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Towards Trusted Data Sharing and Exchange in Agro-Food Supply Chains: Design Principles for Agricultural Data Spaces

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Abstract: In the modern agricultural landscape, realizing data's full potential requires a unified infrastructure where stakeholders collaborate and share their data to gain insights and create business value. The agricultural data ecosystem (ADE) serves as a crucial socio-technical infrastructure, aggregating diverse data from various platforms and, thus, advertising sustainable agriculture and digitalization. Establishing trustworthy data sharing and exchange in agro-food value chains involves socioeconomic and technological elements addressed by the agricultural data space (ADS) and its trust principles. This paper outlines key challenges to data sharing in agro-food chains impeding ADE establishment based on the review of 27 studies in scientific literature. Challenges mainly arise from stakeholders' mistrust in the data-sharing process, inadequate data access and use policies, and unclear data ownership agreements. In the ADE context, interoperability is a particularly challenging topic for ensuring the long-term sustainability of the system. Considering these challenges and data space principles and building blocks, we propose a set of design principles for ADS design and implementation that aim to mitigate the adverse impact of these challenges and facilitate agricultural data sharing and exchange.

Keywords: data sharing and exchange; agro-food supply chain; design principles; agricultural data space; agricultural data ecosystem

Citation: Šestak, M.; Copot, D. Towards Trusted Data Sharing and Exchange in Agro-Food Supply Chains: Design Principles for Agricultural Data Spaces. *Sustainability* **2023**, *15*, 13746. https://doi.org/10.3390/su151813746

Academic Editors: Joe Bogue and Lana Repar

Received: 31 July 2023
Revised: 8 September 2023
Accepted: 13 September 2023
Published: 14 September 2023

1. Introduction

Digitalization and accelerated technological development have transformed numerous sectors in recent years, with the agricultural sector being no exception to the changes. The agricultural sector aims to achieve social and economic sustainability in agro-food value chains through the exhaustive digital transformation of the sector [1–3]. Agro-food value chains often include numerous stages (e.g., food production, harvesting and distribution, processing and retail) as well as stakeholders (e.g., farmers, food processors, public authorities, consumers) [4]. In the context of the "Farm to Fork" strategy, the life cycle of any product includes being a raw material, followed by processing, distributing, trading, and brokering to being bought by the customer and making it to the customer's table [5]. Different processes across the agro-food value chain produce data, which represent the primary resource for monitoring and data analytics activities in the value chain. Intelligent data analysis and data-driven decision making lead to additional business value being generated from "raw" source data. However, the stakeholders involved in the value chain are often potential producers as well as consumers of data, which brings additional complexity to overall data management.

Nevertheless, constant efforts are being made towards effectively and efficiently using data produced within the agricultural sector. Data are continually recognized as the key resource for various improvements and optimizations in business processes such as production, product distribution, etc. [5]. However, data sets collected by individual

agro-food value chain stakeholders are often only partial and do not reflect the state of the entire value chain. Recent initiatives are showing that the problem of increased data segmentation in the agricultural sector has been recognized. To harness the full benefits of data from agro-food systems for businesses and sustainable agriculture, it is crucial to share the data collected from different systems along the value chain, rather than keeping it fragmented [6]. In this case, data sharing and exchange will help provide a more detailed and comprehensive overview of the entire agro-food value chain and facilitate more informed decision-making practices.

As already mentioned, to unlock the potential and maximize the economic value of gathered agricultural data, it is necessary to establish an infrastructure for the trustful sharing of (potentially sensitive) data between all stakeholders while ensuring traceability as well as the data owner's privacy and sovereignty [7,8]. As a result, this would lead to the establishment of an agricultural data ecosystem (ADE) where all stakeholders could fully harvest benefits from data and contribute to the advancements of the entire sector. As it stands, data ecosystems will eventually become a standard requirement for all data-intensive systems [9,10]. However, the development of such an infrastructure is quite a challenging endeavor with regard to social, economic, technical, legal and other concerns, regardless of the sector in question. Sectors such as manufacturing and public administration are the front-runners in the maturity level of established data ecosystems [11], whereas the agricultural sector faces additional challenges due to the uneven development of rural areas.

