies, and data visualization and virtual navigation tools. Computer vision and spatio-temporal fusion algorithms, voice recognition software, and 3D modeling and virtual simulation tools further extended reality environments.

Computer vision and deep learning algorithms, metaverse engagement metrics, and geospatial mapping and image processing tools (Barnes, 2022; Chen, 2022; Dolata and Schwabe, 2023; Zhang et al., 2023) articulate extended reality and simulated 3D modeling environments. Cognitive enhancement and 3D visual technologies, virtual navigation and collaborative intelligence tools, and synthetic biometric data are instrumental in extended reality environments.

Machine vision and spatio-temporal fusion algorithms, dynamic routing and extended reality technologies, and real-time data tracking and deep reinforcement learning tools (Ahn et al., 2023; Cheng et al., 2022; Huynh-The et al., 2023; Rowland and Newell, 2022) configure a fully connected metaverse. Deep learning-based ambient sound processing, spatial audio and edge computing technologies, and event modeling and forecasting tools configure hyper-realistic 3D worlds. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Blockchain-based virtual worlds and extended reality environments necessitate context awareness and simulation modeling algorithms, image recognition and cognitive enhancement technologies, and data visualization and virtual navigation tools.	Bojic, 2022; Mircică, 2022; Park and Kim, 2023; Ramadan, 2023
Computer vision and deep learning algorithms, metaverse engagement metrics, and geospatial mapping and image processing tools articulate extended reality and simulated 3D modeling environments.	Barnes, 2022; Chen, 2022; Dolata and Schwabe, 2023; Zhang et al., 2023
Machine vision and spatio-temporal fusion algorithms, dynamic routing and extended reality technologies, and real-time data tracking and deep reinforcement learning tools configure a fully connected metaverse.	Ahn et al., 2023; Cheng et al., 2022; Huynh-The et al., 2023; Rowland and Newell, 2022

5. Holographic Telepresence and Digital Twin Simulation Technologies, Environment Mapping and Cognitive Artificial Intelligence Algorithms, and 3D Virtual Space Networking and Machine Learning-based Image Recognition Tools in the Blockchain-based Metaverse

Spatio-temporal fusion and machine learning prediction algorithms, image recognition and cognitive computing technologies, and virtual navigation and real-time data tracking tools (Dincelli and Yayla, 2022; Han et al., 2023; Zhu et al., 2023) shape intelligent connectivity infrastructures in immersive 3D environments. The virtual environment of the metaverse integrate modeling and forecasting tools, spatio-temporal fusion and deep learning algorithms, and predictive modeling processes.

Holographic telepresence and digital twin simulation technologies, 3D virtual space networking and machine learning-based image recognition tools, and photorealistic synthetic images and data (Ding et al., 2022; Giang Barrera and Shah, 2023; Shen, 2022; Valaskova et al., 2022) optimize the blockchain-based metaverse. Synthetic digitally-mediated and 3D virtual environments require smart sensor devices, 3D generative adversarial and multi-modal deep neural networks, and digital twin simulation and synthetic data tools.

Cloud computing and infrastructure virtualization technologies, digital twin modeling and simulation tools, and environment mapping and cognitive artificial intelligence algorithms (Beckett, 2022; Golf-Papez et al., 2022; Li et al., 2023; Oh et al., 2023) assist collaborative 3D design environments. Environment perception sensors, edge artificial intelligence-based and ambient scent technologies, and 3D modeling and virtual mapping tools are pivotal in immersive 3D worlds. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Spatio-temporal fusion and machine learning prediction algorithms, image recognition and cognitive computing technologies, and virtual navigation and real-time data tracking tools shape intelligent connectivity infrastructures in immersive 3D environments.	Dincelli and Yayla, 2022; Han et al., 2023; Zhu et al., 2023
Holographic telepresence and digital twin simulation technologies, 3D virtual space networking and machine learning-based image recognition tools, and photorealistic synthetic images and data optimize the blockchain-based metaverse.	Ding et al., 2022; Giang Barrera and Shah, 2023; Shen, 2022; Valaskova et al., 2022c
Cloud computing and infrastructure virtualization technologies, digital twin modeling and simulation tools, and environment mapping and cognitive artificial intelligence algorithms assist collaborative 3D design environments.	Beckett, 2022; Golf-Papez et al., 2022; Li et al., 2023; Oh et al., 2023

6. Digital Twin Modeling and Contextual Intelligence Tools, Geospatial Mapping and Deep Learning-based Sensing Technologies, and Neuromorphic Image Processing and Haptic Object Recognition Systems in the Metaverse Interactive Environment

Augmented reality environments (Kozinets, 2023; Meng et al., 2023; Yoo et al., 2023; Zarantonello and Schmitt, 2023) require digital twin simulation and ambient intelligence tools, geospatial artificial intelligence and digital contact tracing technologies, and Internet of Things-based decision support systems. Realistic 3D simulation environments develop on immersive and extended reality technologies, automated speech recognition and data acquisition tools, and big geospatial data and real-time predictive analytics.

Digital twin modeling and contextual intelligence tools, networked embedded sensing devices, and geospatial mapping and deep learning-based sensing technologies (Bordegoni and Ferrise, 2023; McStay, 2023; Smart, 2022; Xu et al., 2023) shape immersive photorealistic virtual spaces. Big data computing and automated speech recognition systems, behavioral biometric and data fusion technologies, and cognitive digital twins enable immersive 3D virtual environments.

Immersive interconnected virtual worlds (Hancock, 2022; Panagiotakopoulos et al., 2022; Shi et al., 2023; Tang et al., 2023) develop on neuromorphic image processing and haptic object recognition systems, digital twin and virtual modeling technologies, and automated speech recognition and geospatial mapping tools. The metaverse interactive environment necessitates affective and perceptual technologies, movement and behavior tracking tools, and immersive visualization and cognitive computing systems. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Augmented reality environments require digital twin simulation and ambient intelligence tools, geospatial artificial intelligence and digital contact tracing technologies, and Internet of Things-based decision support systems.	Kozinets, 2023; Meng et al., 2023; Yoo et al., 2023; Zarantonello and Schmitt, 2023
Digital twin modeling and contextual intelligence tools, networked embedded sensing devices, and geospatial mapping and deep learning-based sensing technologies shape immersive photorealistic virtual spaces.	Bordegoni and Ferrise, 2023; McStay, 2023; Smart, 2022; Xu et al., 2023
Immersive interconnected virtual worlds develop on neuromorphic image processing and haptic object recognition systems, digital twin and virtual modeling technologies, and automated speech recognition and geospatial mapping tools.	Hancock, 2022; Panagiotakopoulos et al., 2022; Shi et al., 2023; Tang et al., 2023

7. Discussion

I integrate my systematic review throughout research indicating how the virtual environment of the metaverse integrate modeling and forecasting tools, spatio-temporal fusion and deep learning algorithms, and predictive modeling processes. My research complements recent analyses clarifying how realistic 3D simulation environments develop on immersive and extended reality technologies, automated speech recognition and data acquisition tools, and big geospatial data and real-time predictive analytics. I elucidate, by cumulative evidence, previous research demonstrating how synthetic digitally-mediated and 3D virtual environments require smart sensor devices, 3D generative adversarial and multi-modal deep neural networks, and digital twin simulation and synthetic data tools.

8. Synopsis of the Main Research Outcomes

Deep learning-based ambient sound processing, spatial audio and edge computing technologies, and event modeling and forecasting tools configure hyper-realistic 3D worlds. Cognitive enhancement and 3D visual technologies, virtual navigation and collaborative intelligence tools, and synthetic biometric data are instrumental in extended reality environments. Environment perception sensors, edge artificial intelligence-based and ambient scent technologies, and 3D modeling and virtual mapping tools are pivotal in immersive 3D worlds.

9. Conclusions

Relevant research has investigated whether computer vision and spatio-temporal fusion algorithms, voice recognition software, and 3D modeling and virtual simulation tools further extended reality environments. This systematic literature review presents the published peer-reviewed sources covering how big data computing and automated speech recognition systems, behavioral biometric and data fusion technologies, and cognitive digital twins enable immersive 3D virtual environments. The research outcomes drawn from the above analyses indicate that the metaverse interactive environment necessitates affective and perceptual technologies, movement and behavior tracking tools, and immersive visualization and cognitive computing systems.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on holographic telepresence and digital twin simulation technologies,

3D virtual space networking and machine learning-based image recognition tools, and environment mapping and cognitive artificial intelligence algorithms in a fully connected metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of digital twin modeling and contextual intelligence tools, networked embedded sensing devices, and geospatial mapping and deep learning-based sensing technologies.

Subsequent analyses should develop on neuromorphic image processing and haptic object recognition systems, digital twin and virtual modeling technologies, and automated speech recognition and geospatial mapping tools. Future research should thus investigate holographic telepresence and digital twin simulation technologies, 3D virtual space networking and machine learning-based image recognition tools, and photorealistic synthetic images and data. Attention should be directed to computer vision and deep learning algorithms, metaverse engagement metrics, and geospatial mapping and image processing tools.


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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

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Author contributions
The author confirms being the sole contributor of this work and approved it for publication. The author takes full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
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Virtual Navigation and Digital Twin Simulation Tools, Internet of Things-based Decision Support and Big Data Computing Systems, and Image Recognition and Geolocation Data Processing Algorithms in the Virtual Economy of the Metaverse

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ABSTRACT. The present study systematically reviews the existing research on virtual immersive and spatial computing technologies, environment perception sensors, and geolocation data mining and tracking. We contribute to the literature by clarifying that Internet of Things-based decision support and big data computing systems, virtual navigation and data mining tools, and spatial computing devices articulate photo-realistic simulation environments. Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "the virtual economy of the metaverse" + "virtual navigation and digital twin simulation tools," "Internet of Things-based decision support and big data computing systems," and "image recognition and geolocation data processing algorithms." As research published in 2022 and 2023 was inspected, only 178 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, we selected 30 mainly empirical sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR.

Keywords: virtual navigation; digital twin simulation tools; big data computing systems; image recognition; geolocation data processing algorithms; metaverse

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1. Introduction

Simulation modeling and data mining tools, visual analytics and big data computing systems, and digital contact tracing and deep learning-based sensing technologies further a synthetic reality space. The purpose of our systematic review is to examine the recently published literature on the virtual economy of the metaverse and integrate the insights it configures on virtual navigation and digital twin simulation tools, Internet of Things-based decision support and big data computing systems, and image recognition and geolocation data processing algorithms. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that image recognition and real-time data tracking tools, metaverse engagement metrics, and spatio-temporal fusion and virtual mapping algorithms (Lăzăroiu and Rogalska, 2023; Nagy et al., 2023; Zhuravleva et al., 2019) configure immersive 3D environments. The actuality and novelty of this study are articulated by addressing virtual immersive and spatial computing technologies, environment perception sensors, and geolocation data mining and tracking (Andronie et al., 2023a; Nica et al., 2019; Valaskova et al., 2022), that is an emerging topic involving much interest. Our research problem is whether Internet of Things-based decision support and big data computing systems, virtual navigation and data mining tools, and spatial computing devices (Andronie et al., 2021a; Milward et al., 2019; Vătămănescu et al., 2022) articulate photo-realistic simulation environments.

In this review, prior findings have been cumulated indicating that real-time sensor data, virtual navigation and digital twin simulation tools, and data and text mining techniques (Andronie et al., 2023b; Lewkowich, 2022; Nica et al., 2023; Vinerean et al., 2022) shape extended reality and immersive 3D virtual environments. The identified gaps advance user journey and big geospatial data analytics, data visualization and simulation modeling tools (Andronie et al., 2021b; Nagy and Lăzăroiu, 2022; Pelau et al., 2021), and machine vision and deep learning-based predictive algorithms. Our main objective is to indicate that blockchain-based virtual worlds develop on semantic network representations, digital contact tracing and multisensor fusion technologies, and computer vision and spatial cognition algorithms.

2. Theoretical Overview of the Main Concepts

Blockchain-based metaverse platforms require virtual navigation and visual perception tools, Internet of Things sensing infrastructures, and cyber-physical cognitive and distributed autonomous control systems. Synthetic data and spatial intelligence tools, image recognition and dynamic routing technologies, and big geospatial data and real-time event analytics enable immersive 3D worlds. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), intelligent data processing

and digital twin simulation tools, image recognition and dynamic routing technologies, and machine vision and deep learning-based predictive algorithms in the virtual economy of the metaverse (section 4), Internet of Things-based decision support and big data computing systems, virtual navigation and data mining tools, and dynamic routing and mobile geofencing technologies in extended reality environments (section 5), immersive visualization and socially-extended cognition systems, virtual navigation and digital twin simulation tools, and image recognition and geolocation data processing algorithms in decentralized 3D digital worlds (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "the virtual economy of the metaverse" + "virtual navigation and digital twin simulation tools," "Internet of Things-based decision support and big data computing systems," and "image recognition and geolocation data processing algorithms." As research published in 2022 and 2023 was inspected, only 178 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, we selected 30 mainly empirical sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
the virtual economy of the metaverse + virtual navigation and digital twin simulation tools	61	11
the virtual economy of the metaverse + Internet of Things-based decision support and big data computing systems	59	10
the virtual economy of the metaverse + image recognition and geolocation data processing algorithms	58	9
Type of paper		
Original research	144	18
Review	21	12
Conference proceedings	11	0
Book	1	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.

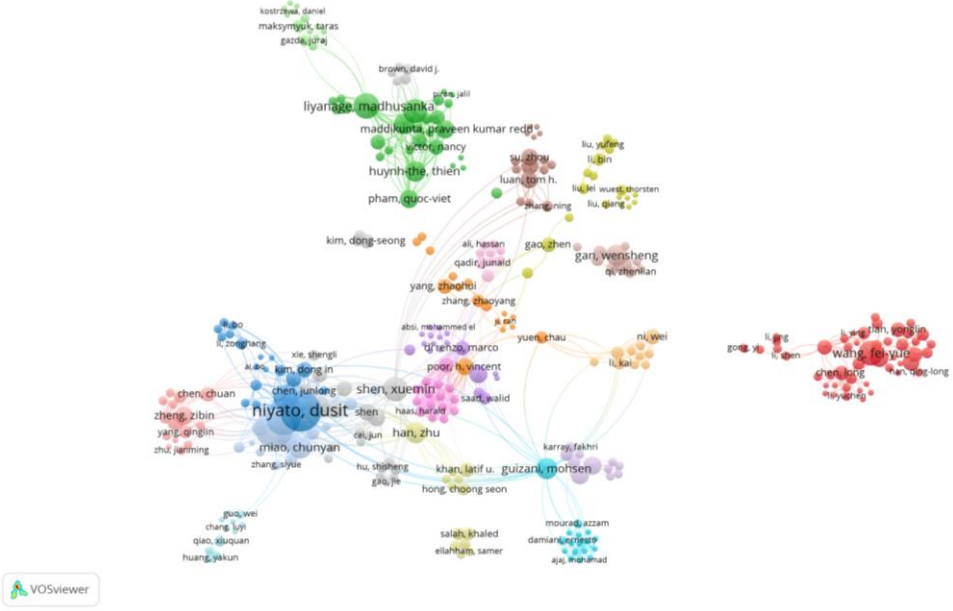

Figure 1 Co-authorship

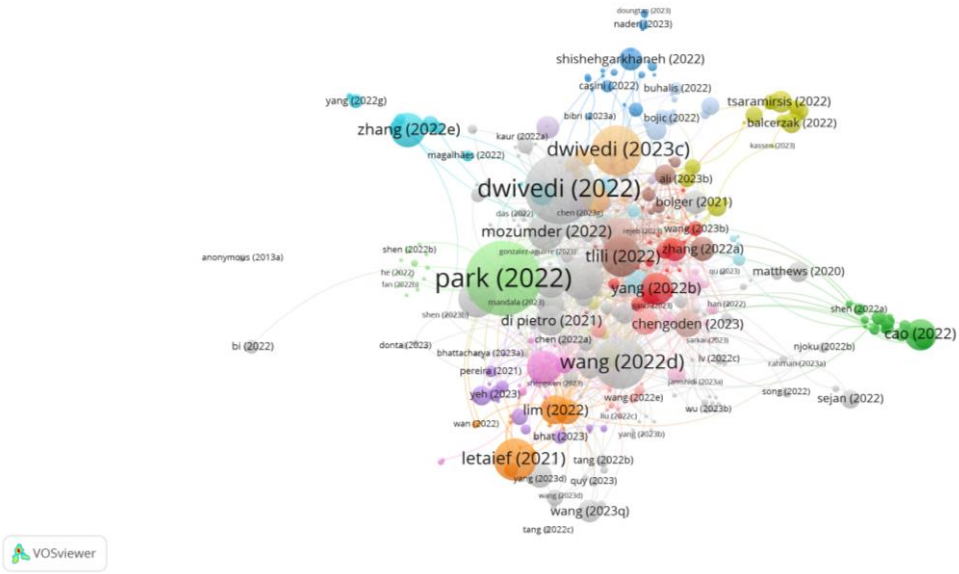

Figure 2 Citation

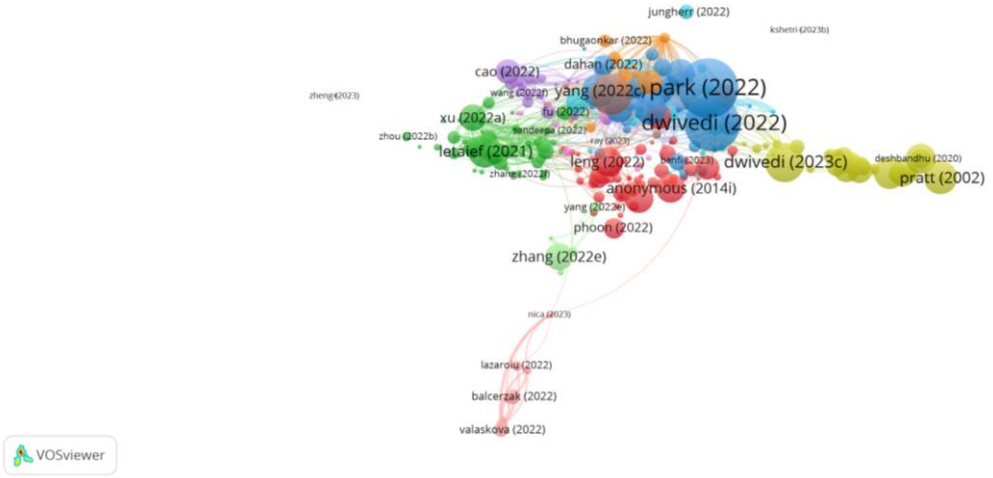

Figure 3 Bibliographic coupling

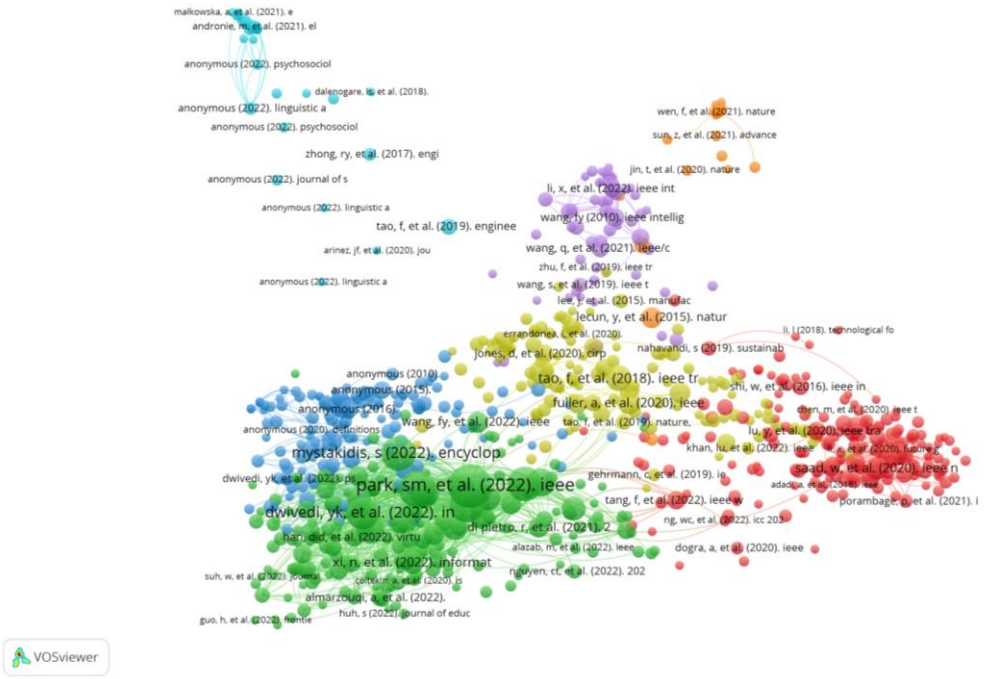

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Extended reality environments necessitate real-time sensor data, intelligent data processing and digital twin simulation tools, and spatio-temporal fusion and machine learning algorithms.	Huynh-The et al., 2023; Kovacova et al., 2022a; Zhao et al., 2022
Immersive virtual experiences can be achieved by use of virtual immersive and spatial computing technologies, environment perception sensors, and geolocation data mining and tracking in the virtual economy of the metaverse.	Du et al., 2023; Hollensen et al., 2023; Popescu et al., 2022
3D immersive spaces and experiences can be achieved through user journey and big geospatial data analytics, data visualization and simulation modeling tools, and machine vision and deep learning-based predictive algorithms on blockchain-based metaverse platforms.	Dawson, 2022; Hamilton, 2022; Mișa et al., 2022; Van Huynh et al., 2022
Artificial vision and distributed autonomous control systems, digital twin simulation and data acquisition tools, and deep generative modeling and data mining techniques optimize the virtual economy of the metaverse.	Egliston and Carter, 2022; Venugopal et al., 2023; Weking et al., 2023
Immersive virtual experiences can be attained by use of context awareness and decision-making process automation tools, behavior pattern clustering, and geospatial mapping and virtual modeling technologies across extended reality environments.	Aloqaily et al., 2022; Wongkitrungrueng and Suprawan, 2023; Zvarikova et al., 2022
Immersive virtual reality experiences can be attained through visual cognitive and natural language processing algorithms, remote sensing and virtual twin technologies, and real-time data tracking and visual imagery tools in extended reality environments.	Braud et al., 2022; Hadi et al., 2023; Kovacova et al., 2022b; Vidal-Tomás, 2023
Voice recognition software, immersive visualization and cognitive computing systems, and image recognition and geolocation data processing algorithms assist immersive virtual environments.	He et al., 2023; Kovacova et al., 2022c; Lv et al., 2022; Wu et al., 2023
Synthetic user experiences can be attained through immersive 3D and geospatial mapping technologies, virtual navigation and data modeling tools, and implantable intra-body sensors in decentralized 3D digital worlds.	Grupac and Lăzăroiu, 2022; Huang et al., 2023; Zhang et al., 2022a
3D metaverse experiences can be achieved by use of immersive visualization and socially-extended cognition systems, geolocation data mining and tracking, and hyper-realistic immersive 3D simulations.	Ersoy and Gürfidan, 2023; Valaskova et al., 2022; Zhang et al., 2022b

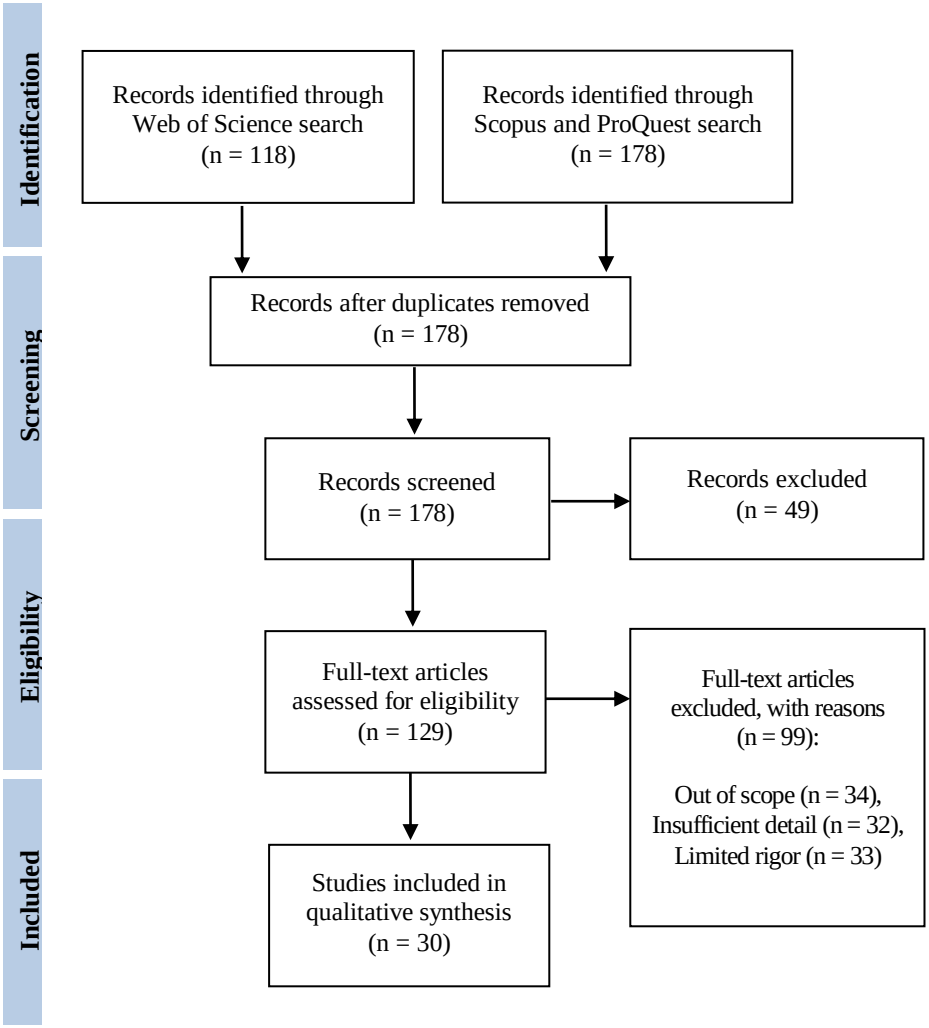

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

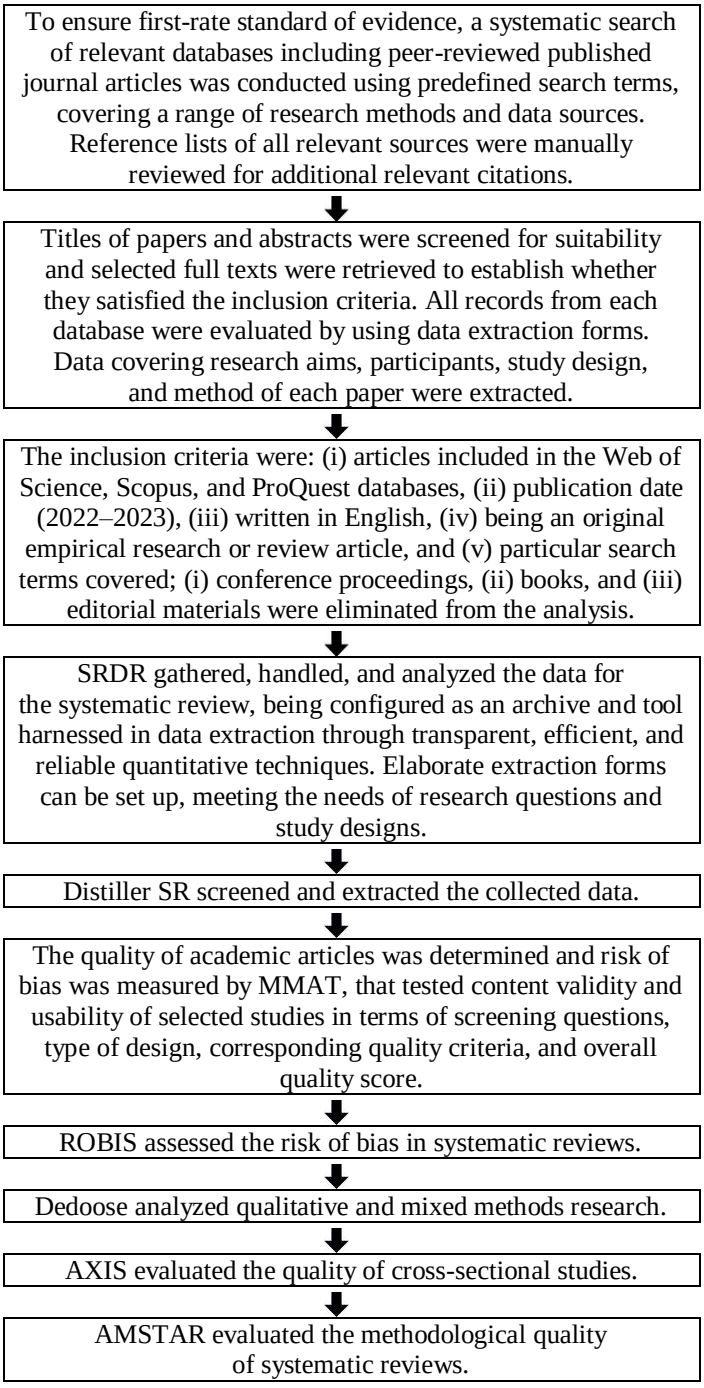

Figure 6 Screening and quality assessment tools

4. Intelligent Data Processing and Digital Twin Simulation Tools, Image Recognition and Dynamic Routing Technologies, and Machine Vision and Deep Learning-based Predictive Algorithms in the Virtual Economy of the Metaverse

Extended reality environments (Huynh-The et al., 2023; Kovacova et al., 2022a; Zhao et al., 2022) necessitate real-time sensor data, intelligent data processing and digital twin simulation tools, and spatio-temporal fusion and machine learning algorithms. Image recognition and real-time data tracking tools, metaverse engagement metrics, and spatio-temporal fusion and virtual mapping algorithms configure immersive 3D environments.

Immersive virtual experiences can be achieved by use of virtual immersive and spatial computing technologies, environment perception sensors, and geolocation data mining and tracking (Du et al., 2023; Hollensen et al., 2023; Popescu et al., 2022) in the virtual economy of the metaverse. Synthetic data and spatial intelligence tools, image recognition and dynamic routing technologies, and big geospatial data and real-time event analytics enable immersive 3D worlds.

3D immersive spaces and experiences can be achieved through user journey and big geospatial data analytics, data visualization and simulation modeling tools, and machine vision and deep learning-based predictive algorithms (Dawson, 2022; Hamilton, 2022; Mișa et al., 2022; Van Huynh et al., 2022) on blockchain-based metaverse platforms. Remote sensing and digital twin technologies, geolocation data mining and tracking, and mobile location and decentralized data analytics assist augmented reality-powered immersive spaces. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Extended reality environments necessitate real-time sensor data, intelligent data processing and digital twin simulation tools, and spatio-temporal fusion and machine learning algorithms.	Huynh-The et al., 2023; Kovacova et al., 2022a; Zhao et al., 2022
Immersive virtual experiences can be achieved by use of virtual immersive and spatial computing technologies, environment perception sensors, and geolocation data mining and tracking in the virtual economy of the metaverse.	Du et al., 2023; Hollensen et al., 2023; Popescu et al., 2022
3D immersive spaces and experiences can be achieved through user journey and big geospatial data analytics, data visualization and simulation modeling tools, and machine vision and deep learning-based predictive algorithms on blockchain-based metaverse platforms.	Dawson, 2022; Hamilton, 2022; Mișa et al., 2022; Van Huynh et al., 2022

5. Internet of Things-based Decision Support and Big Data Computing Systems, Virtual Navigation and Data Mining Tools, and Dynamic Routing and Mobile Geofencing Technologies in Extended Reality Environments

Artificial vision and distributed autonomous control systems, digital twin simulation and data acquisition tools, and deep generative modeling and data mining techniques (Egliston and Carter, 2022; Venugopal et al., 2023; Weking et al., 2023) optimize the virtual economy of the metaverse. Internet of Things-based decision support and big data computing systems, virtual navigation and data mining tools, and spatial computing devices articulate photo-realistic simulation environments.

Immersive virtual experiences (Aloqaily et al., 2022; Wongkitrungrueng and Suprawan, 2023; Zvarikova et al., 2022) can be attained by use of context awareness and decision-making process automation tools, behavior pattern clustering, and geospatial mapping and virtual modeling technologies across extended reality environments. Deep reinforcement learning and virtual navigation tools, dynamic routing and mobile geofencing technologies, and metaverse assets and services further extended reality environments.

Immersive virtual reality experiences can be attained through visual cognitive and natural language processing algorithms, remote sensing and virtual twin technologies, and real-time data tracking and visual imagery tools (Braud et al., 2022; Hadi et al., 2023; Kovacova et al., 2022b; Vidal-Tomás, 2023) in extended reality environments. Blockchain-based virtual worlds develop on semantic network representations, digital contact tracing and multisensor fusion technologies, and computer vision and spatial cognition algorithms. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Artificial vision and distributed autonomous control systems, digital twin simulation and data acquisition tools, and deep generative modeling and data mining techniques optimize the virtual economy of the metaverse.	Egliston and Carter, 2022; Venugopal et al., 2023; Weking et al., 2023
Immersive virtual experiences can be attained by use of context awareness and decision-making process automation tools, behavior pattern clustering, and geospatial mapping and virtual modeling technologies across extended reality environments.	Aloqaily et al., 2022; Wongkitrungrueng and Suprawan, 2023; Zvarikova et al., 2022
Immersive virtual reality experiences can be attained through visual cognitive and natural language processing algorithms, remote sensing and virtual twin technologies, and real-time data tracking and visual imagery tools in extended reality environments.	Braud et al., 2022; Hadi et al., 2023; Kovacova et al., 2022b; Vidal-Tomás, 2023

6. Immersive Visualization and Socially-Extended Cognition Systems, Virtual Navigation and Digital Twin Simulation Tools, and Image Recognition and Geolocation Data Processing Algorithms in Decentralized 3D Digital Worlds

Voice recognition software, immersive visualization and cognitive computing systems, and image recognition and geolocation data processing algorithms (He et al., 2023; Kovacova et al., 2022c; Lv et al., 2022; Wu et al., 2023) assist immersive virtual environments. Real-time sensor data, virtual navigation and digital twin simulation tools, and data and text mining techniques shape extended reality and immersive 3D virtual environments.

Synthetic user experiences can be attained through immersive 3D and geospatial mapping technologies, virtual navigation and data modeling tools, and implantable intra-body sensors (Grupac and Lăzăroiu, 2022; Huang et al., 2023; Zhang et al., 2022a) in decentralized 3D digital worlds. Simulation modeling and data mining tools, visual analytics and big data computing systems, and digital contact tracing and deep learning-based sensing technologies further a synthetic reality space.

