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A systematic review of the soft computing methods shaping the future of the metaverse

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HIGHLIGHTS

- We present a systematic review of research on soft computing methods in the metaverse.
- We show how soft computing revolutionizes the metaverse and our interaction with the digital world.
- The study highlights the interdisciplinary nature of soft computing methods in the metaverse.
- We categorize soft computing into five main classes.
- We present a decision framework for selecting the most suitable soft computing method.

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ABSTRACT

The metaverse is an emerging technology with the potential to revolutionize our interactions with digital environments. Soft computing presents exciting opportunities in shaping this immersive virtual world. This paper provides a systematic review of the research on soft computing methods in the metaverse, highlighting the interdisciplinary nature of the field and the need for coordination to shape its future. The systematic literature review conducted in this article identifies the contributors and domains in soft computing, emphasizing the need for new developments and joint applications in soft computing and the metaverse. The study categorizes soft computing techniques into five classes - machine learning, fuzzy systems, evolutionary computing, probability analysis, and mixed/hybrid methods - contributing to the emerging metaverse-related research and development. We propose a decision framework for selecting the most suitable soft computing method to assist researchers and developers in methodically assessing the alternative methods. The findings provide a roadmap and opportunities for soft computing models and applications shaping the future of the metaverse. This article can serve as a useful reference for researchers, practitioners, and policymakers working in soft computing and the metaverse.

1. Introduction

The metaverse refers to a digital virtual world where users can create identities and live, learn, and work [1]. The metaverse is expected to be a massive, immersive virtual world that will change the way we live, work, and interact with one another [2]. The development of the metaverse poses significant challenges [3,4]. As Park and Kim [3] point out, the metaverse has been the subject of plenty of research effort, but most of which has focused on its social implications rather than its systems. One of the greatest challenges is the need for powerful computational techniques to offer this virtual experience [5]. Traditional computing techniques, also known as hard computing [6], are limited in their ability to create realistic environments responsive to user input; this is where soft computing methods come in [7]. Soft computing methods can potentially address these challenges and shape the metaverse's future [5,8]. Compared to traditional computing methods, soft computing can handle imprecision and uncertainty [9,10], making them suitable for developing the metaverse, where the virtual environment must respond

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naturally and realistically. Metaverse and soft computing methods have received increased attention in recent years. Soft computing can enhance metaverse capabilities by creating a more immersive and engaging virtual experience.

This paper comprehensively reviews the literature on soft computing methods in the metaverse. There are limited literature studies related to the metaverse [1,11,12]. This work will review the various soft computing methods and their potential applications in the metaverse. The paper is organized as follows. In the following section, The manuscript will briefly overview the metaverse, its roots, and its significance in shaping the future of digital interactions in Section 2. It then discusses soft computing methods and their potential metaverse applications. The methodology section (Section 3) will describe the methods used to conduct the review, including the data sources and the criteria for selecting the studies. Section 4 analyzes the results, and Section 5 discusses the implications of our findings for developing the metaverse. Finally, the manuscript concludes the effort by summarizing the main points and providing a final reflection on the importance of soft computing methods in shaping the metaverse's future in Section 6.

2. Literature review

The metaverse is a post-reality world, a continuous and perpetual multi-user environment where physical and digital virtuality are seamlessly fused [13]. Mystakidis [13] explains that extended reality (XR) is a concept founded on merging technologies that allow multisensory interactions between digital items, virtual environments, and persons. Correspondingly, this section aims to construct familiarity with XR and the metaverse and draw connections to soft computing concepts.

2.1. Extended reality

XR is a term that encompasses all forms of immersive technologies that augment or replace the physical world with digital content; it includes virtual reality (VR), mixed reality (MR), and augmented reality (AR) [14–16]. These technologies have gained much traction recently, with applications in various fields [15]. Virtual reality (VR) is a fully immersive experience that replaces the physical world with a digital environment. The user is completely immersed in a simulated world, and the experience is often enhanced using specialized headsets and haptic feedback devices [17]. Mixed reality (MR) is a hybrid reality that combines elements of the physical and digital worlds to create a seamless experience [18]. This is achieved using sensors to track the user's movements and overlay digital content onto the physical world. Augmented reality (AR) adds digital elements to the real world, enhancing users' perception of their surroundings [19]. In short, XRs are immersive technologies that seek to imitate reality in many ways, including the senses of sight, sound, touch, and motion; all forms of XR share a common goal: to create a more immersive and engaging experience for the user [14]. These technologies are constantly evolving, and as they become more advanced, they are pushing the boundaries of what is possible regarding human-computer interaction; they are the base of the metaverse [20].

2.2. Metaverse

The metaverse is a term used to describe a collective virtual shared space where users can interact with a computer-generated environment and with each other in real time [13,20]. Although it is a term that has gained traction in recent years [2,21], it has been around with its roots in science fiction literature. The concept of the metaverse was first introduced in Neal Stephenson's novel "Snow Crash" in 1992 [11,22–24] as a combination of two words, "meta" and "universe" [11,23]. In that novel, the metaverse served as a place to escape their daily lives and experience something new [24]. Since then, the concept has evolved, and with the advancement of technology, it is now becoming a reality [25]. Since the early 2000 s, few scholars have often used the metaverse expression to describe technologies and infrastructure development for second-life systems [1]. In its initial stages, scholars used and understood the term "metaverse" inconsistently [1]. Nonetheless, 2020 is the metaverse movement initiations [1,2,22], as, in the early 2020 s, the term rose to prominence because of Facebook's rebranding efforts [1]; since then, the metaverse has emerged as a new normal in social networking [16]. Besides that, the worldwide outbreak of COVID-19 encouraged more people to consider the potential of the metaverse [12]. The metaverse was frequently described in its early stages as a virtual world accessible via computers and VR headsets. However, it has undergone significant changes from its earlier versions, and these changes can be classified into three distinct categories [3]:

- The first significant change is the rapid development of deep learning, which has significantly improved the accuracy of vision and language recognition, resulting in a more immersive and natural environment. The introduction of generative models has also facilitated natural movement within the metaverse. Additionally, multimodal models have helped reduce processing time and complexity, resulting in more efficient end-to-end solutions.
- Secondly, the metaverse has evolved from being accessible only via bigger computers to access through mobile devices connected to the internet, allowing users to access it anytime, anywhere. This change has increased the number of users and usage time. Furthermore, the metaverse has a virtuous cycle ecosystem where the inflow and income of producers increase as users and usage time increase, resulting in more immersive and engaging virtual environments.
- The third significant change in the metaverse is the ability to perform program coding within the metaverse world, making it more bonded to real life with virtual currency. Based on immersive interaction, the metaverse has expanded to include various social meanings, such as fashion, events, games, education, and office work. Cryptocurrencies act as an economic bridge between the metaverse and the real world, resulting in deeper social meaning.

Artificial intelligence, blockchain, 5G mobile networks, and the Internet of Things are some of the cutting-edge technologies that have found their way into the online realm in recent years [1]. The metaverse is not a single platform or application but a collection of interconnected virtual environments [26]. These environments can take many forms, from virtual game worlds to social networks. Hence, the metaverse can potentially revolutionize how we interact with each other and the digital world [27]. Similar to the real world, the metaverse presents a wide range of events and activities [28], and it has the potential to become an integral part of our lives in the future [26,29,30]. It could offer a new way to connect with people [26]. Metaverse enables individuals to reside and engage in professional activities within a simulated environment [23]. As technology advances, the metaverse becomes a place where we work, learn, and socialize [26,27,29]. Utilizing the latest technologies in the metaverse is feasible and encouraged. For one, researchers assert that autonomous vehicles hold potential for various applications within the digital realm [31,32]. The metaverse is growing, and as a consequence of the preceding discussion, shaping its future is an important job beneficial to everyone.

2.3. Soft computing mathematics in metaverse

By holding gatherings, collaborating on initiatives, engaging in activities, and growing in virtual settings, the metaverse offers revolutionary potential for people across every field that enhance the user experience in their second/digital life [1]. As the metaverse becomes more prevalent, the need for decision-making tools within this virtual environment becomes increasingly important. Besides, Deveci et al. [33] emphasize the importance of employing measurement systems to assess the consistency of data and decision-making processes to evaluate the sustainability, direction, and resilience of systems. Mathematics has played a significant role in various applications, including decision-making, in various fields [34], and it is no different in the metaverse. Mathematical models and algorithms can help optimize decision-making in the metaverse, leading to better user outcomes. When complex contemporary issues are the focus, scholars have shown much interest in soft computing [35,36]. Soft computing encompasses various techniques designed to mimic human-like decision-making and problem-solving [9,10,37] and is flexible enough to handle situations of imperfect knowledge [38]. Soft computing became more popular with Zadeh in 1992 [7,39], and the idea behind it is to use flexibility in the face of uncertainty and partial information [9]. These techniques can be used for pattern recognition, optimization, prediction, and control tasks. In the context of the metaverse, soft computing techniques can be used for various applications [5,8], such as natural language processing, computer vision, and machine learning. These techniques can help create more immersive and engaging virtual environments by making interactions with the virtual world more intuitive and natural.

The widespread acceptance of soft computing and its fast expansion indicate that it will have a growing influence in the future [30]. Thus, these techniques can be applied to the metaverse to help optimize decision-making more naturally and intuitively. Falcone and colleagues [40] explain that soft computing involves approximate reasoning and randomized search:

- Approximate reasoning is a collection of knowledge-driven techniques that forgo either validity or completeness to accelerate the reasoning process significantly.
- Randomized search is a family of numerical optimization methods like direct-search, derivative-free, and black-box methods that operate by iteratively moving in the search space towards improved locations chosen from a hypersphere encircling the current position.