As part of the European research landscape, several research and development projects have successfully been initiated to develop federated data ecosystems for different domains. For example, the Gaia-X project aims to develop a common data infrastructure for digital ecosystems through collaborations between companies, research institutions, public administrations, and government authorities altogether (https://www.data-infrastructure.eu/GAIAX/Navigation/EN/Home/home.html, accessed on 28 July 2023). Nevertheless, the theoretical and technical knowledge on establishing data ecosystems is still limited and in its early stages of development. Many of these projects are still ongoing, so there are still many questions and challenges regarding this topic that are yet to be resolved. On the other hand, studies have indicated that digitalization efforts within the agricultural sector focus on establishing data ecosystems for specific sub-sector activities, such as fruit or vegetable production [11]. As a result, there remains a notable research gap in establishing an ADE that covers a broader range of agricultural sector activities while guaranteeing secure and trustworthy data sharing and sovereignty via the agricultural data space (ADS). Furthermore, it is also still quite unclear how an ADS should operate or be developed [12]. Establishing such an environment would also help address the concerns that are currently impeding the adoption of the ADE.

Therefore, this study aims to raise awareness of the main inhibitors to establish an ADE, which would facilitate data sharing and exchange in agro-food value chains. To the best of our knowledge, a comprehensive review of these challenges discussed in the context of an ADE has not yet been published. Thus, we start by performing an extensive literature search of the scientific literature to identify the most significant challenges and proposed solutions to data sharing in agro-food value chains. This study focuses on (1) reviewing the challenges to agricultural data sharing and discussing the role of an ADE and ADS in addressing these challenges, and (2) proposing a set of design principles for ADS implementation with regard to the identified challenges relevant to the agricultural sector. In this way, we aim to examine the potential benefits of establishing an ADE in addressing the data-sharing challenges and contribute to reducing the limited knowledge of ADS design and implementation practices that are currently still hindering the ADE establishment and adoption.

Section 2 presents the research methodology comprising the literature review and conceptualization of design principles of ADS implementation. In Section 3, the main contributions of our paper are presented, which include an overview of the most significant

challenges and solutions for agricultural data sharing and exchange in agro-food value chains, and we provide a description of basic notions and principles behind data ecosystems and data spaces as potential novel solutions to address those challenges. Based on the identified challenges, we propose design principles for ADS implementation in Section 4 to provide guidelines that can help mitigate the impact of the identified challenges in the agricultural sector. Finally, we summarize our findings and discuss prospective future research directions in Section 5.

2. Research Methodology

Our research approach involved an extensive review of the existing scientific literature concerning data sharing within agro-food value chains in relation to the goals of an agricultural data ecosystem (ADE). To identify the most significant challenges and proposed solutions related to agricultural data sharing that might impact the establishment of an ADE, we conducted a comprehensive search across the Scopus and ScienceDirect databases. Specifically, we used the following combination of search keywords:

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(agriculture OR food) AND ("data sharing" OR "data exchange" OR
"data ecosystem") AND (challenge OR obstacle OR solution)
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We focused our search within the Computer Science and Agricultural sciences fields to increase the relevance of the retrieved studies. This process yielded a total of 185 studies (175 from Scopus and 10 from ScienceDirect), which underwent a detailed abstract screening. Ultimately, we identified 27 studies that were pertinent to our analysis. After a detailed examination of these 27 studies, we compiled a comprehensive list of challenges associated with data sharing in agro-food value chains presented in Section 3.

3. Challenges and Solutions for Data Sharing in Agro-Food Systems

In the past few decades, the topic of data sharing in agro-food value chains has been discussed in numerous studies [1,2,5,6,13–21]. According to their findings, the agricultural sector faces some specific challenges regarding a (still) low digitalization level, infrastructure readiness and digital skills of value chain actors compared to other sectors. Existing studies also highlight the importance of data provenance and challenges related to highly fragmented source systems affecting their reliability [22–24]. Furthermore, this also significantly impacts the complexity of the data collection process [13,25], which, in turn, affects data availability. Besides technological readiness, the agricultural sector also faces challenges in terms of the maturity of relevant policy frameworks and standards (legal, organizational, technical, semantic, and others) [12,26–30]. Some studies also highlight the need for interdisciplinary methods for creating value for creating value for all stakeholders due to the complex interactions often involving numerous stakeholders [31,32]. To promote active involvement from all relevant actors in agro-food value chains, there is a need to establish trust as a foundation for facilitating data sharing. The data space concept holds the potential to address certain obstacles in this regard.