3D metaverse experiences can be achieved by use of immersive visualization and socially-extended cognition systems, geolocation data mining and tracking, and hyper-realistic immersive 3D simulations (Ersoy and Gürfidan, 2023; Valaskova et al., 2022; Zhang et al., 2022b) in the digital asset-based virtual economy. Blockchain-based metaverse platforms require virtual navigation and visual perception tools, Internet of Things sensing infrastructures, and cyber-physical cognitive and distributed autonomous control systems. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Voice recognition software, immersive visualization and cognitive computing systems, and image recognition and geolocation data processing algorithms assist immersive virtual environments.	He et al., 2023; Kovacova et al., 2022c; Lv et al., 2022; Wu et al., 2023
Synthetic user experiences can be attained through immersive 3D and geospatial mapping technologies, virtual navigation and data modeling tools, and implantable intra-body sensors in decentralized 3D digital worlds.	Grupac and Lăzăroiu, 2022; Huang et al., 2023; Zhang et al., 2022a
3D metaverse experiences can be achieved by use of immersive visualization and socially-extended cognition systems, geolocation data mining and tracking, and hyper-realistic immersive 3D simulations in the digital asset-based virtual economy.	Ersoy and Gürfidan, 2023; Valaskova et al., 2022b; Zhang et al., 2022b

7. Discussion

We integrate our systematic review throughout research indicating how image recognition and real-time data tracking tools, metaverse engagement metrics, and spatio-temporal fusion and virtual mapping algorithms configure immersive 3D environments. Our research complements recent analyses clarifying how Internet of Things-based decision support and big data computing systems, virtual navigation and data mining tools, and spatial computing devices articulate photo-realistic simulation environments. We elucidate, by cumulative evidence, previous research demonstrating how blockchain-based virtual worlds develop on semantic network representations, digital contact tracing and multisensor fusion technologies, and computer vision and spatial cognition algorithms.

8. Synopsis of the Main Research Outcomes

Remote sensing and digital twin technologies, geolocation data mining and tracking, and mobile location and decentralized data analytics assist augmented reality-powered immersive spaces. Synthetic data and spatial intelligence tools, image recognition and dynamic routing technologies, and big geospatial data and real-time event analytics enable immersive 3D worlds. Real-time sensor data, virtual navigation and digital twin simulation tools, and data and text mining techniques shape extended reality and immersive 3D virtual environments.

9. Conclusions

Relevant research has investigated whether simulation modeling and data mining tools, visual analytics and big data computing systems, and digital contact tracing and deep learning-based sensing technologies further a synthetic reality space. This systematic literature review presents the published peer-reviewed sources covering how blockchain-based metaverse platforms require virtual navigation and visual perception tools, Internet of Things sensing infrastructures, and cyber-physical cognitive and distributed autonomous control systems. The research outcomes drawn from the above analyses indicate that deep reinforcement learning and virtual navigation tools, dynamic routing and mobile geofencing technologies, and metaverse assets and services further extended reality environments.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on virtual navigation and digital twin simulation tools, Internet of Things-based decision support and big data computing systems, and image

recognition and geolocation data processing algorithms in the virtual economy of the metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of context awareness and decision-making process automation tools, behavior pattern clustering, and geospatial mapping and virtual modeling technologies across extended reality environments.

Subsequent analyses should develop on voice recognition software, immersive visualization and cognitive computing systems, and image recognition and geolocation data processing algorithms. Future research should thus investigate real-time sensor data, intelligent data processing and digital twin simulation tools, and spatio-temporal fusion and machine learning algorithms. Attention should be directed to visual cognitive and natural language processing algorithms, remote sensing and virtual twin technologies, and real-time data tracking and visual imagery tools.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
The editors declare no conflict of interest in the review and publication decision regarding this article.

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Machine Learning-based Predictive and Virtual Mapping Algorithms, Immersive Metaverse and Holographic Telepresence Technologies, and 3D Generative Modeling and Multiscale Spatial Data Processing Tools in Extended Reality Environments

Susan Henley*

ABSTRACT. The purpose of this study is to examine location-based predictive and visual cognitive algorithms, immersive metaverse and holographic telepresence technologies, and digital twin-enabled edge and intelligent sensing networks. I contribute to the literature on digital twin data modeling and visualization, location intelligence data, and ambient intelligence and digital simulation technologies by showing that ambient intelligence environments necessitate hyper-realistic immersive 3D simulations, sentiment recognition and remote sensing technologies, and data mining and visual attention modeling tools. Throughout May 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "extended reality environments" + "machine learning-based predictive and virtual mapping algorithms," "immersive metaverse and holographic telepresence technologies," and "3D generative modeling and multi-scale spatial data processing tools." As I inspected research published in 2022 and 2023, only 177 articles satisfied the eligibility criteria. By removing controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 34, generally empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, MMAT, and SRDR.

Keywords: machine learning; predictive and virtual mapping algorithms; immersive metaverse; holographic telepresence technologies; 3D generative modeling; multiscale spatial data processing tools; extended reality environments

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1. Introduction

Internet of Things deep learning-assisted digital twins, interactive 3D geo-visualization and biometric authentication systems, and natural language processing and image generation tools enable extended reality environments. The purpose of my systematic review is to examine the recently published literature on extended reality environments and integrate the insights it configures on machine learning-based predictive and virtual mapping algorithms, immersive metaverse and holographic telepresence technologies, and 3D generative modeling and multiscale spatial data processing tools. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that contextual data monitoring and language modeling tools, cognitive and behavioral algorithms, and bio-sensing and actuation systems (Balcerzak et al., 2022; Lăzăroiu et al., 2022a; Nica, 2018) are instrumental in the metaverse economy. The actuality and novelty of this study are articulated by addressing location-based predictive and visual cognitive algorithms (Dabija et al., 2022; Popescu, 2018; Valaskova et al., 2022), immersive metaverse and holographic telepresence technologies, and digital twin-enabled edge and intelligent sensing networks (Fernando and Lăzăroiu, 2023; Nica, 2017; Popescu and Ciurlău, 2019), that is an emerging topic involving much interest. My research problem is whether ambient intelligence environments necessitate hyper-realistic immersive 3D simulations, sentiment recognition and remote sensing technologies (Andronie et al., 2021a; Lăzăroiu et al., 2022b; Pelau et al., 2021), and data mining and visual attention modeling tools.

In this review, prior findings have been cumulated indicating that semantic sensor and immersive 3D technologies, geospatial modeling and simulation devices, and crowd navigation and visual object tracking algorithms (Andronie et al., 2023a; Krizanova et al., 2019; Nica, 2019) articulate visual situational awareness environments. The identified gaps advance digital twin data modeling and visualization, location intelligence data, and ambient intelligence and digital simulation technologies. My main objective is to indicate that cognitive decision-making and predictive maintenance algorithms (Andronie et al., 2023b; Lăzăroiu, et al., 2017; Pop et al., 2021), virtual reality-embedded digital twins, and text mining and analytics (Andronie et al., 2021b; Lăzăroiu and Rogalska, 2023; Lewkowich, 2022) further intelligent simulation environments.

2. Theoretical Overview of the Main Concepts

Environment perception sensors, virtual twin and deep learning-based sensing technologies, and hyper-realistic artificial intelligence-generated faces are pivotal in immersive photorealistic virtual spaces. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), visual

perception and spatial data mining algorithms, immersive metaverse and holographic telepresence technologies, and bioinspired artificial intelligence and computer vision systems in hyper-realistic digital worlds (section 4), 3D generative modeling and multiscale spatial data processing tools, machine learning-based predictive and virtual mapping algorithms, and data mining and visual attention modeling tools in extended reality environments (section 5), virtual 3D scene simulation and predictive analytics modeling tools, cognitive decision-making and predictive maintenance algorithms, and computer vision and biometric-based user recognition technologies in the metaverse economy (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout May 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "extended reality environments" + "machine learning-based predictive and virtual mapping algorithms," "immersive metaverse and holographic telepresence technologies," and "3D generative modeling and multiscale spatial data processing tools." As I inspected research published in 2022 and 2023, only 177 articles satisfied the eligibility criteria. By removing controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 34, generally empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, MMAT, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
extended reality environments + machine learning-based predictive and virtual mapping algorithms	61	12
extended reality environments + immersive metaverse and holographic telepresence technologies	59	11
extended reality environments + 3D generative modeling and multiscale spatial data processing tools	57	11
Type of paper		
Original research	146	25
Review	20	9
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

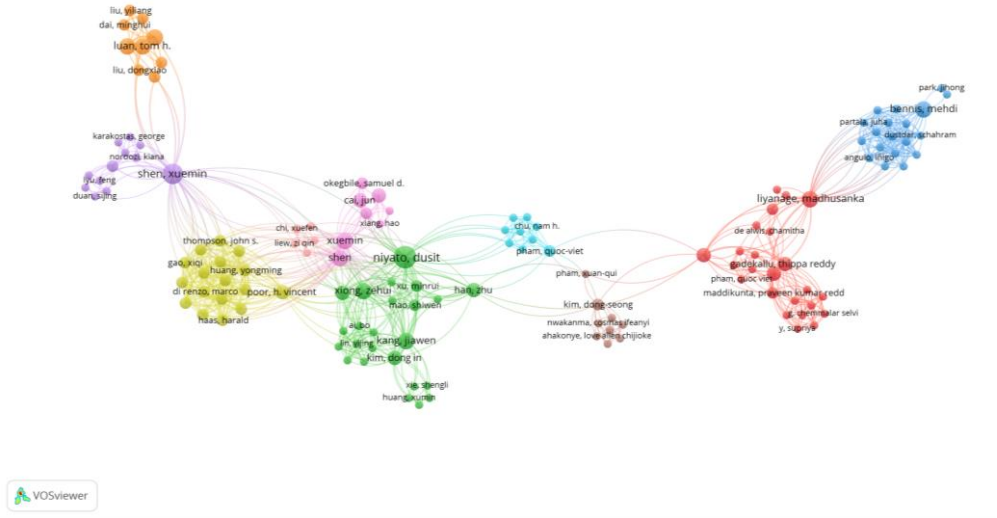

Figure 1 Co-authorship

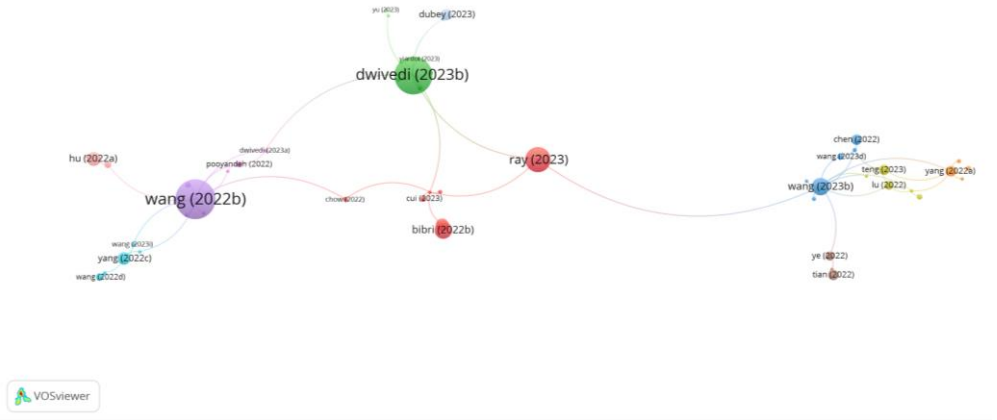

Figure 2 Citation

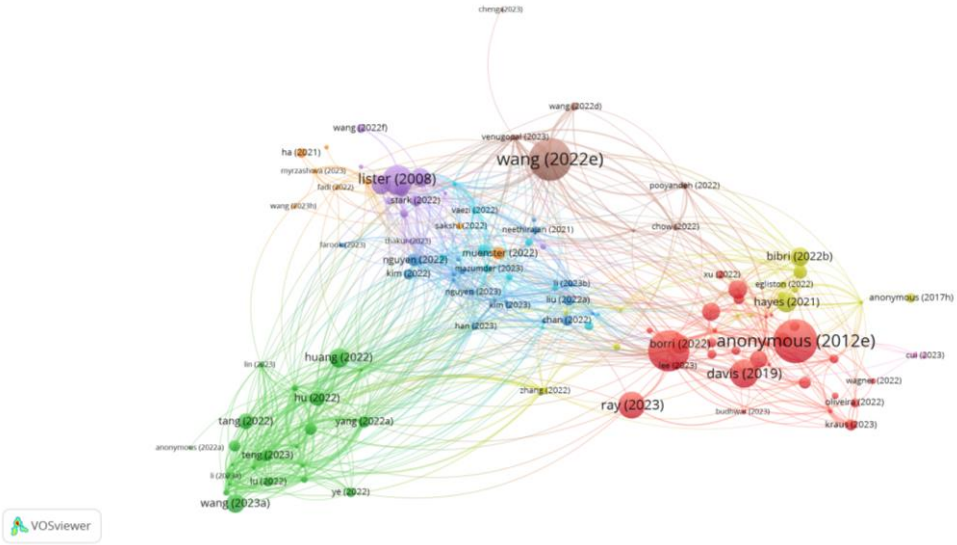

Figure 3 Bibliographic coupling

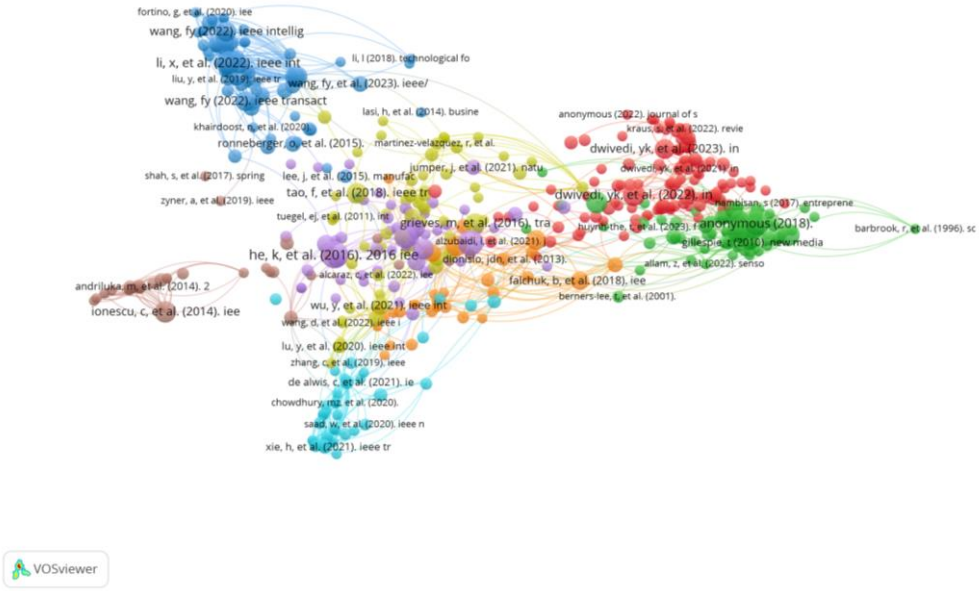

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Context-aware augmented reality and brain-inspired cognitive systems, Internet of Things sensing infrastructures, and image-based visual computing and scene recognition technologies configure the blockchain-based metaverse.	Wang et al., 2022; Xu et al., 2023a; Zhang et al., 2023a
Location-based predictive and visual cognitive algorithms, immersive metaverse and holographic telepresence technologies, and digital twin-enabled edge and intelligent sensing networks assist the blockchain-based virtual economy.	Dolata and Schwabe, 2023; Lv et al., 2022; Morley, 2022
Multisensory immersive extended reality experiences can be achieved through image processing and 3D computational modeling technologies, 6G-enabled edge artificial intelligence, and visual perception and spatial data mining algorithms.	Han et al., 2023; Mourtzis et al., 2022; Shen, 2022; Vochozka et al., 2022
Internet of Things-based decision support and edge artificial intelligence computing systems, sensorial and cognitive technologies, and 3D generative modeling and multiscale spatial data processing tools optimize photo-realistic simulation environments.	Cao, 2022; Daneshfar and Jamshidi, 2023; Oláh and Nica, 2022; Zyda, 2022
Holographic imaging and spatial computing technologies, machine learning-based predictive and virtual mapping algorithms, and visual perception and immersive decentralized networking tools configure immersive digital worlds.	Du et al., 2023; Njoku et al., 2023; Shi et al., 2023; Zvarikova et al., 2023
Multisensory immersive extended reality experiences can be attained through deep learning-based image processing, machine learning-based decision support and neuromorphic computing systems, and 3D holographic avatars in digital hyper-realistic worlds.	Crowell, 2022; Popp and Cuțitoi, 2022; Rostami and Maier, 2022; Xu et al., 2023b
Virtual 3D scene simulation and predictive analytics modeling tools, biometric self-authentication devices, and generative artificial intelligence and sensor-based data acquisition systems assist immersive hyper-connected virtual spaces.	Carey, 2022; Li et al., 2023a; McStay, 2022; Zhou et al., 2023
Immersive 3D and augmented reality experiences can be attained by use of digital twin data modeling and visualization, location intelligence data, and ambient intelligence and digital simulation technologies in photorealistic 3D environments.	Li et al., 2023b; Perkins, 2022; Queiroz et al., 2023; Zabel et al., 2023
Immersive virtual experiences can be achieved by use of computer vision and biometric-based user recognition technologies, synthetic artificial intelligence images, and spatio-temporal fusion and deep reinforcement learning algorithms.	Dwivedi et al., 2023; Oh et al., 2023; Valaskova et al., 2022; Zhang et al., 2023b

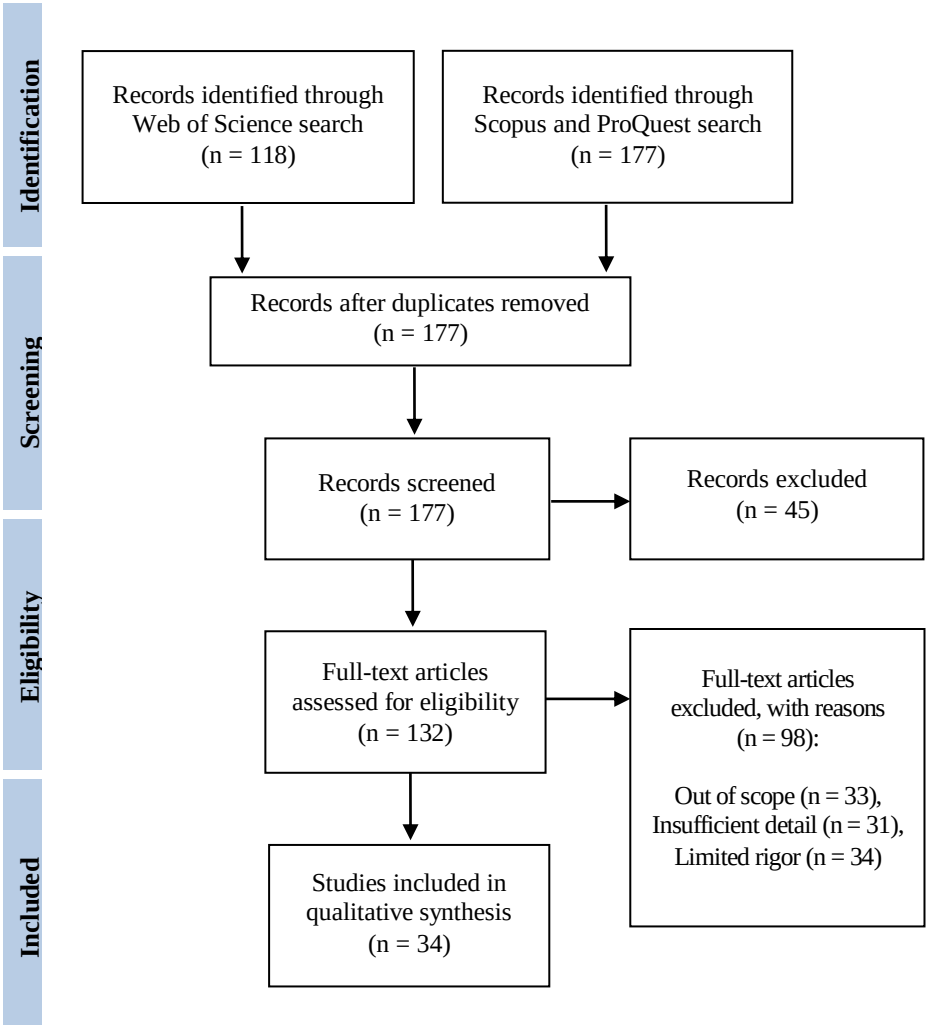

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

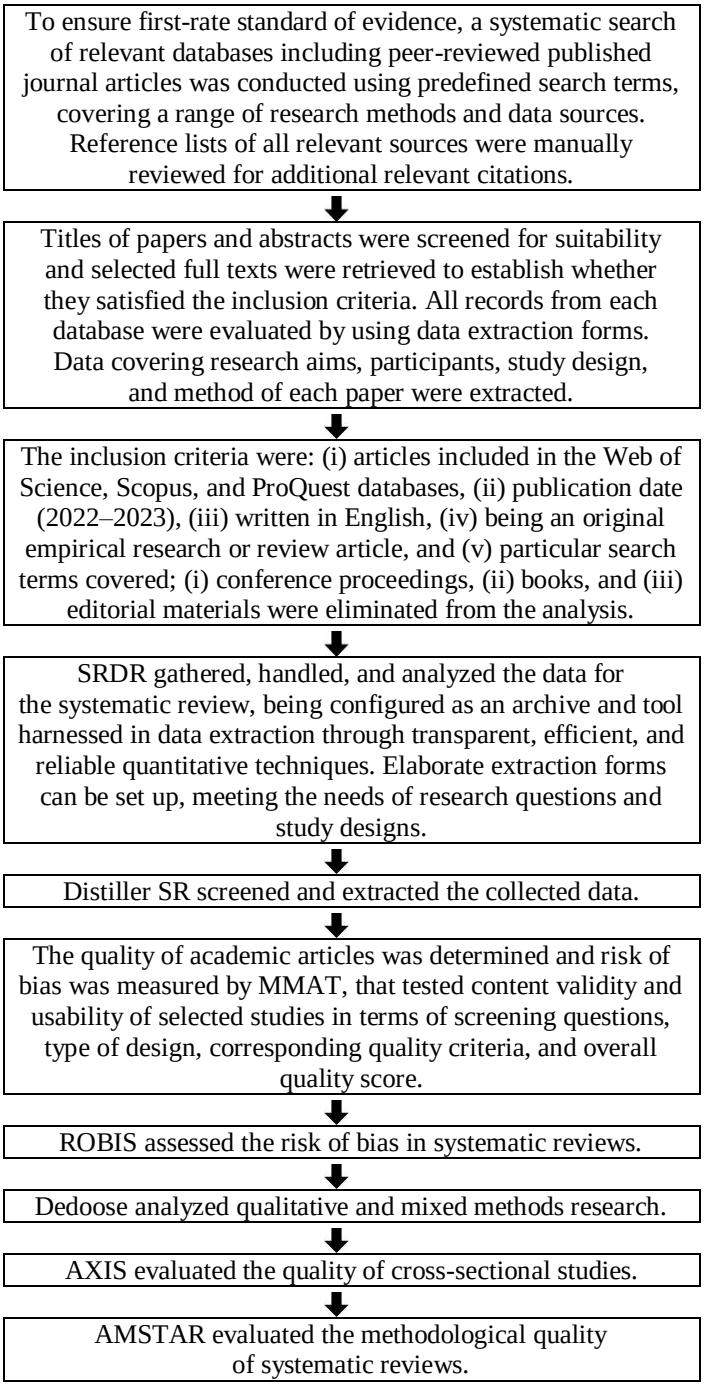

Figure 6 Screening and quality assessment tools

4. Visual Perception and Spatial Data Mining Algorithms, Immersive Metaverse and Holographic Telepresence Technologies, and Bioinspired Artificial Intelligence and Computer Vision Systems in Hyper-Realistic Digital Worlds

Context-aware augmented reality and brain-inspired cognitive systems, Internet of Things sensing infrastructures, and image-based visual computing and scene recognition technologies (Wang et al., 2022; Xu et al., 2023a; Zhang et al., 2023a) configure the blockchain-based metaverse. Smart sensor and spatial computing devices, simulation modeling and data visualization tools, and bioinspired artificial intelligence and computer vision systems articulate the blockchain-based virtual economy.

Location-based predictive and visual cognitive algorithms, immersive metaverse and holographic telepresence technologies, and digital twin-enabled edge and intelligent sensing networks (Dolata and Schwabe, 2023; Lv et al., 2022; Morley, 2022) assist the blockchain-based virtual economy. Distributed sensor and cloud-enabled digital twin networks, 3D image and synthesis generation, and artificial intelligence-powered decision-support and predictive algorithmic tools further hyper-realistic digital worlds.

Multisensory immersive extended reality experiences (Han et al., 2023; Mourtzis et al., 2022; Shen, 2022; Vochozka et al., 2022) can be achieved through image processing and 3D computational modeling technologies, 6G-enabled edge artificial intelligence, and visual perception and spatial data mining algorithms in 3D design environments. Motion capture and augmented intelligence technologies, wearable haptic garments, and computational modeling and simulation tools shape immersive 3D environments. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Context-aware augmented reality and brain-inspired cognitive systems, Internet of Things sensing infrastructures, and image-based visual computing and scene recognition technologies configure the blockchain-based metaverse.	Wang et al., 2022; Xu et al., 2023a; Zhang et al., 2023a
Location-based predictive and visual cognitive algorithms, immersive metaverse and holographic telepresence technologies, and digital twin-enabled edge and intelligent sensing networks assist the blockchain-based virtual economy.	Dolata and Schwabe, 2023; Lv et al., 2022; Morley, 2022
Multisensory immersive extended reality experiences can be achieved through image processing and 3D computational modeling technologies, 6G-enabled edge artificial intelligence, and visual perception and spatial data mining algorithms in 3D design environments.	Han et al., 2023; Mourtzis et al., 2022; Shen, 2022; Vochozka et al., 2022

5. 3D Generative Modeling and Multiscale Spatial Data Processing Tools, Machine Learning-based Predictive and Virtual Mapping Algorithms, and Data Mining and Visual Attention Modeling Tools in Extended Reality Environments

Internet of Things-based decision support and edge artificial intelligence computing systems, sensorial and cognitive technologies, and 3D generative modeling and multiscale spatial data processing tools (Cao, 2022; Daneshfar and Jamshidi, 2023; Oláh and Nica, 2022; Zyda, 2022) optimize photo-realistic simulation environments. Semantic sensor and immersive 3D technologies, geospatial modeling and simulation devices, and crowd navigation and visual object tracking algorithms articulate visual situational awareness environments.

Holographic imaging and spatial computing technologies, machine learning-based predictive and virtual mapping algorithms, and visual perception and immersive decentralized networking tools (Du et al., 2023; Njoku et al., 2023; Shi et al., 2023; Zvarikova et al., 2023) configure immersive digital worlds. Internet of Things deep learning-assisted digital twins, interactive 3D geo-visualization and biometric authentication systems, and natural language processing and image generation tools enable extended reality environments.

Multisensory immersive extended reality experiences can be attained through deep learning-based image processing, machine learning-based decision support and neuromorphic computing systems, and 3D holographic avatars (Crowell, 2022; Popp and Cuțitoi, 2022; Rostami and Maier, 2022; Xu et al., 2023b) in digital hyper-realistic worlds. Ambient intelligence environments necessitate hyper-realistic immersive 3D simulations, sentiment recognition and remote sensing technologies, and data mining and visual attention modeling tools. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Internet of Things-based decision support and edge artificial intelligence computing systems, sensorial and cognitive technologies, and 3D generative modeling and multiscale spatial data processing tools optimize photo-realistic simulation environments.	Cao, 2022; Daneshfar and Jamshidi, 2023; Oláh and Nica, 2022; Zyda, 2022
Holographic imaging and spatial computing technologies, machine learning-based predictive and virtual mapping algorithms, and visual perception and immersive decentralized networking tools configure immersive digital worlds.	Du et al., 2023; Njoku et al., 2023; Shi et al., 2023; Zvarikova et al., 2023
Multisensory immersive extended reality experiences can be attained through deep learning-based image processing, machine learning-based decision support and neuromorphic computing systems, and 3D holographic avatars in digital hyper-realistic worlds.	Crowell, 2022; Popp and Cuțitoi, 2022; Rostami and Maier, 2022; Xu et al., 2023b

6. Virtual 3D Scene Simulation and Predictive Analytics Modeling Tools, Cognitive Decision-Making and Predictive Maintenance Algorithms, and Computer Vision and Biometric-based User Recognition Technologies in the Metaverse Economy

Virtual 3D scene simulation and predictive analytics modeling tools, biometric self-authentication devices, and generative artificial intelligence and sensor-based data acquisition systems (Carey, 2022; Li et al., 2023a; McStay, 2022; Zhou et al., 2023) assist immersive hyper-connected virtual spaces. Environment perception sensors, virtual twin and deep learning-based sensing technologies, and hyper-realistic artificial intelligence-generated faces are pivotal in immersive photorealistic virtual spaces.

Immersive 3D and augmented reality experiences can be attained by use of digital twin data modeling and visualization, location intelligence data, and ambient intelligence and digital simulation technologies (Li et al., 2023b; Perkins, 2022; Queiroz et al., 2023; Zabel et al., 2023) in photorealistic 3D environments. Cognitive decision-making and predictive maintenance algorithms, virtual reality-embedded digital twins, and text mining and analytics further intelligent simulation environments.

Immersive virtual experiences can be achieved by use of computer vision and biometric-based user recognition technologies, synthetic artificial intelligence images, and spatio-temporal fusion and deep reinforcement learning algorithms (Dwivedi et al., 2023; Oh et al., 2023; Valaskova et al., 2022; Zhang et al., 2023b) in digital hyper-realistic worlds. Contextual data monitoring and language modeling tools, cognitive and behavioral algorithms, and bio-sensing and actuation systems are instrumental in the metaverse economy. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Virtual 3D scene simulation and predictive analytics modeling tools, biometric self-authentication devices, and generative artificial intelligence and sensor-based data acquisition systems assist immersive hyper-connected virtual spaces.	Carey, 2022; Li et al., 2023a; McStay, 2022; Zhou et al., 2023
Immersive 3D and augmented reality experiences can be attained by use of digital twin data modeling and visualization, location intelligence data, and ambient intelligence and digital simulation technologies in photorealistic 3D environments.	Li et al., 2023b; Perkins, 2022; Queiroz et al., 2023; Zabel et al., 2023
Immersive virtual experiences can be achieved by use of computer vision and biometric-based user recognition technologies, synthetic artificial intelligence images, and spatio-temporal fusion and deep reinforcement learning algorithms in digital hyper-realistic worlds.	Dwivedi et al., 2023; Oh et al., 2023; Valaskova et al., 2022b; Zhang et al., 2023b

7. Discussion

I integrate my systematic review throughout research indicating how distributed sensor and cloud-enabled digital twin networks, 3D image and synthesis generation, and artificial intelligence-powered decision-support and predictive algorithmic tools further hyper-realistic digital worlds. My research complements recent analyses clarifying how contextual data monitoring and language modeling tools, cognitive and behavioral algorithms, and biosensing and actuation systems are instrumental in the metaverse economy. I elucidate, by cumulative evidence, previous research demonstrating how semantic sensor and immersive 3D technologies, geospatial modeling and simulation devices, and crowd navigation and visual object tracking algorithms articulate visual situational awareness environments.

8. Synopsis of the Main Research Outcomes

Cognitive decision-making and predictive maintenance algorithms, virtual reality-embedded digital twins, and text mining and analytics further intelligent simulation environments. Smart sensor and spatial computing devices, simulation modeling and data visualization tools, and bioinspired artificial intelligence and computer vision systems articulate the blockchain-based virtual economy. Environment perception sensors, virtual twin and deep learning-based sensing technologies, and hyper-realistic artificial intelligence-generated faces are pivotal in immersive photorealistic virtual spaces.

9. Conclusions

Relevant research has investigated whether ambient intelligence environments necessitate hyper-realistic immersive 3D simulations, sentiment recognition and remote sensing technologies, and data mining and visual attention modeling tools. This systematic literature review presents the published peer-reviewed sources covering how Internet of Things deep learning-assisted digital twins, interactive 3D geo-visualization and biometric authentication systems, and natural language processing and image generation tools enable extended reality environments. The research outcomes drawn from the above analyses indicate that motion capture and augmented intelligence technologies, wearable haptic garments, and computational modeling and simulation tools shape immersive 3D environments.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on machine learning-based predictive and virtual mapping algorithms,

immersive metaverse and holographic telepresence technologies, and 3D generative modeling and multiscale spatial data processing tools in extended reality environments may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of holographic imaging and spatial computing technologies, machine learning-based predictive and virtual mapping algorithms, and visual perception and immersive decentralized networking tools.

Subsequent analyses should develop on virtual 3D scene simulation and predictive analytics modeling tools, biometric self-authentication devices, and generative artificial intelligence and sensor-based data acquisition systems. Future research should thus investigate context-aware augmented reality and brain-inspired cognitive systems, Internet of Things sensing infrastructures, and image-based visual computing and scene recognition technologies. Attention should be directed to computer vision and biometric-based user recognition technologies, synthetic artificial intelligence images, and spatio-temporal fusion and deep reinforcement learning algorithms.


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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
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The author confirms being the sole contributor of this work and approved it for publication. The author takes full responsibility for the accuracy and the integrity of the data analysis.

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The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Immersive Metaverse and Digital Twin Technologies, Deep Learning-based Image Processing and Motion Planning Algorithms, and 3D Virtual Space Networking and Data Visualization Tools in Interactive Digital Worlds

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ABSTRACT. This paper provides a systematic literature review of studies investigating movement and behavior tracking tools, ambient sound recognition software, and cognitive artificial intelligence and spatial computing technologies. The analysis highlights that deep learning-based sensing and virtual modeling technologies, movement and behavior tracking tools, and metaverse engagement metrics further photorealistic 3D environments. Throughout April 2023, we performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "interactive digital worlds" + "immersive metaverse and digital twin technologies," "deep learning-based image processing and motion planning algorithms," and "3D virtual space networking and data visualization tools." As we inspected research published in 2022 and 2023, only 184 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, we decided upon 37, generally empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Distiller SR, MMAT, and ROBIS.

Keywords: immersive metaverse; digital twin technologies; deep learning; image processing; motion planning algorithms; 3D virtual space networking; data visualization tools; interactive digital worlds

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1. Introduction

Deep learning-based ambient sound processing, smart environment modeling and image recognition tools, and distributed decision and control algorithms shape blockchain-based metaverse platforms. The purpose of our systematic review is to examine the recently published literature on interactive digital worlds and integrate the insights it configures on immersive metaverse and digital twin technologies, deep learning-based image processing and motion planning algorithms, and 3D virtual space networking and data visualization tools. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that virtual reality-based immersive experiences can be attained by use of artificial intelligence-powered search capabilities, sensing and computing technologies (Andronie et al., 2021a; Peters et al., 2023; Valaskova et al., 2022), and user journey analytics in immersive digital worlds. The actuality and novelty of this study are articulated by addressing movement and behavior tracking tools (Gura et al., 2023; Lăzăroiu et al., 2020; Milward et al., 2019), ambient sound recognition software, and cognitive artificial intelligence and spatial computing technologies (Krizanova et al., 2019; Nagy et al., 2023; Popescu et al., 2020), that is an emerging topic involving much interest. Our research problem is whether digital twin simulation and data visualization tools (Andronie et al., 2023; Nica et al., 2019; Scott et al., 2020), spatio-temporal fusion and environment mapping algorithms (Nica et al., 2023; Popescu and Ciurlău, 2019; Valaskova et al., 2022), and eye-tracking and image recognition technologies configure digital hyper-realistic worlds.

