Blockchain-Based Self-Sovereign Identities: Current Landscape and Research Opportunities

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Abstract

Managing identities has become increasingly crucial for various organizations, including banks, government agencies, and healthcare providers. Furthermore, the privacy of personal data has gained increasing importance and concern. In this context, Self-Sovereign Identity (SSI) systems have emerged as a cutting-edge solution that builds on traditional identity management. They empower individuals with unprecedented control over their data, allowing them to selectively share information with authorized entities while retaining their privacy. This paper presents a Systematic Literature Review (SLR) of blockchain-based Self-Sovereign Identities. We analyzed ninety-four articles from eight academic databases and categorized the findings into six major groups, identifying eighteen distinct areas of interest. Our results underscore the growing importance of SSI in digital identity research and its implications for privacy, security, and regulatory compliance. Furthermore, we provide a comprehensive map of the literature, elucidating areas of substantial scholarly attention and those necessitating further exploration.

Keywords: Self-Sovereign Identity, Digital Identity, Blockchain, DLT

1. Introduction

Progress in digital identity has ignited significant interest in utilizing blockchain technology to manage its data. This enthusiasm originates from the robust security features inherent in these distributed ledger systems, such as their decentralization and tamper-proofness. A decentralized identity model, popularly called "self-sovereign identity" (SSI) [6] is emerging as a paradigm shift in digital identification models. It empowers individuals with complete autonomy to manage their personal data. Embracing SSI liberates individuals from the constraints of centralized authorities or third-party ID providers.

To provide a comprehensive overview of the current state of the art in this area, we present a Systematic Literature Review (SLR) of the current research on blockchain-based SSI, analyzing ninety-four articles from eight different academic databases, classifying them into six major groups and categorizing them into eighteen distinct areas of interest. Although we found a growing number of studies in the area, we also observed that works that do not directly address the topic sometimes misuse the term SSI.

The rest of this paper is organized as follows. Section 2 describes the protocol used to perform the SLR. Section 3 presents our overview about the identified papers. Section 4 provides a Discussion and Future Research possibilities. Finally, Section 5 closes with conclusions.

2. Methodology

To execute the Systematic Literature Review, we followed the recommendations of [95] and [42]. First, we defined the Research Question, namely: *What is the state of the art for Self-*

Sovereign ID using Blockchains? Second, we initiated the process of formulating search expressions. Initially, we searched Google Scholar using the term "Blockchain Self-Sovereign" and examined the results to identify additional keywords to refine our expressions. We repeated this process a few times until we defined the following search expression: *(Blockchain OR "Distributed Ledger Technology") AND ("Digital ID" OR "Digital IDs" OR "Digital Identity" OR "Digital Identities" OR KYC OR "Know Your Customer" OR "Self-Sovereign Identity" OR SSI OR "Decentralised identity" OR "Decentralised id").* Third, we executed the search. Since different databases have different user interfaces, we tried to perform the searches in a way closest to the defined search expression. Table 1 lists the databases and the number of results obtained in each. We searched, utilizing titles, abstracts, and keywords to identify the papers, filtered by conferences and journals when possible. Initially, we identified 1,046 articles, subsequently exported to Rayyan, a collaborative systematic literature review web tool. After the removal of duplicate papers, the remaining unique studies totaled 808.

Table 1. Numbers of Search Results by Database

Database	Results	Database	Results
ACM	55	Scopus	474
EBSCO	62	SpringerLink	94
IEEExplore	317	Taylor & Francis	5
ScienceDirect	29	Wiley Online Library	10
Total:	1,046	Unique:	808

In the fourth step of our review process, the authors made independent blind reviews to decide about paper inclusion, screening their relevance based on title, abstract, and keywords, considering the following inclusion criteria: (i) must focus on SSI for individuals, (ii) must be published in conferences or journals, (iii) must be written in English; and the exclusion criteria: (i) does not address SSI systems, (ii) deals with SSI for devices such as IoT or vehicles, (iii) work published in workshops, book chapters or lectures. We had a total of 665 papers excluded in this step, resulting in 143 articles selected for full-text analysis. Using the same criteria, we excluded 49 additional articles in this latter step, leaving a final selection of 94 relevant papers.

