

# Mitigating Sovereign Data Exchange Challenges: A Mapping to Apply Privacy- and Authenticity-Enhancing Technologies

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**Abstract.** Harmful repercussions from sharing sensitive or personal data can hamper institutions' willingness to engage in data exchange. Thus, institutions consider Authenticity-Enhancing Technologies (AETs) and Privacy-Enhancing Technologies (PETs) to engage in *Sovereign Data Exchange (SDE)*, i.e., sharing data with third parties without compromising their own or their users' data sovereignty. However, these technologies are often technically complex, which impedes their adoption. To support practitioners select PETs and AETs for SDE use cases and highlight SDE challenges researchers and practitioners should address, this study empirically constructs a challenge-oriented technology mapping. First, we compile challenges of SDE by conducting a systematic literature review and expert interviews. Second, we map PETs and AETs to the SDE challenges and identify which technologies can mitigate which challenges. We validate the mapping through investigator triangulation. Although the most critical challenge concerns data usage and access control, we find that the majority of PETs and AETs focus on data processing issues.

**Keywords:** sovereign data exchange · technology mapping · privacy-enhancing technologies · authenticity-enhancing technologies

## 1 Introduction

Companies seeking growth collect and analyze increasing amounts of data to innovate and improve their products and services. Thereby, data becomes a valuable resource [12]. However, despite the upside potential of collecting more data, institutions are reluctant to share (often sensitive) information with third parties as they may lose control over who and how their data is accessed, used, or distributed [4,29]. European initiatives (e.g., Gaia-X [6], International Data Spaces Association (IDSA) [56]) were formed to entice the industry into considering data sharing without risking unauthorized distribution or misuse of data (i.e., data sovereignty). We refer to *Sovereign Data Exchange (SDE)* as the ability of a digital subject to share their data with third parties without compromising their data sovereignty, i.e., the self-determination over accessing, processing, managing, or securing their data.

As institutions work towards SDE, Privacy-Enhancing Technologies (PETs) and Authenticity-Enhancing Technologies (AETs) receive increasing attention. PETs manage or modify data to protect sensitive personal information [35] and AETs enhance authenticity, and integrity of data and information in a system [51] to incentivize data sharing [66]. Some PETs can also be AETs, but not all AETs are PETs and vice versa [51]. However, researchers and practitioners struggle to understand the technologies due to their technical complexity, low maturity, the wide range of possible variations and combinations, and potential economic risks [51,79,80]. While researchers focused on SDE challenges [4,44,79] or capabilities of PETs and AETs [62,20], we are the first to help practitioners select PETs or AETs according to the challenges in SDE use cases.

We build our contribution by first identifying the challenges of SDE with a Systematic Literature Review (SLR) and Expert Interviews (EIs). Consecutively, we map PETs and AETs against the challenges they can tackle via investigator triangulation. We provide four contributions. We (1) compile a list of relevant *SDE challenges* (Section 4.1), (2) thoroughly research PETs and AETs relevant to mitigate SDE challenges (Section 3) in a *technology classification*, (3) map PETs and AETs against the SDE challenges, summarized into a *technology mapping*, and (4) outline five *key findings* (Section 5). Our study thereby synthesizes previous research in an actionable way: the technology mapping is a challenge-oriented approach supporting the identification of appropriate PETs and AETs to tackle SDE challenges.

## 2 Research Methods

### 2.1 Methodologic Triangulation

**RQ1:** *Based on researchers and industry stakeholders, what challenges hinder SDE?* We conduct an SLR and complement the findings through EIs to answer RQ1. We consolidate the results into 13 challenges of SDE (Table 3), classified into organizational issues, data processing and publishing, and infrastructure challenges (Table 4).