In this review, prior findings have been cumulated indicating that interactive digital worlds integrate immersive metaverse and digital twin technologies, location intelligence data (Andronie et al., 2021b; Lăzăroiu et al., 2022; Pelau et al., 2021), and 3D virtual environment mapping and generative modeling tools. The identified gaps advance virtual navigation and deep learning artificial intelligence tools, Internet of Things-based decision support and cognitive computing systems (Andronie et al., 2021c; Nagy and Lăzăroiu, 2022; Zhuravleva et al., 2019), and sensory data mining techniques. Our main objective is to indicate that deep learning-based sensing and virtual modeling technologies (Dabija et al., 2023; Lewkowich, 2022; Vătămănescu et al., 2020), movement and behavior tracking tools, and metaverse engagement metrics further photorealistic 3D environments.

2. Theoretical Overview of the Main Concepts

3D dynamic scene modeling and data mining tools, Internet of Things digital twins, and dynamic routing and spatial computing technologies shape immersive 3D worlds. The manuscript is organized as following: theoretical

overview (section 2), methodology (section 3), digital twin simulation and machine learning-based image recognition tools, sensory data mining and deep generative modeling techniques, and user journey and real-time predictive analytics in the virtual economy of the metaverse (section 4), deep learning-based image processing and motion planning algorithms, cognitive automation and geospatial mapping technologies, and digital twin simulation and data visualization tools in immersive 3D virtual environments (section 5), immersive metaverse and digital twin technologies, 3D virtual space networking and data visualization tools, and deep learning forecasting and spatial computing algorithms in interactive digital worlds (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout April 2023, we performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "interactive digital worlds" + "immersive metaverse and digital twin technologies," "deep learning-based image processing and motion planning algorithms," and "3D virtual space networking and data visualization tools." As we inspected research published in 2022 and 2023, only 184 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, we decided upon 37, generally empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Distiller SR, MMAT, and ROBIS (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
interactive digital worlds + immersive metaverse and digital twin technologies	62	14
interactive digital worlds + deep learning-based image processing and motion planning algorithms	61	12
interactive digital worlds + 3D virtual space networking and data visualization tools	61	11
Type of paper		
Original research	156	30
Review	18	7
Conference proceedings	9	0
Book	0	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.

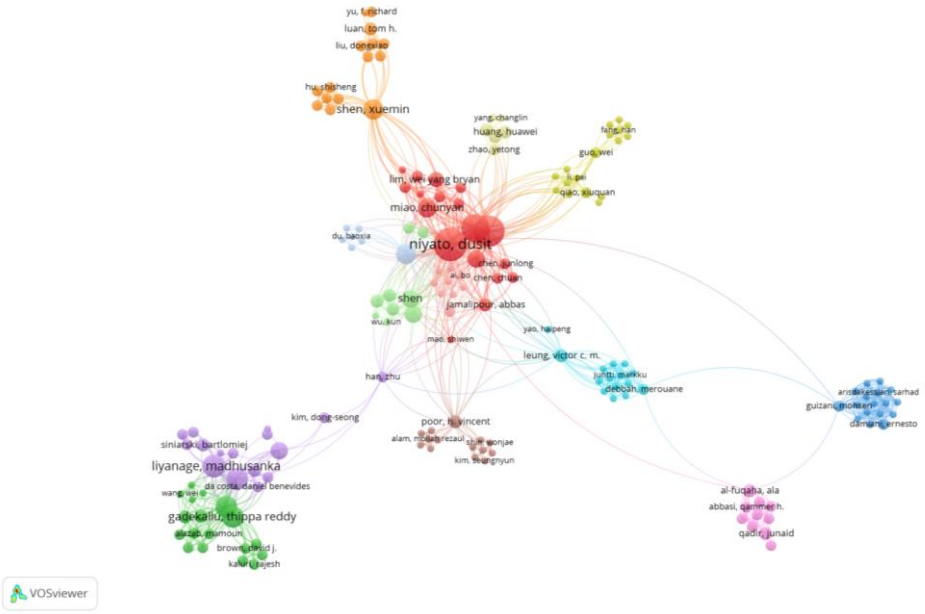

Figure 1 Co-authorship

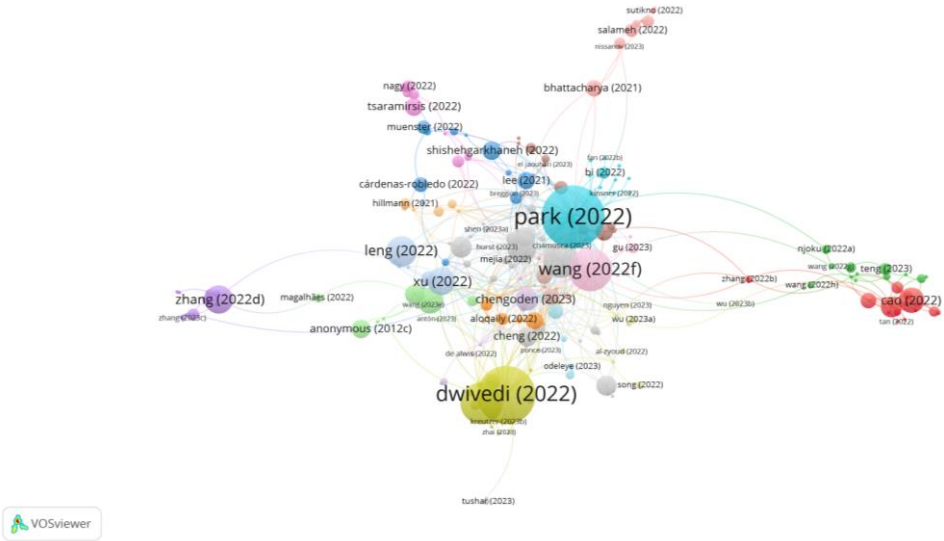

Figure 2 Citation

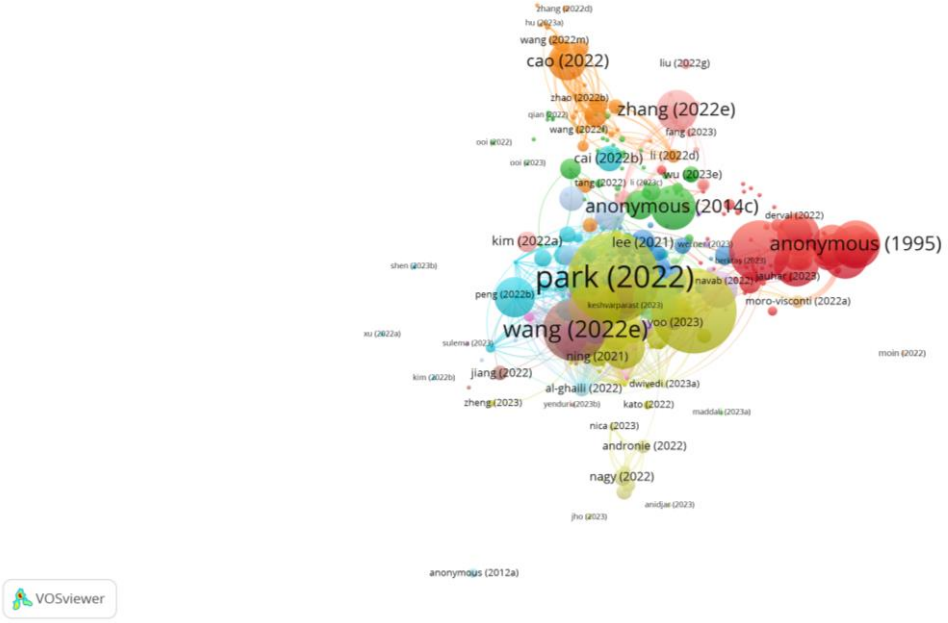

Figure 3 Bibliographic coupling

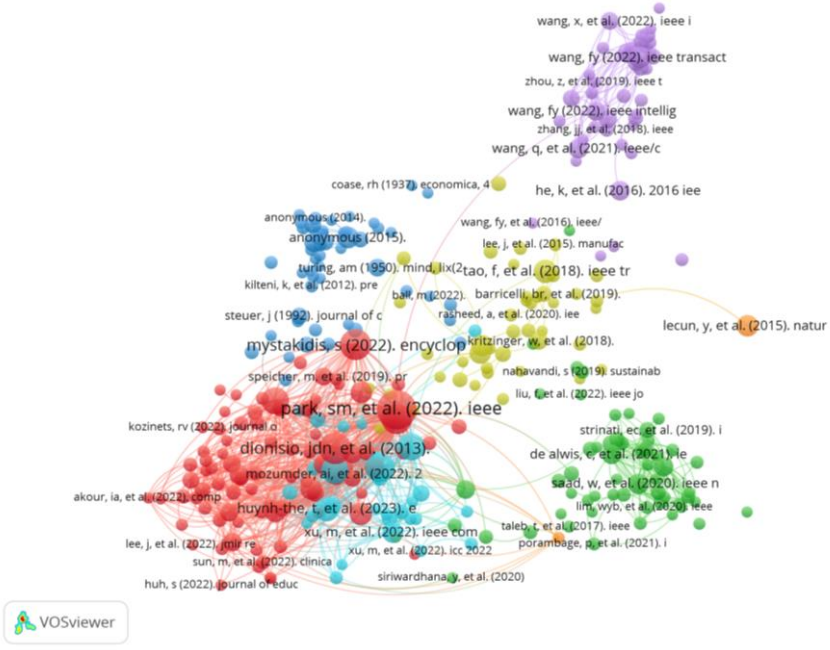

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Artificial vision and autonomous cognitive systems, digital twin simulation and machine learning-based image recognition tools, and geospatial mapping and digital contact tracing technologies articulate extended reality environments.	Chen, 2022; Du et al., 2023; Giang Barrera and Shah, 2023; Zhao et al., 2022
Immersive holographic virtual experiences can be achieved through movement and behavior tracking tools, computer vision and deep learning algorithms, and sensor data fusion in the virtual economy of the metaverse.	Golf-Papez et al., 2022; Huynh-The et al., 2023; Smart, 2022; Zhu et al., 2023
Immersive virtual reality experiences can be attained by use of natural language processing and synthetic data tools, environment perception sensors, and user journey and real-time predictive analytics in the blockchain-based virtual economy.	Han et al., 2022; Kozinets, 2023; Panagiotakopoulos et al., 2022; Venugopal et al., 2023
Data fusion and geospatial mapping technologies, data mining and decision-making process automation tools, and computer vision and visual perception algorithms are instrumental in immersive 3D virtual environments.	Ahn et al., 2023; Dincelli and Yayla, 2022; Vidal-Tomás, 2023; Zainab et al., 2022
Deep learning-based image processing and motion planning algorithms, virtual twin modeling and automated speech recognition tools, and machine perception and wearable scent technologies enable immersive decentralized 3D digital worlds.	Ersoy and Gürfidan, 2023; Han et al., 2023; Nica et al., 2022; Wongkitrungrueng and Suprawan, 2023
Immersive 3D environments develop on data mining and visual imagery tools, cognitive automation and geospatial mapping technologies, and remote sensing and spatio-temporal fusion algorithms.	Cuțitoi, 2022; Faraboschi et al., 2022; Shi et al., 2023; Valaskova et al., 2022**;** Zallio and Clarkson, 2022
Virtual navigation and deep learning artificial intelligence tools, Internet of Things-based decision support and cognitive computing systems, and sensory data mining techniques assist 3D digital environments.	Hennig-Thurau et al., 2022; Kwok and Tang, 2023; Yoo et al., 2023; Zarantonello and Schmitt, 2023
Immersive metaverse experiences can be attained through deep learning-based digital image generators, cognitive artificial intelligence and computer vision algorithms, and remote sensing and biometric authentication systems.	Huang et al., 2023; Nagendran et al., 2022; Polas et al., 2022; Zheng and Yuan, 2023
Hyper-realistic personalized interactive experiences can be achieved by use of movement and behavior tracking tools, ambient sound recognition software, and cognitive artificial intelligence and spatial computing technologies in immersive 3D worlds.	Gauttier et al., 2022; Meng et al., 2023; Ramadan, 2023; Zhang et al., 2022

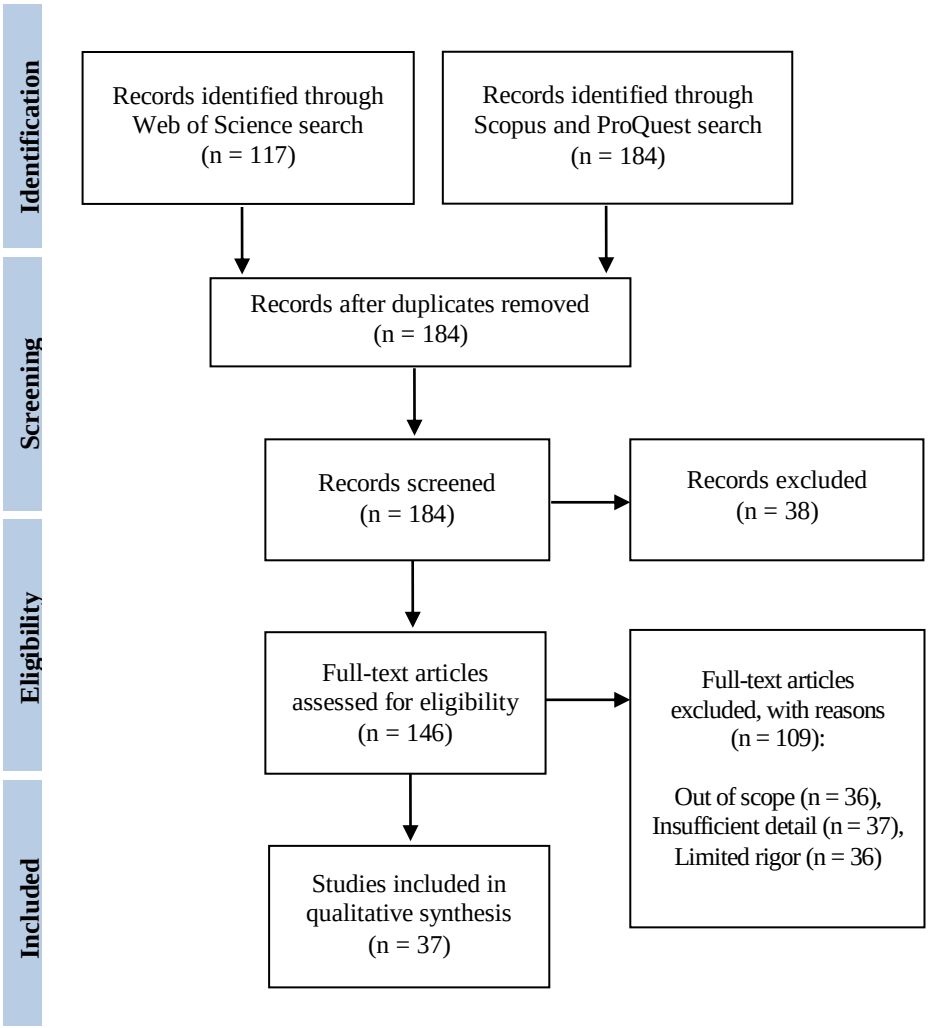

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

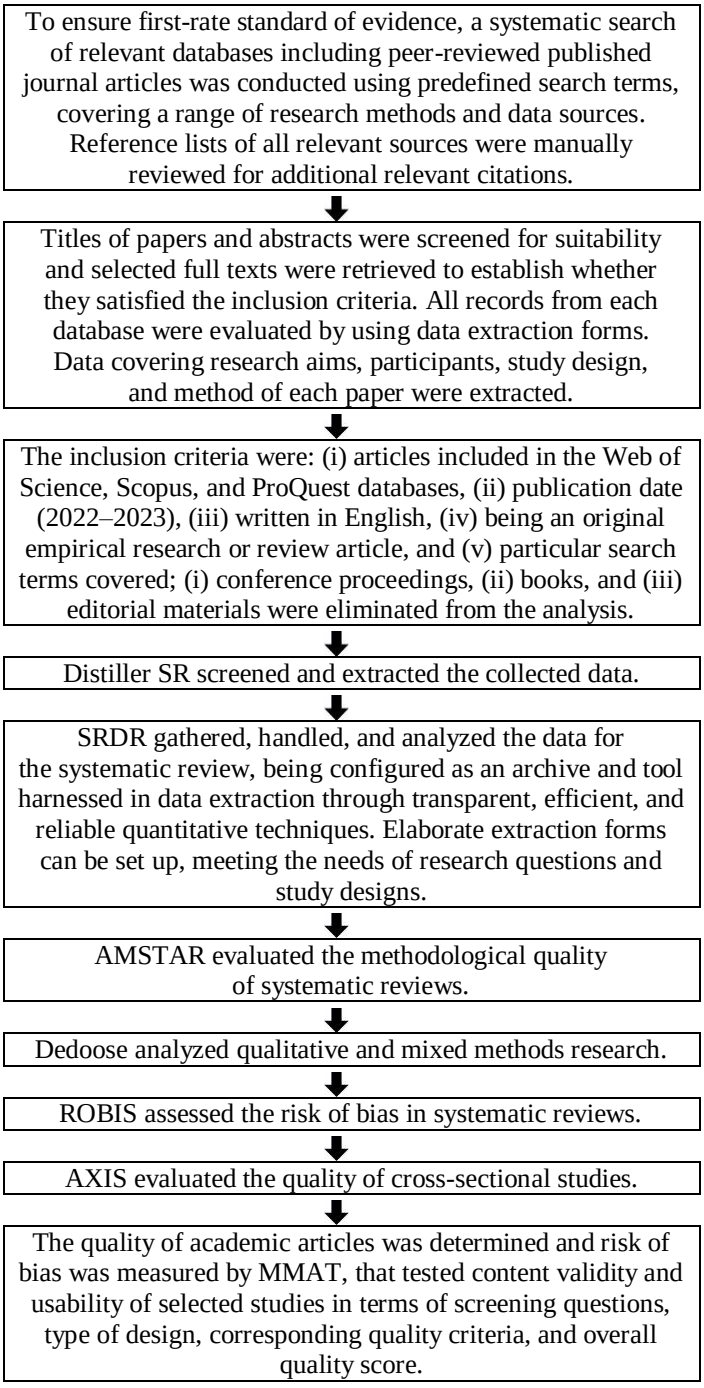

Figure 6 Screening and quality assessment tools

4. Digital Twin Simulation and Machine Learning-based Image Recognition Tools, Sensory Data Mining and Deep Generative Modeling Techniques, and User Journey and Real-Time Predictive Analytics in the Virtual Economy of the Metaverse

Artificial vision and autonomous cognitive systems, digital twin simulation and machine learning-based image recognition tools, and geospatial mapping and digital contact tracing technologies (Chen, 2022; Du et al., 2023; Giang Barrera and Shah, 2023; Zhao et al., 2022) articulate extended reality environments. Immersive 3D worlds require cloud computing machines, sensory data mining and deep generative modeling techniques, and digital twin simulation and virtual mapping tools.

Immersive holographic virtual experiences can be achieved through movement and behavior tracking tools, computer vision and deep learning algorithms, and sensor data fusion (Golf-Papez et al., 2022; Huynh-The et al., 2023; Smart, 2022; Zhu et al., 2023) in the virtual economy of the metaverse. Deep learning-based sensing and virtual modeling technologies, movement and behavior tracking tools, and metaverse engagement metrics further photorealistic 3D environments.

Immersive virtual reality experiences can be attained by use of natural language processing and synthetic data tools, environment perception sensors, and user journey and real-time predictive analytics (Han et al., 2022; Kozinets, 2023; Panagiotakopoulos et al., 2022; Venugopal et al., 2023) in the blockchain-based virtual economy. 3D dynamic scene modeling and data mining tools, Internet of Things digital twins, and dynamic routing and spatial computing technologies shape immersive 3D worlds. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Artificial vision and autonomous cognitive systems, digital twin simulation and machine learning-based image recognition tools, and geospatial mapping and digital contact tracing technologies articulate extended reality environments.	Chen, 2022; Du et al., 2023; Giang Barrera and Shah, 2023; Zhao et al., 2022
Immersive holographic virtual experiences can be achieved through movement and behavior tracking tools, computer vision and deep learning algorithms, and sensor data fusion in the virtual economy of the metaverse.	Golf-Papez et al., 2022; Huynh-The et al., 2023; Smart, 2022; Zhu et al., 2023
Immersive virtual reality experiences can be attained by use of natural language processing and synthetic data tools, environment perception sensors, and user journey and real-time predictive analytics in the blockchain-based virtual economy.	Han et al., 2022; Kozinets, 2023; Panagiotakopoulos et al., 2022; Venugopal et al., 2023

5. Deep Learning-based Image Processing and Motion Planning Algorithms, Cognitive Automation and Geospatial Mapping Technologies, and Digital Twin Simulation and Data Visualization Tools in Immersive 3D Virtual Environments

Data fusion and geospatial mapping technologies, data mining and decision-making process automation tools, and computer vision and visual perception algorithms (Ahn et al., 2023; Dincelli and Yayla, 2022; Vidal-Tomás, 2023; Zainab et al., 2022) are instrumental in immersive 3D virtual environments. Digital twin simulation and data visualization tools, spatio-temporal fusion and environment mapping algorithms, and eye-tracking and image recognition technologies configure digital hyper-realistic worlds.

Deep learning-based image processing and motion planning algorithms, virtual twin modeling and automated speech recognition tools, and machine perception and wearable scent technologies (Ersoy and Gürfidan, 2023; Han et al., 2023; Nica et al., 2022; Wongkitrungrueng and Suprawan, 2023) enable immersive decentralized 3D digital worlds. Virtual reality-based immersive experiences can be attained by use of artificial intelligence-powered search capabilities, sensing and computing technologies, and user journey analytics in immersive digital worlds.

Immersive 3D environments (Cuțitoi, 2022; Faraboschi et al., 2022; Shi et al., 2023; Valaskova et al., 2022**;** Zallio and Clarkson, 2022) develop on data mining and visual imagery tools, cognitive automation and geospatial mapping technologies, and remote sensing and spatio-temporal fusion algorithms. Deep learning-based ambient sound processing, smart environment modeling and image recognition tools, and distributed decision and control algorithms shape blockchain-based metaverse platforms. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Data fusion and geospatial mapping technologies, data mining and decision-making process automation tools, and computer vision and visual perception algorithms are instrumental in immersive 3D virtual environments.	Ahn et al., 2023; Dincelli and Yayla, 2022; Vidal-Tomás, 2023; Zainab et al., 2022
Deep learning-based image processing and motion planning algorithms, virtual twin modeling and automated speech recognition tools, and machine perception and wearable scent technologies enable immersive decentralized 3D digital worlds.	Ersoy and Gürfidan, 2023; Han et al., 2023; Nica et al., 2022; Wongkitrungrueng and Suprawan, 2023
Immersive 3D environments develop on data mining and visual imagery tools, cognitive automation and geospatial mapping technologies, and remote sensing and spatio-temporal fusion algorithms.	Cuțitoi, 2022; Faraboschi et al., 2022; Shi et al., 2023; Valaskova et al., 2022c; Zallio and Clarkson, 2022

6. Immersive Metaverse and Digital Twin Technologies, 3D Virtual Space Networking and Data Visualization Tools, and Deep Learning Forecasting and Spatial Computing Algorithms in Interactive Digital Worlds

Virtual navigation and deep learning artificial intelligence tools, Internet of Things-based decision support and cognitive computing systems, and sensory data mining techniques (Hennig-Thurau et al., 2022; Kwok and Tang, 2023; Yoo et al., 2023; Zarantonello and Schmitt, 2023) assist 3D digital environments. 3D virtual space networking and data visualization tools, machine learning and sensory data mining techniques, and voice recognition software optimize interactive digital worlds.

Immersive metaverse experiences can be attained through deep learning-based digital image generators, cognitive artificial intelligence and computer vision algorithms, and remote sensing and biometric authentication systems (Huang et al., 2023; Nagendran et al., 2022; Polas et al., 2022; Zheng and Yuan, 2023) on blockchain-based metaverse platforms. Explainable artificial intelligence-based decision support and artificial vision systems, photorealistic synthetic imagery, and deep learning forecasting and spatial computing algorithms optimize a fully connected metaverse.

Hyper-realistic personalized interactive experiences can be achieved by use of movement and behavior tracking tools, ambient sound recognition software, and cognitive artificial intelligence and spatial computing technologies (Gauttier et al., 2022; Meng et al., 2023; Ramadan, 2023; Zhang et al., 2022) in immersive 3D worlds. Interactive digital worlds integrate immersive metaverse and digital twin technologies, location intelligence data, and 3D virtual environment mapping and generative modeling tools. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Virtual navigation and deep learning artificial intelligence tools, Internet of Things-based decision support and cognitive computing systems, and sensory data mining techniques assist 3D digital environments.	Hennig-Thurau et al., 2022; Kwok and Tang, 2023; Yoo et al., 2023; Zarantonello and Schmitt, 2023
Immersive metaverse experiences can be attained through deep learning-based digital image generators, cognitive artificial intelligence and computer vision algorithms, and remote sensing and biometric authentication systems on blockchain-based metaverse platforms.	Huang et al., 2023; Nagendran et al., 2022; Polas et al., 2022; Zheng and Yuan, 2023
Hyper-realistic personalized interactive experiences can be achieved by use of movement and behavior tracking tools, ambient sound recognition software, and cognitive artificial intelligence and spatial computing technologies in immersive 3D worlds.	Gauttier et al., 2022; Meng et al., 2023; Ramadan, 2023; Zhang et al., 2022

7. Discussion

We integrate our systematic review throughout research indicating how digital twin simulation and data visualization tools, spatio-temporal fusion and environment mapping algorithms, and eye-tracking and image recognition technologies configure digital hyper-realistic worlds. Our research complements recent analyses clarifying how deep learning-based ambient sound processing, smart environment modeling and image recognition tools, and distributed decision and control algorithms shape blockchain-based metaverse platforms. We elucidate, by cumulative evidence, previous research demonstrating how 3D dynamic scene modeling and data mining tools, Internet of Things digital twins, and dynamic routing and spatial computing technologies shape immersive 3D worlds.

8. Synopsis of the Main Research Outcomes

Immersive 3D worlds require cloud computing machines, sensory data mining and deep generative modeling techniques, and digital twin simulation and virtual mapping tools. 3D virtual space networking and data visualization tools, machine learning and sensory data mining techniques, and voice recognition software optimize interactive digital worlds. Explainable artificial intelligence-based decision support and artificial vision systems, photorealistic synthetic imagery, and deep learning forecasting and spatial computing algorithms optimize a fully connected metaverse.

9. Conclusions

Relevant research has investigated whether interactive digital worlds integrate immersive metaverse and digital twin technologies, location intelligence data, and 3D virtual environment mapping and generative modeling tools. This systematic literature review presents the published peer-reviewed sources covering how deep learning-based sensing and virtual modeling technologies, movement and behavior tracking tools, and metaverse engagement metrics further photorealistic 3D environments. The research outcomes drawn from the above analyses indicate that virtual reality-based immersive experiences can be attained by use of artificial intelligence-powered search capabilities, sensing and computing technologies, and user journey analytics in immersive digital worlds.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on immersive metaverse and digital twin technologies, deep learning-

based image processing and motion planning algorithms, and 3D virtual space networking and data visualization tools in interactive digital worlds may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of artificial vision and autonomous cognitive systems, digital twin simulation and machine learning-based image recognition tools, and geospatial mapping and digital contact tracing technologies.

Subsequent analyses should develop on deep learning-based image processing and motion planning algorithms, virtual twin modeling and automated speech recognition tools, and machine perception and wearable scent technologies. Future research should thus investigate deep learning-based digital image generators, cognitive artificial intelligence and computer vision algorithms, and remote sensing and biometric authentication systems. Attention should be directed to movement and behavior tracking tools, computer vision and deep learning algorithms, and sensor data fusion.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

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Conflict of interest statement
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Neural Network-based Recognition and Virtual Simulation Algorithms, Interactive 3D Geo-Visualization and Neuromorphic Computing Systems, and Tactile Sensing and Cognitive Modeling Technologies in Web3-powered Metaverse Worlds

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ABSTRACT. We draw on a substantial body of theoretical and empirical research on movement and behavior tracking tools, remote sensing and geospatial artificial intelligence technologies, and metaverse assets and services. We carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout May 2023, with search terms including "Web3-powered metaverse worlds" + "neural network-based recognition and virtual simulation algorithms," "interactive 3D geo-visualization and neuromorphic computing systems," and "tactile sensing and cognitive modeling technologies." As we analyzed research published in 2022 and 2023, only 187 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, we decided on 41, chiefly empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Distiller SR, ROBIS, and SRDR.

Keywords: neural network; recognition and virtual simulation algorithms; interactive 3D geo-visualization; neuromorphic computing systems; tactile sensing; cognitive modeling technologies; Web3-powered metaverse worlds

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1. Introduction

Biometric and behavioral data, deep generative modeling and data mining techniques, and edge artificial intelligence computing and remote sensing systems articulate immersive interconnected virtual worlds. The purpose of our systematic review is to examine the recently published literature on Web3-powered metaverse worlds and integrate the insights it configures on neural network-based recognition and virtual simulation algorithms, interactive 3D geo-visualization and neuromorphic computing systems, and tactile sensing and cognitive modeling technologies. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that movement and behavior tracking tools, picture-making neural and intelligent sensing networks, and predictive maintenance and computer vision algorithms (Andronie et al., 2021a; Balcerzak et al., 2022; Nica, 2019) articulate immersive 3D worlds. The actuality and novelty of this study are articulated by addressing movement and behavior tracking tools, remote sensing and geospatial artificial intelligence technologies, and metaverse assets and services (Andronie et al., 2021b; Nica, 2018; Vătămănescu et al., 2022), that is an emerging topic involving much interest. Our research problem is whether immersive decentralized networking and ambient scene detection tools, 3D holographic avatars, and digital scent and spatial computing technologies (Andronie et al., 2021c; Nagy and Lăzăroiu, 2022; Trettin et al., 2019) are pivotal in the blockchain-based virtual economy.

In this review, prior findings have been cumulated indicating that emotion detection and sensor fusion algorithms, 3D imaging and display technologies, and natural language processing and data visualization tools (Andronie et al., 2021d; Kliestik et al., 2020; Lăzăroiu et al., 2022; Vinerean et al., 2022) optimize immersive and interoperable spaces. The identified gaps advance artificial vision and socially-extended cognition systems, 3D modeling and simulation technologies (Lyons and Lăzăroiu, 2020; Pelau et al., 2021; Valaskova et al., 2022a), and deep learning and image data-based predictive algorithms. Our main objective is to indicate that the virtual environment of the metaverse develop on sensorial and cognitive technologies, data visualization and decision support tools (Andronie et al., 2023; Lewkowich, 2022; Valaskova et al., 2022b), and predictive modeling and context awareness algorithms.

2. Theoretical Overview of the Main Concepts

Sensor and actuator devices, digital twin simulation and visual perception tools, and tactile sensing and cognitive modeling technologies assist spatial virtual reality environments. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), distributed autonomous control and bio-inspired artificial vision systems, neural network-

based recognition and virtual simulation algorithms, and tactile sensing and cognitive modeling technologies in immersive and interoperable spaces (section 4), environment perception and 3D virtual immersive technologies, machine learning-based image recognition and socially-oriented location tracking tools, and predictive maintenance and computer vision algorithms in synthetic simulation environments (section 5), immersive decentralized networking and ambient scene detection tools, interactive 3D geo-visualization and neuromorphic computing systems, and predictive modeling and context awareness algorithms in Web3-powered metaverse worlds (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

We carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout May 2023, with search terms including "Web3-powered metaverse worlds" + "neural network-based recognition and virtual simulation algorithms," "interactive 3D geo-visualization and neuromorphic computing systems," and "tactile sensing and cognitive modeling technologies." As we analyzed research published in 2022 and 2023, only 187 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, we decided on 41, chiefly empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Distiller SR, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
Web3-powered metaverse worlds + neural network-based recognition and virtual simulation algorithms	64	15
Web3-powered metaverse worlds + interactive 3D geo-visualization and neuromorphic computing systems	62	14
Web3-powered metaverse worlds + tactile sensing and cognitive modeling technologies	61	12
Type of paper		
Original research	158	34
Review	18	7
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.