3. Overview of Blockchain-Based SSI Papers

We have observed a growing interest in research at the intersection of digital identities and blockchain over the years, evidenced by the increasing number of publications. The trend began in 2017 with the first study we found. Subsequently, there was an increase to seven papers in 2018, followed by six papers in 2019. Since then, there has been a steady rise, with 13 publications in 2020, 16 in 2021, and a peak of 51 publications in 2022. To categorize the included papers, we classified them into six major groups, each representing a distinct focus area, as follows:

Conceptual Solutions (29 papers): propose innovative approaches to address problems or challenges related to blockchain and digital identities. Often introduce new frameworks, theories, or models based on general or theoretical ideas.

Implemented Solutions (20 papers): present the development of new processes, systems, or the application of existing theories or frameworks to solve specific problems within the realm of blockchain and digital identity.

Reviews or Case Studies (14 papers): offer critical analyses of technologies, specific situations, or examples related to blockchain and digital identity. Provide valuable insights into real-world applications and examine their effectiveness.

Technology Analysis (21 papers): focus on the study and evaluation of projects, protocols, and the utilization of various technologies within digital identity ecosystems. Delve into the

technical aspects and assess their implications.

Systematic Mappings (6 papers): literature reviews that systematically research, select, and evaluate existing research from different perspectives. Provide a comprehensive overview of the existing body of knowledge in the field.

Views and Opinions (4 papers): express personal perspectives or discuss blockchain and self-sovereign identity. Some of these papers present new ideas and challenges associated with the emerging identity paradigm.

Among the **Systematic Mappings** that address the intersection of blockchain and self-sovereign identity were found in four studies contemplating a broad and generalist perspective on the subject matter. In [16], the authors analyzed 120 papers published between January 2013 and January 2021, in IEEE Xplore and the Science Direct databases. In [73], Rathee and Singh selected 30 primary studies about blockchain and identity management, published from 2009 to 2020 in five electronic databases: IEEE Xplore, ACM Digital Library, Science Direct, Springer Link, and Wiley. In [5], the authors present a bibliometric analysis of 1,395 peer-reviewed articles and their 44,412 references, where the primary studies were collected from the Web of Science database in April 2020. Another paper we found, [3], discusses 63 articles published between October 2015 and January 2022 in academic databases (e.g., IEEE Xplore, ScienceDirect, ACM Digital Library, Wiley, Springer Link, Taylor & Francis, and MDPI), patents, and Google Scholar. Additionally, [78] focused explicitly on reviewing the current state of healthcare applications. Furthermore, [96] discusses how blockchain could process sensitive and large identity datasets among different domains.

Our review complements existing ones by including the most up-to-date dataset focused on academic articles dealing with blockchain-based SSI, presenting a comprehensive map of the literature and elucidating areas that garner substantial academic attention and those needing further exploration.

In addition to the systematic mapping studies, we encountered four papers presenting authors' **Views and Opinions** on blockchain-based self-sovereign identity. Kubach et al. [44] discuss the challenges faced in the realm of digital identity. In [22], the authors emphasize the socio-technical nature of self-sovereign identity, offering insights on social and technological aspects and suggesting directions for future research. In [82], Seifert explores the prospects of SSI, specifically in the context of national identification implementation, addressing considerations, benefits, and challenges. Lastly, [10] investigates information sharing and governance in the digital society using blockchain-based SSI.

As suggested by [95], after completing the reading, we grouped the papers by identified concepts. We did it by categorizing them into 18 distinct areas of interest that emerged from our analysis: Architecture and Design Patterns, Authentication and Authorization, Banks and Financial, Blockchain Redaction, Education, Formal Definitions, Government and National IDs, Healthcare, Interoperability, Laws and Regulations, Metaverse, Morals and ethics, Organizational Management, Other Applications, Privacy and Security, SaaS, Trustworthiness, Vulnerable Individuals. Table 2 presents a distribution of the papers considering their contributions to Blockchain-based Digital Identities literature.