**Systematic Literature Review** The SLR process consists of three phases [76,77], which are documented to increase transparency and reproducibility of the SLR. First, we define a search strategy by choosing search terms and databases. We apply the search term “*data sovereign\**” to multiple databases (Table 1) to ensure a coverage of software engineering and information systems literature. As of April 2021, we identified 205 search hits. Second, we define inclusion criteria and exclusion criteria. At first, we included all publications satisfying formal requirements (e.g., unique English journal and conference hits). Then, we exclude articles based on titles and abstracts (e.g., unrelated data sovereignty subject, too broad focus) followed by exclusion based on full-text analysis (e.g., no data exchange focus, generic challenges of technologies). We exclude 191 hits, resulting in a subset of 14 final hits (6.8% relevance rate). We identified 2 more hits from the backward search. The final hits were published between 2014 and 2021.

**Table 1.** Selection Process of the SLR

Selection Criteria	ACM Digital Library <sup>a</sup>	IEEE Xplore Digital Library <sup>b</sup>	Web of Science <sup>c</sup>	Total
Total search hits	71	49	85	205
Unique journal/conference hits	49	64	26	139
Title and abstract hits	17	14	15	46
Full-text hits	5	4	5	14
Backward search final hits	-	-	-	2
<b>Total final hits</b>	-	-	-	<b>16</b>

<sup>a</sup><https://dl.acm.org/>, <sup>b</sup><https://ieeexplore.ieee.org/>, <sup>c</sup><https://www.webofknowledge.com/>

Third, we analyze the final hits using content analysis. We extract, summarize, thematically compare, and theoretically generalize text passages describing SDE challenges [48]. Overall, 13 challenges are highlighted (Table 3).

**Expert Interviews** Following the guidelines by Runeson and Höst [63], we conduct EIs to enrich the findings of the SLR with opinions from the industry [49] to reduce bias from the SLR. The empirical method consists of two parts. First, we devise a questionnaire<sup>3</sup> with independently reviewed questions. Second, participants are recruited by contacting individuals who have co-authored journal and conference papers on SDE (e.g., [12]), who have worked directly or indirectly data sovereignty projects, and who come from different institutions. Six individuals (IT project managers, computer science and security researchers) agreed to participate in April and May 2021. Two interviews were conducted as synchronous, semi-structured online interviews [63], while the remaining interviews occurred via E-Mail correspondence. Participants are informed about organizational matters (e.g., study purpose, removal of personal information, right to withdraw responses). The findings are summarized before concluding the interviews to counter selection bias and avoid misinterpretation [63]. Similar to the data analysis in the SLR, the expert interview responses are paraphrased and analyzed using content analysis. Then, the challenges are consolidated with challenges from the SLR (Table 3).

## 2.2 Investigator Triangulation

**RQ2:** *Which PETs and AETs have the potential to mitigate the SDE challenges identified through RQ1?* We apply investigator triangulation [74] to map which PETs and AETs from the technology classification (Section 3) can mitigate the SDE challenges from RQ1. The evaluation of the individual technologies was conducted by each researcher to decrease bias in the evaluation stage and contribute to the findings’ internal validity [74]. First, every researcher selects one technology from the technology classification (Section 3). Second, each researcher individually goes through the challenges from RQ1 one by one, and gauges whether the technology fully or partially addresses the challenge on a theoretical or technical basis. Third, the researchers’ evaluations are consoli-

<sup>3</sup> Questionnaire: <https://anonymous.4open.science/r/trustbus2022-5C26/>

dated with one another through rigorous discussions, and recorded.<sup>4</sup> The final results are summarized in a technology mapping (Table 5).

### 3 Technology Classification

*Privacy-Enhancing Technologies (PETs)* manage data through privacy principled architectures and policies or *modify* data with heuristics or mathematical privacy guarantees to protect personal or sensitive information while minimally disturbing data utility [51,35,75]. In contrast, *Authenticity-Enhancing Technologies (AETs)* support and improve the assessment of authenticity and integrity of data in a digital system [51]. AETs thus facilitate the assessment of trust and confidence between parties [18,40] and ensure accountability and compliance [7].