This section starts with an exploration of core concepts related to data ecosystems and data spaces, highlighting their potential as contemporary solutions for streamlining data sharing within agro-food value chains. Then, we proceed with an in-depth examination of the significant challenges associated with data sharing in agro-food value chains and discuss them in the context of ADEs and ADSs as potential solutions for mitigating their negative effect on agricultural data sharing.

3.1. Proposed Infrastructures for Sharing Agricultural Data

Lately, novel concepts have emerged to supplement the array of potential solutions for addressing the challenges outlined in Section 3. Primarily, these include the concepts of data ecosystems and data spaces, which aim to provide an infrastructure for sharing data with trust.

A data ecosystem (DE) can be defined as a "socio-technical complex network in which actors interact and collaborate to find, archive, publish, consume, or reuse data as well as

to foster innovation, create value, and support new business" [33]. Looking from a broader perspective, to create added value, DEs mainly rely on the value being co-created between its actors throughout different activities such as data collection, data sharing, or service provision [32]. The multi-actor approach is particularly relevant for agro-food systems, and it is recommended to be considered when developing conceptual frameworks for ADE design [3].

Due to the current lack of methodologies for the description and maturity level assessment of DEs, van den Homberg and Susha introduced an integrated framework to characterize DEs in terms of five dimensions [23]:

- Actors and roles—describes which organizations/entities produce and provide the data (provider), or use the data (consumer) as well as who or what facilitates the data exchange (e.g., data-related functions, intermediary organization, etc.);
- Data supply—describes the format of data available, the degree of access to data (e.g., access to raw data or data processed to a certain degree, access to open data), content accuracy and quality, data source reliability, granularity level, etc.;
- Data infrastructure—describes platforms and software used to store, archive, or catalog data and the technical architecture to manage data;
- Data demand—describes the expected and desired outcome of using data;
- DE governance—describes the terms of data usage for all participants together with the description of their roles and responsibilities.

Within the DE network's social dimension, three primary actor groups interact, often assuming multiple roles simultaneously. These groups include (1) Data Providers, (2) Data Consumers, and (3) Service Providers, as illustrated in Figure 1.

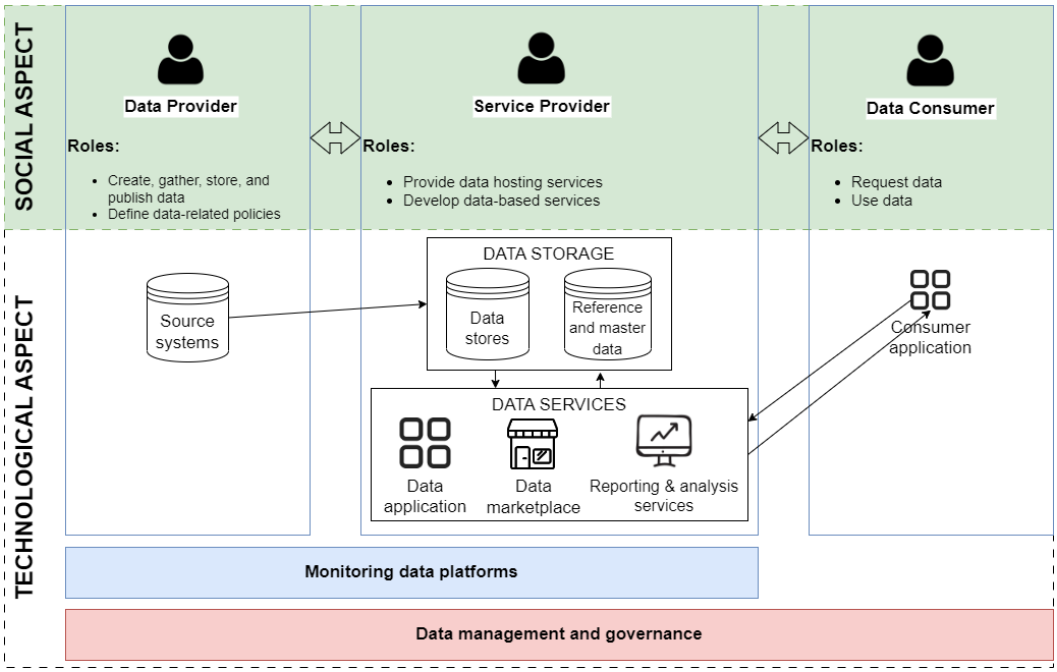

Figure 1. An overview of a DE as a socio-technical network [22,34].