In the **Conceptual Solutions** category, we encountered a diverse range of articles proposing innovative ideas and frameworks for blockchain-based self-sovereign identity systems. These contributions include [50], which introduced 17 distinct design patterns specifically tailored for blockchain-based SSI systems. In [53], the authors present a decentralized SSI authentication protocol, while [32] proposed the OrgID, a comprehensive data management platform incorporating identity registration and authorization procedures. A multi-tiered architecture for scalable SSI is presented in [57], while [71] presents a digital agent (ssDA) as an essential building block for a grassroots digital economy and society, and in [45] the authors prototype a system with document attestation credibility checking and record sharing. Finally, [76] proposes an SSI plat-

form that provides a ZeroKnowledge Proof (ZKP) mechanism to verify the information. The Conceptual Solutions category also featured papers addressing authentication architectures, SSI frameworks for the banking sector in [2] and [81], and an SSI framework specifically tailored for Higher Education Institutions [55]. In [74] the authors proposed the EASEID model for a Session-based Single sign-on SSI, and [21] describes a hybrid of SSI, cryptographic authentication, and biometric authentication. We also encountered a formal and rigorous treatment of the concept of self-sovereign identity, employing a mathematical model [26]. Two papers bring Conceptual Solutions to SSI and Healthcare ([77], [40]), and another two propose solutions to SSI and metaverse [11], including interoperability [29]. The papers in this category further explored evaluation models for international engagement in decentralized identity systems in [49]. Besides, [17] introduced an identity relationship model that spans multiple Identity Management systems, facilitating interoperability and integration. Moreover, [68] presented a compliance SSI system property set. In addition, we encountered a paper focusing on access control and data security in permissionless blockchains, as well as architecture and system protocols for Sybil-Resistant SSI [58]. Frameworks and models emphasizing the importance of trust and reputation mechanisms were found in [33] and [60]. In [47] the authors propose a decentralized attribute-based SSI, in [69] a method for detecting common weaknesses, and [52] a scheme to strike a balance between privacy and accountability. Finally, we found one paper that analyses the possible use cases for blockchain redaction (to modify or delete some data) in SSI [9].

Most articles in the **Implemented Solutions** category deal with system architecture and design patterns, such as in [98], where authors constructed a blockchain-based framework for verification, authorization and recovery of self-sovereign identity using smart contracts. Moreover, [51] presented a platform architecture that supports the idea of the design pattern as a service (DPaaS). In [91], the authors propose a decentralized access control system for inter-enterprise data sharing, and in [18], a selective disclosure method based on keying hash functions. Many authors proposed different Digital Identity platforms based on blockchain, such as [93], [72], and [13] using Hyperledger and Ethereum technologies. Moreover, [30] presents the design and implementation of the Elesto protocol as an identity infrastructure, and [92] proposes the AlgoCert as a solution to educational certificates with Non-transferable NFT and DIDs. Furthermore, [87] implemented a trusted and robust authentication mechanism for users who share data between distinct blockchain platforms, [27] provided an SSI-based event ticketing framework, and [80] introduced a novel tool to perform metadata matching on Sovrin. Regarding processes banks and other financial institutions use to confirm the identity of the organizations and individuals (Know Your Customer), [88] created a framework to take a step toward tackling weaknesses in old KYC models. Furthermore, [89] presents a digital identity with passport-level attributes. A group of papers is focused on SSI as a Service [20] and Credentials as a Service [86], while [48] addresses audit and accountability issues in Self-Sovereign Identity Blockchain Systems using Archival Science Principles. Abraham et al. [1] proposed "deriving identity data from an existing identity system into an SSI in a fully privacy-preserving way by additionally supporting offline verification." Additionally, [79] presents a framework for online document verification using SSI. Lastly, [67] proposes a novel solution to address identity issues faced by Indian migrant workers.