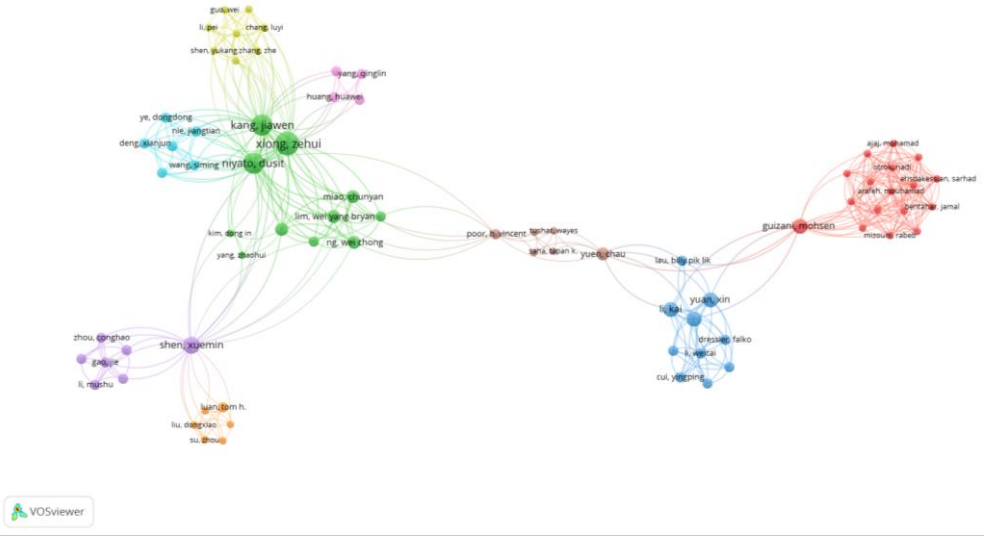

Figure 1 Co-authorship

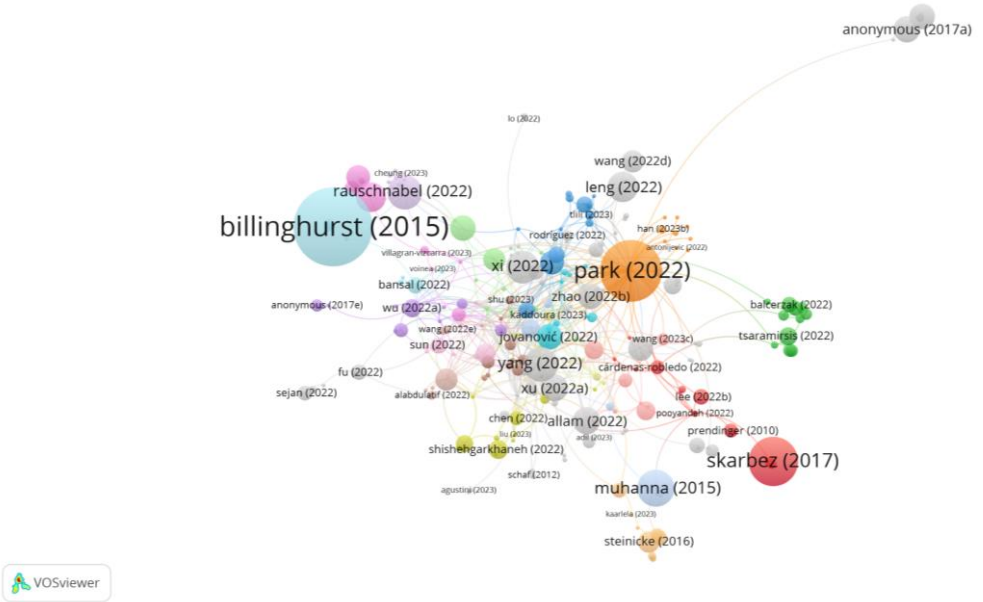

Figure 2 Citation

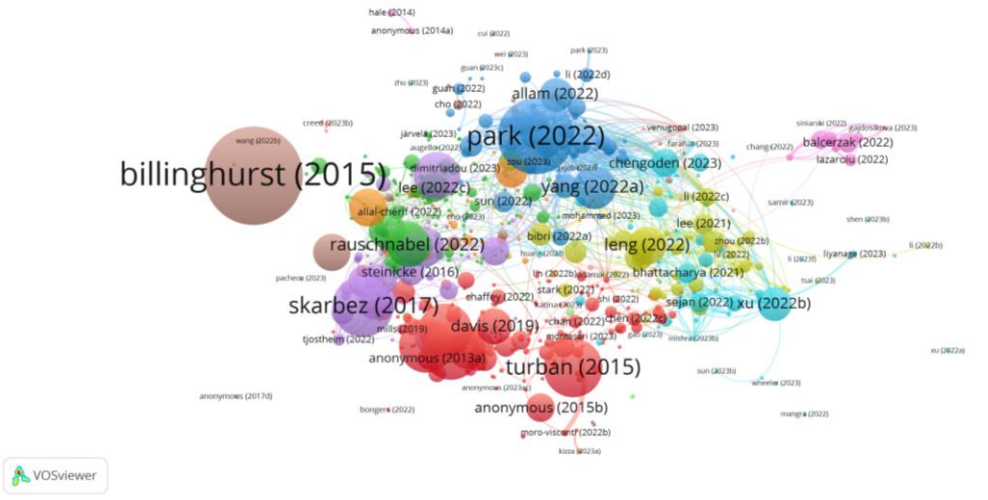

Figure 3 Bibliographic coupling

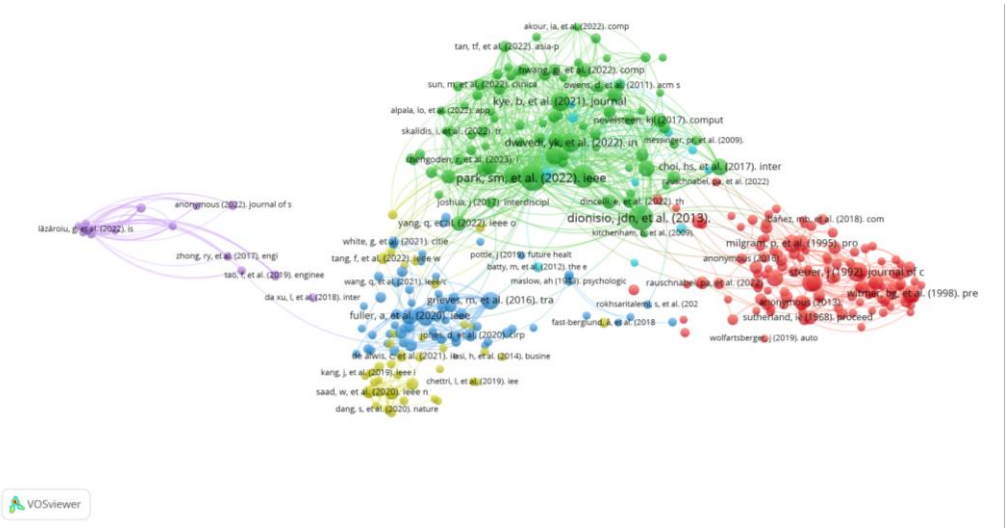

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive visual and big geospatial data analytics, motion capture and sensor-based data acquisition systems, and crowd navigation and spatial data mining algorithms optimize photorealistic virtual reality environments.	Aloqaily et al., 2022; Hollensen et al., 2023; Njoku et al., 2023; Weking et al., 2023
3D immersive spaces and experiences can be achieved by use of neural network-based recognition and virtual simulation algorithms, visual attention modeling and immersive analytics tools, and empathetic computing and extended cognitive systems.	Ahn et al., 2023; Ding et al., 2022; Giang Barrera and Shah, 2023; Tang et al., 2023; Zvarikova et al., 2023)
Photo-realistic simulation environments necessitate movement and behavior tracking tools, remote sensing and geospatial artificial intelligence technologies, and metaverse assets and services.	Cheng et al., 2022; Faraboschi et al., 2022; He et al., 2023; Jenkins, 2022; Zabel et al., 2023
Network virtualization and artificial cognitive systems, data sharing and holographic imaging technologies, and immersive decentralized networking and deep generative modeling tools further spatial virtual reality environments.	Li et al., 2023a; Van Huynh et al., 2022; McStay, 2023; Valaskova et al., 2022c; Wu et al., 2023
Auditory and visual immersion systems, machine learning-based image recognition and socially-oriented location tracking tools, and decentralized data and behavioral predictive analytics configure augmented reality-powered immersive spaces.	Huynh-The et al., 2023; Mourtzis et al., 2022; Venugopal et al., 2023; Xu et al., 2023
Artificial vision and socially-extended cognition systems, 3D modeling and simulation technologies, and deep learning and image data-based predictive algorithms further blockchain-based metaverse platforms.	Cao, 2022; Daneshfar and Jamshidi, 2023; Duncan, 2022; Lv et al., 2022; Zhang et al., 2023
Hyperconnected virtual experiences can be attained through geospatial mapping and remote sensing technologies, cognitive and behavioral algorithms, and hyper-realistic immersive 3D simulations.	Du et al., 2023; Park and Kim, 2023; Rostami and Maier, 2022; Zhang et al., 2022
3D interactive digital spaces develop on sentiment recognition and virtual immersive technologies, artificial intelligence-powered decision-support and visual attention modeling tools, and interactive 3D geo-visualization and neuromorphic computing systems.	Bordegoni and Ferrise, 2023; Braud et al., 2022; Wongkitrungrueng and Suprawan, 2023; Zallio and Clarkson, 2022
Internet of Things sensing infrastructures in Web3-powered metaverse worlds integrate immersive and extended reality technologies, geospatial modeling and simulation devices, and bioinspired artificial intelligence systems.	Bojic, 2022; Grupac and Lăzăroiu, 2022; Li et al., 2023b; Shi et al., 2023; Zhou et al., 2023

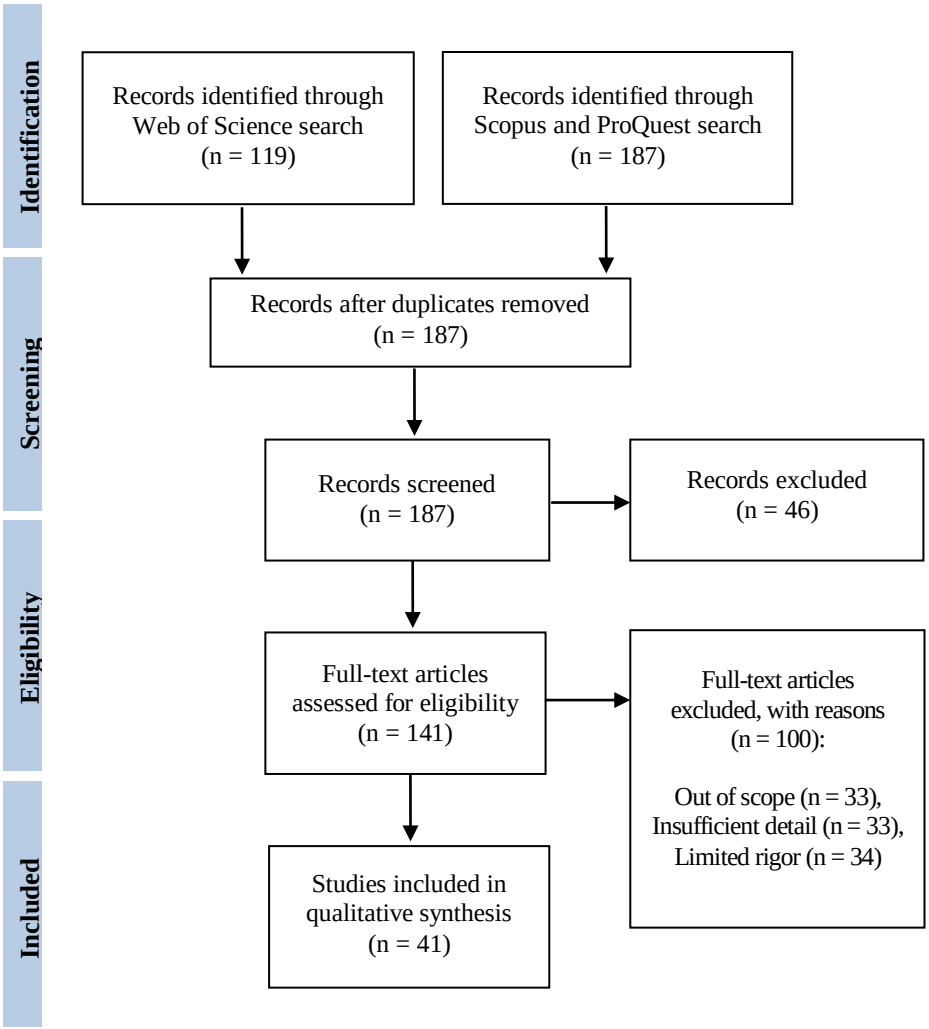

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

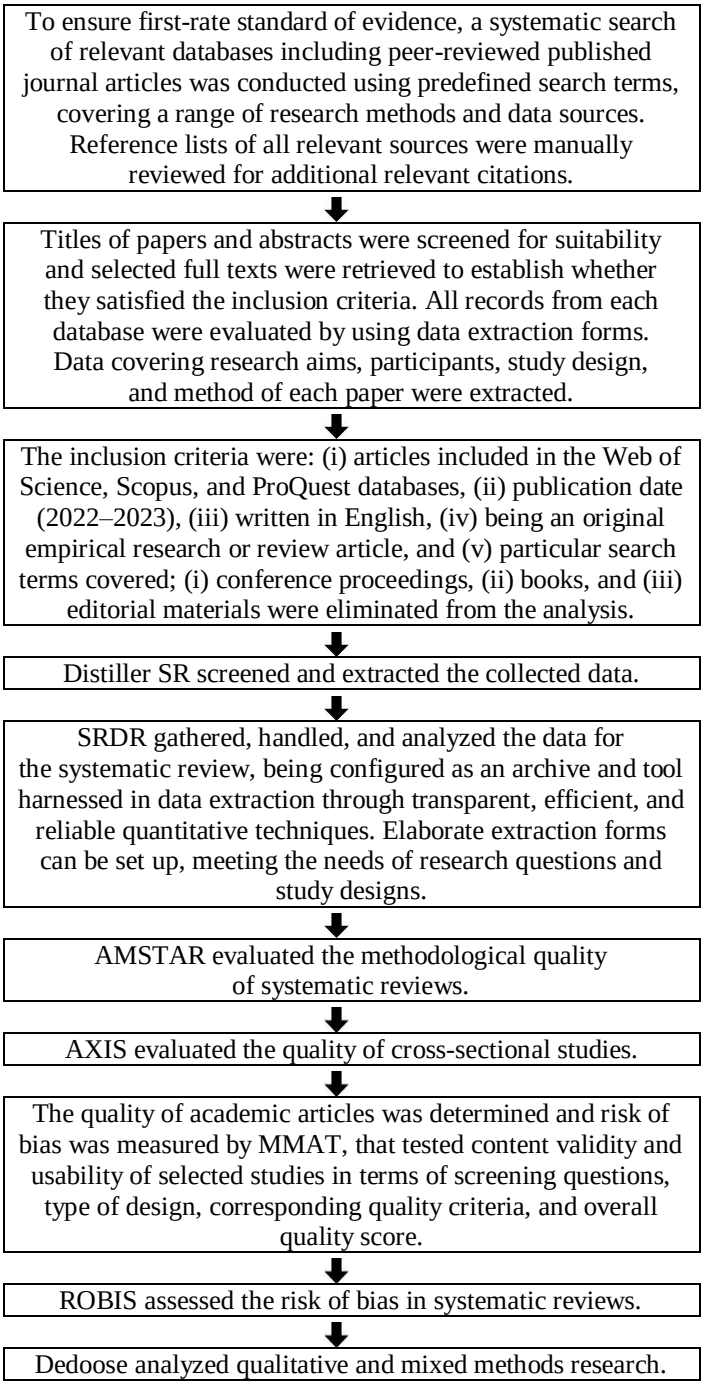

Figure 6 Screening and quality assessment tools

4. Distributed Autonomous Control and Bio-inspired Artificial Vision Systems, Neural Network-based Recognition and Virtual Simulation Algorithms, and Tactile Sensing and Cognitive Modeling Technologies in Immersive and Interoperable Spaces

Immersive visual and big geospatial data analytics, motion capture and sensor-based data acquisition systems, and crowd navigation and spatial data mining algorithms (Aloqaily et al., 2022; Hollensen et al., 2023; Njoku et al., 2023; Weking et al., 2023) optimize photorealistic virtual reality environments. Visual object tracking and edge intelligence algorithms, distributed autonomous control and bio-inspired artificial vision systems, and haptic and sensory technologies configure immersive 3D worlds.

3D immersive spaces and experiences can be achieved by use of neural network-based recognition and virtual simulation algorithms, visual attention modeling and immersive analytics tools, and empathetic computing and extended cognitive systems (Ahn et al., 2023; Ding et al., 2022; Giang Barrera and Shah, 2023; Tang et al., 2023; Zvarikova et al., 2023) across interoperable extended reality environments. Emotion detection and sensor fusion algorithms, 3D imaging and display technologies, and natural language processing and data visualization tools optimize immersive and interoperable spaces.

Photo-realistic simulation environments (Cheng et al., 2022; Faraboschi et al., 2022; He et al., 2023; Jenkins, 2022; Zabel et al., 2023) necessitate movement and behavior tracking tools, remote sensing and geospatial artificial intelligence technologies, and metaverse assets and services. Sensor and actuator devices, digital twin simulation and visual perception tools, and tactile sensing and cognitive modeling technologies assist spatial virtual reality environments. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive visual and big geospatial data analytics, motion capture and sensor-based data acquisition systems, and crowd navigation and spatial data mining algorithms optimize photorealistic virtual reality environments.	Aloqaily et al., 2022; Hollensen et al., 2023; Njoku et al., 2023; Weking et al., 2023
3D immersive spaces and experiences can be achieved by use of neural network-based recognition and virtual simulation algorithms, visual attention modeling and immersive analytics tools, and empathetic computing and extended cognitive systems across interoperable extended reality environments.	Ahn et al., 2023; Ding et al., 2022; Giang Barrera and Shah, 2023; Tang et al., 2023; Zvarikova et al., 2023)
Photo-realistic simulation environments necessitate movement and behavior tracking tools, remote sensing and geospatial artificial intelligence technologies, and metaverse assets and services.	Cheng et al., 2022; Faraboschi et al., 2022; He et al., 2023; Jenkins, 2022; Zabel et al., 2023

5. Environment Perception and 3D Virtual Immersive Technologies, Machine Learning-based Image Recognition and Socially-oriented Location Tracking Tools, and Predictive Maintenance and Computer Vision Algorithms in Synthetic Simulation Environments

Network virtualization and artificial cognitive systems, data sharing and holographic imaging technologies, and immersive decentralized networking and deep generative modeling tools (Li et al., 2023a; Van Huynh et al., 2022; McStay, 2023; Valaskova et al., 2022; Wu et al., 2023) further spatial virtual reality environments. Semantic network representations, environment perception and 3D virtual immersive technologies, and digital twin simulation and data visualization tools enable synthetic simulation environments.

Auditory and visual immersion systems, machine learning-based image recognition and socially-oriented location tracking tools, and decentralized data and behavioral predictive analytics (Huynh-The et al., 2023; Mourtzis et al., 2022; Venugopal et al., 2023; Xu et al., 2023) configure augmented reality-powered immersive spaces. Biometric and behavioral data, deep generative modeling and data mining techniques, and edge artificial intelligence computing and remote sensing systems articulate immersive interconnected virtual worlds.

Artificial vision and socially-extended cognition systems, 3D modeling and simulation technologies, and deep learning and image data-based predictive algorithms (Cao, 2022; Daneshfar and Jamshidi, 2023; Duncan, 2022; Lv et al., 2022; Zhang et al., 2023) further blockchain-based metaverse platforms. Movement and behavior tracking tools, picture-making neural and intelligent sensing networks, and predictive maintenance and computer vision algorithms articulate immersive 3D worlds. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Network virtualization and artificial cognitive systems, data sharing and holographic imaging technologies, and immersive decentralized networking and deep generative modeling tools further spatial virtual reality environments.	Li et al., 2023a; Van Huynh et al., 2022; McStay, 2023; Valaskova et al., 2022c; Wu et al., 2023
Auditory and visual immersion systems, machine learning-based image recognition and socially-oriented location tracking tools, and decentralized data and behavioral predictive analytics configure augmented reality-powered immersive spaces.	Huynh-The et al., 2023; Mourtzis et al., 2022; Venugopal et al., 2023; Xu et al., 2023
Artificial vision and socially-extended cognition systems, 3D modeling and simulation technologies, and deep learning and image data-based predictive algorithms further blockchain-based metaverse platforms.	Cao, 2022; Daneshfar and Jamshidi, 2023; Duncan, 2022; Lv et al., 2022; Zhang et al., 2023

6. Immersive Decentralized Networking and Ambient Scene Detection Tools, Interactive 3D Geo-Visualization and Neuromorphic Computing Systems, and Predictive Modeling and Context Awareness Algorithms in Web3-powered Metaverse Worlds

Hyperconnected virtual experiences can be attained through geospatial mapping and remote sensing technologies, cognitive and behavioral algorithms, and hyper-realistic immersive 3D simulations (Du et al., 2023; Park and Kim, 2023; Rostami and Maier, 2022; Zhang et al., 2022) in digitally-networked mediated spaces. Immersive decentralized networking and ambient scene detection tools, 3D holographic avatars, and digital scent and spatial computing technologies are pivotal in the blockchain-based virtual economy.

3D interactive digital spaces (Bordegoni and Ferrise, 2023; Braud et al., 2022; Wongkitrungrueng and Suprawan, 2023; Zallio and Clarkson, 2022) develop on sentiment recognition and virtual immersive technologies, artificial intelligence-powered decision-support and visual attention modeling tools, and interactive 3D geo-visualization and neuromorphic computing systems. 3D image processing and virtual mapping algorithms, intelligent connectivity infrastructures, and geolocation data mining and tracking shape photorealistic synthetic environments.

Internet of Things sensing infrastructures in Web3-powered metaverse worlds (Bojic, 2022; Grupac and Lăzăroiu, 2022; Li et al., 2023b; Shi et al., 2023; Zhou et al., 2023) integrate immersive and extended reality technologies, geospatial modeling and simulation devices, and bioinspired artificial intelligence systems. The virtual environment of the metaverse develop on sensorial and cognitive technologies, data visualization and decision support tools, and predictive modeling and context awareness algorithms. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Hyperconnected virtual experiences can be attained through geospatial mapping and remote sensing technologies, cognitive and behavioral algorithms, and hyper-realistic immersive 3D simulations in digitally-networked mediated spaces.	Du et al., 2023; Park and Kim, 2023; Rostami and Maier, 2022; Zhang et al., 2022
3D interactive digital spaces develop on sentiment recognition and virtual immersive technologies, artificial intelligence-powered decision-support and visual attention modeling tools, and interactive 3D geo-visualization and neuromorphic computing systems.	Bordegoni and Ferrise, 2023; Braud et al., 2022; Wongkitrungrueng and Suprawan, 2023; Zallio and Clarkson, 2022
Internet of Things sensing infrastructures in Web3-powered metaverse worlds integrate immersive and extended reality technologies, geospatial modeling and simulation devices, and bioinspired artificial intelligence systems.	Bojic, 2022; Grupac and Lăzăroiu, 2022; Li et al., 2023b; Shi et al., 2023; Zhou et al., 2023

7. Discussion

We integrate our systematic review throughout research indicating how immersive decentralized networking and ambient scene detection tools, 3D holographic avatars, and digital scent and spatial computing technologies are pivotal in the blockchain-based virtual economy. Our research complements recent analyses clarifying how biometric and behavioral data, deep generative modeling and data mining techniques, and edge artificial intelligence computing and remote sensing systems articulate immersive interconnected virtual worlds. We elucidate, by cumulative evidence, previous research demonstrating how the virtual environment of the metaverse develop on sensorial and cognitive technologies, data visualization and decision support tools, and predictive modeling and context awareness algorithms.

8. Synopsis of the Main Research Outcomes

Visual object tracking and edge intelligence algorithms, distributed autonomous control and bio-inspired artificial vision systems, and haptic and sensory technologies configure immersive 3D worlds. Semantic network representations, environment perception and 3D virtual immersive technologies, and digital twin simulation and data visualization tools enable synthetic simulation environments. 3D image processing and virtual mapping algorithms, intelligent connectivity infrastructures, and geolocation data mining and tracking shape photorealistic synthetic environments.

9. Conclusions

Relevant research has investigated whether movement and behavior tracking tools, picture-making neural and intelligent sensing networks, and predictive maintenance and computer vision algorithms articulate immersive 3D worlds. This systematic literature review presents the published peer-reviewed sources covering how sensor and actuator devices, digital twin simulation and visual perception tools, and tactile sensing and cognitive modeling technologies assist spatial virtual reality environments. The research outcomes drawn from the above analyses indicate that emotion detection and sensor fusion algorithms, 3D imaging and display technologies, and natural language processing and data visualization tools optimize immersive and interoperable spaces.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on neural network-based recognition and virtual simulation algo-

rithms, interactive 3D geo-visualization and neuromorphic computing systems, and tactile sensing and cognitive modeling technologies in Web3-powered metaverse worlds may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of immersive visual and big geospatial data analytics, motion capture and sensor-based data acquisition systems, and crowd navigation and spatial data mining algorithms.

Subsequent analyses should develop on auditory and visual immersion systems, machine learning-based image recognition and socially-oriented location tracking tools, and decentralized data and behavioral predictive analytics. Future research should thus investigate sentiment recognition and virtual immersive technologies, artificial intelligence-powered decision-support and visual attention modeling tools, and interactive 3D geo-visualization and neuromorphic computing systems. Attention should be directed to network virtualization and artificial cognitive systems, data sharing and holographic imaging technologies, and immersive decentralized networking and deep generative modeling tools.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Remote Sensing and Edge Artificial Intelligence Computing Systems, Environment Perception and Geospatial Mapping Technologies, and Simulation Modeling and Machine Learning-based Image Recognition Tools in the 3D Cognitive Digital Twin Metaverse

Claudia-Irina Aldea*

ABSTRACT. This article reviews and advances existing literature concerning geo-location data mining and tracking, machine learning-based object recognition and digital twin technologies, and metaverse engagement metrics. I contribute to the literature by indicating that remote sensing and edge artificial intelligence computing systems, context awareness and machine learning-based image recognition tools, and wearable haptic garments enable immersive hyper-connected virtual spaces. Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "3D cognitive digital twin metaverse" + "remote sensing and edge artificial intelligence computing systems," "environment perception and geospatial mapping technologies," and "simulation modeling and machine learning-based image recognition tools." As research published in 2022 and 2023 was inspected, only 184 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/ irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, I selected 41 mainly empirical sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, MMAT, ROBIS, and SRDR.

Keywords: remote sensing; edge artificial intelligence computing systems; environment perception; geospatial mapping technologies; simulation modeling; machine learning; image recognition tools; 3D cognitive digital twin metaverse

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1. Introduction

Virtual personas and identities, digital scent and edge computing technologies, and hyper-realistic immersive 3D simulations (Andronie et al., 2023a; Fernando and Lăzăroiu, 2023; Lăzăroiu, et al., 2017) enable extended reality environments. The purpose of my systematic review is to examine the recently published literature on the 3D cognitive digital twin metaverse and integrate the insights it configures on remote sensing and edge artificial intelligence computing systems, environment perception and geospatial mapping technologies, and simulation modeling and machine learning-based image recognition tools. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that physics-based modeling and simulation tools, multi-sensor fusion and big data computing systems, and biometric and behavioral data (Andronie et al., 2023b; Lăzăroiu and Rogalska, 2023; Nica, 2017) articulate immersive 3D worlds. The actuality and novelty of this study are articulated by addressing geolocation data mining and tracking, machine learning-based object recognition and digital twin technologies, and metaverse engagement metrics (Lăzăroiu, 2018; Lăzăroiu et al., 2022a; Nagy et al., 2023), that is an emerging topic involving much interest. My research problem is whether remote sensing and edge artificial intelligence computing systems, context awareness and machine learning-based image recognition tools, and wearable haptic garments (Lăzăroiu et al., 2022b; Nica et al., 2023; Scott et al., 2020) enable immersive hyper-connected virtual spaces.

In this review, prior findings have been cumulated indicating that computational intelligence and simulation modeling tools, digital contact tracing and digital twinning technologies, and remote sensing and image processing computational algorithms (Krizanova et al., 2019; Lăzăroiu et al., 2020; Popescu et al., 2020) shape immersive 3D worlds. The identified gaps advance ambient sound recognition software, cognitive decision-making and virtual mapping algorithms (Dabija et al., 2022; Valaskova et al., 2022; Zhuravleva et al., 2019), and metaverse and immersive technologies. My main objective is to indicate that machine learning and text mining techniques, contextual awareness and 3D modeling tools, and biometric and behavioral data (Lewkowich, 2022; Pelau et al., 2021; Vătămănescu et al., 2022) are pivotal in spatial virtual reality environments.

2. Theoretical Overview of the Main Concepts

The digital asset-based virtual economy necessitates wireless sensor and deep convolutional neural networks, movement and behavior tracking tools, and predictive maintenance and visual cognitive algorithms. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), metaverse and immersive technologies, simulation modeling and machine

learning-based image recognition tools, and remote sensing and edge artificial intelligence computing systems in extended reality environments (section 4), 3D object recognition and dynamic routing technologies, predictive maintenance and visual cognitive algorithms, and multi-sensor fusion and big data computing systems in the virtual environment of the metaverse (section 5), multiscale spatial data processing and simulation modeling tools, environment perception and geospatial mapping technologies, and location-based predictive and deep learning algorithms in immersive hyper-connected virtual spaces (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout April 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "3D cognitive digital twin metaverse" + "remote sensing and edge artificial intelligence computing systems," "environment perception and geospatial mapping technologies," and "simulation modeling and machine learning-based image recognition tools." As research published in 2022 and 2023 was inspected, only 184 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, I selected 41 mainly empirical sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, MMAT, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
3D cognitive digital twin metaverse + remote sensing and edge artificial intelligence computing systems	64	15
3D cognitive digital twin metaverse + environment perception and geospatial mapping technologies	62	14
3D cognitive digital twin metaverse + simulation modeling and machine learning-based image recognition tools	58	12
Type of paper		
Original research	155	34
Review	19	7
Conference proceedings	9	0
Book	0	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

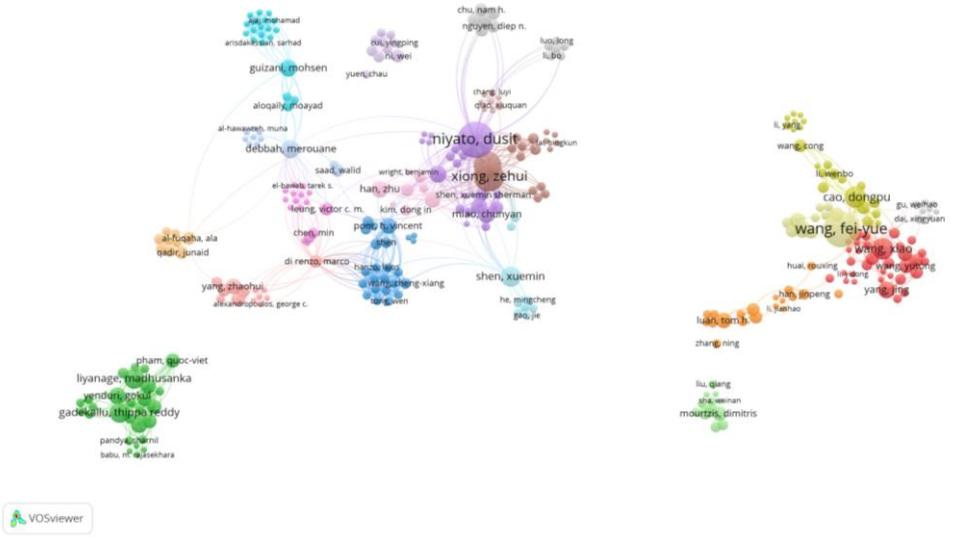

Figure 1 Co-authorship

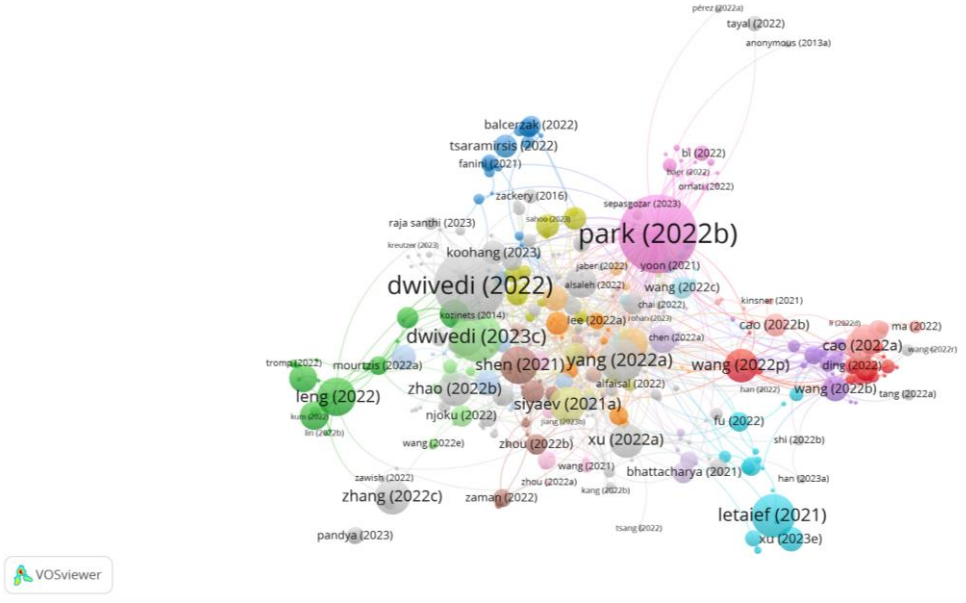

Figure 2 Citation

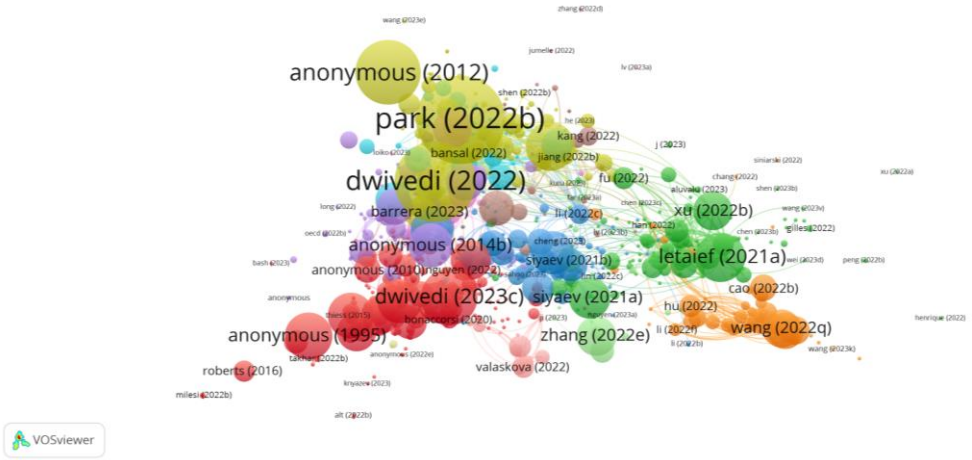

Figure 3 Bibliographic coupling

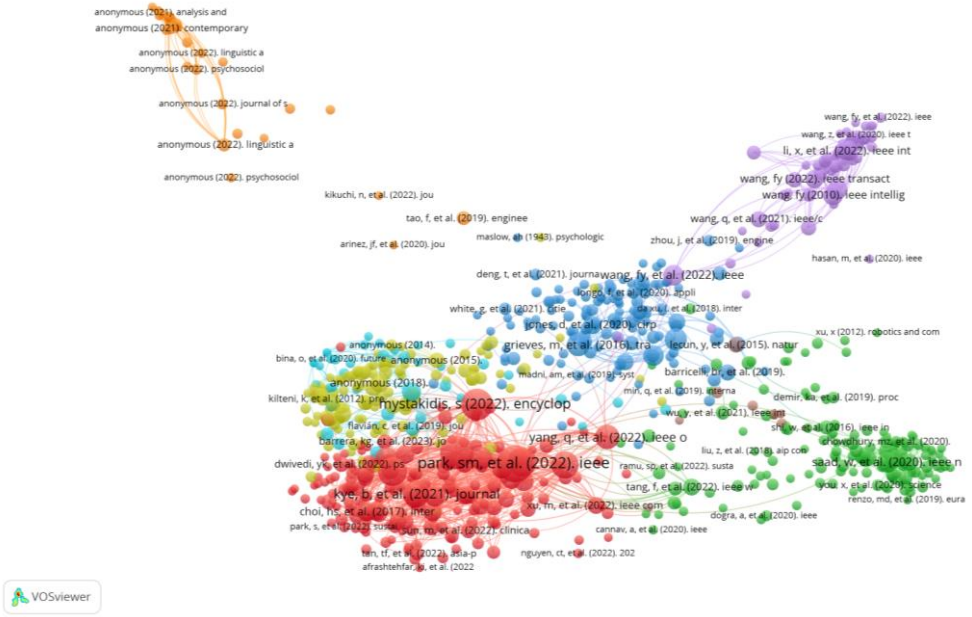

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Bio-sensing and actuation systems, hyper-realistic immersive 3D simulations, and simulation modeling and machine learning-based image recognition tools configure photorealistic synthetic environments.	Ersoy and Gürfidan, 2023; He et al., 2023; McStay, 2022; Perkins, 2022; Zhao et al., 2022
3D virtual environments integrate 3D immersive virtual reality and machine learning-based object recognition technologies, interoperable virtual networks, and ambient intelligence and socially-oriented location tracking tools.	Dwivedi et al., 2023; Tang et al., 2023; Vidal-Tomás, 2023; Zarantonello and Schmitt, 2023
Hyper-realistic personalized interactive experiences can be attained through ambient sound recognition software, cognitive decision-making and virtual mapping algorithms, and metaverse and immersive technologies in extended reality environments.	Golf-Papez et al., 2022; Han et al., 2023a; Polas et al., 2022; Zheng and Yuan, 2023
Interconnected digital spaces necessitate text and data mining techniques, context recognition tools, visual analytics systems, user behavior data mining, behavioral predictive analytics, and 3D object recognition and dynamic routing technologies.	Faraboschi et al., 2022; Han et al., 2022; Kozinets, 2023; Park and Kim, 2023
3D metaverse experiences can be achieved through sensorial and cognitive technologies, biometrics data fusion, and socio-spatial analytics and smart environment modeling tools in the blockchain-based virtual economy.	Dolata and Schwabe, 2023; Grupac and Lăzăroiu, 2022; Han et al., 2023b; Shi et al., 2023; Zyda, 2022
3D metaverse experiences can be achieved by use of geolocation data mining and tracking, machine learning-based object recognition and digital twin technologies, and metaverse engagement metrics in immersive virtual environments.	Grupac et al., 2022; Huang et al., 2023; Lv et al., 2022; Queiroz et al., 2023; Zhang et al., 2023
Deep learning-based ambient sound processing and 3D generative modeling tools, image processing computational and object perception algorithms, and sentiment recognition and eye-tracking technologies are instrumental in immersive photorealistic virtual spaces.	Bordegoni and Ferrise, 2023; Egliston and Carter, 2022; Kwok and Tang, 2023; Panagiotakopoulos et al., 2022
Affective and perceptual technologies, location-based predictive and deep learning algorithms, and multiscale spatial data processing and simulation modeling tools further immersive 3D environments.	Bratu and Sabău, 2022; Du et al., 2023; Li et al., 2023; Meng et al., 2023; Shen, 2022
Hyperconnected virtual experiences can be attained by use of mobile location and big geospatial data analytics, movement and behavior tracking tools, and environment perception and geospatial mapping technologies across extended reality environments.	Chen, 2022; Hadi et al., 2023; Morley, 2022; Smart, 2022; Weking et al., 2023