Inspired by [20,51], we classify PETs and AETs into five layers. The layers correspond to data communication, storage, processing, verification, and sovereignty (Table 2). The *data communication layer* and *storage layer* address how to transfer and store data, respectively, in a secure and trustworthy manner. The *data processing layer* includes technologies that enhance the privacy of the data input, its computation, and output [75,51]. The *data verification layer* is concerned with certification of identities, properties of individuals, and attributes of datasets or resources. Lastly, the *sovereignty layer* includes mechanisms that enforce usage control and privacy protection on a policy basis [24].

### 4 Challenges & Technology Mapping

#### 4.1 SDE Challenges (RQ1)

The concept matrix (Table 3) lists 13 SDE challenges identified from analyzing the final 16 literature hits and interviewing 6 experts. The SDE challenges are described and grouped into organizational issues, data processing and publishing, and infrastructure issues (Table 4). The *organizational challenges* relate to institutions’ uncertainties regarding legislation, technology standards, opportunity costs of data exchange, and by extension, SDE. The *data processing and publishing challenges* are primarily concerned with protecting digital subjects’ personal interests and privacy in data exchange. Lastly, *Infrastructure challenges* relate to data security and privacy beyond processing and publishing data. Specifically, the challenges deal with implementation issues regarding data access and usage control, strengthening trust in the infrastructure and amongst data exchange participants, as well as enforcing accountability and auditability.

As described in the methodology (Section 2.1), the individual challenges are derived through content analysis. For example, *missing standards* (C2) is mentioned by three literature sources and two interviewees. Researchers highlighted the challenge of missing standardizing guidelines on data sharing [59] or faced missing standards regarding the publishing of smart city data [19]. The missing end-to-end standards are also mentioned [14]. More generally, Grünewald and

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<sup>4</sup> Assessment tables: <https://anonymous.4open.science/r/trustbus2022-5C26/>

**Table 2.** Overview of PETs and AETs

Technology
<i>Data Communication Layer</i>
<b>Encryption.</b> A core cryptographic technique to send data between entities, which only intended recipients can decrypt [23].
<b>Anonymous Routing.</b> As the backbone of The Onion Router (TOR) [25], the protocol anonymously relays messages through a distributed network while being resistant to eavesdropping and traffic analysis [73].
<i>Data Storage Layer</i>
<b>Decentralized Storage.</b> Distributed Hash Tables (DHTs) are at the core of decentralized storage systems and can be used to store and retrieve data distributed across the nodes of a Peer-to-Peer (P2P) network [58].
<b>Searchable Encryption (SE).</b> SE supports search functionality on the server-side without decrypting data and losing data confidentiality [70,11] through Searchable Symmetric Encryption (SSE) or Public-Key Encryption with Keyword Search (PEKS).
<i>Data Processing Layer</i>
<b>Homomorphic Encryption (HE).</b> Arithmetic operations directly on ciphertext, such that only authorized entities can decrypt and access the output of the operations [47,16].
<b>Secure Multi-Party Computation (MPC).</b> Data exchange participants can jointly compute functions on data without revealing their data inputs to other participants. Popular implementations are based on secret-sharing [68] and garbled circuits [78].
<b>Federated Learning (FL).</b> Multiple participants can train machine learning models collaboratively over remote devices [42,46], i.e., participants keep their data localized and only share local model updates with a coordinating central server. Thus, data privacy is enhanced as data never leaves the data owner's device [60,46].
<b>Trusted Execution Environment (TEE).</b> Secure memory areas physically isolated from the device's operating system and applications [55,37]. Unique encryption keys are associated with hardware, making software tampering as challenging as hardware tampering [51].
<b>Differential Privacy (DP).</b> Algorithms fulfilling this privacy definition enhance privacy by adding randomized noise to an analysis, such that its results are practically identical with or without the presence of an individual data subject [26], providing plausible deniability.
<b>k-Anonymity.</b> This privacy model uses syntactic building blocks (suppression and generalization) to transform a dataset such that an individual cannot be distinguished from at least $k - 1$ others in the dataset [64,72].
<b>Pseudonymization.</b> Replaces identifiers with pseudonyms via encryption, hash functions, or tokenization to decrease the linkability to individuals [54,69].
<i>Verification Layer</i>
<b>Distributed Ledger Technology (DLT).</b> Distributed and tamper-proof database, where the state is stored on multiple nodes of a cryptographically secured P2P network [10]. The state is updated on all nodes using a consensus algorithm.
<b>Verifiable Credential (VC).</b> VCs are sets of verifiable claims that can prove the authenticity of attributes or identities [52]. The standardized digital credentials use Decentralized Identifiers (DIDs) and Digital Signatures (DSs) to form attestation systems.
<b>Zero-Knowledge Proof (ZKP).</b> Cryptographic protocol allowing to authenticate knowledge without revealing the knowledge itself [32,31]. ZKPs can provide data authenticity, identity authenticity, and computational integrity.
<i>Sovereignty Layer</i>
<b>Privacy-by-Design (PbD).</b> The seven-step guidelines can protect privacy in systems' designs by acknowledging privacy within risk management and design processes (e.g., privacy by default settings, end-to-end security of personal data) [34,13].
<b>Privacy Policy (PP).</b> PPs (e.g., through smart contracts [51] or on a contractual basis [12]) embody privacy requirements and guidelines of data governance models [71], such that different policies can be applied to different data consumers.