As **Reviews or Case Studies**, we encountered a survey focusing on the essential components of an SSI [59], opportunities for the public sector [54], and discussion about national digital identities in India [35], Finland, Sweden, Taiwan [8], and the Estonian E-Residency [90]. Other authors review the applicability of SSI solutions in the healthcare domain [83] and the aspects of these applications during pandemic situations like COVID-19 [84]. In more analyses of SSI technologies, we found [38] that illustrated three distinct paths in the evolution of digital identity and some key technical elements in decentralized identity. In [61], Mulaji and Roodt ex-

plain how technological, organizational and environmental (TOE) factors affect organizations' adoption behavior toward SSI. The authors in [97] conducted a comprehensive study comparing 31 blockchain-based Identity management (IdM) solutions against various functional and non-functional requirements and emerging SSI standards. The article [85] highlights the limitations of existing identity solutions, the advantages of SSI, and its application in the blockchain-based land registry system. Additionally, [43] examined issues related to the European Union General Data Protection Regulation (GDPR) associated with three specific systems (uPort, Sovrin, and Jolocom). Furthermore, [37] outlined the moral foundation for claims on the desirability of SSI solutions. In the context of human rights, [14] conducted a thorough survey on the utilization of blockchain technology to support the rights of migrants and refugees. The study examined two cases: the Building Blocks initiative by the World Food Programme in Jordan and the Rohingya Project. Finally, [12] examines the implications of 'self-sovereign identity' (SSI) for border politics and migration management, identifying a series of competing logics in the debates around SSI's emancipatory potential.

Table 2. Current Landscape of SSI Contributions

	Conceptual Solutions	**Implemented Solutions**	**Reviews or Case Studies**	**Technology Analysis**
Architecture and Design Patterns	[50] [57] [45] [76] [71]	[93] [98] [51] [13] [72] [91] [18] [30]	[59]	[22] [36] [63] [64] [31] [39] [46] [25] [24] [15] [4] [94] [70] [7]
Authentication and Authorization	[34] [53] [32] [21] [74]			
Banks and Financial	[2] [81]	[88]		
Education	[55]	[92]		
Formal Definitions	[26]			
Government and National IDs	[49]	[89]	[90] [8] [35] [54]	[19]
Healthcare	[40] [77]		[83] [84]	
Interoperability	[17]	[87]		
Laws and Regulations	[68]			[43] [65] [56] [66]
Morals and Ethics			[37]	
Metaverse	[29] [11]			
Organizational Management			[61]	
Other Applications		[27]	[85]	
Privacy and Security	[41] [58] [52] [69] [47]	[1] [80]	[38] [97]	[62]
Redaction	[9]			
SaaS		[86] [20]		
Trustworthiness	[33] [60]	[48] [79]		[28]
Vulnerable Individuals		[67]	[14] [12]	

Lastly, within the **Technology Analysis** category, most papers focused on evaluating architecture and design patterns. In [64], the authors conducted an assessment specifically on uPort, while [24] and [63] provided comparisons of uPort with other systems like Sovrin and Civic.