Sharma and colleagues [41] classified soft computing methods into fuzzy logic, artificial neural networks, and evolutionary algorithms. Das and colleagues [29] classified soft computing into four classes: probabilistic reasoning and fuzzy logic (as knowledge-driven reasoning methods) and neuro computing and evolutionary computing (as data-driven search and optimization methods). In contrast, Lin et al. [37] classified soft computing into fuzzy sets, evolutionary computation, artificial neural networks, and swarm intelligence. Falcone et al. [40] have proposed five general classes of soft computing methods, as shown in Fig. 1. Salam et al. [42] have proposed Fig. 2 to classify soft computing methods into six classes:

Although there is no general agreement on the soft computing techniques' classification, they play an important role in the future development of various disciplines needing to represent imprecision, uncertainty, and partial truth [6,40,43]. Soft computing is utilized to achieve tractability and adaptation and provide a low-cost solution for our paradelle second life, the metaverse, by tolerating imprecision, uncertainty, partial truth, and approximation [44]. As the metaverse continues to evolve, the need for soft computing techniques becomes increasingly important. Understanding the various soft computing methods shaping the metaverse's future is necessary to understand their potential and limitations. Although soft computing techniques have been successfully used in various situations, the methodology has evolved to provide better solutions for even more effective, robust, and trustworthy answers [44]; therefore, pointing in the right direction is essential. A systematic literature review could help identify areas where these soft computing methods can be applied most effectively to shape the future of metaverse. It can also classify soft computing techniques without a standard classification system for effective utilization and development.

Huang et al. [44] say that soft computing techniques have advantages and disadvantages. On the positive side, they explain that they offer powerful capabilities for approximating functions, learning and adapting to new data, and handling complex and diverse information. Yet, they further explain the limitations and challenges of using soft computing techniques. One major issue is the interpretability of results. Additionally, soft computing techniques require significant computational resources and can be time-consuming, especially when training on large and noisy datasets. This can lead to longer development times and increased costs. Furthermore, soft computing techniques may produce biased or inaccurate results due to the inherent subjectivity in design and implementation [45]. Therefore, when using soft computing techniques, it is important to weigh the potential benefits against the limitations and challenges and to carefully consider the appropriateness of these techniques for the given problem domain, for one, the future of the metaverse.

3. Methodology

The authors combined a systematic literature review and bibliometric analysis to comprehensively review the literature on soft computing methods in the metaverse. This methodology was chosen because it allows us to identify the most relevant and high-quality studies on the topic and provide a quantitative analysis of the research trends and patterns [46,47]. The systematic literature review process

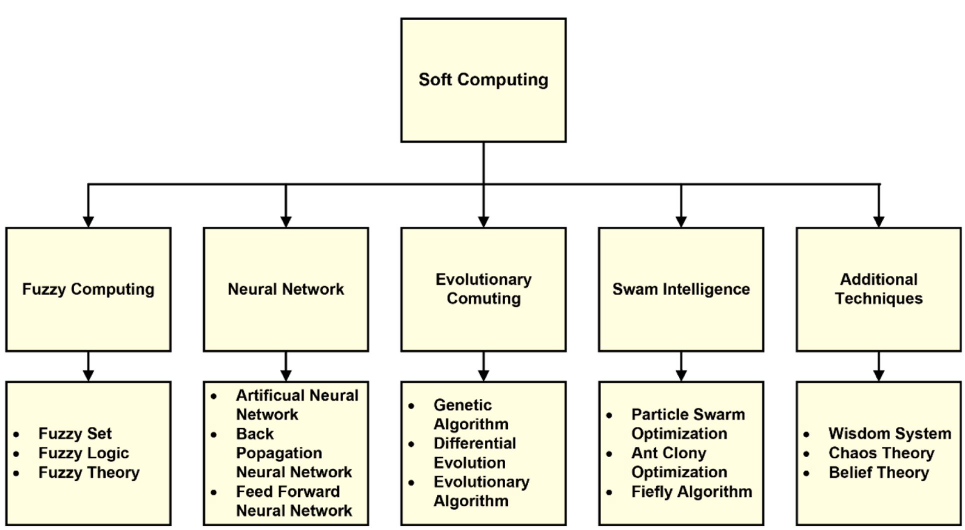

Fig. 1. Soft computing techniques by Falcone et al. [40].

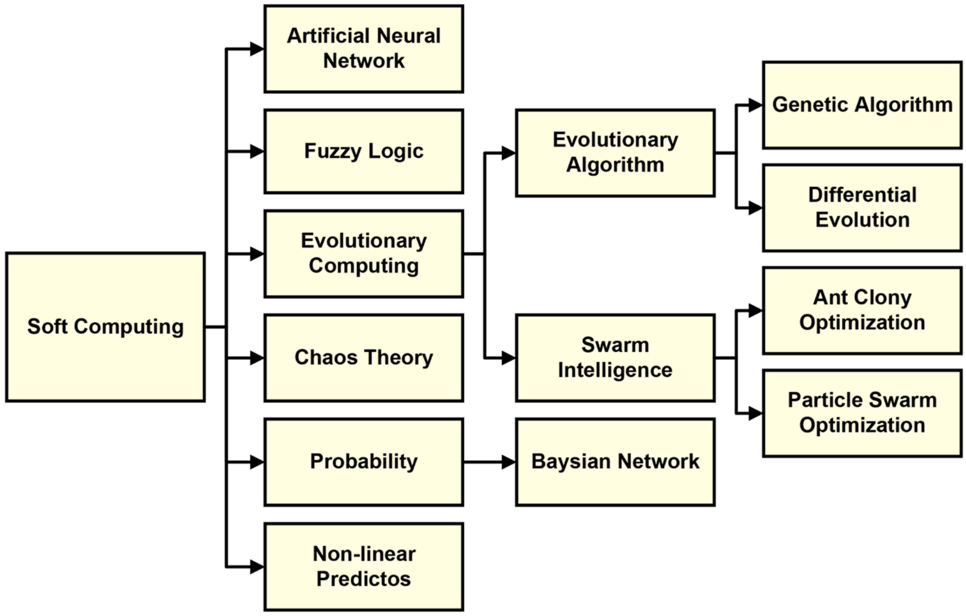

Fig. 2. Soft computing techniques by Salam et al. [42].

involves a comprehensive search for all relevant studies on a particular topic, followed by a critical appraisal of the studies' quality and relevance [48,49], and bibliometric analysis is a quantitative method for studying scientific literature [50]. In this study, the authors followed the guidelines for conducting systematic reviews known as PRISMA (preferred reporting items for systematic reviews and meta-analyses), as this ensures that the outcome is transparent, rigorous, and replicable [51]. Then, the literature analysis involves bibliometrics to visualize patterns, networks, and trends [52]. The feasibility of the chosen methodology has been tested before, and the outcomes showed a detailed and nuanced understanding of the research topics and patterns.

The search for relevant studies was conducted in Scopus (www.scopus.com) electronic database. Metaverse was used as the keyword in the document title search. Using a star symbol (*), or wildcard character, at the end of a searched keyword was performed as a placeholder to represent one or more characters in a search query [53]. So, searching for "metaverse* " produced results for metaverse and metaverses. Then, the search was limited to studies written in English to avoid language barriers. Articles (#438) and conferences papers (#331) were continued after the removal of reviews (#56), editorials (#43), book chapters (#23), letters (#19), notes (#17), conference reviews (#3), erratums (#3), short surveys (#2), and books (#1). The search (data collection I) performed on 11/April/2023 and its outcomes are shown using the frame of Fig. 3.

A second search (data collection II) was conducted, on 13/April/2023, using keywords as it is explained in Table 1 to identify relevant academic publications related to the XR root of the metaverse. As XR is a well-established field with applications across various domains, it is necessary to focus on a specific area to achieve the paper's objectives. Therefore, only academic publications related to mathematics and decision sciences were considered in this study. This ensures a focused analysis and enables a deeper exploration of the potential of soft computing techniques for shaping the future of the metaverse. The search was then refined to include documents published after 2020, the year of the initiation of the metaverse movement [2,22]. Moreover, only articles and conference papers published in English were kept in the search results.

Fig. 3. Metaverse search and filtration outcomes.

Table 1
XR Search and filtration outcomes.

Focuses area	XR	VR	AR	MR
Search code	TITLE-ABS-KEY ("extended realit*")	TITLE-ABS-KEY ("virtual realit*")	TITLE-ABS-KEY ("augmented realit*")	TITLE-ABS-KEY ("mixed realit*")
Search results:	1415 documents	158691 documents	43474 documents	8509 documents
Filtrations	Document results	Document results	Document results	Document results
only fields of mathematics and decision sciences	296	18174	8593	2017
published after 2020	268	6709	3392	823
only in English	267	6628	3346	819
published as an article or conference paper	225	6251	3047	738
outcome	**225**	**6251**	**3047**	**738**

The resulting literature from data collection I and II and their filtration process were analyzed with a bibliometric approach; the catchwords of the title, abstract, and authors listed keywords identified and mapped to the soft computing techniques.