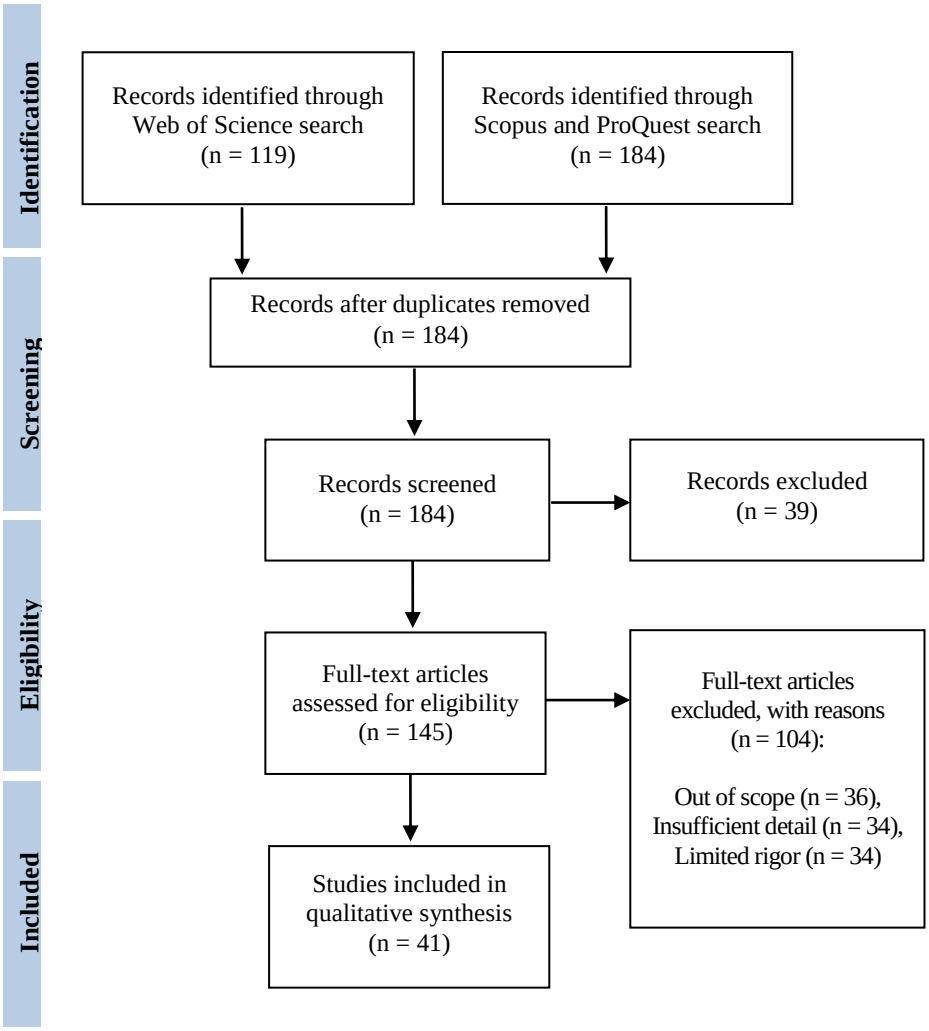

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

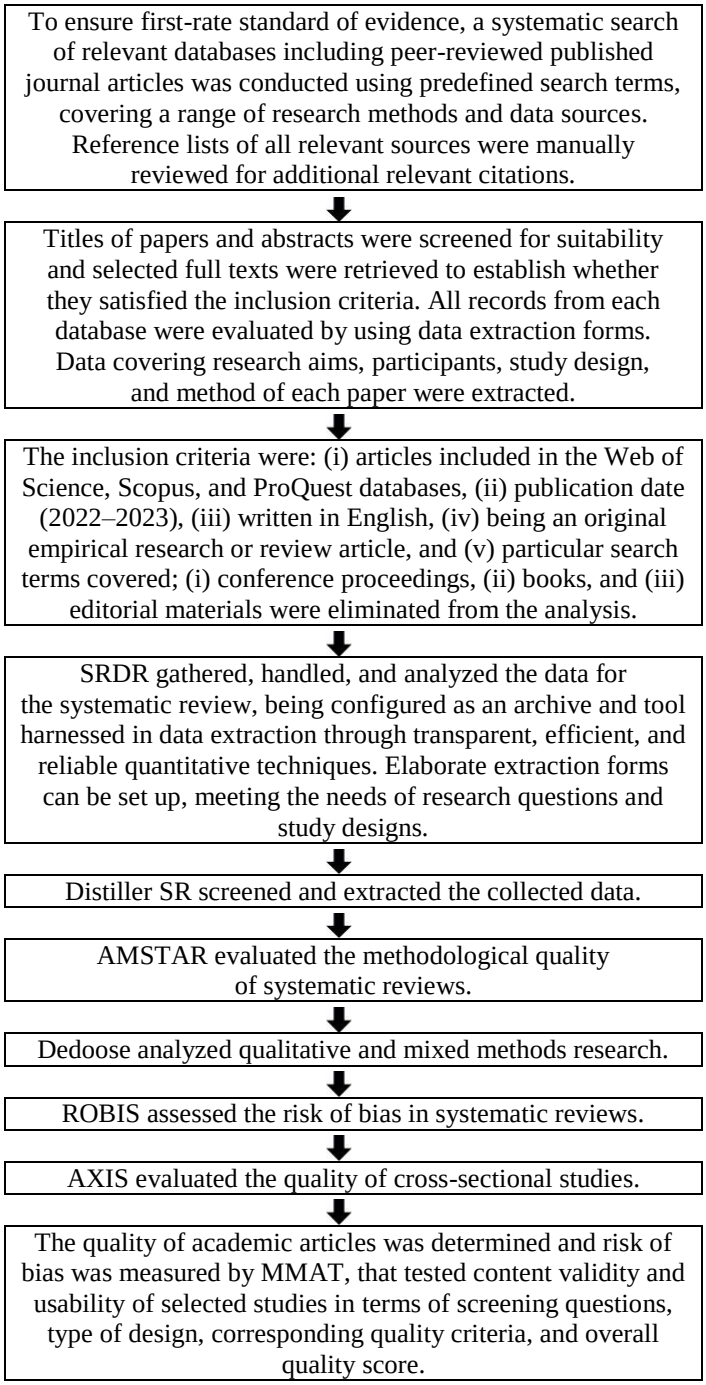

Figure 6 Screening and quality assessment tools

4. Metaverse and Immersive Technologies, Simulation Modeling and Machine Learning-based Image Recognition Tools, and Remote Sensing and Edge Artificial Intelligence Computing Systems in Extended Reality Environments

Bio-sensing and actuation systems, hyper-realistic immersive 3D simulations, eye-tracking and immersive 3D technologies, and simulation modeling and machine learning-based image recognition tools (Ersoy and Gürfidan, 2023; He et al., 2023; McStay, 2022; Perkins, 2022; Zhao et al., 2022) configure photorealistic synthetic environments. Virtual personas and identities, digital scent and edge computing technologies, and hyper-realistic immersive 3D simulations enable extended reality environments.

3D virtual environments (Dwivedi et al., 2023; Tang et al., 2023; Vidal-Tomás, 2023; Zarantonello and Schmitt, 2023) integrate 3D immersive virtual reality and machine learning-based object recognition technologies, interoperable virtual networks, and ambient intelligence and socially-oriented location tracking tools. Remote sensing and edge artificial intelligence computing systems, context awareness and machine learning-based image recognition tools, and wearable haptic garments enable immersive hyper-connected virtual spaces.

Hyper-realistic personalized interactive experiences can be attained through ambient sound recognition software, cognitive decision-making and virtual mapping algorithms, and metaverse and immersive technologies (Golf-Papez et al., 2022; Han et al., 2023a; Polas et al., 2022; Zheng and Yuan, 2023) in extended reality environments. Environment perception and deep learning-based sensing technologies, text mining and immersive visual analytics, and blockchain token-based digital assets configure 3D virtual immersive environments. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Bio-sensing and actuation systems, hyper-realistic immersive 3D simulations, and simulation modeling and machine learning-based image recognition tools configure photorealistic synthetic environments.	Ersoy and Gürfidan, 2023; He et al., 2023; McStay, 2022; Perkins, 2022; Zhao et al., 2022
3D virtual environments integrate 3D immersive virtual reality and machine learning-based object recognition technologies, interoperable virtual networks, and ambient intelligence and socially-oriented location tracking tools.	Dwivedi et al., 2023; Tang et al., 2023; Vidal-Tomás, 2023; Zarantonello and Schmitt, 2023
Hyper-realistic personalized interactive experiences can be attained through ambient sound recognition software, cognitive decision-making and virtual mapping algorithms, and metaverse and immersive technologies in extended reality environments.	Golf-Papez et al., 2022; Han et al., 2023a; Polas et al., 2022; Zheng and Yuan, 2023

5. 3D Object Recognition and Dynamic Routing Technologies, Predictive Maintenance and Visual Cognitive Algorithms, and Multi-Sensor Fusion and Big Data Computing Systems in the Virtual Environment of the Metaverse

Interconnected digital spaces (Faraboschi et al., 2022; Han et al., 2022; Kozinets, 2023; Park and Kim, 2023) necessitate text and data mining techniques, context recognition tools, visual analytics systems, user behavior data mining, behavioral predictive analytics, and 3D object recognition and dynamic routing technologies. Physics-based modeling and simulation tools, multi-sensor fusion and big data computing systems, and biometric and behavioral data articulate immersive 3D worlds.

3D metaverse experiences can be achieved through sensorial and cognitive technologies, biometrics data fusion, and socio-spatial analytics and smart environment modeling tools (Dolata and Schwabe, 2023; Grupac and Lăzăroiu, 2022; Han et al., 2023b; Shi et al., 2023; Zyda, 2022) in the blockchain-based virtual economy. Spatial computing devices, visual perceptive and empathetic computing systems, and 3D modeling and simulation technologies articulate digitally-networked mediated spaces and the virtual environment of the metaverse.

3D metaverse experiences can be achieved by use of geolocation data mining and tracking, machine learning-based object recognition and digital twin technologies, and metaverse engagement metrics (Grupac et al., 2022; Huang et al., 2023; Lv et al., 2022; Queiroz et al., 2023; Zhang et al., 2023) in immersive virtual environments. The digital asset-based virtual economy necessitates wireless sensor and deep convolutional neural networks, movement and behavior tracking tools, and predictive maintenance and visual cognitive algorithms. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Interconnected digital spaces necessitate text and data mining techniques, context recognition tools, visual analytics systems, user behavior data mining, behavioral predictive analytics, and 3D object recognition and dynamic routing technologies.	Faraboschi et al., 2022; Han et al., 2022; Kozinets, 2023; Park and Kim, 2023
3D metaverse experiences can be achieved through sensorial and cognitive technologies, biometrics data fusion, and socio-spatial analytics and smart environment modeling tools in the blockchain-based virtual economy.	Dolata and Schwabe, 2023; Grupac and Lăzăroiu, 2022; Han et al., 2023b; Shi et al., 2023; Zyda, 2022
3D metaverse experiences can be achieved by use of geolocation data mining and tracking, machine learning-based object recognition and digital twin technologies, and metaverse engagement metrics in immersive virtual environments.	Grupac et al., 2022; Huang et al., 2023; Lv et al., 2022; Queiroz et al., 2023; Zhang et al., 2023

6. Multiscale Spatial Data Processing and Simulation Modeling Tools, Environment Perception and Geospatial Mapping Technologies, and Location-based Predictive and Deep Learning Algorithms in Immersive Hyper-Connected Virtual Spaces

Deep learning-based ambient sound processing and 3D generative modeling tools, image processing computational and object perception algorithms, and sentiment recognition and eye-tracking technologies (Bordegoni and Ferrise, 2023; Egliston and Carter, 2022; Kwok and Tang, 2023; Panagiotakopoulos et al., 2022) are instrumental in immersive photorealistic virtual spaces. Intelligent data processing and digital twinning tools, machine learning-based predictive and virtual simulation algorithms, and 3D holographic avatars assist immersive hyper-connected virtual spaces.

Affective and perceptual technologies, location-based predictive and deep learning algorithms, and multiscale spatial data processing and simulation modeling tools (Bratu and Sabău, 2022; Du et al., 2023; Li et al., 2023; Meng et al., 2023; Shen, 2022) further immersive 3D environments. Computational intelligence and simulation modeling tools, digital contact tracing and digital twinning technologies, and remote sensing and image processing computational algorithms shape immersive 3D worlds.

Hyperconnected virtual experiences can be attained by use of mobile location and big geospatial data analytics, movement and behavior tracking tools, and environment perception and geospatial mapping technologies (Chen, 2022; Hadi et al., 2023; Morley, 2022; Smart, 2022; Weking et al., 2023) across extended reality environments. Machine learning and text mining techniques, contextual awareness and 3D modeling tools, and biometric and behavioral data are pivotal in spatial virtual reality environments. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Deep learning-based ambient sound processing and 3D generative modeling tools, image processing computational and object perception algorithms, and sentiment recognition and eye-tracking technologies are instrumental in immersive photorealistic virtual spaces.	Bordegoni and Ferrise, 2023; Egliston and Carter, 2022; Kwok and Tang, 2023; Panagiotakopoulos et al., 2022
Affective and perceptual technologies, location-based predictive and deep learning algorithms, and multiscale spatial data processing and simulation modeling tools further immersive 3D environments.	Bratu and Sabău, 2022; Du et al., 2023; Li et al., 2023; Meng et al., 2023; Shen, 2022
Hyperconnected virtual experiences can be attained by use of mobile location and big geospatial data analytics, movement and behavior tracking tools, and environment perception and geospatial mapping technologies across extended reality environments.	Chen, 2022; Hadi et al., 2023; Morley, 2022; Smart, 2022; Weking et al., 2023

7. Discussion

I integrate my systematic review throughout research indicating how machine learning and text mining techniques, contextual awareness and 3D modeling tools, and biometric and behavioral data are pivotal in spatial virtual reality environments. My research complements recent analyses clarifying how virtual personas and identities, digital scent and edge computing technologies, and hyper-realistic immersive 3D simulations enable extended reality environments. I elucidate, by cumulative evidence, previous research demonstrating how physics-based modeling and simulation tools, multi-sensor fusion and big data computing systems, and biometric and behavioral data articulate immersive 3D worlds.

8. Synopsis of the Main Research Outcomes

Environment perception and deep learning-based sensing technologies, text mining and immersive visual analytics, and blockchain token-based digital assets configure 3D virtual immersive environments. Intelligent data processing and digital twinning tools, machine learning-based predictive and virtual simulation algorithms, and 3D holographic avatars assist immersive hyperconnected virtual spaces. Spatial computing devices, visual perceptive and empathetic computing systems, and 3D modeling and simulation technologies articulate digitally-networked mediated spaces and the virtual environment of the metaverse.

9. Conclusions

Relevant research has investigated whether computational intelligence and simulation modeling tools, digital contact tracing and digital twinning technologies, and remote sensing and image processing computational algorithms shape immersive 3D worlds. This systematic literature review presents the published peer-reviewed sources covering how the digital asset-based virtual economy necessitates wireless sensor and deep convolutional neural networks, movement and behavior tracking tools, and predictive maintenance and visual cognitive algorithms. The research outcomes drawn from the above analyses indicate that remote sensing and edge artificial intelligence computing systems, context awareness and machine learning-based image recognition tools, and wearable haptic garments enable immersive hyperconnected virtual spaces.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant

sources on remote sensing and edge artificial intelligence computing systems, environment perception and geospatial mapping technologies, and simulation modeling and machine learning-based image recognition tools in the 3D cognitive digital twin metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of bio-sensing and actuation systems, hyper-realistic immersive 3D simulations, eye-tracking and immersive 3D technologies, and simulation modeling and machine learning-based image recognition tools.

Subsequent analyses should develop on sensorial and cognitive technologies, biometrics data fusion, and socio-spatial analytics and smart environment modeling tools. Future research should thus investigate deep learning-based ambient sound processing and 3D generative modeling tools, image processing computational and object perception algorithms, and sentiment recognition and eye-tracking technologies. Attention should be directed to 3D immersive virtual reality and machine learning-based object recognition technologies, interoperable virtual networks, and ambient intelligence and socially-oriented location tracking tools.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

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Immersive Extended Reality and Sensor-based Object Recognition Technologies, Socially-oriented Location Tracking and Simulation Modeling Tools, and Artificial Vision and Haptic Augmented Reality Systems in the Metaverse Interactive Environment

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ABSTRACT. The objective of this paper is to systematically review autonomous visual object detection and digital twin modeling tools, cognitive decision-making and bio-inspired computational intelligence algorithms, and metaverse and immersive technologies. The findings and analyses highlight that real-time event and big geo-spatial data analytics, emotion detection and recognition technologies, and socially-oriented location tracking and simulation modeling tools enable 3D virtual environments. Throughout May 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "the metaverse interactive environment" + "immersive extended reality and sensor-based object recognition technologies," "socially-oriented location tracking and simulation modeling tools," and "artificial vision and haptic augmented reality systems." As research published in 2022 and 2023 was inspected, only 175 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, we selected 37 mainly empirical sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR.

Keywords: immersive extended reality; sensor-based object recognition technologies; socially-oriented location tracking; simulation modeling tools; artificial vision; haptic augmented reality systems; metaverse interactive environment

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1. Introduction

Immersive geospatial data visualization and 3D modeling technologies, spatial awareness and image processing tools, and virtual mapping and object recognition algorithms (Balcerzak et al., 2022; Gura et al., 2023; Pop et al., 2021; Nica, 2019) optimize immersive virtual environments. The purpose of our systematic review is to examine the recently published literature on the metaverse interactive environment and integrate the insights it configures on immersive extended reality and sensor-based object recognition technologies, socially-oriented location tracking and simulation modeling tools, and artificial vision and haptic augmented reality systems. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that real-time event and big geospatial data analytics, emotion detection and recognition technologies, and socially-oriented location tracking and simulation modeling tools (Andronie et al., 2021a; Lewkowich, 2022; Vătămănescu et al., 2022) enable 3D virtual environments. The actuality and novelty of this study are articulated by addressing autonomous visual object detection and digital twin modeling tools, cognitive decision-making and bio-inspired computational intelligence algorithms, and metaverse and immersive technologies (Andronie et al., 2021b; Barbu et al., 2021; Lăzăroiu et al., 2022), that is an emerging topic involving much interest. Our research problem is whether photorealistic synthetic environments integrate haptic and sensory technologies, visual analytics and edge artificial intelligence computing systems, and motion control and data processing algorithms.

In this review, prior findings have been cumulated indicating that object tracking and image processing computational algorithms, extended cognitive computing systems, and virtual immersive and digital twin technologies (Andronie et al., 2021c; Novak et al., 2022; Scott et al., 2020) articulate immersive and interoperable spaces. The identified gaps advance network virtualization and neuromorphic image processing systems, immersive extended reality and sensor-based object recognition technologies (Andronie et al., 2023; Nica et al., 2019; Popescu, 2018), and conversational artificial intelligence and visual tracking algorithms. Our main objective is to indicate that predictive maintenance and spatial data mining algorithms, movement and behavior tracking tools, and data sharing and cognitive modeling technologies (Milward et al., 2019; Popescu and Ciurlău, 2019; Valaskova et al., 2022a; Zhuravleva et al., 2019) articulate the metaverse interactive environment.

2. Theoretical Overview of the Main Concepts

The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), visual analytics and edge artificial intelligence computing systems, immersive extended reality and sensor-based object

recognition technologies, and predictive maintenance and spatial data mining algorithms in the metaverse interactive environment (section 4), metaverse and immersive technologies, digital twin simulation and contextual data monitoring tools, and artificial vision and haptic augmented reality systems in the digital asset-based virtual economy (section 5), socially-oriented location tracking and simulation modeling tools, object tracking and image processing computational algorithms, and geospatial big data and immersive visual analytics across Web3-powered metaverse worlds (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

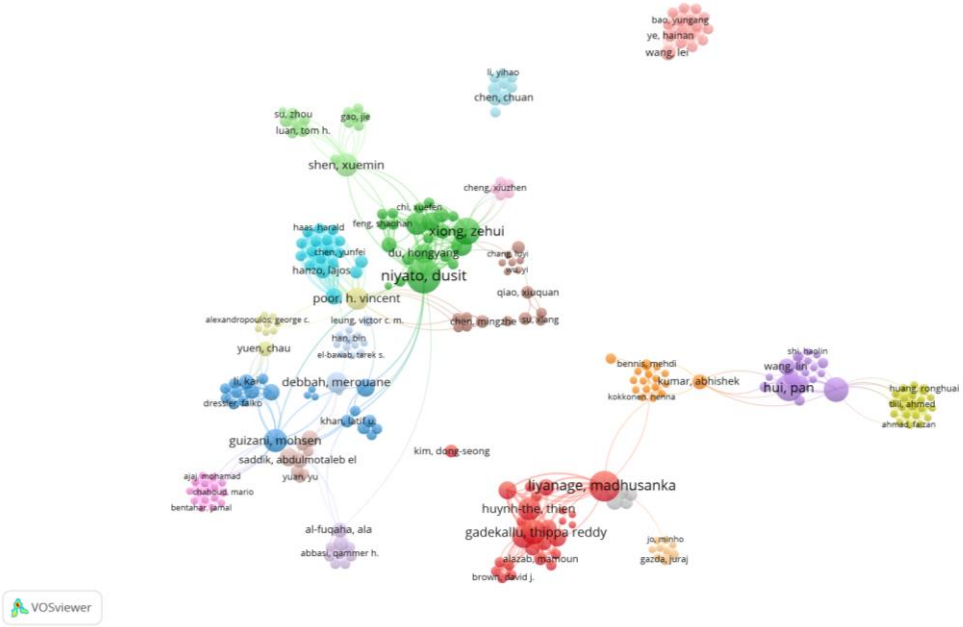
3. Methodology

Throughout May 2023, a quantitative literature review of the Web of Science, Scopus, and ProQuest databases was performed, with search terms including "the metaverse interactive environment" + "immersive extended reality and sensor-based object recognition technologies," "socially-oriented location tracking and simulation modeling tools," and "artificial vision and haptic augmented reality systems." As research published in 2022 and 2023 was inspected, only 175 articles satisfied the eligibility criteria. By taking out controversial or ambiguous findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, too general material, or studies with nearly identical titles, we selected 37 mainly empirical sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AMSTAR, Dedoose, Distiller SR, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

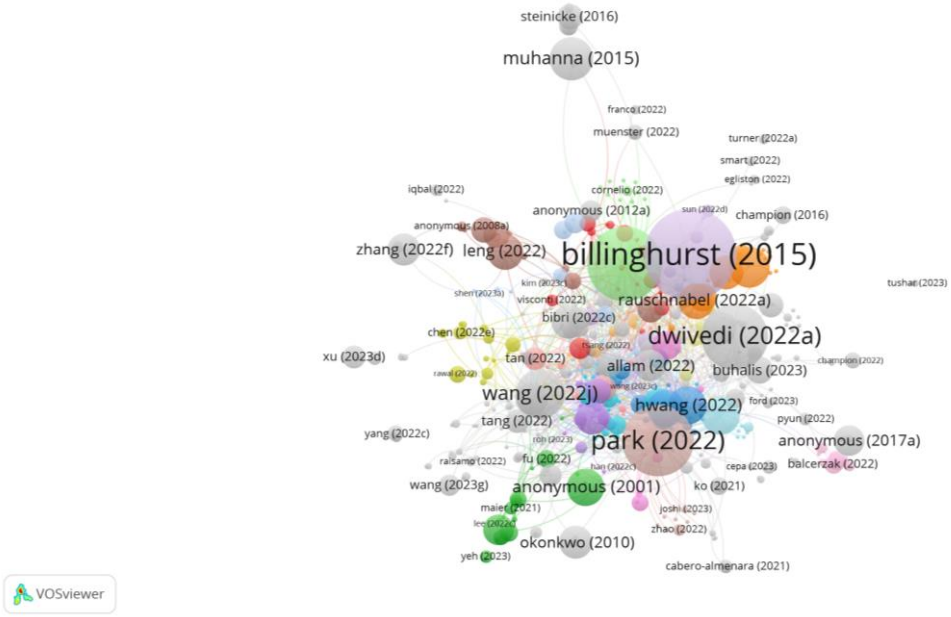
Topic	**Identified**	**Selected**
the metaverse interactive environment + immersive extended reality and sensor-based object recognition technologies	60	14
the metaverse interactive environment + socially-oriented location tracking and simulation modeling tools	58	12
the metaverse interactive environment + artificial vision and haptic augmented reality systems	57	11
Type of paper		
Original research	144	27
Review	21	10
Conference proceedings	8	0
Book	1	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.



VOSviewer

Figure 1 Co-authorship



VOSviewer

Figure 2 Citation

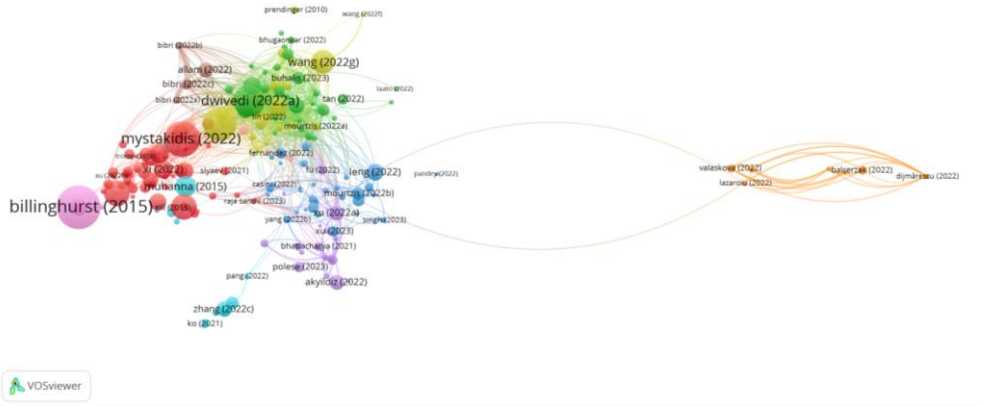


Figure 3 Bibliographic coupling

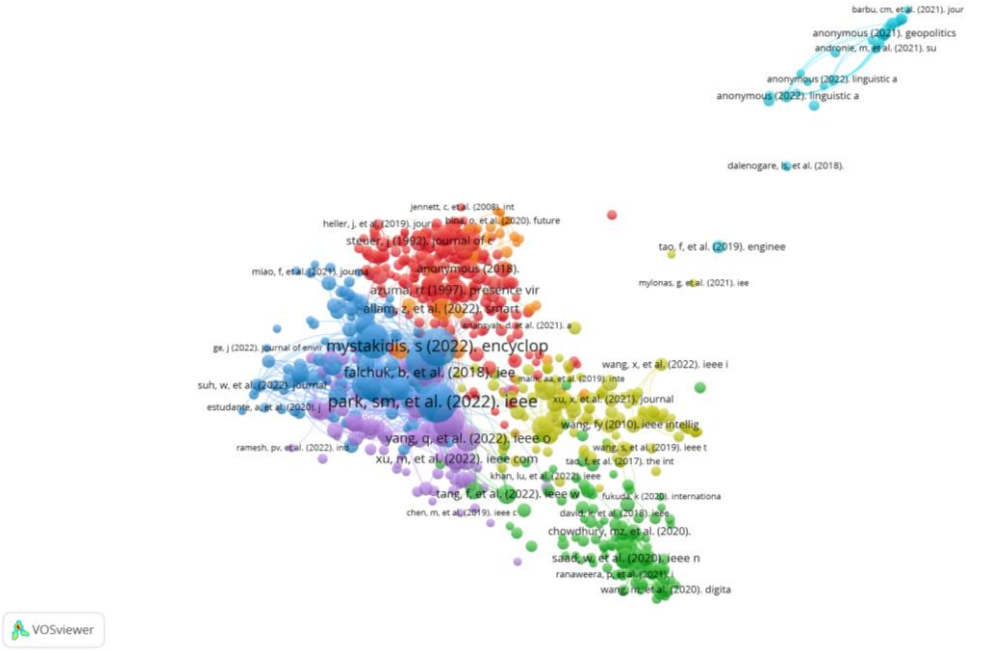


Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

3D metaverse experiences can be achieved through digital twinning and haptic feedback technologies, automated perception and haptic object recognition systems, and body-tracking data metrics.	Ahn et al., 2023; Braud et al., 2022; Huynh-The et al., 2023a; Xu et al., 2023a
Network virtualization and neuromorphic image processing systems, immersive extended reality and sensor-based object recognition technologies, and conversational artificial intelligence and visual tracking algorithms assist 3D immersive environments.	Daneshfar and Jamshidi, 2023; Hollensen et al., 2023; Kovacova et al., 2022; Zhang et al., 2022
3D metaverse experiences can be attained through contextual intelligence and digital twin simulation tools, 3D modeling and multi-sensory extended reality technologies, and predictive modeling and visual cognitive algorithms.	Cheng et al., 2022; Hadi et al., 2023; Valaskova et al., 2022b; Zainab et al., 2022
Autonomous visual object detection and digital twin modeling tools, cognitive decision-making and bio-inspired computational intelligence algorithms, and metaverse and immersive technologies configure the digital asset-based virtual economy.	Dincelli and Yayla, 2022; Gauttier et al., 2022; Oláh and Nica, 2022; Zhu et al., 2023
Hyper-realistic personalized interactive experiences can be attained through 3D object recognition and multisensor fusion technologies, artificial vision and haptic augmented reality systems, and virtual and augmented reality tools.	Du et al., 2023; Giang Barrera and Shah, 2023; Oh et al., 2023; Venugopal et al., 2023
Immersive virtual reality experiences can be attained by use of simulation and modeling technologies, big spatio-temporal data analytics, and synthetic data and virtual navigation tools.	Kliestik et al., 2022; Li et al., 2023; Van Huynh et al., 2022; Zhou et al., 2023
Immersive virtual experiences can be attained through machine learning-based image recognition and digital twinning tools, photorealistic synthetic imagery, and multimodal sensing and big data computing systems.	Hennig-Thurau et al., 2022; McStay, 2022; Valaskova et al., 2022c; Xu et al., 2023b
The virtual environment of the metaverse require artificial cognitive and empathetic computing systems, physics-based modeling and simulation tools, and visual cognitive and spatio-temporal fusion algorithms.	Duncan, 2022; Huynh-The et al., 2023b; Nagendran et al., 2022; Zhang et al., 2023
Virtual reality-based immersive experiences can be achieved through brain-inspired artificial intelligence and neural network-based recognition algorithms, geospatial big data and immersive visual analytics, and digital twinning and holographic imaging technologies.	Ding et al., 2022; Lv et al., 2022; Njoku et al., 2023; Popescu et al., 2022; Yoo et al., 2023

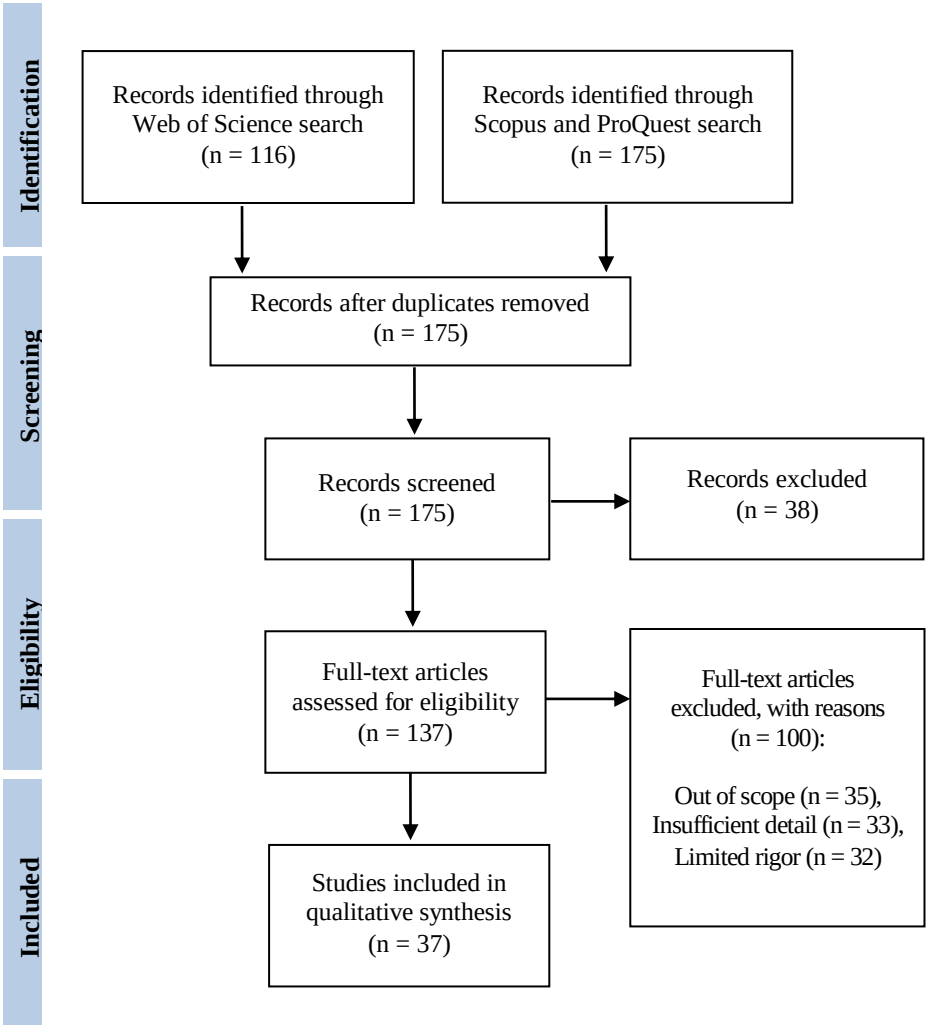


Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

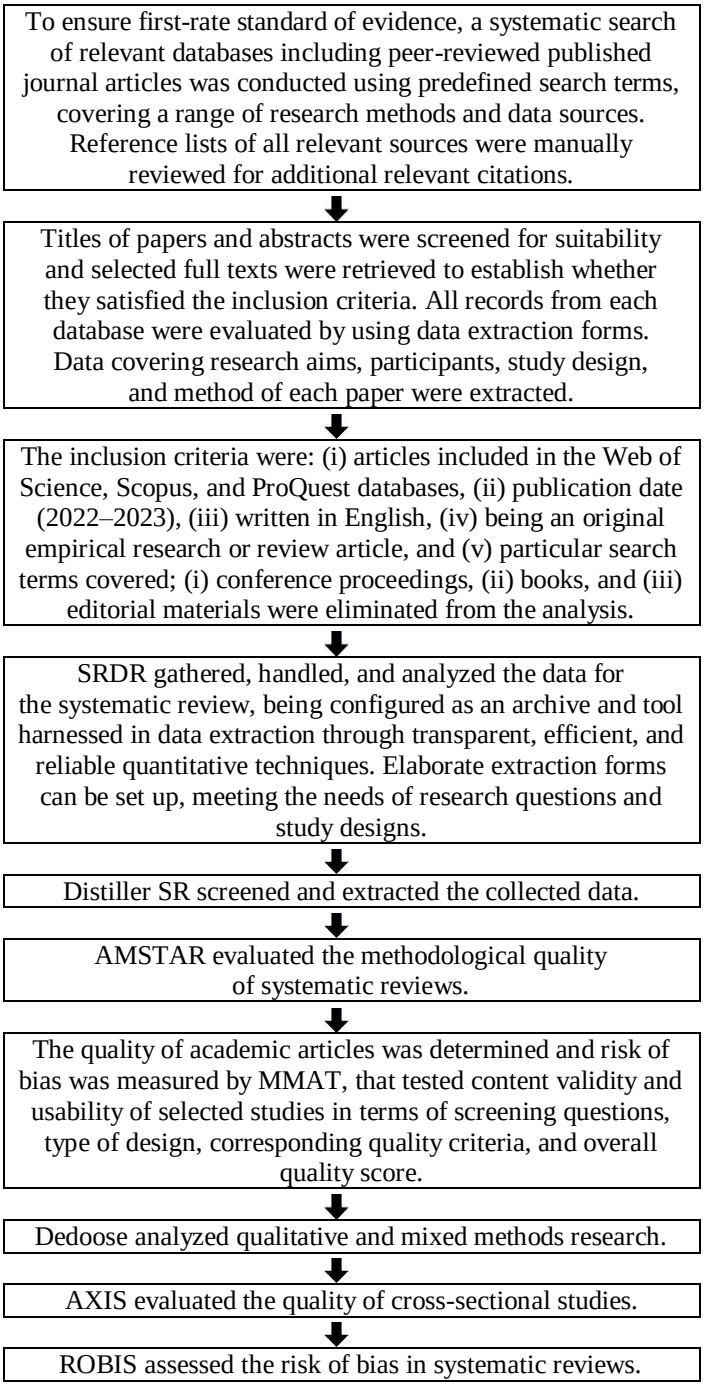


Figure 6 Screening and quality assessment tools

4. Visual Analytics and Edge Artificial Intelligence Computing Systems, Immersive Extended Reality and Sensor-based Object Recognition Technologies, and Predictive Maintenance and Spatial Data Mining Algorithms in the Metaverse Interactive Environment

3D metaverse experiences can be achieved through digital twinning and haptic feedback technologies, automated perception and haptic object recognition systems, and body-tracking data metrics (Ahn et al., 2023; Braud et al., 2022; Huynh-The et al., 2023a; Xu et al., 2023a) across mobile edge computing environments. Photorealistic synthetic environments integrate haptic and sensory technologies, visual analytics and edge artificial intelligence computing systems, and motion control and data processing algorithms.