Data Providers play a pivotal role by either creating or gathering data within the DE and making it accessible to others. Their responsibility extends to defining data usage policies for each data resource, specifying who can access and utilize the data and under what conditions. In agricultural DEs, Data Providers frequently comprise farmers or individuals operating equipment and sensors used to measure phenomena like crop yield, soil moisture, temperature, and rainfall [29]. On the other hand, Data Consumers are informed about data usage policies when requesting specific data resources and must comply with them when using the data for their respective purposes. In the agricultural domain, Data Consumers

can encompass a diverse array of stakeholders, ranging from farmers and agronomic associations to research institutions, government bodies, and machinery manufacturers.

Lastly, Service Providers serve as intermediaries that facilitate connections between Data Providers and Data Consumers. They offer essential data hosting services to assist Data Providers in sharing their data within the DE and create data-related services designed to extract additional value from the source data, benefiting both Data Providers and Consumers. In the agricultural sector, potential Service Providers may include research agencies, digital hubs (both privately and publicly funded), agronomic and agribusiness associations, and government agencies [29].

From a technological perspective, a DE operates as a sophisticated network of multiple IT systems that must collaborate effectively to fulfill the DE's objectives. As shown earlier, a fundamental requirement for sharing agricultural data involves establishing trust among participants, and this can be addressed through the trust infrastructure offered by data spaces.

Data spaces operate as decentralized infrastructures for secure data sharing based on widely accepted principles [35]. They promote a model where data remain stored in source systems [36] while semantic-level integration occurs, fostering trust among DE actors and enabling secure data sharing and exchange between distributed source systems. This trust infrastructure is fortified by integrating data governance and economic models, culminating in DEs where participants securely share data, reaping benefits from collaborative data usage. In the agri-food domain, building an ADS requires a holistic approach that combines legal design with infrastructural opportunities [19]. The initial solution concepts and proposals towards building an ADS reference architecture are somewhat limited and are currently only partially addressing certain aspects of trust such as data sovereignty [37].

Nagel and Lycklama offered a technical overview of the essential building blocks for constructing the data space infrastructure in [38], depicted in Figure 2. The primary approach emphasizes reusing existing solutions to minimize redundancy in the technology ecosystem. In Figure 2, the building blocks are categorized based on their roles in addressing distinct aspects of the data space infrastructure:

1. Facilitating interoperability (Data Models and Formats, Data Exchange APIs, Provenance and traceability),
2. Trust (Identity Management, Access and Usage Control, Trusted Exchange),
3. Data Value (Metadata and Discovery Protocol, Data Usage Accounting, Publication and Marketplace Services), and
4. Governance (Business, Operational and Organizational agreements).

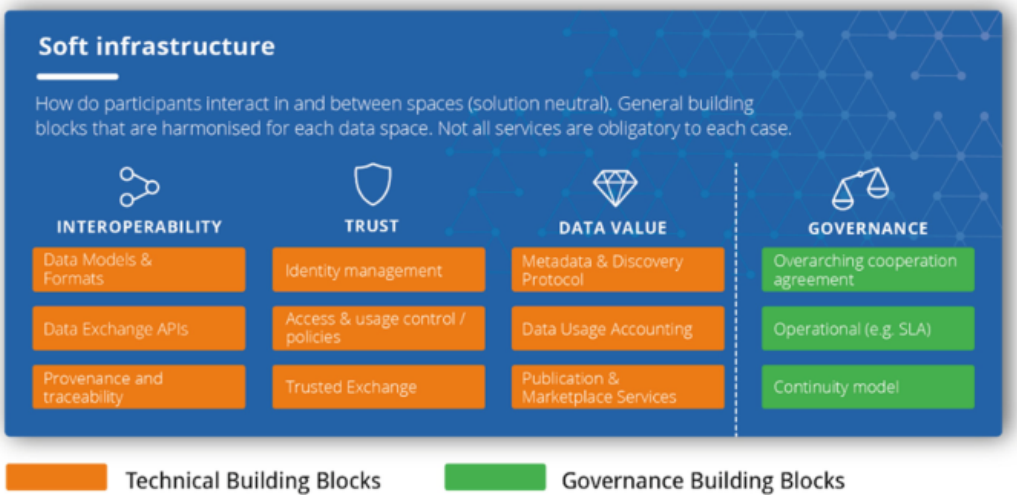

Figure 2. An overview of technical and governance building blocks for data spaces [38].