Besides the two explained data collections, data collection III was to perform a search using soft computing-related keywords. The third search (data collection III) was conducted on 13/April/2023 to locate relevant studies on soft computing applications in the metaverse-related research. Soft computing-related keywords of "fuzzy logic," "fuzzy sets," "artificial neural network," "evolutionary algorithms," "neuro computing," "partial swarm optimization," "wisdom system," "chaos theory," "belief theory," "differential evolution," "ant clone algorithm," and "Firefly algorithm," were taken into account concerning the aforementioned soft computing discussion. As an added note, this work is being prepared for publication in Applied Soft Computing, the scope (https://www.sciencedirect.com/journal/applied-soft-computing/about/aims-and-scope) of which includes such areas as Ant Colony, Chaos Theory, Evolutionary Computing, Fuzzy Computing, Hybrid Methods, Immunological Computing, Morphic Computing, Neuro Computing, Particle Swarm, Probabilistic Computing, Rough Sets, Wavelet, and Neuro Computing. Because of this, the search formula generated is (TITLE-ABS-KEY (*"metaverse*" OR "extended realit*" OR "virtual realit*" OR "augmented realit*" OR "mixed realit*"*) AND TITLE-ABS-KEY (*"Soft comput*" OR "Fuzzy" OR "Artificial Neural Network" OR "Evolutionary Algorithms" OR "Ant Colony Algorithm" OR "Firefly Algorithm" OR "Neuro Comput*" OR "Swarm Optimization" OR "Wisdom System*" OR "Chaos Theory" OR "Belief Theory" OR "Differential Evolution" OR "Immunological Computing" OR "Morphic Computing" OR "Probabil*" OR "Rough Sets" OR "Wavelet"*)).

However, in this investigation, the search was limited to scholarly documents published after 2020 (the year the metaverse movement began). Table 2 shows the search filtration processes where only articles and conference papers in English were retained from the initial search. Last, a bibliometric analysis was applied to the documents from data collection III to visualize patterns and trends of soft computing techniques and pinpoint their untapped potential for future metaverses.

It should be noted that although the data (from all data collections I, II, and III) from 2023 were not complete at the time of data collection, they were still included in the analysis. This may impact the accuracy and completeness of the findings, and future research may benefit from using a complete and up-to-date picture of the data. However, the available data still provides valuable insights and can serve as a basis for further research and analysis in soft computing. We also note that Pareto charts are used in addition to histograms and network diagrams for data visualization. A Pareto chart is a graphical representation based on the Pareto principle, which posits that a significant majority of effects arise from a minority of causes [54,55]. The chart sorts categories of data in descending order, from the most frequent (or largest frequency) on the left to the least frequent on the right, allowing for easy identification of the most significant factors or issues [55].

4. Results

This section of the article includes a bibliometric analysis that is presented in a few sub-sections, with each subsection focusing on the three rounds of data collected for this study (data collection I, II, and III). Data collection I focused on seeing soft computing from the metaverse studies point of view, data collection II saw soft computing from the root of metaverse viewpoint, and data collection III focused on soft computing itself in the metaverse research domain. This approach provides a comprehensive analysis to address the pre-defined research objective, followed by another subsection for an overview and discussion of findings.

4.1. Metaverse

Fig. 4 displays the trend of metaverse-related publications over the years, indicating the first document was published in 2000 [56]. However, it should be noted that the metaverse movement is considered to have started in 2020, as verified by the literature review. The figure highlights the growing interest and research in the field and sets the context for exploring the role of Applied Soft Computing in shaping the future of the metaverse.

Table 2
Soft computing search filtration.

Filtration	Document results
Initial search results	5340
Published after 2020	1158
Only in English	1123
Published as an article or conference paper	920
Outcome	**920**

Fig. 5 illustrates that only a few countries are highly productive in metaverse-related research, with Eastern countries such as China, South Korea, Japan, Singapore, and Indonesia taking the lead. This highlights the need for more global collaboration and knowledge exchange to foster further research and development of future metaverse.

Fig. 6 emphasizes the importance of multidisciplinary efforts for a better future of the metaverse. Computer science, engineering, and social sciences lead the way, closely following mathematics and decision sciences. This reinforces the relevance of this article's scope in addressing the role of soft computing techniques, closely related to mathematics and decision sciences, in shaping the future of the metaverse.

Using VOSviewer software version 1.6.19 (www.vosviewer.com), a network, Fig. 7, was created based on data collected from the titles and abstracts of documents. This co-occurrence network shows the occurrence of terms more than five times, with binary counting, which means that the presence or absence of each term in each document is only counted. This resulted in two clusters of terms, each representing a concentration of publications. The first cluster was more related to applications and sectors that benefit from the metaverse. In contrast, the second cluster consists of terms that can technically benefit the metaverse. However, upon screening the terms and comparing them with other mathematical and non-mathematical problem-solving techniques, it was found that not many soft computing-related terms were identified, highlighting the need for more research in this area. Thus, future research should focus on soft computing involvement to direct the future of the metaverse.

Moreover, the data was analyzed for top keywords via the ScienceScape (http://medialab.github.io/sciencescape/) tool, and the analysis yielded a very similar conclusion. Besides, from the Scopus search outcome, it was found that a list of 160 keywords related to the metaverse was repeated in a range of 600 times and up to 6 times. Among these keywords, only a few soft computing terms were identified, including "deep learning" (with 277 repetitions), "machine learning" (with 35 repetitions), and "computation theory" (with 12 repetitions). The analysis was performed in two ways: ChatGPT (https://chat.openai.com/chat), an artifactual intelligence model trained to generate input responses by natural language processing approach [57], and human researchers' (the authors') assessment of the keywords list. While this study augments the work of Bochkay et al. [58] by underscoring the application of natural language processing models as a formidable research methodology for projects centered around textual data, Cribben et al. [59] maintains that human expertise remains an essential player in the process. Consequently, we have incorporated both approaches. Both ways, in parallel, did the occurrence analysis, reviewing to find soft computing-related terms among the list.

4.2. Extended reality

The metaverse is the obvious answer that unifies all XR-related technology globally, and XR is a necessary technology for the metaverse [16]. Table 3 shows the documents found from the four XR-related searches according to the year of their publication. In addition, from the collected total of 222 keywords and/or terms, an occurrence analysis of the outcomes is shown in Table 4. Since this study aimed to identify soft-computing related keywords among a list of keywords, a similar occurrence analysis was performed again, as explained in the previous section. This analysis also highlighted the lack of soft computing-related terms, emphasizing the need for more attention by future metaverse and XR researchers.

4.3. Soft computing

The data collected in data collection III is summarized in Table 5 and 6 . However, analysis reveals that China is the leading country with over 80% of the publications, followed by the USA and India, as shown in

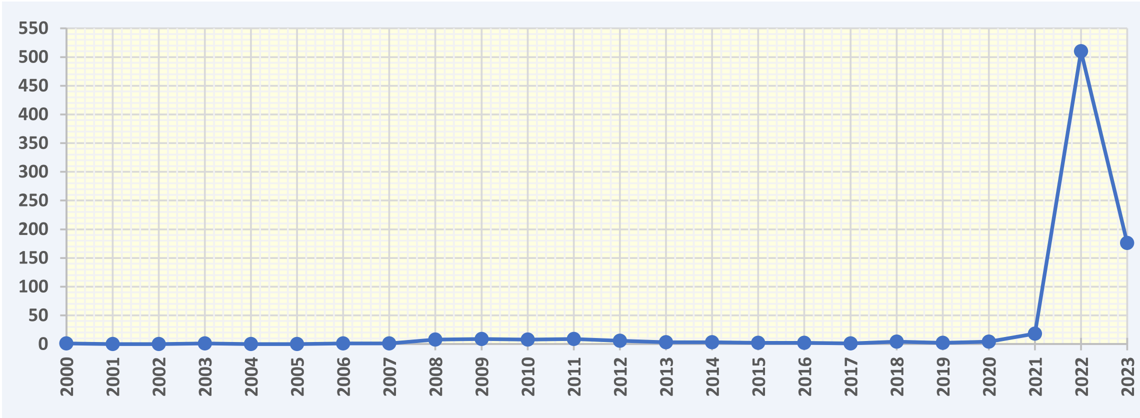

Fig. 4. Indexed documents per year.

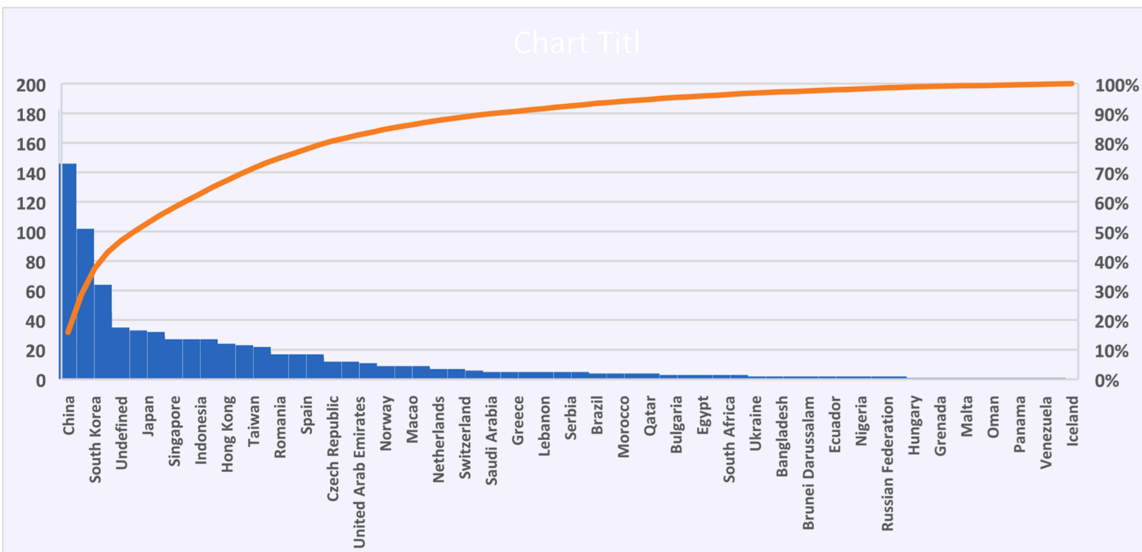

Fig. 5. Documents by country.