**Table 3.** Concept Matrix of Identified SDE Challenges

	Managing Jurisdictions	Missing Standards	Reluctance	Ensuring Data Privacy	Ensuring Data Quality	Ensuring Computational Privacy	Interoperability	Minimizing Computational Complexity	Inter-Organizational Trust	Cyber Security & Trust in Infrastructure	Data Provenance	Data Usage & Access Control	Auditability
Data Source	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Systematic Literature Review													
Panhuis et al. [59]	✓	✓	✓	✓	✓		✓		✓			✓	
Lablans et al. [43]			✓			✓	✓						
Ahmadian et al. [2]	✓			✓				✓		✓	✓		✓
Bennett et al. [5]				✓	✓					✓		✓	
Brost et al. [9]									✓			✓	
Demchenko et al. [21]		✓								✓			
Celik et al. [14]	✓		✓			✓							
Cuno et al. [19]	✓	✓	✓										
Otto et al. [57]				✓	✓		✓	✓	✓	✓	✓	✓	
Sarabia-Jacome et al. [65]							✓						
Zrenner et al. [79]				✓			✓	✓				✓	
Gil et al. [29]									✓		✓	✓	
Lee et al. [45]				✓									
Nast et al. [53]						✓						✓	
Andreas et al. [3]	✓			✓			✓	✓					
Grünewald et al. [33]		✓		✓						✓	✓		
Count from SLR	5	4	4	8	3	3	6	4	4	5	4	7	1
Expert Interviews													
Interviewee 1 [I1]					✓		✓				✓	✓	
Interviewee 2 [I2]									✓			✓	
Interviewee 3 [I3]						✓						✓	
Interviewee 4 [I4]		✓	✓	✓		✓	✓					✓	✓
Interviewee 5 [I5]				✓		✓			✓		✓	✓	✓
Interviewee 6 [I6]		✓									✓	✓	
Count from Interviews	-	2	1	2	1	3	2	-	2	-	3	6	2
Total No. References	5	6	5	10	4	6	8	4	6	5	7	13	3

Pallas [33] and Demchenko et al. [21] encounter challenges of missing standardization in inter-system communication, standardization of transparency information items, and reusable open-source solutions to technically ensure that GDPR rights are met. The technical limitations are also picked up by Interviewee 6 [I6]. The limitations caused by missing data format and architecture challenges were summarized into one challenge. As standardization processes typically require collaborative working groups or experts (e.g., ISO), C2 was considered an organizational challenge. The remaining challenges were derived in a similar manner.