These building blocks serve as the building foundation for establishing a DE, promoting collaboration, innovation, and value creation in data-driven environments. The described IDS components follow the approach of considering existing digital ecosystems/technologies instead of starting from scratch during ADS design [4].

Once implemented, the ADS building blocks bring an additional level of trust into data sharing flows between participants, and therefore, help address data-sharing challenges in agro-food value chains discussed in the following subsections.

3.2. Establishing Trust in Agro-Food Value Chains

For most stakeholders, building trust refers to building trust in the data-sharing process between Data Providers and Data Consumers. However, according to Calvin et al. [20], the major three trust-related challenges in DE design are:

1. Fear of participants to share their (sensitive) data;
2. Developing an ecosystem that enables its participants to create value with available data without access to all data; and
3. Identifying and presenting benefits from DE participation to all actors.

In the context of agro-food value chains, participants generate and utilize specific data to document their activities at various stages of the value chain. To enable effective data sharing and exchange among value chain stakeholders, it is imperative to cultivate trust in the data-sharing process from multiple perspectives. Building such an environment entails addressing several challenges listed in Table 1.

First and foremost, establishing a well-defined legal framework serves as a foundation for ensuring the accuracy and legitimacy of all data-sharing activities. This framework should explicitly outline which resources are shared, who the responsible parties are, and the terms and conditions governing these exchanges. Within the design of the data ecosystem (DE), it becomes crucial to clearly delineate the resources (products and services generated, provided, or consumed by DE participants), roles (the functions performed by these actors within the DE), and the relationships between actors and their interactions. Moreover, it is imperative to formulate precise specifications that are universally comprehensible to all stakeholders and incorporate them into the data governance framework.

In a broader context, data governance entails the proper management and upkeep of data resources and related activities [39]. In the context of the DE, data governance extends to encompass a set of shared principles and regulations that all participants must uphold to establish a trusted data space where diverse stakeholders can access and utilize data with confidence.

Data governance in DEs and data spaces comprises the following subset of principles [39]:

- General conditions on participation and data sharing in terms of confidentiality, data monetization, data property rights, etc.;
- Conditions for the protection of data owners' rights, including the right to manage consent on data access and use;
- Compliance with the rules related to preventing unlawful access and use of data, which is highly relevant in case of private or sensitive data;
- Specific provisions to be made for certain types of data, such as data anonymization;
- Conditions and rules for sharing data with third-party services.

On the European level, several policies and acts are specified to provide the legal baseline for DE governance. For instance, the Data Governance Act (https://digital-strategy.ec.europa.eu/en/policies/data-governance-act, accessed 29 July 2023) provides a framework to enhance trust in data sharing with DEs. However, Kosior [12] argues that existing EU regulations have not entirely resolved problems related to limited trust in data sharing or data access and portability, which would facilitate data flows within and between EU Member States in different sectors. Therefore, there is a lack of a standardized framework for data governance in the agricultural sector in general. Consequently, most projects tend

to create their own legal frameworks that prioritize data security and privacy, as outlined by the Data Governance Act and General Data Protection Regulation (GDPR), while neglecting other crucial aspects of data governance. This leads to partial descriptions of the rules and conditions to participate in the DE, which manifests in other challenges, such as unclear assignments and rules of conduct for participants, unclear data sharing procedures, etc. In the absence of overall legal frameworks and standards for data sharing in a DE, DE participants are encouraged to sign data-sharing agreements (DSAs) [40] as the minimum data governance requirement. These agreements, whether applied universally or between a specific Data Provider and Data Consumer, often impose additional administrative burdens and operational costs due to their limited scope.

Addressing governance challenges is critical, as it can potentially mitigate other challenges in the DE ecosystem. Monitoring and controlling interactions related to governance rules are addressed through data spaces, using mechanisms established with the data governance building blocks proposed by IDSA. These building blocks offer the possibility of repurposing existing legal agreements with modifications tailored to relevant actors, roles, and use case-specific rules.

Trust remains a significant challenge, impacting Data Providers' willingness to share data within the DE, which, in turn, affects the quantity of relevant data shared. Building societal trust is vital for enabling novel uses of data [41]. Encouraging participation requires understanding stakeholders' concerns and incorporating their needs into ADE governance, especially for farmers and landholders, who may require confidence in data sharing, curation, licensing [5], and the benefits of joining the ADE [41]. Similarly, Data Providers must have transparency regarding data usage and the option to withdraw their data [1]. Incentives for Data Providers should elucidate the advantages of active participation, particularly for companies concerned about the impact of data sharing on their competitive advantage.