Fig. 8.

Fig. 9 depicts the research domains contributing to this field, showing that computer science and engineering, accounting for more than 50% of the total documents, make greater use of soft computing than mathematics fields. This result emphasizes the interdisciplinary nature of soft computing and highlights the importance of collaborations among different areas to advance the development and applications of soft computing techniques.

Overlay and density visualization are techniques used in bibliometrics to analyze scholarly publications and citation patterns [60]. Overlay visualization identifies correlations between different topics, while density visualization represents the distribution and frequency of publications and citations over time. These visualization techniques help researchers quickly identify patterns, trends, and hotspots of research activity [60,61]. Figs. 10 and 11 show overlay and density visualizations of data from data collection II, helping understand the structure and dynamics of scholarly communication in the targeted zone. Based on the collected data, overlay visualization did not show any visible trend or change over time, likely due to the relatively small time zone after 2020 and incomplete 2023 data. However, density visualization suggested a balanced scholarly focus, with an almost equal distribution of interest among the research areas. Kirby [62] asserts that bibliometrics can be employed to conduct exploratory research and to pave the way for new lines of inquiry. In light of this, from Figs. 10 and 11, keywords such as XR performance, requirement, opportunities and challenges, and users' experiences are garnering increased scholarly attention in the XR research field.

Scopus search also provided 203 top-appeared keywords used with the searched documents. This list refers to the keywords that appear most frequently across the resulting set of documents. The list is a collection of topics, mostly related to computer science, technology, and related fields. The list includes techniques and tools such as neural networks, fuzzy control, Bayesian networks, and wavelet transforms. Several mentions of specific applications such as e-learning, healthcare, and 5 G mobile communication systems exist.

Excluding not soft computing-related keywords provides a list of 30 items, which can be divided into four classes. This classification is helpful to understand better the various topics in computer science and related fields and their relationships. Here, the choice of four classes was based on the number of distinct themes and techniques the authors could identify. The classes are described below.

- **Machine Learning:** This class includes artificial neural networks, neural networks, machine learning, artificial intelligence, deep learning, and big data. These techniques are used to develop intelligent systems that can learn from data and make predictions or decisions, such as in image recognition, speech recognition, natural language processing, and recommender systems.

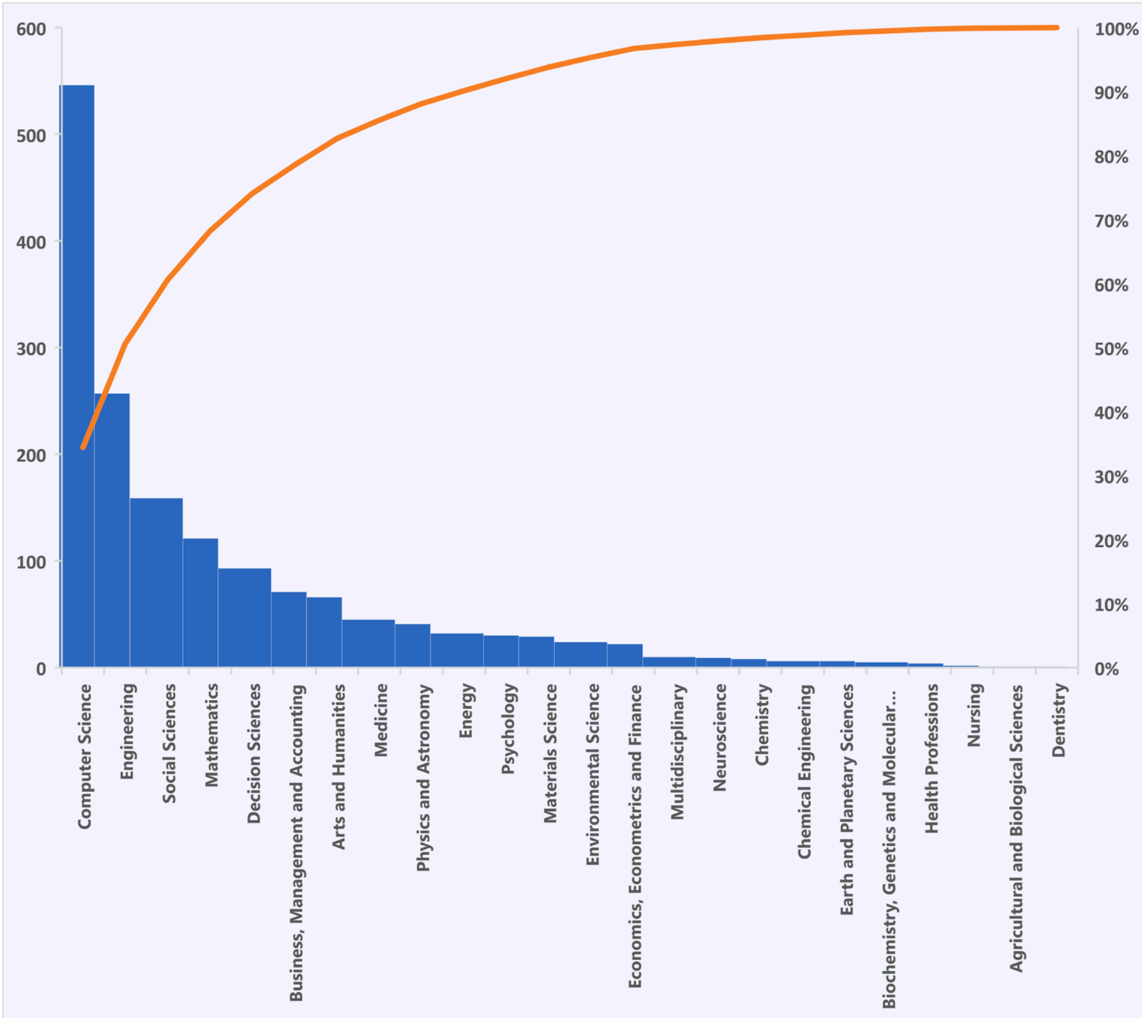

Fig. 6. Documents by subject area.

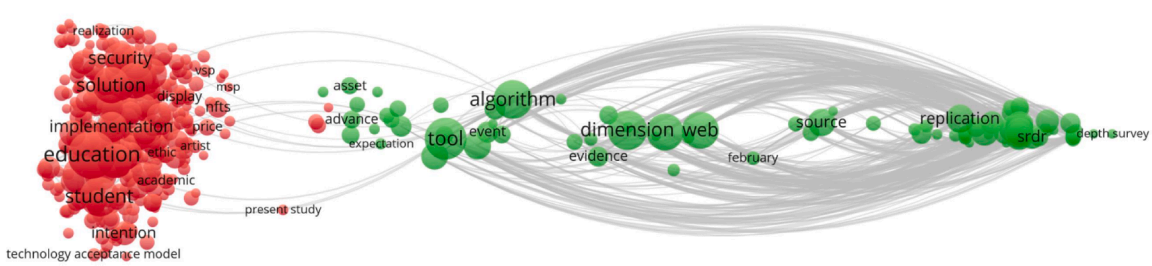

Fig. 7. Metaverse: network visualization.

Table 3
XR-related documents per year.

Year	XR	VR	AR	MR
2023	20	217	98	20
2022	122	2571	1107	242
2021	56	1952	858	220
2020	27	1511	984	256

- **Fuzzy Systems:** This class includes items such as fuzzy logic, fuzzy inference, fuzzy control, fuzzy sets, and fuzzy systems. Fuzzy logic is a mathematical framework for dealing with uncertainty and

Table 4
Keywords and terms occurrence.

Focuses area	Keywords and terms occurrence
XR	None of the more repeated keywords and terms identified appear explicitly related to soft computing techniques.
VR	"Deep learning" and "Machine Learning" are the two soft computing techniques listed among the more-repeated keywords and terms.
AR	None of the more-repeated keywords and terms listed in this set explicitly relate to soft computing techniques.
MR	None of the more-repeated keywords and terms listed in this set explicitly relate to soft computing techniques.

Table 5
soft computing-related documents per year.

Year	Documents
2023	80
2022	323
2021	275
2020	242

imprecision, and fuzzy systems are intelligent systems that use fuzzy logic to model and control complex processes and systems.

- **Evolutionary Computing:** This class includes particle swarm optimization, genetic algorithms, heuristic algorithms, and ant colony optimization. These techniques are often used to find the optimal solution in complex and dynamic environments.
- **Probability Analysis:** This class includes Bayesian networks, probability, and uncertainty analysis. Bayesian networks are graphical models that represent the probabilistic relationships between variables, and uncertainty analysis is the process of modeling and analyzing uncertainty and risk in complex systems.

This classification of soft computing-related items highlights the diversity and applicability of soft computing techniques used across various fields of the metaverse. This classification also suggests several promising research directions and opportunities in soft computing, which can lead to breakthroughs and innovations in the future of the metaverse.