## 4.2 Technology Mapping (RQ2)

As described in Section 2.2, PETs and AETs (Section 3) are evaluated based on their potential to mitigate the SDE challenges identified in RQ1. We summarize the evaluation in a *technology mapping* (Table 5). For example, DP achieves anonymization in a dataset by adding randomized noise to the data. We find that DP does not support any organizational challenge as it only addresses datasets' contents. Thus, challenges C1, C2, and C3 are not addressed, and the cells re-

**Table 4.** Identified SDE Challenges (RQ1)

No.	SDE Challenge Description
<i>Organizational Challenges</i>	
<b>C1</b>	<b>Managing Jurisdictions.</b> Uncertainties about interpreting and implementing legal guidelines in technological infrastructures [2] (e.g., data sharing, copyright, data ownership, or personal data) in different jurisdictions [3,14,59]. Varying regulations for (at times hard to distinguish) personal and anonymized datasets cause further complications [19,59].
<b>C2</b>	<b>Missing Standards.</b> The definition and implementation of suitable technological solutions for SDE use cases lack standards [12], e.g., lack of end-to-end standards [15] for data exchange, use, and replication [19], technologically translating data protection regulations [33,21], data formats [59], and proving data integrity and authenticity [16].
<b>C3</b>	<b>Reluctance.</b> Despite trustworthy technical guarantees, organizations hesitate to engage in data exchange because the terminology “sharing/exchange” suggests that raw data is transferred to third parties [14]. Organizations lack incentives [59], as the benefits of data exchange rarely outweigh high opportunity costs (e.g., privacy and (sensitive) data breaches) [43].
<i>Data Processing and Publishing Challenges</i>	
<b>C4</b>	<b>Ensuring Data Privacy.</b> Data privacy requires data to be manipulated and protected (e.g., minimize data disclosure, secure data storage) [5,57] to prevent unauthorized third party to draw conclusions about individual entities [14] and following privacy regulations (e.g., General Data Protection Regulation (GDPR)) [45,33].
<b>C5</b>	<b>Ensuring Data Quality.</b> Privacy-sensitive data should be usable after anonymization. Thus, the challenge is to enable C4 while preserving data usability [57], i.e., to meet data quality requirements of data consumers [11], to incentivize data exchange.
<b>C6</b>	<b>Ensuring Computational Privacy.</b> Computational privacy refers to keeping the metadata, and semantic views of a data transaction secret [43]: who transferred data to whom, what algorithm was applied, and which dataset was accessed [14]. Thus, ensuring computational privacy is a challenge that extends C4 beyond the dataset’s content.
<b>C7</b>	<b>Interoperability.</b> Technological interoperability standardizes interactions between parties, e.g., authentication, authorization, or data exchange agreement protocols [57]. Semantic interoperability describes datasets through standardized metadata schemes stored in central metadata repositories [59] to facilitate the search of heterogeneous or non-standardized datasets or handle datasets that have been normalized differently [11].
<b>C8</b>	<b>Minimizing Computational Complexity.</b> Data processing and publishing needs scalable and affordable SDE implementations [79]. Data exchange requires low latency, computational complexity, and parallel processing to limit calculation time and memory usage [3] to make privacy-preserving alternatives affordable and usable [57].
<i>Infrastructure Challenges</i>	
<b>C9</b>	<b>Inter-Organizational Trust.</b> Parties do not share data unless they trust the other parties [29] (e.g., platform operators). Companies are more likely to trust others if they have had contact with one another before [12], apply unenforceable, and untrackable soft agreements [14], or operate in a data ecosystem with a trusted root of trust [11].
<b>C10</b>	<b>Cyber Security &amp; Trust in Infrastructure.</b> SDE must ensure <i>confidentiality</i> , <i>integrity</i> , <i>availability</i> , and <i>resilience</i> of data and the infrastructure (soft- and hardware). Specifically, the infrastructure must be transparent [33,2], data communication and storage secured, and unauthorized access prohibited [9].
<b>C11</b>	<b>Data Provenance.</b> For data exchange, data provenance is often enabled through blockchain-based technologies, logging, and monitoring transactions [57] to establish <i>accountability</i> [2], integrity, non-manipulation of data [11], and authentication processes [33,29]. Decisions include how long data is stored, what data is stored, and how privacy protection is handled [33].
<b>C12</b>	<b>Data Usage &amp; Access Control.</b> Legal and technological data control is lost after data is exchanged [79,19], i.e., there is a high risk of unauthorized copying, redistribution, or reusing data for unintended purposes [15] by unauthorized parties [16]. Liabilities and accountability must be transferred with data to revoke access rights, specify a data storage location, intervene manually, or specify purpose- and time-based access rights to data [9].
<b>C13</b>	<b>Auditability.</b> Proving the legitimacy of claims about complying with data-related guidelines [2] (e.g., proving that datasets have been anonymized by applying PETs, proving that consent and policy agreements are followed) is required for accountability.