Furthermore, [36] and [23] analyzed uPort, Sovrin, and Shocard systems. On the other hand, some authors expanded their analyses to include additional technologies. For instance, [31] examined Blockstack and Selfkey, while [39] added EverID, Life ID, Sora, and Selfkey technologies to their analysis. In [7], the authors analyzed and compared ShoCard, WeIdentity, Microsoft DID, Cambridge Blockchain, uPort, and Sovrin. Nevertheless, [70] presents a detailed latency analysis of a permissioned blockchain system built with Indy and Aries, and [15] provides an overview and analysis of SSI properties from the literature. Related to government use, [19] analyzed SSI and Blockchain to access services of a Public Administration (Italy). While [56] collected and presented the major technological and regulatory information related to Identity and Access Management and blockchain technology, [66] examined the real sovereignty of digital identity in the SSI model. In [4], Alizadeh et al. explored six different Decentralized Identifier methods encompassing various architectural designs, such as public permissioned, public permissionless, and pairwise DIDs. Furthermore, [46] conducted a systematic criteria-driven survey of blockchain-based IdM solutions, covering features, prerequisites, market availability, readiness for enterprise integration, costs, and estimated maturity. In [25], the authors focused on evaluating a selection of distributed identity methods and analyzing their properties based on the categorization specified in the W3C recommendation rubric. Moreover, [75] evaluated six decentralized identifiers (DID) methods based on the guidelines provided by the W3C DID method rubric. Regarding security breaches, [62] proposed an approach for evaluating potential attacks on the SSI system, and in [28], the authors aimed to uncover the benefits that blockchain can bring to SSI systems. Finally, [43] not only analyzed Sovrin, uPort, and Jolocom but also engaged in a discussion on the GDPR compliance of the blockchain-based identity concept. Similarly, [65] evaluated this aspect of SSI, analyzing compliance and alignment with the principles of GDPR. Their findings suggest SSI systems based on a public permissioned blockchain can comply with the most key GDPR principles.

4. Discussion and Future Research

After analyzing the studies identified in this literature review, it becomes evident that Self-Sovereign Identities are a central focus of much research. While a growing number of studies directly address the SSI topic, there are also instances where the term was used without proper alignment with the concept. Some studies misapply the term, describing systems that do not truly adhere to the principles of Self-Sovereign Identity, such as storage control, portability, or Interoperability.

Many selected works present architectures and design patterns for SSI systems, but few have been tested in production. Additionally, we observed that some works do not utilize W3C patterns such as Decentralized Identifiers (DID) and Verifiable Credentials (VC), and none of those presenting different solutions provided a comparison between these models.

The inherent qualities of identity systems using blockchain have also proven valuable for the Financial and Banking sectors and Healthcare, which are following the trend of increasing research using SSIs.

Other points we highlight in the evolution of these systems include concerns about wallet key recovery and compliance with data protection regulations such as GDPR, especially regarding the right to be forgotten, given the immutable nature of blockchains. In this sense, we also note opportunities for debate and research on how SSIs can be used or integrated by official national identity systems, such as the European electronic identity system eIDAS.

The findings underscore the importance of further research and practical testing of SSI architectures and design patterns, as well as exploring the integration of SSIs with official national identity systems. Additionally, addressing key concerns such as wallet key recovery and GDPR compliance is crucial for blockchain-based identity solutions' broader adoption and effectiveness.

5. Conclusions

This systematic literature review on blockchain-based Self-Sovereign Identities (SSIs) sheds light on this field's growing interest and significance in digital identity research. By analyzing ninety-four articles from various academic databases, this review underscores the dynamic landscape of SSIs and their far-reaching implications for privacy, security, and regulatory compliance. Among the key findings, it becomes evident that SSIs have the potential to revolutionize digital identity management by empowering individuals with unprecedented control over their personal data. The review highlights proposed approaches and architectural designs for SSI systems, along with practical implementations across diverse sectors such as finance, healthcare, and education. However, the review also exposes specific gaps and challenges in the current state of research. Some studies misuse the term "SSI," failing to adhere to its core principles. Furthermore, while theoretical models and design patterns abound, empirical validation and real-world testing of these solutions remain scarce. Key recovery, data privacy, and regulatory compliance concerns present significant hurdles to widespread SSI adoption. Future research should address these issues and explore pathways for integrating SSIs into existing identity systems, including official national identity frameworks. In conclusion, this systematic literature review provides valuable insights into the current state of blockchain-based Self-Sovereign Identities. Identifying trends, gaps, and future research directions contributes to the ongoing discourse on digital identity management and lays the groundwork for further advancements in the field. A limitation of this study is that our review only encompasses papers published up to the end of 2022. Therefore, broadening our analysis to include more recent publications is essential.

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