Network virtualization and neuromorphic image processing systems, immersive extended reality and sensor-based object recognition technologies, and conversational artificial intelligence and visual tracking algorithms (Daneshfar and Jamshidi, 2023; Hollensen et al., 2023; Kovacova et al., 2022; Zhang et al., 2022) assist 3D immersive environments. Ambient intelligence environments develop on networked embedded sensing devices, behavior modeling and multisensor fusion technologies, and implantable intra-body sensors.

3D metaverse experiences can be attained through contextual intelligence and digital twin simulation tools, 3D modeling and multi-sensory extended reality technologies, and predictive modeling and visual cognitive algorithms (Cheng et al., 2022; Hadi et al., 2023; Valaskova et al., 2022a; Zainab et al., 2022) in the digital asset-based virtual economy. Predictive maintenance and spatial data mining algorithms, movement and behavior tracking tools, and data sharing and cognitive modeling technologies articulate the metaverse interactive environment. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

3D metaverse experiences can be achieved through digital twinning and haptic feedback technologies, automated perception and haptic object recognition systems, and body-tracking data metrics across mobile edge computing environments.	Ahn et al., 2023; Braud et al., 2022; Huynh-The et al., 2023a; Xu et al., 2023a
Network virtualization and neuromorphic image processing systems, immersive extended reality and sensor-based object recognition technologies, and conversational artificial intelligence and visual tracking algorithms assist 3D immersive environments.	Daneshfar and Jamshidi, 2023; Hollensen et al., 2023; Kovacova et al., 2022; Zhang et al., 2022
3D metaverse experiences can be attained through contextual intelligence and digital twin simulation tools, 3D modeling and multi-sensory extended reality technologies, and predictive modeling and visual cognitive algorithms.	Cheng et al., 2022; Hadi et al., 2023; Valaskova et al., 2022b; Zainab et al., 2022

5. Metaverse and Immersive Technologies, Digital Twin Simulation and Contextual Data Monitoring Tools, and Artificial Vision and Haptic Augmented Reality Systems in the Digital Asset-based Virtual Economy

Autonomous visual object detection and digital twin modeling tools, cognitive decision-making and bio-inspired computational intelligence algorithms, and metaverse and immersive technologies (Dincelli and Yayla, 2022; Gauttier et al., 2022; Oláh and Nica, 2022; Zhu et al., 2023) configure the digital asset-based virtual economy. Haptic and biometric sensor technologies, distributed sensor and deep convolutional neural networks, and digital twin simulation and contextual data monitoring tools shape immersive virtual worlds.

Hyper-realistic personalized interactive experiences can be attained through 3D object recognition and multisensor fusion technologies, artificial vision and haptic augmented reality systems, and virtual and augmented reality tools (Du et al., 2023; Giang Barrera and Shah, 2023; Oh et al., 2023; Venugopal et al., 2023) in extended reality environments. Immersive geospatial data visualization and 3D modeling technologies, spatial awareness and image processing tools, and virtual mapping and object recognition algorithms optimize immersive virtual environments.

Immersive virtual reality experiences can be attained by use of simulation and modeling technologies, big spatio-temporal data analytics, and synthetic data and virtual navigation tools (Kliestik et al., 2022; Li et al., 2023; Van Huynh et al., 2022; Zhou et al., 2023) across photorealistic virtual reality environments. Haptic bodysuits, distributed decision and control algorithms, and simulation modeling and automated speech recognition tools further extended reality environments. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Autonomous visual object detection and digital twin modeling tools, cognitive decision-making and bio-inspired computational intelligence algorithms, and metaverse and immersive technologies configure the digital asset-based virtual economy.	Dincelli and Yayla, 2022; Gauttier et al., 2022; Oláh and Nica, 2022; Zhu et al., 2023
Hyper-realistic personalized interactive experiences can be attained through 3D object recognition and multisensor fusion technologies, artificial vision and haptic augmented reality systems, and virtual and augmented reality tools in extended reality environments.	Du et al., 2023; Giang Barrera and Shah, 2023; Oh et al., 2023; Venugopal et al., 2023
Immersive virtual reality experiences can be attained by use of simulation and modeling technologies, big spatio-temporal data analytics, and synthetic data and virtual navigation tools across photorealistic virtual reality environments.	Kliestik et al., 2022; Li et al., 2023; Van Huynh et al., 2022; Zhou et al., 2023

6. Socially-oriented Location Tracking and Simulation Modeling Tools, Object Tracking and Image Processing Computational Algorithms, and Geospatial Big Data and Immersive Visual Analytics across Web3-powered Metaverse Worlds

Immersive virtual experiences can be attained through machine learning-based image recognition and digital twinning tools, photorealistic synthetic imagery, and multimodal sensing and big data computing systems (Hennig-Thurau et al., 2022; McStay, 2022; Valaskova et al., 2022b; Xu et al., 2023b) in the virtual environment of the metaverse. Real-time event and big geospatial data analytics, emotion detection and recognition technologies, and socially-oriented location tracking and simulation modeling tools enable 3D virtual environments.

The virtual environment of the metaverse (Duncan, 2022; Huynh-The et al., 2023b; Nagendran et al., 2022; Zhang et al., 2023) require artificial cognitive and empathetic computing systems, physics-based modeling and simulation tools, and visual cognitive and spatio-temporal fusion algorithms. Object tracking and image processing computational algorithms, extended cognitive computing systems, and virtual immersive and digital twin technologies articulate immersive and interoperable spaces.

Virtual reality-based immersive experiences can be achieved through brain-inspired artificial intelligence and neural network-based recognition algorithms, geospatial big data and immersive visual analytics, and digital twinning and holographic imaging technologies (Ding et al., 2022; Lv et al., 2022; Njoku et al., 2023; Popescu et al., 2022; Yoo et al., 2023) across Web3-powered metaverse worlds. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive virtual experiences can be attained through machine learning-based image recognition and digital twinning tools, photorealistic synthetic imagery, and multimodal sensing and big data computing systems.	Hennig-Thurau et al., 2022; McStay, 2022; Valaskova et al., 2022c; Xu et al., 2023b
The virtual environment of the metaverse require artificial cognitive and empathetic computing systems, physics-based modeling and simulation tools, and visual cognitive and spatio-temporal fusion algorithms.	Duncan, 2022; Huynh-The et al., 2023b; Nagendran et al., 2022; Zhang et al., 2023
Virtual reality-based immersive experiences can be achieved through brain-inspired artificial intelligence and neural network-based recognition algorithms, geospatial big data and immersive visual analytics, and digital twinning and holographic imaging technologies.	Ding et al., 2022; Lv et al., 2022; Njoku et al., 2023; Popescu et al., 2022; Yoo et al., 2023

7. Discussion

We integrate our systematic review throughout research indicating how real-time event and big geospatial data analytics, emotion detection and recognition technologies, and socially-oriented location tracking and simulation modeling tools enable 3D virtual environments. Our research complements recent analyses clarifying how haptic bodysuits, distributed decision and control algorithms, and simulation modeling and automated speech recognition tools further extended reality environments. We elucidate, by cumulative evidence, previous research demonstrating how photorealistic synthetic environments integrate haptic and sensory technologies, visual analytics and edge artificial intelligence computing systems, and motion control and data processing algorithms.

8. Synopsis of the Main Research Outcomes

Ambient intelligence environments develop on networked embedded sensing devices, behavior modeling and multisensor fusion technologies, and implantable intra-body sensors. Haptic and biometric sensor technologies, distributed sensor and deep convolutional neural networks, and digital twin simulation and contextual data monitoring tools shape immersive virtual worlds.

9. Conclusions

Relevant research has investigated whether predictive maintenance and spatial data mining algorithms, movement and behavior tracking tools, and data sharing and cognitive modeling technologies articulate the metaverse interactive environment. This systematic literature review presents the published peer-reviewed sources covering how immersive geospatial data visualization and 3D modeling technologies, spatial awareness and image processing tools, and virtual mapping and object recognition algorithms optimize immersive virtual environments. The research outcomes drawn from the above analyses indicate that object tracking and image processing computational algorithms, extended cognitive computing systems, and virtual immersive and digital twin technologies articulate immersive and interoperable spaces.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on immersive extended reality and sensor-based object recognition technologies, socially-oriented location tracking and simulation modeling tools, and artificial vision and haptic augmented reality systems in the meta-

verse interactive environment may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of digital twinning and haptic feedback technologies, automated perception and haptic object recognition systems, and body-tracking data metrics.

Subsequent analyses should develop on simulation and modeling technologies, big spatio-temporal data analytics, and synthetic data and virtual navigation tools. Future research should thus investigate artificial cognitive and empathetic computing systems, physics-based modeling and simulation tools, and visual cognitive and spatio-temporal fusion algorithms. Attention should be directed to contextual intelligence and digital twin simulation tools, 3D modeling and multi-sensory extended reality technologies, and predictive modeling and visual cognitive algorithms.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
The editors declare no conflict of interest in the review and publication decision regarding this article.

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Visual Perceptive and Blockchain-based Decentralized Metaverse Systems, Machine Vision and Geolocation Data Processing Algorithms, and Virtual Twin and Deep Learning-based Sensing Technologies in 3D Immersive Environments

Ann Stevens*

ABSTRACT. The aim of this systematic review is to synthesize and analyze visual digital twins, metaverse and immersive technologies, and machine learning-based image recognition and intelligent data processing tools. In this research, prior findings were cumulated indicating that artificial intelligence-based synthetic media production, bio-sensing and actuation systems, and virtual navigation and autonomous visual object detection tools articulate the blockchain-based virtual economy. I carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout April 2023, with search terms including "3D immersive environments" + "visual perceptive and blockchain-based decentralized metaverse systems," "machine vision and geolocation data processing algorithms," and "virtual twin and deep learning-based sensing technologies." As I analyzed research published in 2022 and 2023, only 176 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, I decided on 34, chiefly empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Distiller SR, ROBIS, and SRDR.

Keywords: visual perceptive; blockchain-based decentralized metaverse systems; machine vision; geolocation data processing algorithms; virtual twin; deep learning; sensing technologies; 3D immersive environments

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1. Introduction

Decentralized data and mobile location analytics, spatio-temporal fusion and computer vision algorithms, and data visualization and digital twin simulation tools (Kovacova et al., 2022; Lewkowich, 2022; Peters et al., 2023; Scott et al., 2020) are pivotal across extended reality environments. The purpose of my systematic review is to examine the recently published literature on 3D immersive environments and integrate the insights it configures on visual perceptive and blockchain-based decentralized metaverse systems, machine vision and geolocation data processing algorithms, and virtual twin and deep learning-based sensing technologies. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that predictive modeling and machine vision algorithms, socio-spatial analytics and immersive decentralized networking tools, and virtual twin and deep learning-based sensing technologies (Lăzăroiu and Rogalska, 2023; Novak et al., 2022; Trettin et al., 2019) assist 3D immersive environments. The actuality and novelty of this study are articulated by addressing visual digital twins, metaverse and immersive technologies, and machine learning-based image recognition and intelligent data processing tools (Balcerzak et al., 2022; Nagy et al., 2023; Vinerean et al., 2022), that is an emerging topic involving much interest. My research problem is whether immersive 3D and spatial computing technologies, environment perception sensors, and deep learning-based ambient sound processing and visual data mining tools enable the digital asset-based virtual economy.

In this review, prior findings have been cumulated indicating that ambient sound recognition software, big data computing and artificial vision systems, and simulation modeling and image recognition tools (Andronie et al., 2021; Dabija et al., 2022; Lyons and Lăzăroiu, 2020) articulate interactive digital worlds and blockchain-based metaverse platforms. The identified gaps advance edge computing and deep learning-based ambient sound processing tools, visual perceptive and blockchain-based decentralized metaverse systems, and data sharing and digital twin technologies. My main objective is to indicate that artificial intelligence-based synthetic media production, biosensing and actuation systems, and virtual navigation and autonomous visual object detection tools (Dabija et al., 2018; Lăzăroiu et al., 2022; Popescu and Ciurlău, 2019) articulate the blockchain-based virtual economy.

2. Theoretical Overview of the Main Concepts

Path planning and computer vision algorithms, metaverse assets and services, and language modeling and intelligent data processing tools assist immersive virtual environments. Immersive decentralized 3D digital worlds integrate real-time visual analytics and blockchain-enabled metaverse systems, movement and behavior tracking tools, and voice recognition software. The man-

uscript is organized as following: theoretical overview (section 2), methodology (section 3), visual perceptive and blockchain-based decentralized metaverse systems, virtual twin and deep learning-based sensing technologies, and simulation modeling and image recognition tools in 3D immersive environments (section 4), explainable artificial intelligence-based decision support and big data computing systems, contextual data monitoring and multi-machine cooperation tools, and spatio-temporal fusion and computer vision algorithms across the interconnected metaverse (section 5), immersive 3D and deep learning-based sensing technologies, machine vision and geolocation data processing algorithms, and deep learning-based ambient sound processing and visual data mining tools in the virtual environment of the metaverse (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

I carried out a quantitative literature review of ProQuest, Scopus, and the Web of Science throughout April 2023, with search terms including "3D immersive environments" + "visual perceptive and blockchain-based decentralized metaverse systems," "machine vision and geolocation data processing algorithms," and "virtual twin and deep learning-based sensing technologies." As I analyzed research published in 2022 and 2023, only 176 papers met the eligibility criteria. By removing controversial or unclear findings (scanty/ unimportant data), results unsupported by replication, undetailed content, or papers having quite similar titles, I decided on 34, chiefly empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Distiller SR, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
3D immersive environments + visual perceptive and blockchain-based decentralized metaverse systems	61	12
3D immersive environments + machine vision and geolocation data processing algorithms	59	11
3D immersive environments + virtual twin and deep learning-based sensing technologies	56	11
Type of paper		
Original research	146	27
Review	19	7
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

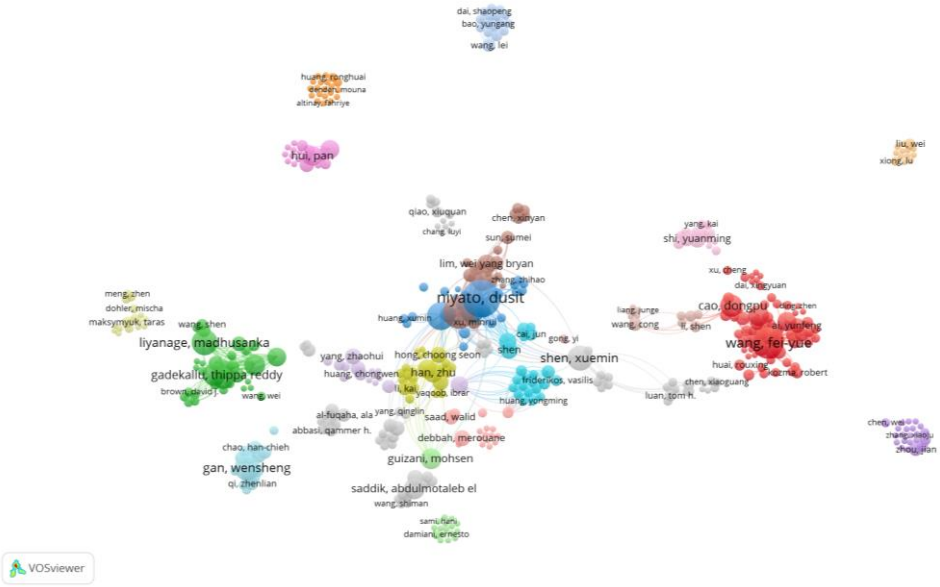

Figure 1 Co-authorship

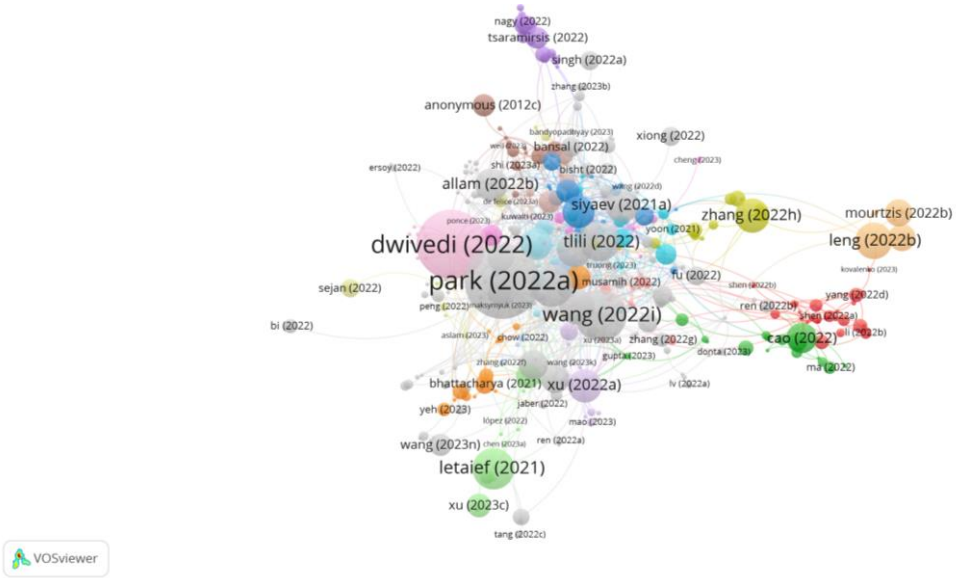

Figure 2 Citation

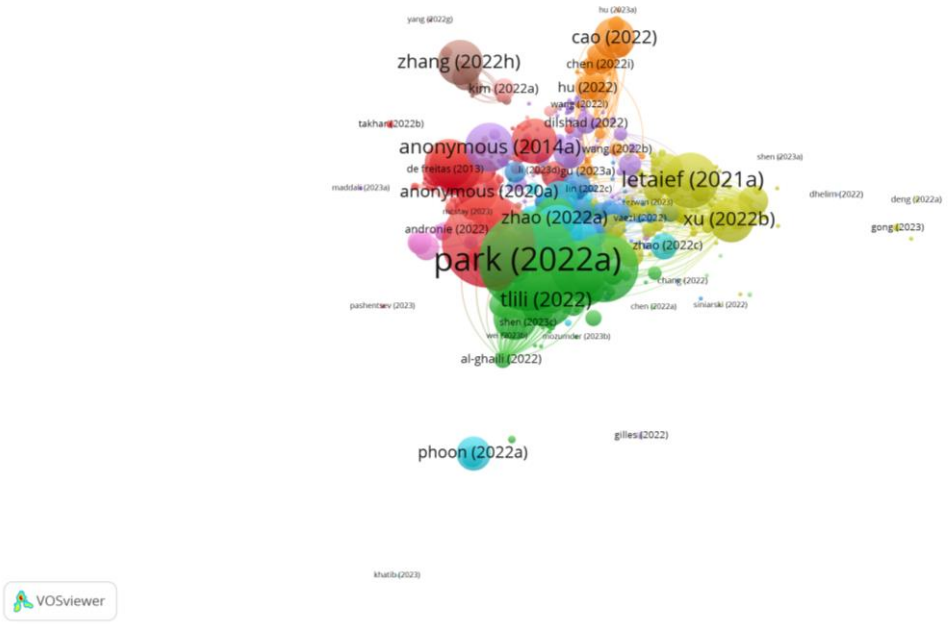

Figure 3 Bibliographic coupling

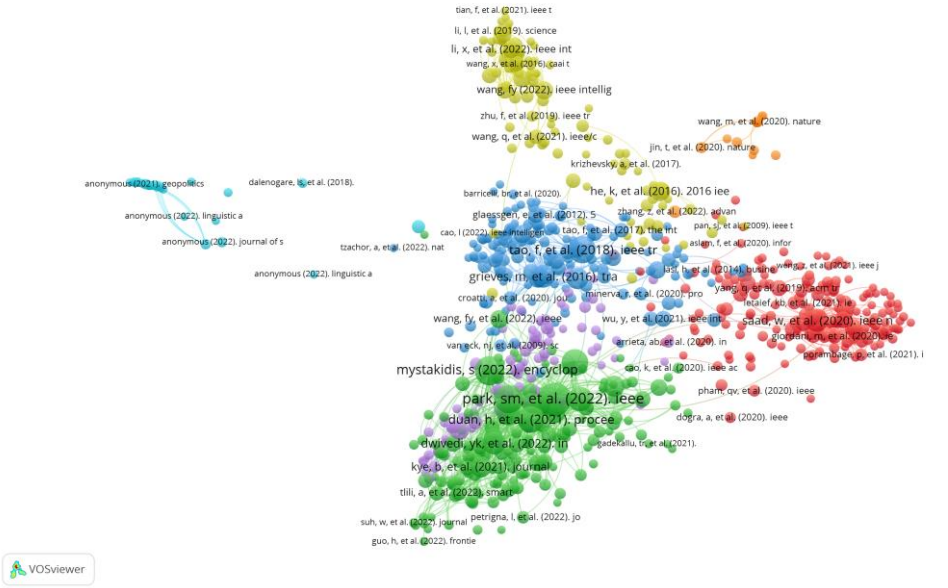

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Context awareness and predictive analytics modeling tools, path planning and deep learning algorithms, and Web3 and cognitive modeling technologies enable in the immersive metaverse environment.	Egliston and Carter, 2022; Shi et al., 2023a; Valaskova et al., 2022; Zyda, 2022
Edge computing and deep learning-based ambient sound processing tools, visual perceptive and blockchain-based decentralized metaverse systems, and data sharing and digital twin technologies further immersive virtual environments.	Kozinets, 2023; Mourtzis et al., 2022; Wu et al., 2023; Zvarikova et al., 2023
Hyper-realistic personalized interactive experiences can be attained through biometric self-authentication devices, immersive extended reality and dynamic routing technologies, and captured image data in the metaverse interactive environment.	Cao, 2022; He et al., 2023; Li et al., 2023; Zabel et al., 2023
Simulation and modeling technologies, context awareness and computational intelligence tools, and explainable artificial intelligence-based decision support and big data computing systems configure digitally-networked mediated spaces.	Queiroz et al., 2023; Zallio and Clarkson, 2022; Zarantonello and Schmitt, 2023
Hyper-realistic personalized interactive experiences can be attained by use of digital twin simulation and machine vision tools, sensory data mining techniques, and virtual personas and identities across the interconnected metaverse.	Bojic, 2022; Grupac and Lăzăroiu, 2022; Weking et al., 2023; Zhang et al., 2022
The blockchain-based virtual economy necessitate visual digital twins, metaverse and immersive technologies, and machine learning-based image recognition and intelligent data processing tools.	Aloqaily et al., 2022; Han et al., 2023; Panagiotakopoulos et al., 2022
Multi-sensory immersive experiences can be achieved by use of 3D immersive virtual reality and spatial computing technologies, body-tracking data metrics, and virtual object behavior modeling and synthetic data tools across the metaverse economy.	Hancock, 2022; Meng et al., 2023; Smart, 2022; Zheng and Yuan, 2023
Immersive virtual experiences can be achieved through image-based object recognition and data sharing technologies, 3D image modeling and virtual navigation tools, and computer vision and natural language processing algorithms in extended reality environments.	Ding et al., 2022; Hopkins, 2022; McStay, 2023; Polas et al., 2022
3D immersive spaces and experiences can be attained through virtual and augmented reality tools, machine vision and geolocation data processing algorithms, and biometrics data fusion in the virtual environment of the metaverse.	Newell, 2022; Rostami and Maier, 2022; Shi et al., 2023b; Zhang et al., 2023

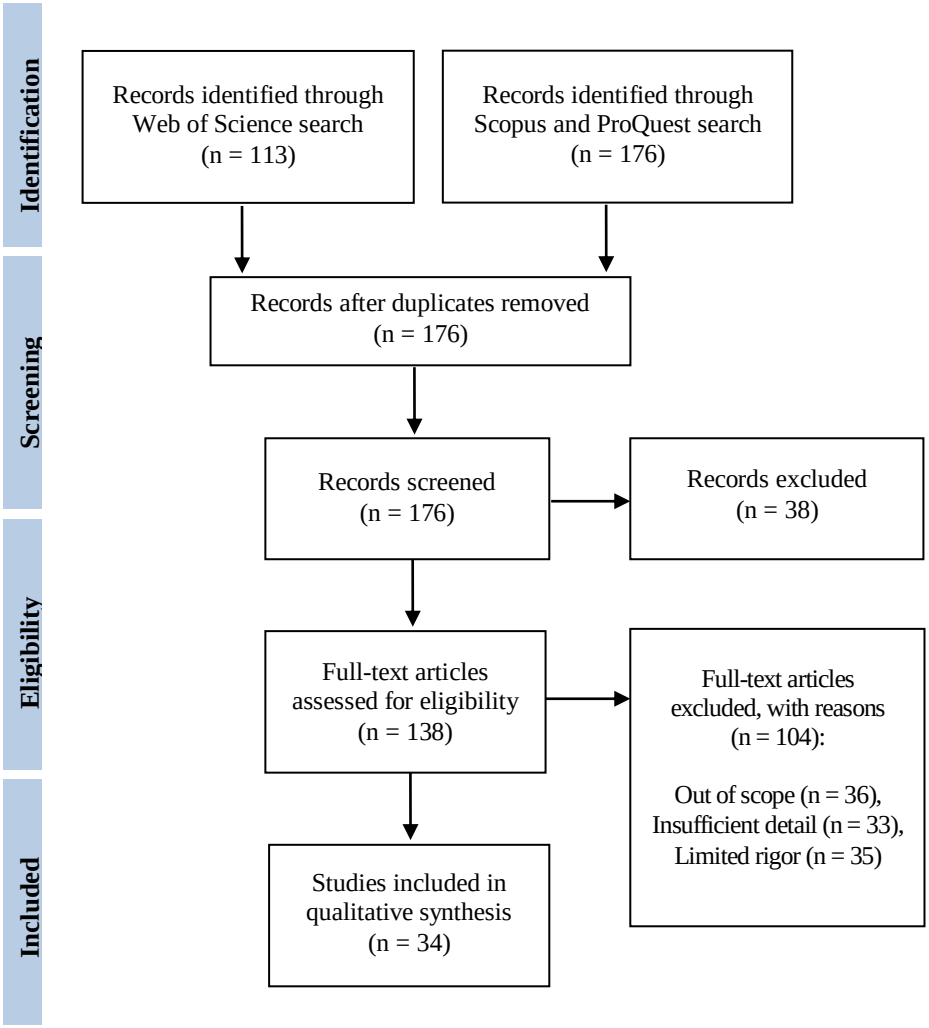

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

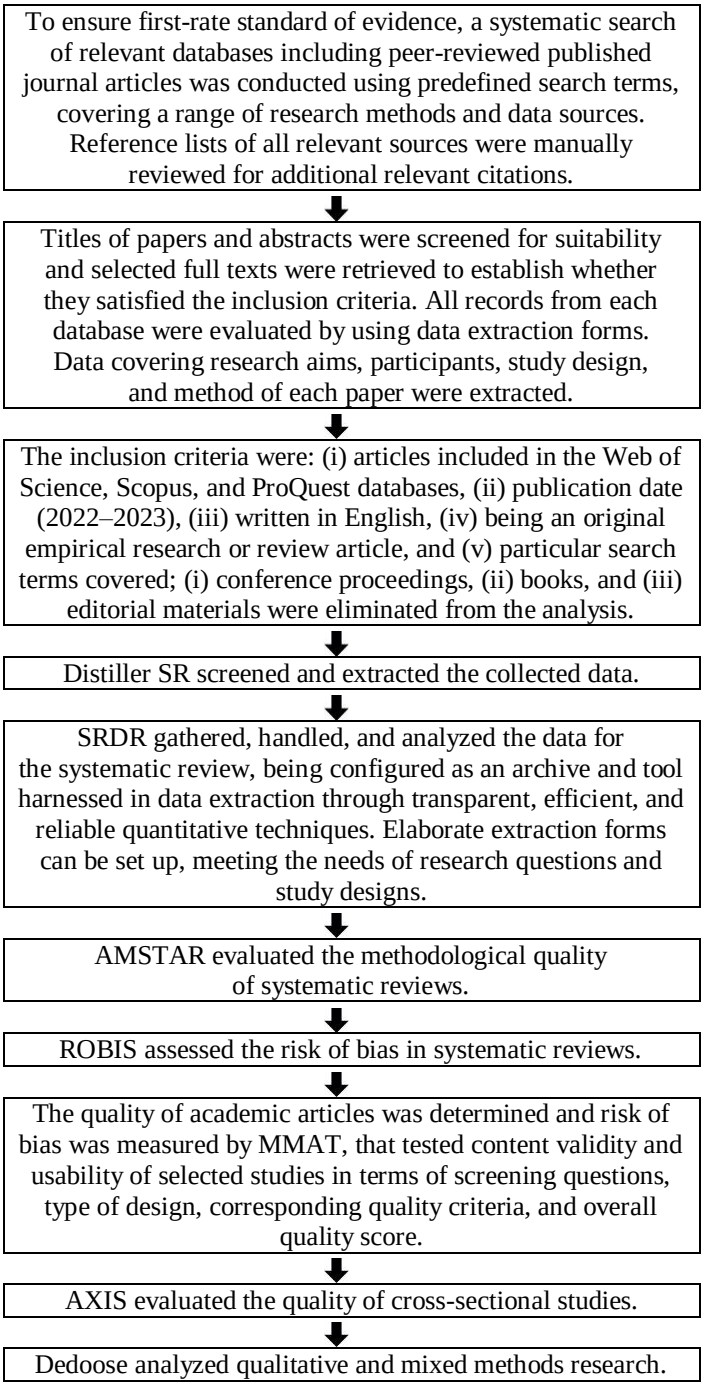

Figure 6 Screening and quality assessment tools

4. Visual Perceptive and Blockchain-based Decentralized Metaverse Systems, Virtual Twin and Deep Learning-based Sensing Technologies, and Simulation Modeling and Image Recognition Tools in 3D Immersive Environments

Context awareness and predictive analytics modeling tools, path planning and deep learning algorithms, and Web3 and cognitive modeling technologies (Egliston and Carter, 2022; Shi et al., 2023a; Valaskova et al., 2022; Zyda, 2022) enable in the immersive metaverse environment. Predictive modeling and machine vision algorithms, socio-spatial analytics and immersive decentralized networking tools, and virtual twin and deep learning-based sensing technologies assist 3D immersive environments.

Edge computing and deep learning-based ambient sound processing tools, visual perceptive and blockchain-based decentralized metaverse systems, and data sharing and digital twin technologies (Kozinets, 2023; Mourtzis et al., 2022; Wu et al., 2023; Zvarikova et al., 2023) further immersive virtual environments. Artificial intelligence-based synthetic media production, bio-sensing and actuation systems, and virtual navigation and autonomous visual object detection tools articulate the blockchain-based virtual economy.