5. Discussion

The key argument in this study is outlined in this section based on the data analysis outcomes. The metaverse is a changeful world [63] in which humans can interact with one another and with a computer-generated environment [1], and here, the article provides a final reflection on the importance of soft computing methods in shaping the future of the metaverse as our expanding second life. Tolerance for imperfect, incomplete, or conflicting data and uncertainties, as well as a desire to find heuristic (potentially suboptimal) solutions through a less-than-extensive search of the solutions space, are all hallmarks of what is collectively known as "Soft Computing" techniques [35]. It is observed by this research that soft computing techniques are not well introduced to the metaverse research. However, the growing field of soft computing is based on a set of approaches that can both learn from past mistakes and generalize to new situations, as Chaturvedi explains [64]. Chaturvedi further says that broadening the field of applications should be achievable if a propensity towards imprecision could be accepted. The driving forces behind this development are the anticipated reduction in computing load and subsequent rise in calculation speeds that permit more robust system architectures. From the findings of this article, members of the soft computing family that have most contributed to the metaverse field include artificial neural networks, neural networks, machine learning, artificial intelligence, deep learning, fuzzy logic, fuzzy inference, fuzzy control, fuzzy sets, and fuzzy systems, particle swarm optimization, genetic algorithms, heuristic algorithms, and ant colony optimization, and Bayesian networks.

Chaturvedi [64] explains that one of the difficulties in soft

Table 6
Top appeared keywords.

Virtual Reality	Fuzzy Logic	Industry 4.0	Soft Computing	Bayesian Networks
Augmented Reality	Adult	Intelligent Systems	Evolutionary Algorithms	Cameras
Human	Particle Swarm Optimization	Learning	Neural Networks	Decision Trees
Article	Internet of Things	Major Clinical Study	Machine Learning	Digital Twin
Humans	Algorithm	Metaverse	E-Learning	Entropy
Artificial Neural Network	Probability	Metaverses	Deep Learning	Errors
Neural Networks	Virtual Reality Technology	Network Architecture	Reinforcement Learning	Long Short-term Memory
Machine Learning	Behavioral Research	Procedures	Controllers	Optimizations
E-learning	Human-Computer Interaction	Quality Control	Fuzzy Control	Support Vector Machines
Artificial Intelligence	Probability Distributions	Robots	Image Reconstruction	Textures
Deep Learning	Students	Scheduling	User Experience	Virtualizations
Decision Making	Three Dimensional Computer Graphics	Soft Computing	Visualization	Wavelet Transforms
Female	Machine-learning	Uncertainty	Convolutional Neural Networks	Adolescent
Male	Forecasting	Uncertainty Analysis	Engineering Education	Ant Colony Optimization
Learning Systems	Human Experiment	Bayesian	Fuzzy Neural Networks	Data Mining
Controlled Study	Robotics	Cameras	Prediction	Electroencephalogram
Fuzzy Logic	Simulation	Decision Trees	Semantics	Image Analysis
Adult	Learning Algorithms	Digital Twin	Support Vector Machines	Immersive Virtual Reality
Particle Swarm Optimization	Network Function Virtualization	Entropy	Clinical Article	Mapping
Internet Of Things	3D Modeling	Errors	Navigation	Mathematical Model
Algorithm	Electroencephalography	Long Short-term Memory	Network Security	Nonhuman
Probability	Fuzzy Inference	Optimizations	Object Detection	Particle Swarm
Virtual Reality Technology	Mixed Reality	Support Vector Machines	Deep Neural Networks	Reproducibility
Behavioral Research	Transfer Functions	Textures	Neural Networks, Computer	Surveys
Human-Computer Interaction	Virtualization	Virtualizations	Physiology	Virtual Reality
Probability Distributions	Genetic Algorithms	Wavelet Transforms	Reliability	Big Data
Students	Image Segmentation	Adolescent	Resource Allocation	Cloud-computing
Three Dimensional Computer Graphics	Optimization	Ant Colony Optimization	Training	Computer Model
Machine-learning	Computer Vision	Data Mining	Automation	Convolution
Forecasting	Energy Utilization	Electroencephalogram	Diagnosis	Design
Human Experiment	User Interfaces	Image Analysis	Edge Computing	Diagnostic Imaging
Robotics	Artificial Neural Networks	Immersive Virtual Reality	Fuzzy Systems	Diseases
Simulation	Cloud Computing	Mapping	Neural-networks	Education
Learning Algorithms	Convolutional Neural Network	Mathematical Model	Risk Assessment	Extraction
Network Function Virtualization	Feature Extraction	Nonhuman	Signal Processing	Face Recognition
3D Modeling	Image Enhancement	Particle Swarm	Stochastic Systems	Fuzzy Sets
Electroencephalography	Priority Journal	Reproducibility	Young Adult	Geometry
Fuzzy Inference	Quality Of Service	Surveys	Classification (of Information)	Image Processing
Mixed Reality	Algorithms	Virtual Reality	Cognition	Maintenance
Transfer Functions	Computer Simulation	Big Data	Computer Circuits	Mobile Edge Computing
Genetic Algorithms	MATLAB	Cloud-computing		

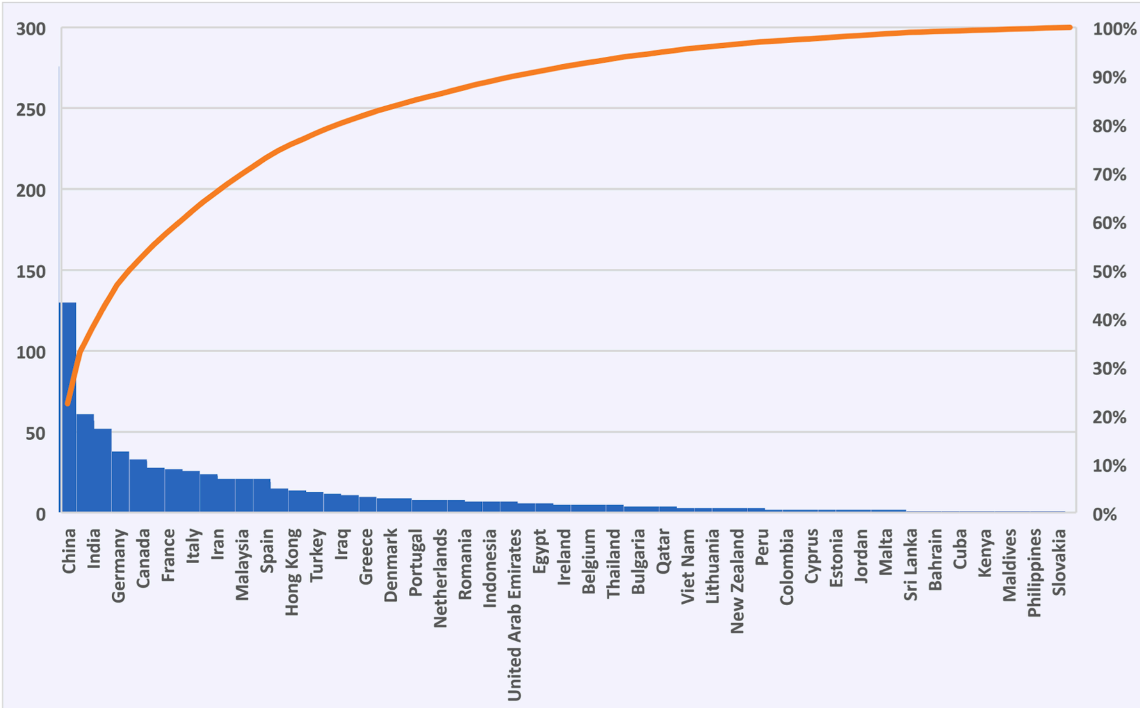

Fig. 8. Contributing countries.

computing research is finding the right balance between the various technologies that make up the field, such that the final product has advantages in decision-making that can't be reached by employing them independently. Hence, mixed/hybrid approaches might be a separate class to be added to the classes of soft computing identified by this research. It includes Mixed soft computing - soft computing techniques or a combination of soft and hard computing techniques.

Unlike soft computing, hard computing is distinguished by rigid mathematical modeling, a thorough search of the solution space, and a non-probabilistic presentation of the results; however, unlike "soft computing," the term "hard computing" is less well-known, and some scholars refer to it using other terms [65]. This term is used to emphasize the distinction between the two approaches. After reviewing several studies focused on specific applications, scholars [54] concluded that traditional hard computing methods and newer soft computing should be considered complementing approaches. Today's advanced environment necessitates the use of both technologies. While there is a clear divide between the hard computing and soft computing research communities, it has been seen that many soft computing researchers are vocally advocating for the different hybrid options. In contrast, the scholars [65] noted that the hard computing sector showed less eagerness to adopt complementary soft computing methods. Fig. 12 depicts a possible combination of soft computing and hard computing approaches.

Consequently, mixed/hybrid approaches are a distinct soft computing class with significant weight. The 5 class of contributing soft computing classes are shown in Fig. 13. There may be soft computing methods that do not align with the five identified classes, but they were not captured in the bibliometric analysis due to their minimal representation in pertinent research publications. Their omission from the provided taxonomy does not negate their potential usability or effectiveness. Nonetheless, the analysis indicates that the five identified classes demonstrate the highest potential for significant contributions to metaverse-related research and its subsequent evolution.

According to Aziz [66], it is imperative to prioritize the most efficient mathematical methods. Therefore, with a soft computing view, this article conducted a classification analysis to inform the progression of the metaverse in the future; it identified five classes of techniques engaging in metaverse research. Such a structure would benefit scholars, as classification simplifies Yenduri et al.'s technique selection guide. Yenduri et al. [7] recommend certain soft computing techniques as the most optimal when deciding. They further explain:

- When selecting a soft computing technique, it is crucial to consider the output quality of the method.
- The intricacy of the employed soft computing approach should also be considered, as the degree of sophistication is directly proportional to the level of challenge in achieving outcomes.
- When adopting a soft computing technique, it is imperative to consider its data requirements and computational efficacy.
- When selecting a soft computing technique, it is imperative to consider the training duration and the convergence rate.