**Table 5.** Mapping PETs and TETs to SDE Challenges (RQ2)

	Managing Jurisdictions	Missing Standards	Reluctance Ensuring Data Privacy	Ensuring Data Quality	Ensuring Computational Privacy	Interoperability	Minimizing Computational Complexity	Inter-Organizational Trust	Cyber Security & Trust in Infrastructure	Data Provenance	Data Usage & Access Control	Auditability	
Technology	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Data Communication Layer													
Encryption										✓	•	•	
Anonymous Routing						•				•			
Data Storage Layer													
Decentralized Storage					✓				•	•	✓		
Searchable Encryption				•	✓	✓	•		•	✓		✓	
Data Processing Layer													
Homomorphic Encryption				✓	✓	•			•	✓		•	
Secure Multiparty Computation				✓	✓	•			•			✓	•
Federated Learning				✓	✓	•		•	•	•		✓	
Trusted Execution Environment				✓	✓	✓				✓	•		
Differential Privacy				✓	•			✓	•				•
k-Anonymity				✓	•			•	•				•
Pseudonymization				•	✓			✓					
Verification Layer													
Distributed Ledger					•			•	✓	•	✓		•
Verifiable Credential		✓		•		•	✓	✓	✓	•	✓	•	
Zero-Knowledge Proof				✓	✓	•		•	✓	•	✓		✓
Sovereignty Layer													
Privacy-by-Design		•	•	•	•	•		•	•	•	•	•	•
Privacy Policies	•		•	•	•	•	•	•	•	•	•	✓	•
Total Count (excl. •)	1	2	2	10	11	8	2	8	10	11	5	7	5
✓ : addressed technically and theoretically													
• : addressed technically or theoretically													
* : characteristics depend on the selected technologies to fulfill the requirements													

main blank. Contrarily, DP addresses data processing and publishing challenges. Specifically, the technique ensures data privacy (C4) while maintaining data quality (C5) and providing parameter that helps balancing privacy and accuracy. However, data quality is reduced as data is perturbed, meaning that C5 is only partially maintained. Furthermore, DP does not have high computational complexity compared to other processing layer technologies and thus mitigates C8. DP can affect inter-organizational trust (C9) in the peripheral and provide the parameters used for DP to partially fulfill compliance verification (C13).

## 5 Discussion

The following section draws key findings (KF) and implications from the SDE challenges (RQ1) and the technology mapping (RQ2), outlines the study's limitations, and proposes research questions for future work.