Hyper-realistic personalized interactive experiences can be attained through biometric self-authentication devices, immersive extended reality and dynamic routing technologies, and captured image data (Cao, 2022; He et al., 2023; Li et al., 2023; Zabel et al., 2023) in the metaverse interactive environment. Ambient sound recognition software, big data computing and artificial vision systems, and simulation modeling and image recognition tools articulate interactive digital worlds and blockchain-based metaverse platforms. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Context awareness and predictive analytics modeling tools, path planning and deep learning algorithms, and Web3 and cognitive modeling technologies enable in the immersive metaverse environment.	Egliston and Carter, 2022; Shi et al., 2023a; Valaskova et al., 2022; Zyda, 2022
Edge computing and deep learning-based ambient sound processing tools, visual perceptive and blockchain-based decentralized metaverse systems, and data sharing and digital twin technologies further immersive virtual environments.	Kozinets, 2023; Mourtzis et al., 2022; Wu et al., 2023; Zvarikova et al., 2023
Hyper-realistic personalized interactive experiences can be attained through biometric self-authentication devices, immersive extended reality and dynamic routing technologies, and captured image data in the metaverse interactive environment.	Cao, 2022; He et al., 2023; Li et al., 2023; Zabel et al., 2023

5. Explainable Artificial Intelligence-based Decision Support and Big Data Computing Systems, Contextual Data Monitoring and Multi-Machine Cooperation Tools, and Spatio-Temporal Fusion and Computer Vision Algorithms across the Interconnected Metaverse

Simulation and modeling technologies, context awareness and computational intelligence tools, and explainable artificial intelligence-based decision support and big data computing systems (Queiroz et al., 2023; Zallio and Clarkson, 2022; Zarantonello and Schmitt, 2023) configure digitally-networked mediated spaces. Path planning and computer vision algorithms, metaverse assets and services, and language modeling and intelligent data processing tools assist immersive virtual environments.

Hyper-realistic personalized interactive experiences can be attained by use of digital twin simulation and machine vision tools, sensory data mining techniques, and virtual personas and identities (Bojic, 2022; Grupac and Lăzăroiu, 2022; Weking et al., 2023; Zhang et al., 2022) across the interconnected metaverse. Decentralized data and mobile location analytics, spatio-temporal fusion and computer vision algorithms, and data visualization and digital twin simulation tools are pivotal across extended reality environments.

The blockchain-based virtual economy (Aloqaily et al., 2022; Han et al., 2023; Panagiotakopoulos et al., 2022) necessitate visual digital twins, metaverse and immersive technologies, and machine learning-based image recognition and intelligent data processing tools. Text mining and analytics, contextual data monitoring and multi-machine cooperation tools, and geospatial mapping and virtual reality-based visual perception technologies optimize immersive 3D virtual environments. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Simulation and modeling technologies, context awareness and computational intelligence tools, and explainable artificial intelligence-based decision support and big data computing systems configure digitally-networked mediated spaces.	Queiroz et al., 2023; Zallio and Clarkson, 2022; Zarantonello and Schmitt, 2023
Hyper-realistic personalized interactive experiences can be attained by use of digital twin simulation and machine vision tools, sensory data mining techniques, and virtual personas and identities across the interconnected metaverse.	Bojic, 2022; Grupac and Lăzăroiu, 2022; Weking et al., 2023; Zhang et al., 2022
The blockchain-based virtual economy necessitate visual digital twins, metaverse and immersive technologies, and machine learning-based image recognition and intelligent data processing tools.	Aloqaily et al., 2022; Han et al., 2023; Panagiotakopoulos et al., 2022

6. Immersive 3D and Deep Learning-based Sensing Technologies, Machine Vision and Geolocation Data Processing Algorithms, and Deep Learning-based Ambient Sound Processing and Visual Data Mining Tools in the Virtual Environment of the Metaverse

Multi-sensory immersive experiences can be achieved by use of 3D immersive virtual reality and spatial computing technologies, body-tracking data metrics, and virtual object behavior modeling and synthetic data tools (Hancock, 2022; Meng et al., 2023; Smart, 2022; Zheng and Yuan, 2023) across the metaverse economy. Immersive decentralized 3D digital worlds integrate real-time visual analytics and blockchain-enabled metaverse systems, movement and behavior tracking tools, and voice recognition software.

Immersive virtual experiences can be achieved through image-based object recognition and data sharing technologies, 3D image modeling and virtual navigation tools, and computer vision and natural language processing algorithms (Ding et al., 2022; Hopkins, 2022; McStay, 2023; Polas et al., 2022) in extended reality environments. Immersive 3D and spatial computing technologies, environment perception sensors, and deep learning-based ambient sound processing and visual data mining tools enable the digital asset-based virtual economy.

3D immersive spaces and experiences can be attained through virtual and augmented reality tools, machine vision and geolocation data processing algorithms, and biometrics data fusion (Newell, 2022; Rostami and Maier, 2022; Shi et al., 2023b; Zhang et al., 2023) in the virtual environment of the metaverse. Immersive 3D and deep learning-based sensing technologies, body-tracking data metrics, and big data management and automated speech recognition tools shape blockchain-based virtual worlds. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Multi-sensory immersive experiences can be achieved by use of 3D immersive virtual reality and spatial computing technologies, body-tracking data metrics, and virtual object behavior modeling and synthetic data tools across the metaverse economy.	Hancock, 2022; Meng et al., 2023; Smart, 2022; Zheng and Yuan, 2023
Immersive virtual experiences can be achieved through image-based object recognition and data sharing technologies, 3D image modeling and virtual navigation tools, and computer vision and natural language processing algorithms in extended reality environments.	Ding et al., 2022; Hopkins, 2022; McStay, 2023; Polas et al., 2022
3D immersive spaces and experiences can be attained through virtual and augmented reality tools, machine vision and geolocation data processing algorithms, and biometrics data fusion in the virtual environment of the metaverse.	Newell, 2022; Rostami and Maier, 2022; Shi et al., 2023b; Zhang et al., 2023

7. Discussion

I integrate my systematic review throughout research indicating how immersive 3D and spatial computing technologies, environment perception sensors, and deep learning-based ambient sound processing and visual data mining tools enable the digital asset-based virtual economy. My research complements recent analyses clarifying how decentralized data and mobile location analytics, spatio-temporal fusion and computer vision algorithms, and data visualization and digital twin simulation tools are pivotal across extended reality environments. I elucidate, by cumulative evidence, previous research demonstrating how immersive decentralized 3D digital worlds integrate real-time visual analytics and blockchain-enabled metaverse systems, movement and behavior tracking tools, and voice recognition software.

8. Synopsis of the Main Research Outcomes

Immersive 3D and deep learning-based sensing technologies, body-tracking data metrics, and big data management and automated speech recognition tools shape blockchain-based virtual worlds. Path planning and computer vision algorithms, metaverse assets and services, and language modeling and intelligent data processing tools assist immersive virtual environments. Text mining and analytics, contextual data monitoring and multi-machine cooperation tools, and geospatial mapping and virtual reality-based visual perception technologies optimize immersive 3D virtual environments.

9. Conclusions

Relevant research has investigated whether predictive modeling and machine vision algorithms, socio-spatial analytics and immersive decentralized networking tools, and virtual twin and deep learning-based sensing technologies assist 3D immersive environments. This systematic literature review presents the published peer-reviewed sources covering how ambient sound recognition software, big data computing and artificial vision systems, and simulation modeling and image recognition tools articulate interactive digital worlds and blockchain-based metaverse platforms. The research outcomes drawn from the above analyses indicate that artificial intelligence-based synthetic media production, bio-sensing and actuation systems, and virtual navigation and autonomous visual object detection tools articulate the blockchain-based virtual economy.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant

sources on visual perceptive and blockchain-based decentralized metaverse systems, machine vision and geolocation data processing algorithms, and virtual twin and deep learning-based sensing technologies in 3D immersive environments may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of 3D immersive virtual reality and spatial computing technologies, body-tracking data metrics, and virtual object behavior modeling and synthetic data tools.

Subsequent analyses should develop on context awareness and predictive analytics modeling tools, path planning and deep learning algorithms, and Web3 and cognitive modeling technologies. Future research should thus investigate virtual and augmented reality tools, machine vision and geolocation data processing algorithms, and biometrics data fusion. Attention should be directed to hyper-realistic personalized interactive experiences can be attained by use of digital twin simulation and machine vision tools, sensory data mining techniques, and virtual personas and identities.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
The author confirms being the sole contributor of this work and approved it for publication. The author takes full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
The editors declare no conflict of interest in the review and publication decision regarding this article.

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Context Modeling and Ambient Scene Detection Tools, Machine Learning-based Object Recognition and Distributed Sensing Technologies, and Immersive Visualization and Haptic Augmented Reality Systems in the Decentralized Metaverse

Milos Poliak[1], Adela Poliakova[1], and Elvira Nica[2]

ABSTRACT. In this article, we cumulate previous research findings indicating that 3D holographic avatars, context modeling and ambient scene detection tools, and tactile sensing and machine intelligence technologies are instrumental in digital hyper-realistic worlds. Throughout May 2023, we performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "the decentralized metaverse" + "context modeling and ambient scene detection tools," "machine learning-based object recognition and distributed sensing technologies," and "immersive visualization and haptic augmented reality systems." As we inspected research published in 2022 and 2023, only 179 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, we decided upon 30, generally empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, ROBIS, and SRDR.

Keywords: context modeling; ambient scene detection tools; machine learning; object recognition; distributed sensing technologies; immersive visualization; haptic augmented reality systems; metaverse

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1. Introduction

Extended reality environments integrate digital twin simulation and socio-spatial analytics tools, motion capture suits, and 3D path planning and edge intelligence algorithms. The purpose of our systematic review is to examine the recently published literature on the decentralized metaverse and integrate the insights it configures on context modeling and ambient scene detection tools, machine learning-based object recognition and distributed sensing technologies, and immersive visualization and haptic augmented reality systems. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, our paper has attempted to prove that 3D holographic avatars, context modeling and ambient scene detection tools, and tactile sensing and machine intelligence technologies (Fernando and Lăzăroiu, 2023; Nagy and Lăzăroiu, 2022; Popescu et al., 2020) are instrumental in digital hyper-realistic worlds. The actuality and novelty of this study are articulated by addressing machine learning-based decision support and visual perceptive systems, 3D modeling and simulation technologies, and spatio-temporal fusion and visual object tracking algorithms (Andronie et al., 2023; Krizanova et al., 2019; Nica et al., 2019), that is an emerging topic involving much interest. Our research problem is whether immersive 3D and motion capture technologies, image detection and predictive maintenance algorithms, and geospatial analytics and big data management tools (Andronie et al., 2021a; Lăzăroiu, 2018; Nica, 2018; Zhuravleva et al., 2019) configure the decentralized metaverse.

In this review, prior findings have been cumulated indicating that decentralized 3D virtual spaces (Andronie et al., 2021b; Lăzăroiu et al., 2022; Nica, 2019) develop on behavior modeling and 3D virtual immersive technologies, synthetic biometric data, and machine learning-based navigation and image processing computational algorithms. The identified gaps advance behavioral simulation and digital twin modeling tools (Kliestik et al., 2020; Lewkowich, 2022; Nica et al., 2023; Vătămănescu et al., 2022), tactile sensing and geospatial mapping technologies, and mobile location and geospatial big data analytics. Our main objective is to indicate that visual and spatial intelligence tools, spatial computing and data sharing technologies, and data-driven artificial intelligence and computer vision algorithms (Gennadyevna Leshkevich and Vladimirovna Kataeva, 2023; Pelau et al., 2021; Vătămănescu et al., 2020) are pivotal in immersive 3D worlds.

2. Theoretical Overview of the Main Concepts

Predictive geospatial modeling and virtual navigation tools, motion capture suits, and emotion detection and recognition technologies optimize immersive virtual environments. The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), cognitive computing and

explainable artificial intelligence-based decision support systems, spatio-temporal fusion and visual object tracking algorithms, and emotion detection and recognition technologies in the decentralized metaverse (section 4), bio-inspired computational intelligence and visual perception algorithms, context modeling and ambient scene detection tools, and machine learning-based object recognition and distributed sensing technologies in the interconnected metaverse (section 5), immersive visualization and haptic augmented reality systems, behavioral simulation and digital twin modeling tools, and real-time 3D rendering and remote sensing technologies, in the blockchain-based virtual economy (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout May 2023, we performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "the decentralized metaverse" + "context modeling and ambient scene detection tools," "machine learning-based object recognition and distributed sensing technologies," and "immersive visualization and haptic augmented reality systems." As we inspected research published in 2022 and 2023, only 179 articles satisfied the eligibility criteria. By eliminating controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, we decided upon 30, generally empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, ROBIS, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
the decentralized metaverse + context modeling and ambient scene detection tools	60	11
the decentralized metaverse + machine learning-based object recognition and distributed sensing technologies	60	10
the decentralized metaverse + immersive visualization and haptic augmented reality systems	59	9
Type of paper		
Original research	150	23
Review	18	7
Conference proceedings	9	0
Book	1	0
Editorial	1	0

Source: Processed by the authors. Some topics overlap.

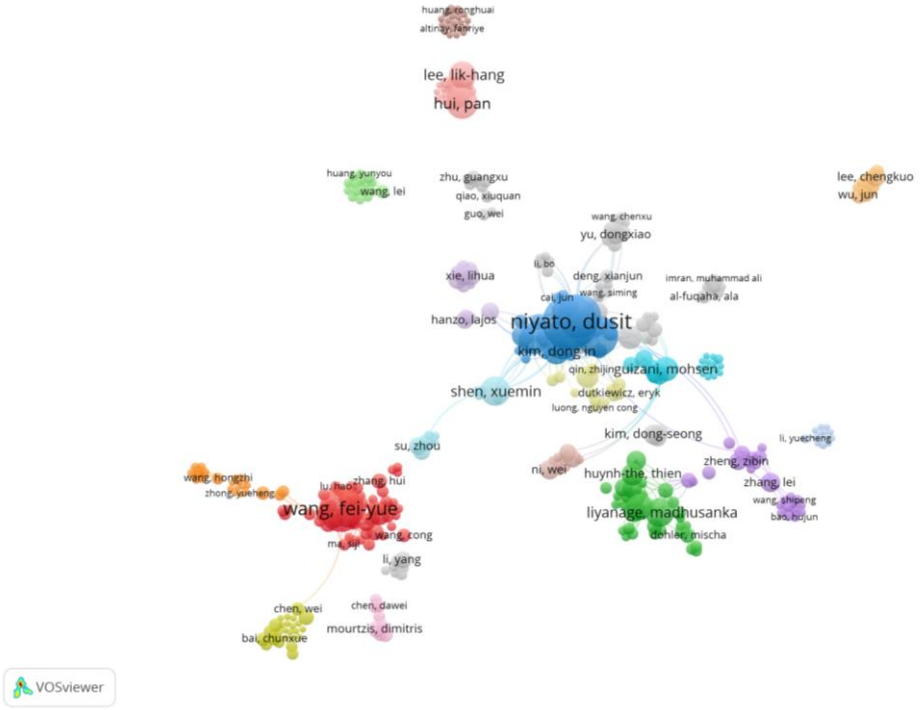

Figure 1 Co-authorship

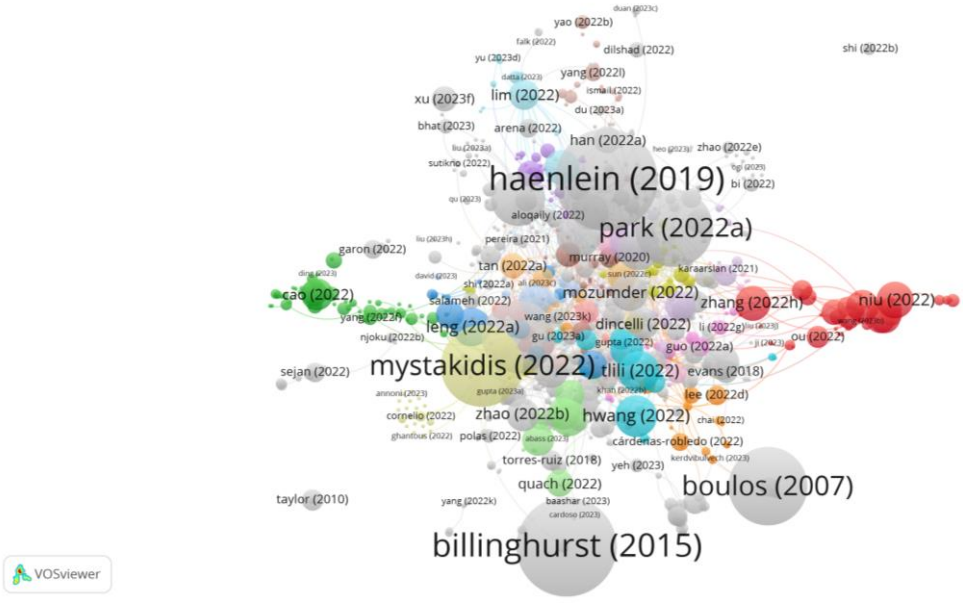

Figure 2 Citation

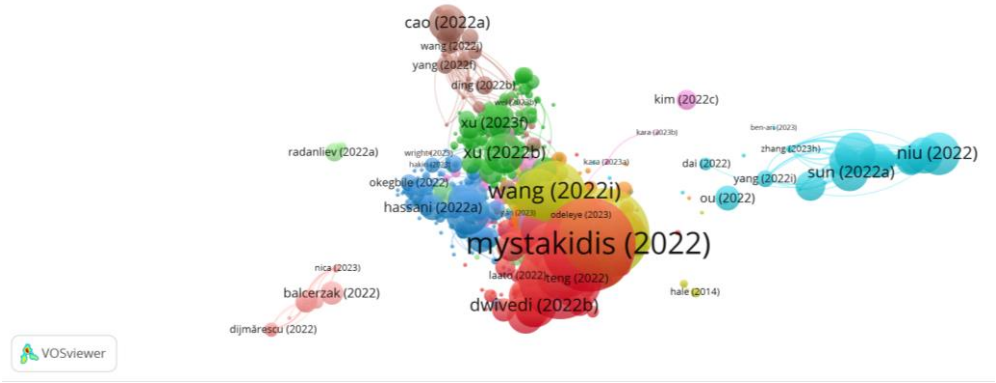

Figure 3 Bibliographic coupling

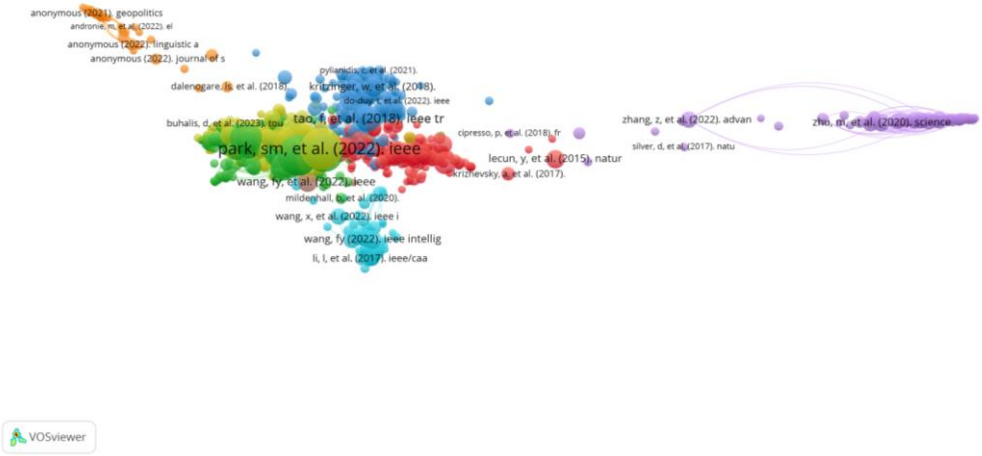

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Cognitive computing and Internet of Things-based sensing systems, spatio-temporal modeling and mapping tools, and digital scent and virtual twin technologies articulate immersive hyper-connected virtual spaces.	Bojic, 2022; Ersoy and Gürfidan, 2023; Kwok and Tang, 2023
Ambient intelligence environments require machine learning-based decision support and visual perceptive systems, 3D modeling and simulation technologies, and spatio-temporal fusion and visual object tracking algorithms.	Bordegoni and Ferrise, 2023; Cheng et al., 2022; Huang et al., 2023
Metaverse engagement and experiences can be attained through cognitive computing and explainable artificial intelligence-based decision support systems, data modeling and computational intelligence tools, and haptic and multisensory technologies.	Balica et al., 2022; Dincelli and Yayla, 2022; Oh et al., 2023
3D metaverse experiences can be attained through bio-inspired computational intelligence and visual perception algorithms, autonomous visual object detection and simulation modeling tools, and machine learning-based object recognition and distributed sensing technologies.	Dwivedi et al., 2023; Han et al., 2022; Valaskova et al., 2022; Wang et al., 2022
Haptic bodysuits and object recognition systems, performance capture and visual immersion technologies, and emotion detection and neuromorphic computing algorithms are pivotal in 3D computer-generated virtual environments.	Gauttier et al., 2022; Han et al., 2023; Kliestik et al., 2022; Venugopal et al., 2023)
Remote sensing and image processing computational algorithms, geospatial intelligence and digital twin simulation tools, and ambient sound recognition software enable the interconnected metaverse.	McStay, 2023; Tang et al., 2023; Yoo et al., 2023
Immersive virtual experiences can be achieved by use of immersive visualization and haptic augmented reality systems, virtual modeling and 3D object recognition technologies, and predictive modeling and virtual reality-based data analytics tools.	Chen, 2022; Huynh-The et al., 2023; Morley, 2022; Zainab et al., 2022
Behavioral simulation and digital twin modeling tools, tactile sensing and geospatial mapping technologies, and mobile location and geospatial big data analytics further interconnected virtual worlds.	Dolata and Schwabe, 2023; Lv et al., 2022; Zhang et al., 2022
Virtual reality-based immersive experiences can be achieved by use of real-time 3D rendering and remote sensing technologies, network virtualization and automated perception systems, and behavioral predictive and mobile location analytics.	Du et al., 2023; Nagendran et al., 2022; Shen, 2022

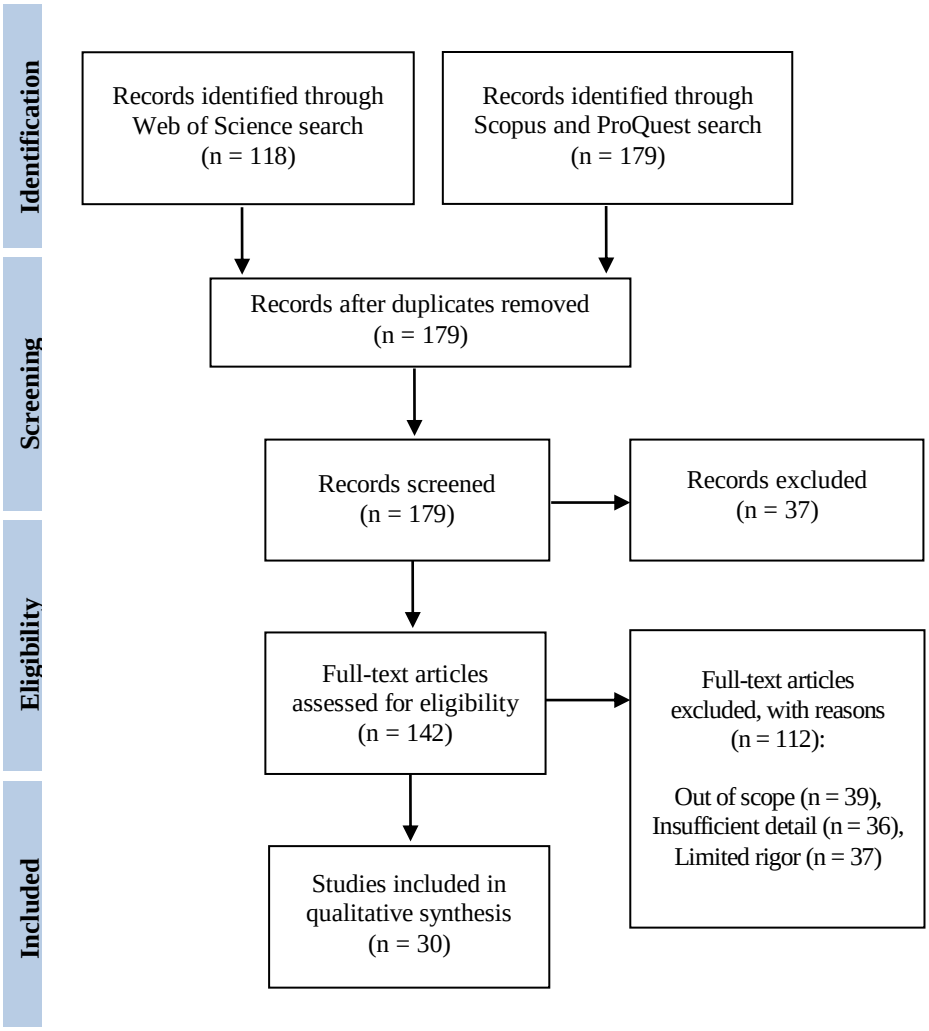

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

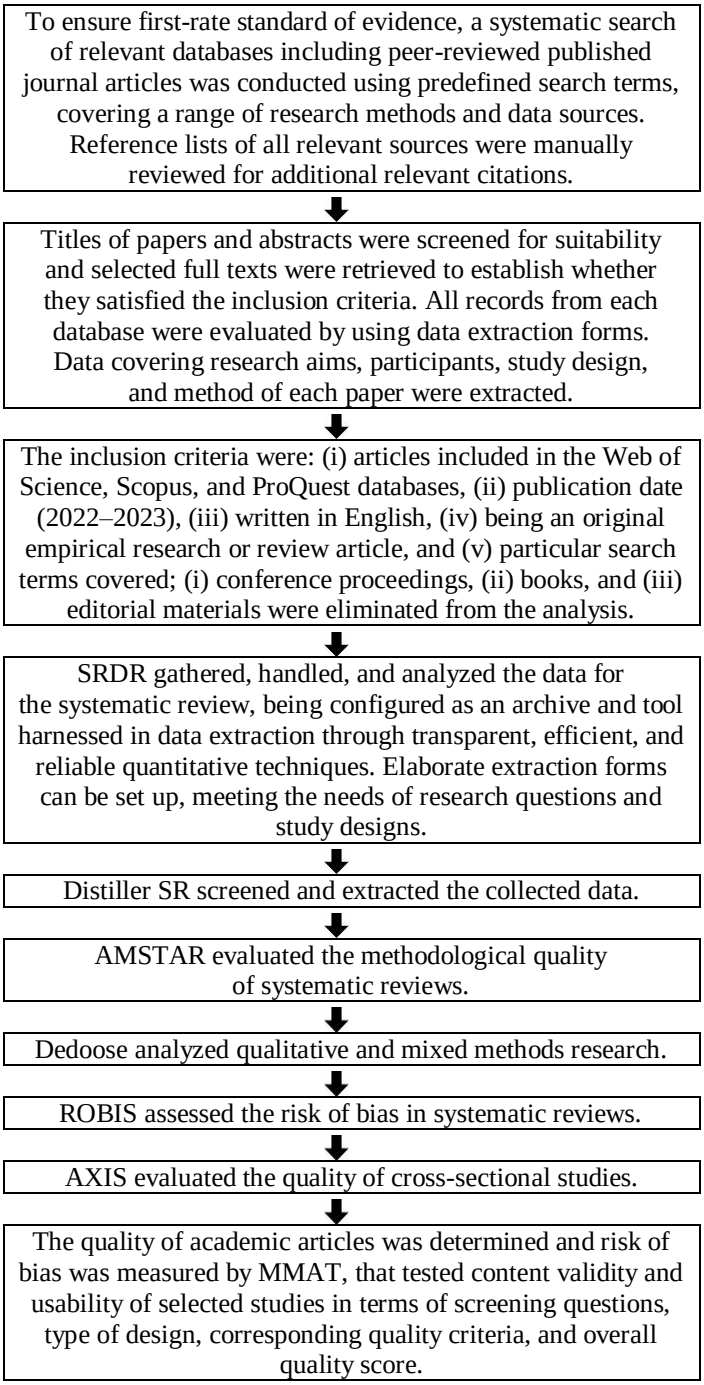

Figure 6 Screening and quality assessment tools

4. Cognitive Computing and Explainable Artificial Intelligence-based Decision Support Systems, Spatio-Temporal Fusion and Visual Object Tracking Algorithms, and Emotion Detection and Recognition Technologies in the Decentralized Metaverse

Cognitive computing and Internet of Things-based sensing systems, spatio-temporal modeling and mapping tools, and digital scent and virtual twin technologies (Bojic, 2022; Ersoy and Gürfidan, 2023; Kwok and Tang, 2023) articulate immersive hyper-connected virtual spaces. Immersive 3D and motion capture technologies, image detection and predictive maintenance algorithms, and geospatial analytics and big data management tools configure the decentralized metaverse.

Ambient intelligence environments (Bordegoni and Ferrise, 2023; Cheng et al., 2022; Huang et al., 2023) require machine learning-based decision support and visual perceptive systems, 3D modeling and simulation technologies, and spatio-temporal fusion and visual object tracking algorithms. Blockchain token-based digital assets, spatial data mining and deep learning computer vision algorithms, and virtual immersive and motion capture technologies shape extended reality environments.

Metaverse engagement and experiences (Balica et al., 2022; Dincelli and Yayla, 2022; Oh et al., 2023) can be attained through cognitive computing and explainable artificial intelligence-based decision support systems, data modeling and computational intelligence tools, and haptic and multisensory technologies. Predictive geospatial modeling and virtual navigation tools, motion capture suits, and emotion detection and recognition technologies optimize immersive virtual environments. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Cognitive computing and Internet of Things-based sensing systems, spatio-temporal modeling and mapping tools, and digital scent and virtual twin technologies articulate immersive hyper-connected virtual spaces.	Bojic, 2022; Ersoy and Gürfidan, 2023; Kwok and Tang, 2023
Ambient intelligence environments require machine learning-based decision support and visual perceptive systems, 3D modeling and simulation technologies, and spatio-temporal fusion and visual object tracking algorithms.	Bordegoni and Ferrise, 2023; Cheng et al., 2022; Huang et al., 2023
Metaverse engagement and experiences can be attained through cognitive computing and explainable artificial intelligence-based decision support systems, data modeling and computational intelligence tools, and haptic and multisensory technologies.	Balica et al., 2022; Dincelli and Yayla, 2022; Oh et al., 2023

5. Bio-inspired Computational Intelligence and Visual Perception Algorithms, Context Modeling and Ambient Scene Detection Tools, and Machine Learning-based Object Recognition and Distributed Sensing Technologies in the Interconnected Metaverse

3D metaverse experiences (Dwivedi et al., 2023; Han et al., 2022; Valaskova et al., 2022; Wang et al., 2022) can be attained through bio-inspired computational intelligence and visual perception algorithms, autonomous visual object detection and simulation modeling tools, and machine learning-based object recognition and distributed sensing technologies. Extended reality environments integrate digital twin simulation and socio-spatial analytics tools, motion capture suits, and 3D path planning and edge intelligence algorithms.

Haptic bodysuits and object recognition systems, performance capture and visual immersion technologies, and emotion detection and neuromorphic computing algorithms (Gauttier et al., 2022; Han et al., 2023; Kliestik et al., 2022; Venugopal et al., 2023) are pivotal in 3D computer-generated virtual environments. Visual and spatial intelligence tools, spatial computing and data sharing technologies, and data-driven artificial intelligence and computer vision algorithms are pivotal in immersive 3D worlds.

Remote sensing and image processing computational algorithms, geospatial intelligence and digital twin simulation tools, and ambient sound recognition software (McStay, 2023; Tang et al., 2023; Yoo et al., 2023) enable the interconnected metaverse. 3D holographic avatars, context modeling and ambient scene detection tools, and tactile sensing and machine intelligence technologies are instrumental in digital hyper-realistic worlds. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

3D metaverse experiences can be attained through bio-inspired computational intelligence and visual perception algorithms, autonomous visual object detection and simulation modeling tools, and machine learning-based object recognition and distributed sensing technologies.	Dwivedi et al., 2023; Han et al., 2022; Valaskova et al., 2022; Wang et al., 2022
Haptic bodysuits and object recognition systems, performance capture and visual immersion technologies, and emotion detection and neuromorphic computing algorithms are pivotal in 3D computer-generated virtual environments.	Gauttier et al., 2022; Han et al., 2023; Kliestik et al., 2022; Venugopal et al., 2023)
Remote sensing and image processing computational algorithms, geospatial intelligence and digital twin simulation tools, and ambient sound recognition software enable the interconnected metaverse.	McStay, 2023; Tang et al., 2023; Yoo et al., 2023

6. Immersive Visualization and Haptic Augmented Reality Systems, Behavioral Simulation and Digital Twin Modeling Tools, and Real-Time 3D Rendering and Remote Sensing Technologies in the Blockchain-based Virtual Economy

Immersive virtual experiences (Chen, 2022; Huynh-The et al., 2023; Morley, 2022; Zainab et al., 2022) can be achieved by use of immersive visualization and haptic augmented reality systems, virtual modeling and 3D object recognition technologies, and predictive modeling and virtual reality-based data analytics tools. Cognitive and behavioral technologies, spatial awareness and digital twin simulation tools, and haptic object recognition and artificial cognitive systems configure blockchain-based virtual worlds.

Behavioral simulation and digital twin modeling tools, tactile sensing and geospatial mapping technologies, and mobile location and geospatial big data analytics (Dolata and Schwabe, 2023; Lv et al., 2022; Zhang et al., 2022) further interconnected virtual worlds. 3D interactive digital spaces necessitate visual and spatial intelligence tools, cognitive modeling and digital twin technologies, and biometric and behavioral data.

Virtual reality-based immersive experiences (Du et al., 2023; Nagendran et al., 2022; Shen, 2022) can be achieved by use of real-time 3D rendering and remote sensing technologies, network virtualization and automated perception systems, and behavioral predictive and mobile location analytics. Sensor and actuator devices, distributed decision and control algorithms, and simulation and modeling technologies assist the blockchain-based virtual economy. Decentralized 3D virtual spaces develop on behavior modeling and 3D virtual immersive technologies, synthetic biometric data, and machine learning-based navigation and image processing computational algorithms. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive virtual experiences can be achieved by use of immersive visualization and haptic augmented reality systems, virtual modeling and 3D object recognition technologies, and predictive modeling and virtual reality-based data analytics tools.	Chen, 2022; Huynh-The et al., 2023; Morley, 2022; Zainab et al., 2022
Behavioral simulation and digital twin modeling tools, tactile sensing and geospatial mapping technologies, and mobile location and geospatial big data analytics further interconnected virtual worlds.	Dolata and Schwabe, 2023; Lv et al., 2022; Zhang et al., 2022
Virtual reality-based immersive experiences can be achieved by use of real-time 3D rendering and remote sensing technologies, network virtualization and automated perception systems, and behavioral predictive and mobile location analytics.	Du et al., 2023; Nagendran et al., 2022; Shen, 2022

7. Discussion

We integrate our systematic review throughout research indicating how visual and spatial intelligence tools, spatial computing and data sharing technologies, and data-driven artificial intelligence and computer vision algorithms are pivotal in immersive 3D worlds. Our research complements recent analyses clarifying how sensor and actuator devices, distributed decision and control algorithms, and simulation and modeling technologies assist the blockchain-based virtual economy. We elucidate, by cumulative evidence, previous research demonstrating how Immersive 3D and motion capture technologies, image detection and predictive maintenance algorithms, and geospatial analytics and big data management tools configure the decentralized metaverse.