Last but not least, the identified five classes of soft computing techniques are gaining popularity among metaverse-field researchers and are expected to play an increasingly active role in shaping the metaverse's future. Yet, more utilization and development of soft computing techniques are crucial for providing innovative solutions to problems in various fields related to the metaverse, including XR and sectors that can benefit from these concepts. The five classes are described further in the following subsections.

5.1. Class 1: machine learning

For class 1, the given Scopus search formula or "TITLE-ABS-KEY ("artificial neural networks" OR "neural networks" OR "machine learning" OR "artificial intelligence" OR "deep learning" OR "big data")" gives a deviation on the progress of techniques and their applications in problem-solving as shown in Fig. 14.

Machine learning and artificial intelligence are closely related fields that involve using algorithms and statistical models to enable computers to learn from data and perform tasks that normally require human intelligence [67,68]. Machine learning and artificial intelligence are powerful tools that can be applied to many aspects of the metaverse [25,

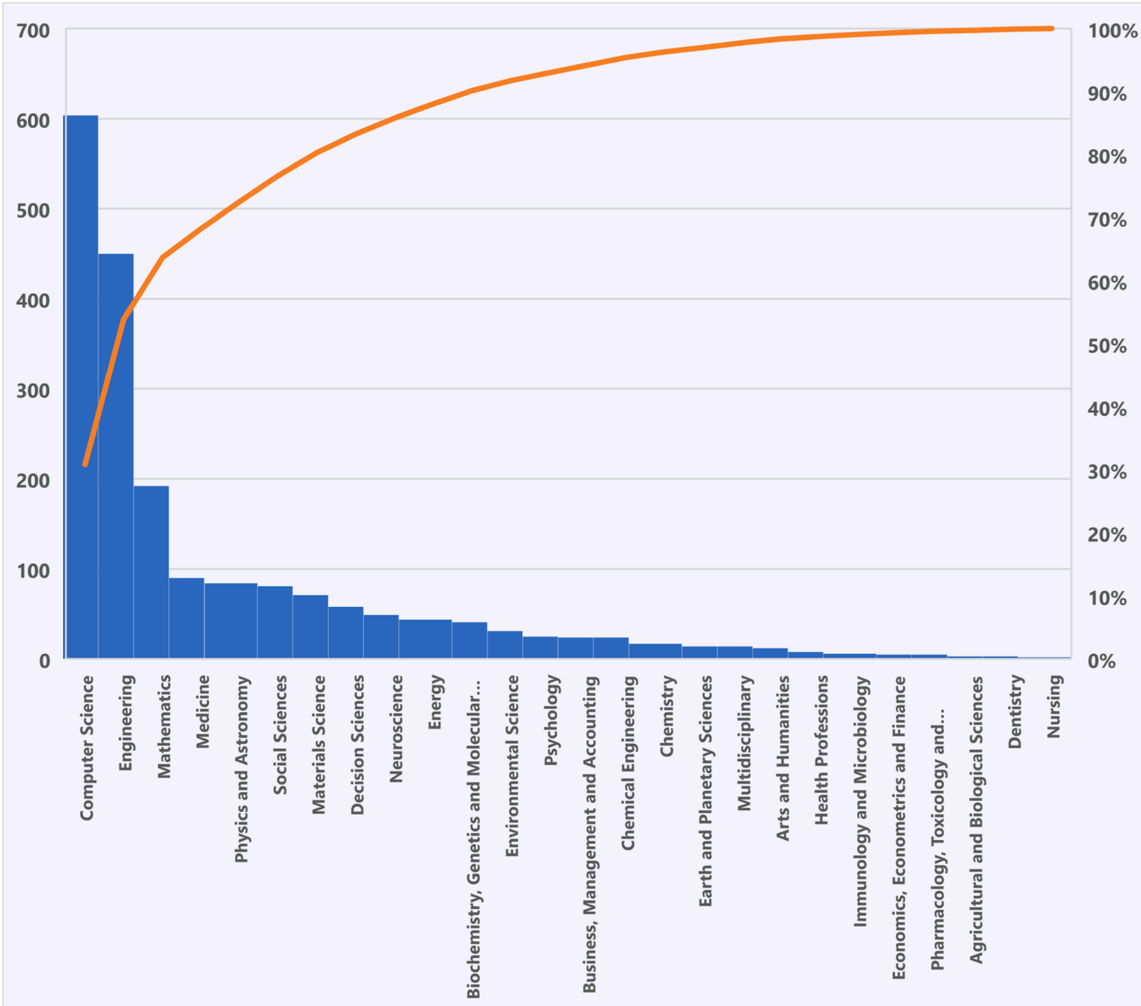

Fig. 9. Contributing subject areas.

69,70], such as virtual environments, avatars, and user behavior analysis. Machine learning and artificial intelligence are critical components of soft computing [9,66], contributing to developing intelligent systems that can learn from data and make predictions or decisions [67,71]. The ability of machine learning and artificial intelligence to handle complex data sets and learn from them makes them a valuable asset [72] in developing soft computing methods for the metaverse. Machine learning and artificial intelligence have the potential to revolutionize the metaverse by enabling more immersive, interactive, and intelligent virtual environments. These technologies can help create more realistic, responsive avatars and more personalized and adaptive user experiences. Furthermore, machine learning and artificial intelligence can be used for behavior analysis, assisting in identifying patterns and trends in user behavior that can be used to improve the metaverse experience.

5.2. Class 2: fuzzy systems

For class 2, the given Scopus search formula or "TITLE-ABS-KEY ("fuzzy logic" OR "fuzzy inference" OR "fuzzy control" OR "fuzzy sets" OR "fuzzy systems")" gives a deviation on the progress of techniques and their applications in problem-solving, as shown in Fig. 15.

Fuzzy systems are a subset of soft computing based on fuzzy logic, a mathematical framework that can deal with imprecise or uncertain data [73]. Fuzzy systems are intended to capture and represent human knowledge and reasoning in a way that computers can understand and use to make decisions. Fuzzy systems contribute to soft computing by providing a powerful tool for modeling and controlling complex processes and systems [74]. Fuzzy systems' ability to deal with imprecise or uncertain data makes them well-suited for many metaverse applications [31,75], such as user behavior analysis, virtual environment design, and avatar control. Fuzzy systems are expected to play a critical role in the metaverse's future, enabling more sophisticated and realistic virtual environments and avatars. They can be used to model and control complex systems such as traffic flow in virtual cities or weather patterns in virtual worlds. Furthermore, fuzzy systems can aid in developing more intelligent and responsive avatars, allowing them to interact with users more naturally and intuitively.

5.3. Class 3: evolutionary computing

For class 3, the given Scopus search formula or "TITLE-ABS-KEY ("Evolutionary Computing" OR "swarm optimization" OR "genetic algorithms" OR "heuristic algorithms" OR "ant colony")" gives a deviation on the progress of techniques and their applications in problem-solving, as shown in Fig. 16.

Evolutionary computing is a subset of soft computing based on the principles of evolution and natural selection [76]. Evolutionary computing techniques, such as particle swarm optimization, genetic algorithms, heuristic algorithms, and ant colony optimization, are intended to simulate the process of evolution to find optimal solutions to complex problems. Evolutionary computing techniques contribute to soft computing by providing a powerful tool for solving complex

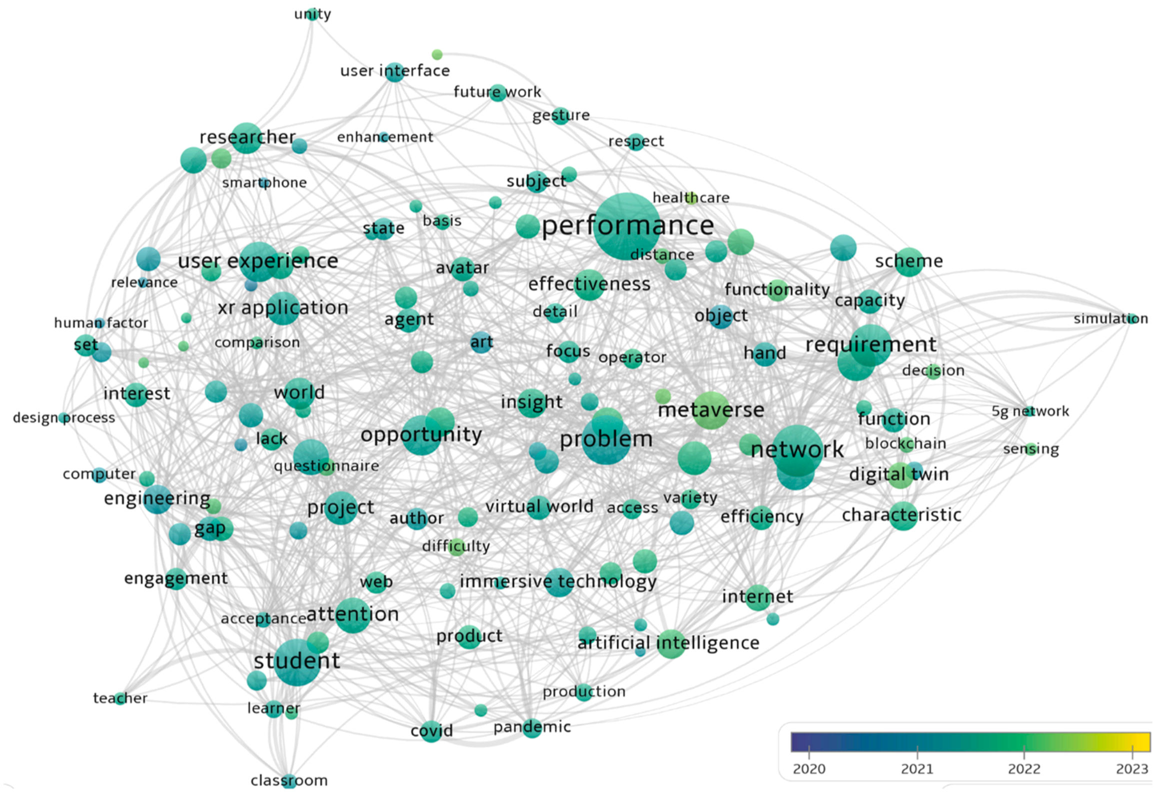

Fig. 10. Overlay visualization.