*KF1: The final literature hits can be categorized into three thematic research streams: security and challenges of data exchange, International Data Spaces*



(IDSs), and design of sovereignty layer technologies. The most recent research stream focuses on sovereignty layer technologies, suggesting an upward trend in the research area of SDE. The first research stream more generally focuses on the security and/or challenges of data exchange (6 studies, published 2014–2021) and the IDS stream describes implementations and use cases for the IDSA’s data governance framework (5 studies, published 2018–2020), e.g., urban [19] or seaport data spaces [65]. The third research stream focuses on technologies of the sovereignty layer (e.g., privacy languages, privacy policies, consent frameworks) and contains 5 publications since 2019.

*KF2: No single PET or AET addresses all SDE challenges, suggesting that PETs or AETs must be carefully chosen, combined, further developed, or complemented with new techniques.* Choosing suitable technologies for SDE use cases is essential. For example, data provenance (C11) requires logging and surveillance to establish accountability. While trackability and traceability (e.g., logging) can support C11, auditability (C13), and inter-organizational trust (C9) [57], it impedes ensuring data privacy (C4) and ensuring computational privacy (C6) and could increase the reluctance (C3) of data exchange participants. Practitioners must therefore carefully select their primary challenge.

*KF3: A large portion of PETs and AETs address data processing and publishing challenges (C4–C8), and barely address organizational challenges (C1–C3). This suggests that the research field of SDE is still maturing and has not yet established best practices.* While data processing and publishing challenges are the core technical concepts of SDE, organizational challenges depict issues that arise in productive SDE systems. However, as best practices for data processing and publishing challenges are still in development [I2,I5], there are no productive SDE systems, rendering the organizational challenges redundant and peripheral. We deduce that research on organizational challenges will likely gain importance once data processing and publishing challenges have been thoroughly explored and state-of-the-art solutions are presented. The first indications are the growing interest in policy and enforcement research [19] (e.g., Gaia-X [6], IDSA [56]) to leverage data sharing while protecting sensitive data [I4].

*KF4: Data usage and access control (C12) is the most critical challenge for researchers and experts.* Mechanisms must inhibit the unauthorized redistribution of data, revoke access rights, and transfer liabilities with data [I5]. The fundamental technical problem is to introduce data sharing without allowing third parties to use privacy-sensitive or confidential data for non-designated purposes [I4]. Access rights, remain a major technological challenge given the fluid nature of data [19,79] and should be addressed by researchers. Thus, more attention should be given to implement C12 (e.g., FL can enable data usage and access control because data is never shared with a third party, MPC can control data usage and access control by exchanging encryption keys regularly).

*KF5: Given that the research field of SDE is still maturing (KF3), challenges that are currently rarely mentioned by researchers and practitioners, i.e., auditability (C13), managing jurisdictions (C1), and minimizing computational complexity (C8), are likely to gain importance as PETs and AETs face real*

*world barriers*. Although the relevance of C1, C8, and C13 is recognized [2,59], the challenges remain on the peripheral of PETs and AETs research. Languages to interpret jurisdictions must be refined [28,33] and the computational complexity of technologies must be managed to become established technologies [3,51]. We thus anticipate an increased need for research on C1, C8, and C13.

**Limitations** Even though a rigorous research design and process was adopted, there are several limitations to SLRs and interviews that may undermine the effectiveness of the conceptual framework. Even though we followed guidelines for the respective methodologies [63,76,77], the findings risked being incomplete, biased, or inaccurate. To minimize bias and strengthen the findings, we defined inclusion and exclusion criteria ex-ante and applied triangulation. Additionally, the sample of interviewees was low and with a varying levels of expertise. However, we employed the EIs as supporting evidence for the SLR and not as standalone findings. Furthermore, the latter limitation was addressed by sharing the questionnaire with interviewees prior to the interview for preparation. Lastly, we note that, while we applied investigator triangulation to map technologies with SDE challenges, we have not tested the usability of the mapping.