8. Synopsis of the Main Research Outcomes

Blockchain token-based digital assets, spatial data mining and deep learning computer vision algorithms, and virtual immersive and motion capture technologies shape extended reality environments. 3D interactive digital spaces necessitate visual and spatial intelligence tools, cognitive modeling and digital twin technologies, and biometric and behavioral data. Cognitive and behavioral technologies, spatial awareness and digital twin simulation tools, and haptic object recognition and artificial cognitive systems configure blockchain-based virtual worlds.

9. Conclusions

Relevant research has investigated whether 3D holographic avatars, context modeling and ambient scene detection tools, and tactile sensing and machine intelligence technologies are instrumental in digital hyper-realistic worlds. This systematic literature review presents the published peer-reviewed sources covering how decentralized 3D virtual spaces develop on behavior modeling and 3D virtual immersive technologies, synthetic biometric data, and machine learning-based navigation and image processing computational algorithms. The research outcomes drawn from the above analyses indicate that extended reality environments integrate digital twin simulation and socio-spatial analytics tools, motion capture suits, and 3D path planning and edge intelligence algorithms.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant sources on context modeling and ambient scene detection tools, machine

learning-based object recognition and distributed sensing technologies, and immersive visualization and haptic augmented reality systems in the decentralized metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of our study also does not move forward the inspection of immersive visualization and haptic augmented reality systems, virtual modeling and 3D object recognition technologies, and predictive modeling and virtual reality-based data analytics tools.

Subsequent analyses should develop on cognitive computing and Internet of Things-based sensing systems, spatio-temporal modeling and mapping tools, and digital scent and virtual twin technologies. Future research should thus investigate real-time 3D rendering and remote sensing technologies, network virtualization and automated perception systems, and behavioral predictive and mobile location analytics. Attention should be directed to bio-inspired computational intelligence and visual perception algorithms, autonomous visual object detection and simulation modeling tools, and machine learning-based object recognition and distributed sensing technologies.

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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

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Author contributions
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Conflict of interest statement
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Bio-inspired Computational Intelligence and Deep Learning Algorithms, 3D Modeling and Cognitive Neuro-Engineering Technologies, and Immersive Visualization and Internet of Things-based Decision Support Systems in the Virtual Environment of the Metaverse

Ray Hayward*

ABSTRACT. The purpose of this study is to examine photorealistic synthetic imagery, digital scent and data analytics technologies, and digital twin simulation and natural language processing tools. In this article, I cumulate previous research findings indicating that immersive visualization and Internet of Things-based decision support systems, user behavior data mining, and digital twin and multi-sensory extended reality technologies shape a blockchain-based virtual world. Throughout April 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "the virtual environment of the metaverse" + "bio-inspired computational intelligence and deep learning algorithms," "3D modeling and cognitive neuro-engineering technologies," and "immersive visualization and Internet of Things-based decision support systems." As I inspected research published in 2022 and 2023, only 174 articles satisfied the eligibility criteria. By removing controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 30, generally empirical, sources. Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, MMAT, and SRDR.

Keywords: bio-inspired computational intelligence; deep learning algorithms; 3D modeling; cognitive neuro-engineering technologies; immersive visualization; Internet of Things-based decision support systems; metaverse

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1. Introduction

Multimodal sensing and visual analytics systems, 3D image processing and situational awareness algorithms, and spatial awareness and tracking tools (Balcerzak et al., 2022; Dabija et al., 2018; Lăzăroiu et al., 2022) configure immersive 3D worlds. The purpose of my systematic review is to examine the recently published literature on the virtual environment of the metaverse and integrate the insights it configures on bio-inspired computational intelligence and deep learning algorithms, 3D modeling and cognitive neuro-engineering technologies, and immersive visualization and Internet of Things-based decision support systems. By analyzing the most recent (2022–2023) and significant (Web of Science, Scopus, and ProQuest) sources, my paper has attempted to prove that immersive visualization and Internet of Things-based decision support systems, user behavior data mining, and digital twin and multi-sensory extended reality technologies (Andronie et al., 2023a; Kovacova et al., 2022a; Lăzăroiu et al., 2020) shape a blockchain-based virtual world. The actuality and novelty of this study are articulated by addressing smart environment modeling and automated speech recognition tools, biometric self-authentication devices, and deep learning-based sensing and ontology-based semantic technologies (Andronie et al., 2023b; Nica et al., 2023; Popescu and Ciurlău, 2019), that is an emerging topic involving much interest. My research problem is whether biometric and behavioral data, 3D modeling and cognitive neuro-engineering technologies, and bio-inspired computational intelligence and deep learning algorithms enable 3D digital environments.

In this review, prior findings have been cumulated indicating that haptic and multisensory technologies, spatial awareness and deep learning-based ambient sound processing tools, and motion capture suits (Andronie et al., 2021a; Lewkowich, 2022; Milward et al., 2019; Vătămănescu et al., 2022) shape blockchain-based metaverse platforms. The identified gaps advance immersive and extended reality technologies, data-driven artificial intelligence and spatial cognition algorithms (Andronie et al., 2021b; Lăzăroiu et al., 2017; Valaskova et al., 2022), and immersive decentralized networking and autonomous visual object detection tools. My main objective is to indicate that 3D capture and digital contact tracing technologies, intelligent connectivity infrastructures, and machine vision and cognitive decision-making algorithms (Peters et al., 2023; Trettin et al., 2019; Vătămănescu et al., 2020) assist extended reality environments..

2. Theoretical Overview of the Main Concepts

The manuscript is organized as following: theoretical overview (section 2), methodology (section 3), digital twin simulation and natural language processing tools, 3D image processing and situational awareness algorithms, and

deep learning-based sensing and ontology-based semantic technologies in 3D computer-generated virtual environments (section 4), bio-inspired computational intelligence and deep learning algorithms, immersive decentralized networking and autonomous visual object detection tools, and 3D modeling and cognitive neuro-engineering technologies in the decentralized metaverse (section 5), deep learning artificial intelligence and location-based predictive algorithms, cognitive neuro-engineering and multisensor fusion technologies, and immersive visualization and Internet of Things-based decision support systems in the virtual environment of the metaverse (section 6), discussion (section 7), synopsis of the main research outcomes (section 8), conclusions (section 9), limitations, implications, and further directions of research (section 10).

3. Methodology

Throughout April 2023, I performed a quantitative literature review of the Web of Science, Scopus, and ProQuest databases, with search terms including "the virtual environment of the metaverse" + "bio-inspired computational intelligence and deep learning algorithms," "3D modeling and cognitive neuro-engineering technologies," and "immersive visualization and Internet of Things-based decision support systems." As I inspected research published in 2022 and 2023, only 174 articles satisfied the eligibility criteria. By removing controversial findings, outcomes unsubstantiated by replication, too imprecise material, or having similar titles, I decided upon 30, generally empirical, sources (Tables 1 and 2). Data visualization tools: Dimensions (bibliometric mapping) and VOSviewer (layout algorithms). Reporting quality assessment tool: PRISMA. Methodological quality assessment tools include: AXIS, Dedoose, MMAT, and SRDR (Figures 1–6).

Table 1 Topics and types of scientific products identified and selected.

Topic	**Identified**	**Selected**
the virtual environment of the metaverse + bio-inspired computational intelligence and deep learning algorithms	60	11
the virtual environment of the metaverse + 3D modeling and cognitive neuro-engineering technologies	57	10
the virtual environment of the metaverse + immersive visualization and Internet of Things-based decision support systems	57	9
Type of paper		
Original research	137	15
Review	28	15
Conference proceedings	8	0
Book	0	0
Editorial	1	0

Source: Processed by the author. Some topics overlap.

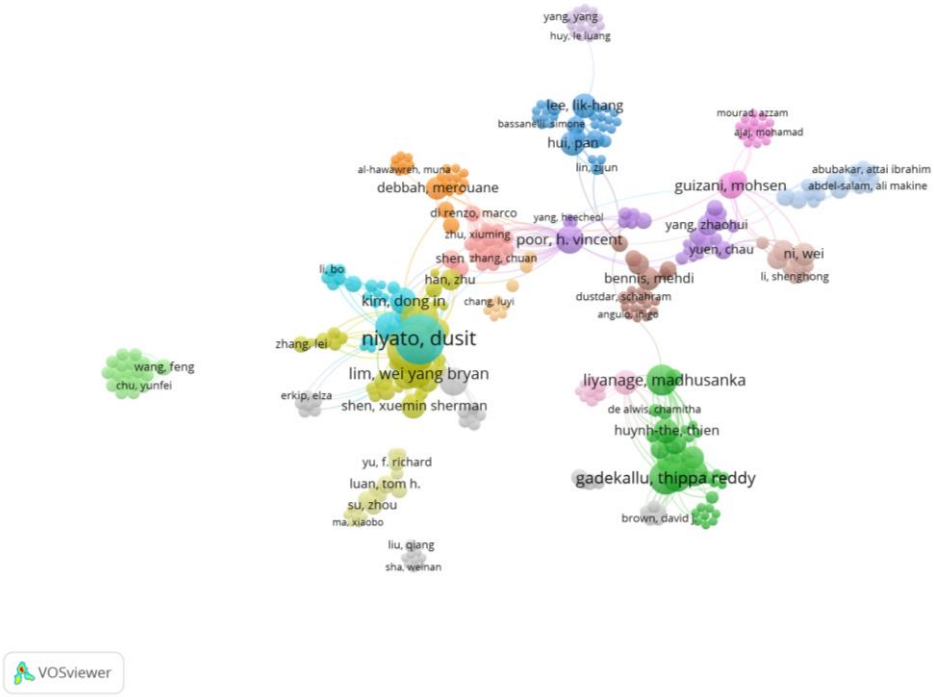

Figure 1 Co-authorship

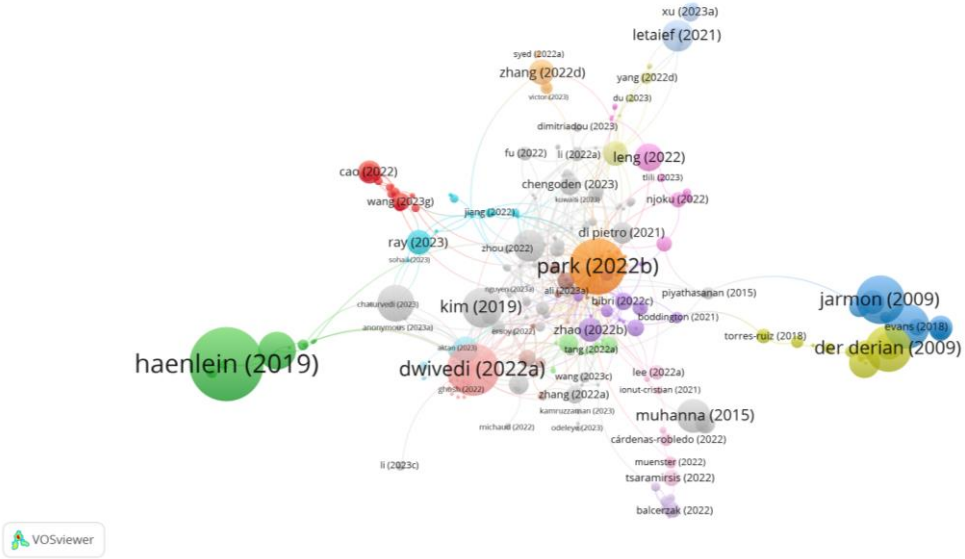

Figure 2 Citation

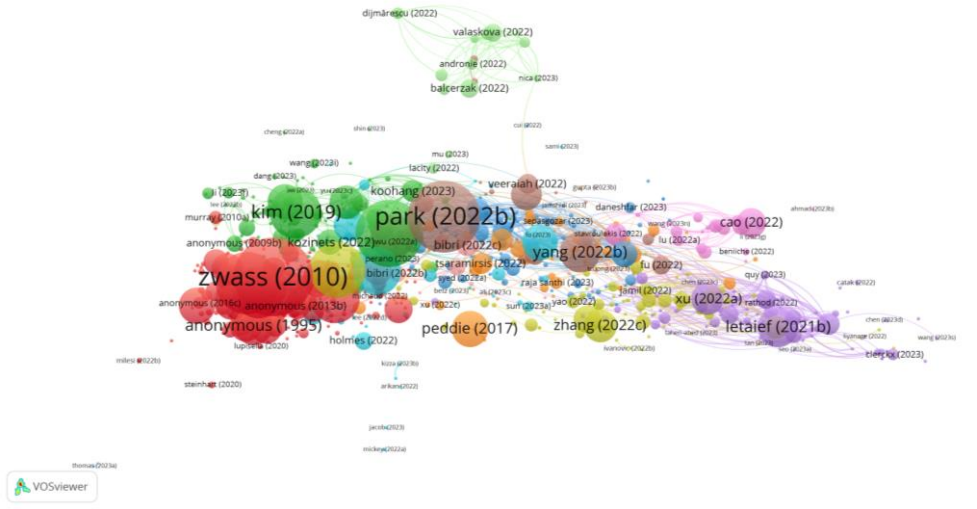

Figure 3 Bibliographic coupling

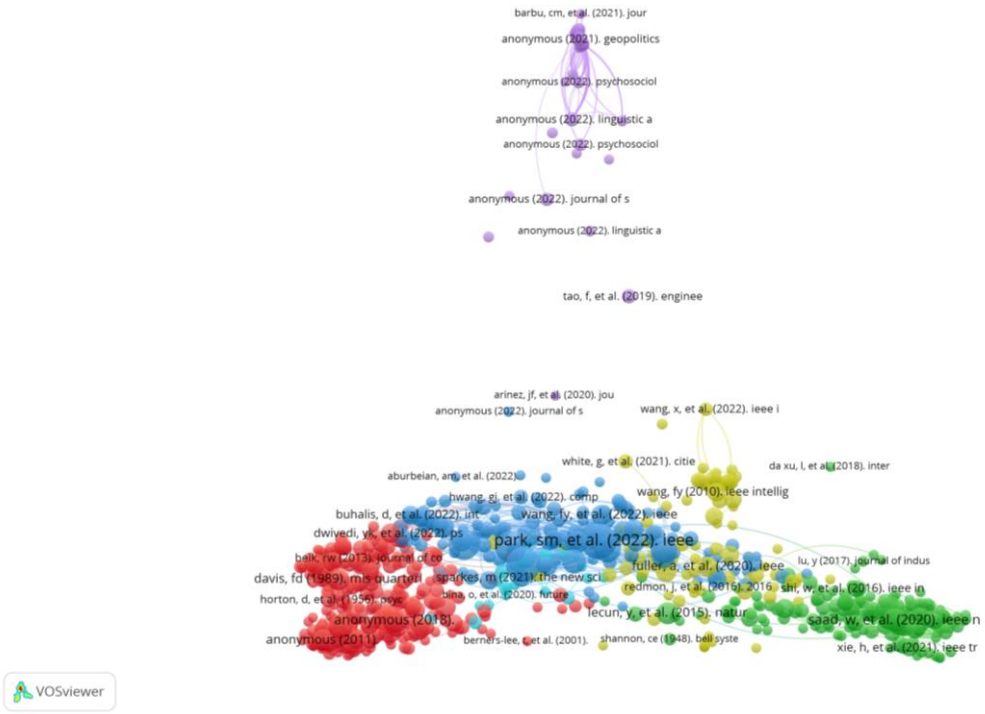

Figure 4 Co-citation

Table 2 General synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive virtual experiences can be attained through photorealistic synthetic imagery, digital scent and data analytics technologies, and digital twin simulation and natural language processing tools in 3D virtual environments.	Barnes, 2022; Daneshfar and Jamshidi, 2023; Xu et al., 2023
Ambient intelligence and immersive analytics tools, behavior pattern clustering, and visual perceptive and immersive visualization systems configure immersive interconnected virtual worlds.	Dawson, 2022; Golf-Papez et al., 2022; Wongkitrungrueng and Suprawan, 2023
Blockchain-based metaverse platforms develop on smart environment modeling and automated speech recognition tools, biometric self-authentication devices, and deep learning-based sensing and ontology-based semantic technologies.	Duncan, 2022; Hennig-Thurau et al., 2022; Morley, 2022
Immersive virtual reality experiences can be achieved through immersive visualization and real-time visual analytics systems, implantable intra-body sensors, and data processing and neural network-based recognition algorithms in immersive interconnected virtual worlds.	Aloqaily et al., 2022; Giang Barrera and Shah, 2023; Hawkins, 2022; Musova et al., 2022
Immersive and extended reality technologies, data-driven artificial intelligence and spatial cognition algorithms, and immersive decentralized networking and autonomous visual object detection tools articulate immersive virtual environments.	Braud et al., 2022; Grupac and Lăzăroiu, 2022; Njoku et al., 2023; Popp and Cuțitoi, 2022
Real-time sensor data, 3D imaging and display technologies, and empathetic computing and Internet of Things-based sensing systems enable synthetic digitally-mediated environments.	Durana et al., 2022; Hadi et al., 2023; Zhang et al., 2022
3D immersive spaces and experiences can be attained by use of haptic bodysuits, 3D modeling and haptic feedback technologies, and deep learning artificial intelligence and location-based predictive algorithms across the virtual environment of the metaverse.	Kliestik et al., 2022; Park and Kim, 2023; Zyda, 2022
Image processing and contextual intelligence tools, affective and perceptual technologies, and machine learning-based recognition and computer vision algorithms further extended reality environments.	Huynh-The et al., 2023; Popescu et al., 2022; Ramadan, 2023
Hyperconnected virtual experiences can be achieved by use of cognitive neuro-engineering and multisensor fusion technologies, virtual holographic objects, and interactional and contextual data in the virtual environment of the metaverse.	Hudson, 2022; Kovacova et al., 2022**;** Newell, 2022; Wu et al., 2023

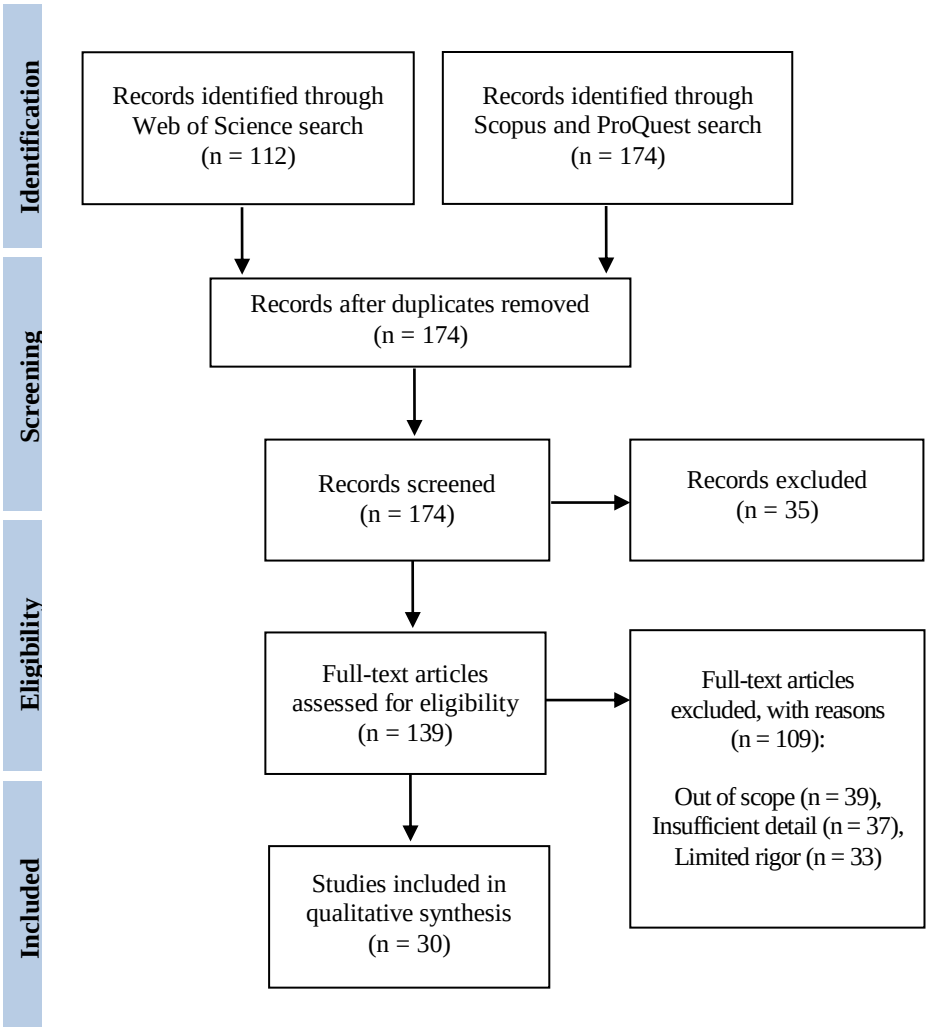

Figure 5 PRISMA flow diagram describing the search results and screening.

Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines were used that ensure the literature review is comprehensive, transparent, and replicable. The flow diagram, produced by employing a Shiny app, presents the stream of evidence-based collected and processed data through the various steps of a systematic review, designing the amount of identified, included, and removed records, and the justifications for exclusions.
To ensure compliance with PRISMA guidelines, a citation software was used, and at each stage the inclusion or exclusion of articles was tracked by use of custom spreadsheet. Justification for the removal of ineligible articles was specified during the full-text screening and final selection.

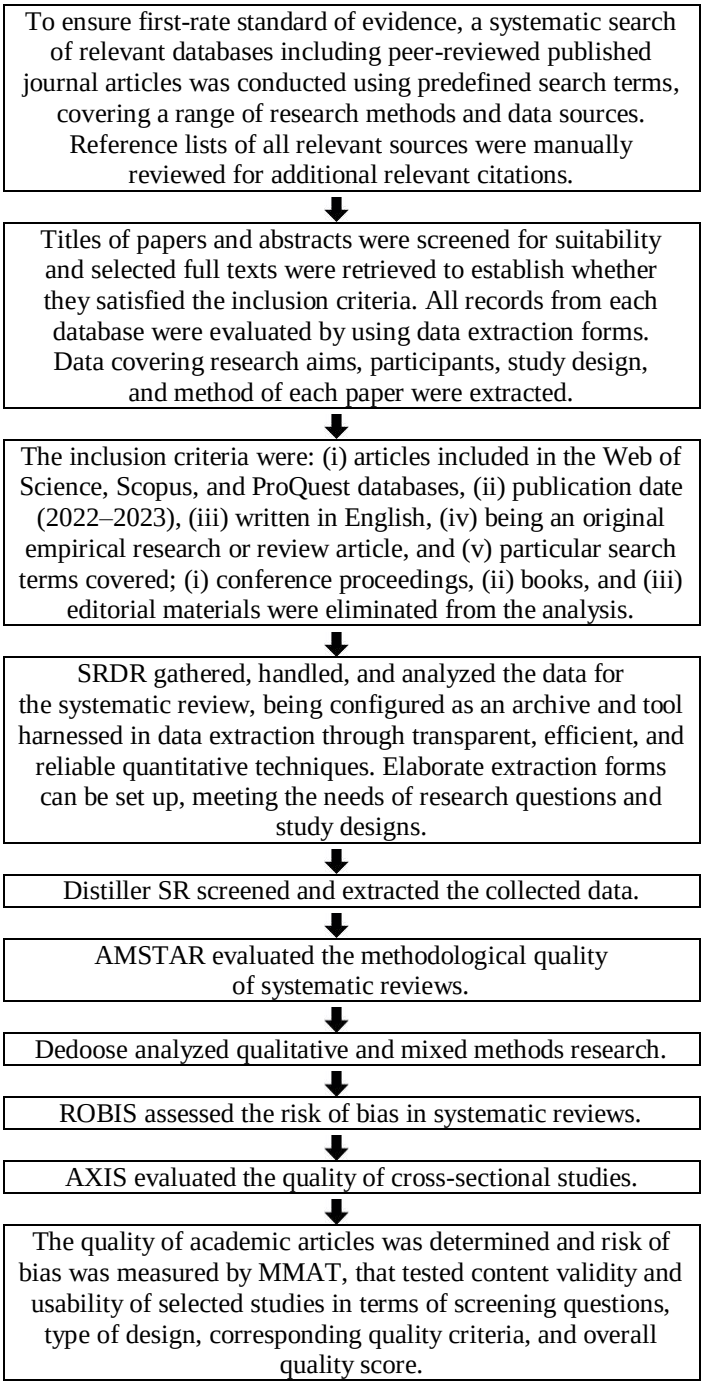

Figure 6 Screening and quality assessment tools

4. Digital Twin Simulation and Natural Language Processing Tools, 3D Image Processing and Situational Awareness Algorithms, and Deep Learning-based Sensing and Ontology-based Semantic Technologies in 3D Computer-generated Virtual Environments

Immersive virtual experiences can be attained through photorealistic synthetic imagery, digital scent and data analytics technologies, and digital twin simulation and natural language processing tools (Barnes, 2022; Daneshfar and Jamshidi, 2023; Xu et al., 2023) in 3D virtual environments. Voice recognition software, 3D modeling and simulation technologies, and neuromorphic computing and deep learning algorithms optimize interconnected digital spaces.

Ambient intelligence and immersive analytics tools, behavior pattern clustering, and visual perceptive and immersive visualization systems (Dawson, 2022; Golf-Papez et al., 2022; Wongkitrungrueng and Suprawan, 2023) configure immersive interconnected virtual worlds. Multimodal sensing and visual analytics systems, 3D image processing and situational awareness algorithms, and spatial awareness and tracking tools configure immersive 3D worlds. Immersive 3D virtual environments develop on voice recognition software, real-time event and sentiment analytics, and multi-sensor fusion and perception systems.

Blockchain-based metaverse platforms (Duncan, 2022; Hennig-Thurau et al., 2022; Morley, 2022) develop on smart environment modeling and automated speech recognition tools, biometric self-authentication devices, and deep learning-based sensing and ontology-based semantic technologies. Digital twinning and multiscale spatial data processing tools, interoperable virtual networks, and haptic and multisensory technologies assist 3D computer-generated virtual environments. (Table 3)

Table 3 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive virtual experiences can be attained through photorealistic synthetic imagery, digital scent and data analytics technologies, and digital twin simulation and natural language processing tools in 3D virtual environments.	Barnes, 2022; Daneshfar and Jamshidi, 2023; Xu et al., 2023
Ambient intelligence and immersive analytics tools, behavior pattern clustering, and visual perceptive and immersive visualization systems configure immersive interconnected virtual worlds.	Dawson, 2022; Golf-Papez et al., 2022; Wongkitrungrueng and Suprawan, 2023
Blockchain-based metaverse platforms develop on smart environment modeling and automated speech recognition tools, biometric self-authentication devices, and deep learning-based sensing and ontology-based semantic technologies.	Duncan, 2022; Hennig-Thurau et al., 2022; Morley, 2022

5. Bio-inspired Computational Intelligence and Deep Learning Algorithms, Immersive Decentralized Networking and Autonomous Visual Object Detection Tools, and 3D Modeling and Cognitive Neuro-Engineering Technologies in the Decentralized Metaverse

Immersive virtual reality experiences can be achieved through immersive visualization and real-time visual analytics systems, implantable intra-body sensors, and data processing and neural network-based recognition algorithms (Aloqaily et al., 2022; Giang Barrera and Shah, 2023; Hawkins, 2022; Musova et al., 2022) in immersive interconnected virtual worlds. Biometric and behavioral data, 3D modeling and cognitive neuro-engineering technologies, and bio-inspired computational intelligence and deep learning algorithms enable 3D digital environments.

Immersive and extended reality technologies, data-driven artificial intelligence and spatial cognition algorithms, and immersive decentralized networking and autonomous visual object detection tools (Braud et al., 2022; Grupac and Lăzăroiu, 2022; Njoku et al., 2023; Popp and Cuțitoi, 2022) articulate immersive virtual environments. Semantic network representations, machine learning-based image recognition and contextual data monitoring tools, and emotion detection and object recognition algorithms articulate the decentralized metaverse.

Real-time sensor data, 3D imaging and display technologies, and empathetic computing and Internet of Things-based sensing systems (Durana et al., 2022; Hadi et al., 2023; Zhang et al., 2022) enable synthetic digitally-mediated environments. Extended reality environments necessitate data sharing and immersive 3D technologies, text mining and analytics, and spatial awareness and tracking tools. (Table 4)

Table 4 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

Immersive virtual reality experiences can be achieved through immersive visualization and real-time visual analytics systems, implantable intra-body sensors, and data processing and neural network-based recognition algorithms in immersive interconnected virtual worlds.	Aloqaily et al., 2022; Giang Barrera and Shah, 2023; Hawkins, 2022; Musova et al., 2022
Immersive and extended reality technologies, data-driven artificial intelligence and spatial cognition algorithms, and immersive decentralized networking and autonomous visual object detection tools articulate immersive virtual environments.	Braud et al., 2022; Grupac and Lăzăroiu, 2022; Njoku et al., 2023; Popp and Cuțitoi, 2022
Real-time sensor data, 3D imaging and display technologies, and empathetic computing and Internet of Things-based sensing systems enable synthetic digitally-mediated environments.	Durana et al., 2022; Hadi et al., 2023; Zhang et al., 2022

6. Deep Learning Artificial Intelligence and Location-based Predictive Algorithms, Cognitive Neuro-Engineering and Multisensor Fusion Technologies, and Immersive Visualization and Internet of Things-based Decision Support Systems in the Virtual Environment of the Metaverse

3D immersive spaces and experiences can be attained by use of haptic bodysuits, 3D modeling and haptic feedback technologies, and deep learning artificial intelligence and location-based predictive algorithms (Kliestik et al., 2022; Park and Kim, 2023; Zyda, 2022) across the virtual environment of the metaverse. Immersive visualization and Internet of Things-based decision support systems, user behavior data mining, and digital twin and multi-sensory extended reality technologies shape a blockchain-based virtual world.

Image processing and contextual intelligence tools, affective and perceptual technologies, and machine learning-based recognition and computer vision algorithms (Huynh-The et al., 2023; Popescu et al., 2022; Ramadan, 2023) further extended reality environments. 3D capture and digital contact tracing technologies, intelligent connectivity infrastructures, and machine vision and cognitive decision-making algorithms assist extended reality environments.

Hyperconnected virtual experiences can be achieved by use of cognitive neuro-engineering and multisensor fusion technologies, virtual holographic objects, and interactional and contextual data (Hudson, 2022; Kovacova et al., 2022; Newell, 2022; Wu et al., 2023) in the virtual environment of the metaverse. Haptic and multisensory technologies, spatial awareness and deep learning-based ambient sound processing tools, and motion capture suits shape blockchain-based metaverse platforms. (Table 5)

Table 5 Synopsis of evidence as regards focus topics and descriptive outcomes (research findings)

3D immersive spaces and experiences can be attained by use of haptic bodysuits, 3D modeling and haptic feedback technologies, and deep learning artificial intelligence and location-based predictive algorithms across the virtual environment of the metaverse.	Kliestik et al., 2022; Park and Kim, 2023; Zyda, 2022
Image processing and contextual intelligence tools, affective and perceptual technologies, and machine learning-based recognition and computer vision algorithms further extended reality environments.	Huynh-The et al., 2023; Popescu et al., 2022; Ramadan, 2023
Hyperconnected virtual experiences can be achieved by use of cognitive neuro-engineering and multisensor fusion technologies, virtual holographic objects, and interactional and contextual data in the virtual environment of the metaverse.	Hudson, 2022; Kovacova et al., 2022b; Newell, 2022; Wu et al., 2023

7. Discussion

I integrate my systematic review throughout research indicating how immersive 3D virtual environments develop on voice recognition software, real-time event and sentiment analytics, and multi-sensor fusion and perception systems. My research complements recent analyses clarifying how multimodal sensing and visual analytics systems, 3D image processing and situational awareness algorithms, and spatial awareness and tracking tools configure immersive 3D worlds. I elucidate, by cumulative evidence, previous research demonstrating how biometric and behavioral data, 3D modeling and cognitive neuro-engineering technologies, and bio-inspired computational intelligence and deep learning algorithms enable 3D digital environments.

8. Synopsis of the Main Research Outcomes

Voice recognition software, 3D modeling and simulation technologies, and neuromorphic computing and deep learning algorithms optimize interconnected digital spaces. Extended reality environments necessitate data sharing and immersive 3D technologies, text mining and analytics, and spatial awareness and tracking tools. Semantic network representations, machine learning-based image recognition and contextual data monitoring tools, and emotion detection and object recognition algorithms articulate the decentralized metaverse. 3D capture and digital contact tracing technologies, intelligent connectivity infrastructures, and machine vision and cognitive decision-making algorithms assist extended reality environments.

9. Conclusions

Relevant research has investigated whether haptic and multisensory technologies, spatial awareness and deep learning-based ambient sound processing tools, and motion capture suits shape blockchain-based metaverse platforms. This systematic literature review presents the published peer-reviewed sources covering how Immersive visualization and Internet of Things-based decision support systems, user behavior data mining, and digital twin and multisensory extended reality technologies shape a blockchain-based virtual world. The research outcomes drawn from the above analyses indicate that digital twinning and multiscale spatial data processing tools, interoperable virtual networks, and haptic and multisensory technologies assist 3D computer-generated virtual environments.

10. Limitations, Implications, and Further Directions of Research

By analyzing only articles published between 2022 and 2023 in journals indexed in the Web of Science, Scopus, and ProQuest databases, relevant

sources on bio-inspired computational intelligence and deep learning algorithms, 3D modeling and cognitive neuro-engineering technologies, and immersive visualization and Internet of Things-based decision support systems in the virtual environment of the metaverse may have been excluded. Limitations of this research comprise particular kinds of publications (original empirical research and review articles) discounting others (conference proceedings articles, books, and editorial materials). The scope of my study also does not move forward the inspection of cognitive neuro-engineering and multisensor fusion technologies, virtual holographic objects, and interactional and contextual data.

Subsequent analyses should develop on ambient intelligence and immersive analytics tools, behavior pattern clustering, and visual perceptive and immersive visualization systems. Future research should thus investigate haptic bodysuits, 3D modeling and haptic feedback technologies, and deep learning artificial intelligence and location-based predictive algorithms. Attention should be directed to image processing and contextual intelligence tools, affective and perceptual technologies, and machine learning-based recognition and computer vision algorithms.


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Compliance with ethical standards
This article does not contain any studies with human participants or animals performed by the author. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement
All data generated or analyzed are included in the published article.

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Author contributions
The author confirms being the sole contributor of this work and approved it for publication. The author takes full responsibility for the accuracy and the integrity of the data analysis.

Conflict of interest statement
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Disclosure by the editors of record
The editors declare no conflict of interest in the review and publication decision regarding this article.

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