Fig. 11. Density visualization.

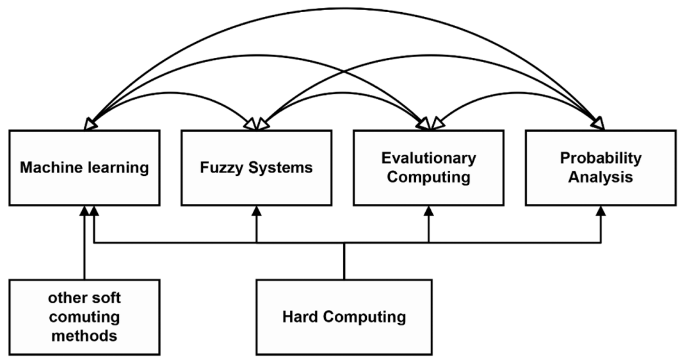

Fig. 12. Fusions for the new class of mixed/hybrid methods.

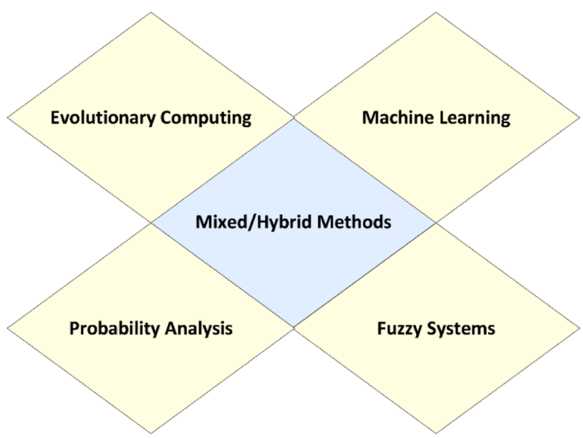

Fig. 13. Soft computing classes for the future of the metaverse.

optimization problems in the metaverse [77]. These techniques can be used to find the best solutions to problems such as avatar control, virtual environment design, and resource allocation. Evolutionary computing techniques are expected to play an increasingly important role in the future of the metaverse, enabling more sophisticated and intelligent virtual environments and avatars. They can optimize many systems and processes [78], such as traffic flow in virtual cities, resource allocation in virtual worlds, and avatar behavior and decision-making.

5.4. Class 4: probability analysis

For class 4, the given Scopus search formula or "TITLE-ABS-KEY ("Bayesian networks" OR "probability")" gives a deviation in the progress of techniques and their applications in problem-solving, as shown in Fig. 17.

Probability analysis is a branch of mathematics that analyzes uncertainty and risk [79]. It is a fundamental concept in soft computing, where dealing with uncertain or imprecise data is a common challenge [80]. Bayesian analysis, a subset of probability analysis, is a powerful tool for modeling and analyzing uncertain systems [81]. Probability analysis and Bayesian techniques contribute to soft computing by providing a rigorous framework for dealing with uncertainty and risk. These techniques are widely used in applications such as natural language processing, image recognition, and decision-making [82]. They can be used to model complex systems and predict future events [83,84]. Probability analysis and Bayesian techniques are expected to play an important role in the metaverse's future. They can be used to analyze user behavior, model complex virtual environments, and make decisions about avatar actions and interactions. These techniques can enable more intelligent and responsive virtual environments and avatars by providing a framework for dealing with uncertainty and risk [83].

5.5. Class 5: mixed/hybrid methods

For class 5, the expansion of other classes indicates this class's problem-solving progress. As the metaverse develops, the fusion of soft computing techniques is expected to become a major trend in soft computing applications [64]. The merging of fuzzy and neuro-fuzzy systems with artificial neural networks can inherit the advantages of both paradigms and avoid their drawbacks [85]. With the development of electronics and information technologies, fuzzy systems are becoming a critical tool to represent extensive human knowledge in metaverse research, using "If-Then" rules to establish explicit forms of knowledge. Furthermore, integrating soft computing techniques with hard computing and non-mathematical problem-solving methods is expected to provide innovative solutions to problems with high performance, cost-effectiveness, and reliable computing systems [86]. The new

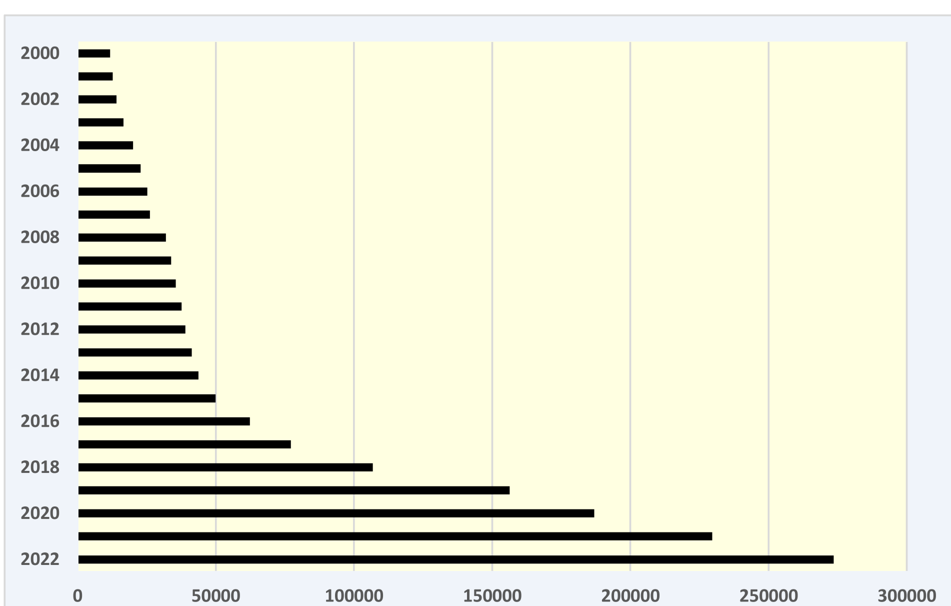

Fig. 14. Class 1 research progress.

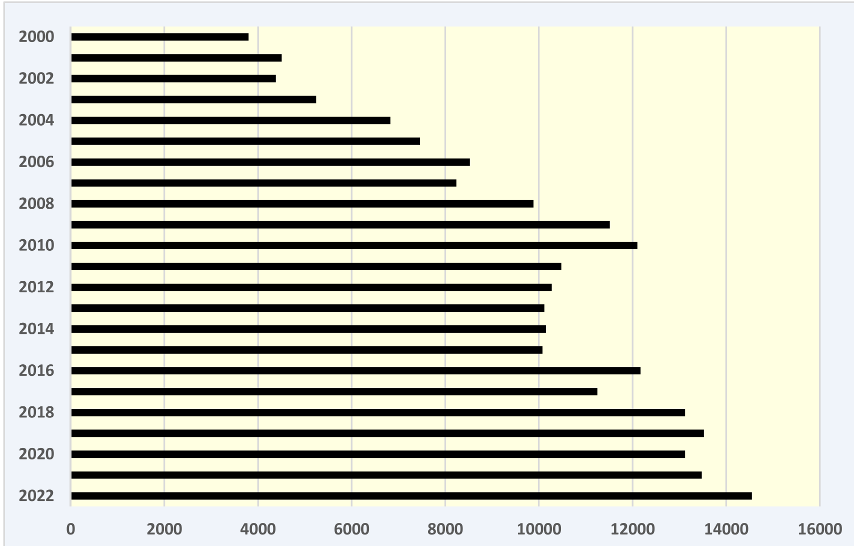

Fig. 15. Class 2 research progress.

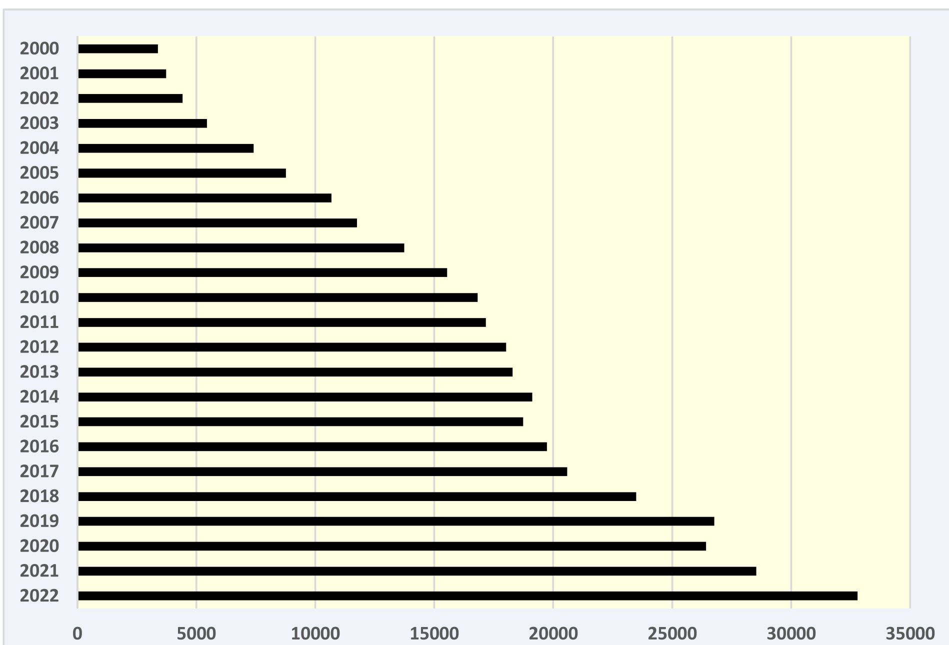

Fig. 16. Class 3 research progress.

member of soft computing, machine learning, is also a promising hybrid trend in developing novel techniques and applications [87,88].