**Future Work** We encourage researchers and practitioners to use the concept matrix (Table 3) and technology mapping (Table 5) as a starting point to locate SDE challenges, identify research gaps, or choose suitable PETs or AETs for SDE use cases. For example, interoperability (C7) is only addressed by SE, VC, and PP. *What solution propositions exist to mitigate interoperability challenges of data and system architectures on a large scale?* Similarly, *how can the auditability challenge be mitigated without compromising data privacy and computational privacy goals?* Additionally, researchers can refine the SDE challenges and the technology mapping to refine the body of knowledge. Potential research questions could read: *Which PETs and AETs have the potential to mitigate or worsen SDE challenges? What are best practices to implement PETs and AETs in SDE use cases? Which PETs and/or AETs act as complements or supplements in the context of SDE?* Furthermore, PET or AET experts can revise and refine the technology mapping. Finally, practitioners can use the existing technology mapping as a starting point to implement SDE use cases, and thereby help evaluate the usability of the technology mapping in a real-world context.

## 6 Related Work

Several surveys presented an overview of PETs and AETs [1,22,67] or taxonomies with the technologies' qualities (e.g., cryptographic foundation, data handling requirements) [36,30], adoption challenges (e.g., legal, social, technical, and economic) [41,80], or PETs in different contexts (e.g., blockchain, personalization) [39,61]. However, while these surveys presented extensive research to understand and contextualize PETs, they did not focus on data exchange. Only few studies investigated PETs and AETs in the context of data exchange [51] and data flow [62]. Although the studies presented useful tables mapping PETs and AETs against characteristics (e.g., authenticity, confidentiality), the privacy-oriented mappings did not focus on supporting the application of PETs and

AETs. Similarly, a data sovereignty challenge-oriented mapping [44] only superficially presented solution approaches instead of concrete PETs and AETs.

Others focused on the application of PETs and AETs. There are handbooks describing how to design privacy-preserving software agents [8], legally implement privacy requirements [20], or how to adopt PETs (without including AETs) using a question-based flowchart [15]. Similarly, there are overviews of business use cases for which PETs can be applied [17,38,27]. In contrast, other researchers [50] outlined which PETs and AETs can address challenges of value chain use cases. However, the use case-oriented mappings did not support the implementation of PETs and AETs. More concretely, Papadopoulos et al. [60] presented a use case that implements FL to meet the privacy and trust requirements of the involved participants. They demonstrated that the challenges of SDE are addressable, but did not provide a framework to support the implementation of similar endeavors. Furthermore, there exist data ecosystem reference architectures (e.g., Gaia-X [6] or IDSA [56]) and policy frameworks [79]. Although the reference architectures have presented holistic solution propositions to SDE challenges, the data ecosystems are not yet practicable.

Overall, studies either (i) investigated the potentials of PETs and AETs without a specific focus on SDE, or (ii) addressed SDE challenges with an individual PET or AET. No study proposes a technology mapping to help practitioners and researchers identify suitable PETs and AETs when implement SDE use cases. However, this work is necessary to support researchers and practitioners in understanding and integrating the technologies in practice.

## 7 Conclusion

With this study, we structure the landscape of SDE challenges and identify suitable mitigating technologies, thereby guiding the implementation of SDE use cases and informing researchers of potential future research areas. A two-pronged approach was pursued. First, we identified 13 SDE challenges through a SLR and EIs (Table 4). Second, we proposed PETs and AETs to mitigate the identified SDE challenges using investigator triangulation, summarized in a technology mapping (Table 5). The technology mapping synthesizes previous research in an actionable way for practitioners and researchers by presenting a challenge-oriented approach that supports the identification of appropriate PETs and AETs to tackle SDE challenges – regardless of the use case. No single technology mitigates all SDE challenges, indicating that PETs and AETs can be combined, further investigated by researchers, or complemented with new solutions. In particular, we suggest focusing on access control and jointly facilitating auditability and data privacy.

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