5.6. Soft computing techniques for metaverse research

An analysis of the trends depicted in Figs. 14, 15, 16, and 17 reveals that machine learning exhibits the most rapid growth in terms of adoption by researchers over time. However, evaluative computing closely follows this growth trajectory. Presently, probability analysis boasts the highest number of users and appears to be in its maturity phase, succeeded by fuzzy systems in popularity and usage. However, each class possesses its distinct advantages and capabilities regarding usage. Thus, a selection framework helps users pinpoint the right approach based on their specific research objectives [89]. Fig. 18 is our suggested soft computing selection framework for metaverse research; it provides a framework for determining which subset of soft computing methods is best suited to solving a given metaverse issue. Based on the characteristics, applications, and foreseen future developments, each decision point aids in narrowing down the appropriate technique.

6. Conclusion

The metaverse is an innovative and dynamic technology that has captured the attention of researchers and practitioners worldwide. Platform providers aim to make it easier for people and organizations to create their virtual worlds, but various issues and challenges still need to be resolved [90]. Besides, the wise direction of the metaverse holds promise for enhancing the state of the physical world [91]. However, several challenges must be resolved to create and manage these virtual worlds, which can be done using soft computing techniques. This paper has comprehensively reviewed soft computing methods in the metaverse, highlighting their potential and contribution to developing this

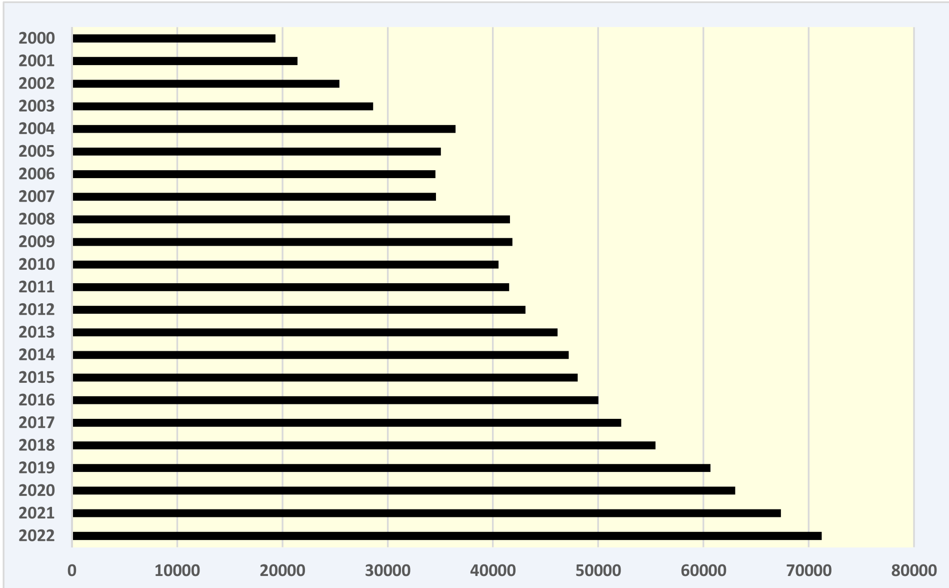

Fig. 17. Class 4 research progress.

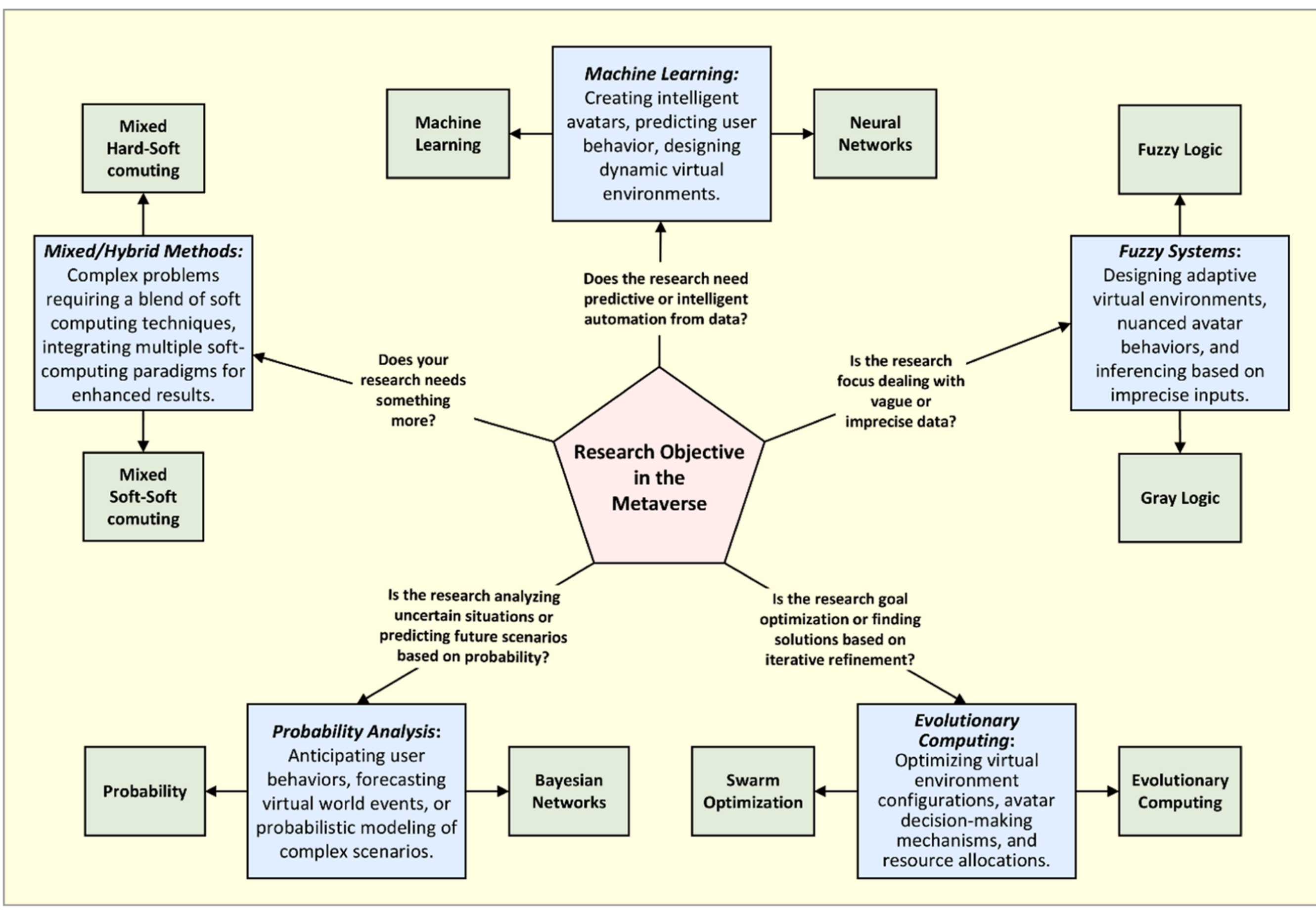

Fig. 18. A soft computing selection framework.

immersive virtual environment. The systematic literature review in this article identified the leading countries and research domains in soft computing, emphasizing the interdisciplinary nature of the field and the need for collaboration. However, the study also highlights the lack of attention given to soft computing techniques in shaping the future of the metaverse. The article has categorized soft computing techniques into five classes - Machine Learning, Fuzzy Systems, Evolutionary Computing, Probability Analysis, and Mixed/Hybrid Methods. Encouraged and commented on by Singh et al. [92], such taxonomies for soft computing could categorize and evaluate various research initiatives.

The proposed taxonomy by this article has the potential to provide innovative solutions to problems in various fields related to the future of the metaverse.

The classification of soft computing-related items presented in this paper provides valuable insight into the diversity and applicability of soft computing techniques across various fields of the metaverse. The article also discusses the potential for hybrid approaches and the fusion of soft computing techniques with other technologies to provide innovative solutions to problems related to the metaverse in various sectors. Moreover, the findings of this paper emphasize the importance of soft computing methods in addressing the challenges and opportunities of the metaverse. The interdisciplinary nature of soft computing and its adaptability and flexibility make it an essential tool for developing intelligent systems that can learn from data and make decisions based on imprecise or uncertain information. Soft computing techniques can also help in modeling and controlling complex processes and systems, finding optimal solutions among possible solutions, and analyzing uncertainty and risk in complex systems. This study proposed a decision framework for researchers and developers to use when determining the most appropriate soft computing technique for their research or metaverse development project.

In conclusion, this study contributes to the ongoing discussion on soft computing methods' role in shaping the metaverse's future. We emphasize the need for interdisciplinary collaboration, the fusion of soft computing techniques with other technologies, and further research and development of soft computing methods in the field. The findings of this study can serve as a valuable reference for researchers, practitioners, and policymakers working in this field, providing valuable insights into the potential of soft computing techniques in shaping the future of the metaverse.

CRediT authorship contribution statement

Madjid Tavana: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft preparation, Visualization, Writing – reviewing & editing. **Shahryar Sorooshian**: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft preparation, Visualization, Writing – reviewing & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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