From the Data Consumer perspective, building trust involves knowing the data source, ensuring transparency in ownership and source information, verifying data timeliness and discoverability, and providing comprehensive documentation and support for data sets, enhancing the confidence of Data Consumers in the data they access [5].

Table 1. An overview of identified studies discussing trust-related challenges.

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[5]	Willingness to participate in an ADE due to trust concerns	Clear participation benefits and trust mechanisms
[41]	Building trust between participants	Understand participants' doubts related to trust, clear participation benefits
[42]	Lack of relevant policy frameworks and long-term visions and projects for food systems	Better exploitation of new technologies and definition of sustainable projects
[43]	Transparent and trustworthy exchange of information in beef supply chains	Multi-signature approach based on blockchain
[44]	Unreliable data transfer due to possible security attacks	Strict routing authentication policies, mechanisms enforcing data integrity and confidentiality
[24]	Protection of users' information	Decentralized blockchain-based system architecture for data integration
[20]	Participants' fear to expose sensitive data, understanding benefits from ecosystem participation	Clearly defining actors, roles, resources and relationships in ADE

Table 1. *Cont.*

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[40]	Resistance from small and medium farms due to data sharing concerns and access control policies of the parties' data	Data-sharing agreements among various actors, role-based access control based on AI
[1]	Farmers' concern of what happens with their data and their willingness to share their data	Development of clear trust mechanisms and enabling farmers to withdraw from the system
[45]	Data exchange between smart devices and other services over public channels prone to security attacks	Ongoing development of (elliptic curve) cryptography-based schemes
[46]	Data privacy and security	-
[47]	Limited access to risk management tools for farmers in developing economies, centralized agricultural IT systems lack trust factors in sharing risk data	Self-sovereign identity approach with decentralized access control for smart contracts in agricultural insurance

In the context of building trust within agro-food value chains, two crucial elements are transparency and data provenance. These aspects demand careful attention when formulating agreements as part of DE governance, especially concerning data access and sharing rules and policies. A recommended approach is to define these rules through open public consultation to ensure comprehensive transparency and credibility in the shared data within agricultural data ecosystems (ADEs).

Complete transparency and trust in the quality and credibility of data shared in ADEs necessitate the meticulous tracing of each data set throughout its entire history within the ecosystem, from its initial entry to subsequent derivative uses [5]. This holds particular significance in the agricultural sector, which features various EU and national initiatives emphasizing supply chain transparency, such as the "farm-to-fork" campaign. Within DEs, data provenance entails thorough documentation of every stage a data set undergoes, from its source system to its ultimate consumption by Data Consumers. Such transparency greatly enhances trust in data sources and addresses concerns regarding the origins of data. This is especially crucial for open data, which are often met with skepticism when source information and entry into the ADE are unclear. Recently, several blockchain-based initiatives have emerged to tackle this challenge, employing blockchain technology to establish collaborative ecosystems with comprehensive supply chain governance, implement advanced authentication models, and deploy decentralized access control mechanisms to ensure trust in the sharing of sensitive data [7,24,43,47].

3.3. Data Ownership and Sovereignty

Modern food IT systems are complex and must often be tailored to meet the needs of a single user or group of users before data can be shared externally [48]. On the other hand, data within DEs are shared digitally, possessing public good properties [29] that allow others to access it according to a specific data economy model. However, some Data Owners may hesitate to share their data in this way due to concerns that competitors could use it against them. They often have difficulties understanding the added value in sharing their data, and their motivation is led by the benefits they receive from such effort, as expected. On the other hand, even though relevant control policies for sharing agricultural data, such as the EU Code of Conduct for Agricultural Data Sharing are sometimes put into practice, the users rarely trust or fully comprehend what they entail and their rights in sharing data. The practical agreements and contracts that need to be signed bring a level of legal obligations that might discourage stakeholders from participating in the data-sharing endeavor. Conversely, Data Owners and Data Providers often have concerns about unknown users potentially using their data to gain a competitive advantage

or using them against them [49]. They may also worry about other stakeholders taking credit and generating monetizable data from their data, leaving them with no benefits [5].

The potential value of public data in DEs is significant, but the willingness of Data Providers to share open-accessible data hinges on factors such as trust, data privacy, and transparency that build upon data ownership-related challenges listed in Table 2. Determining to what extent agricultural data should be treated as a trade secret protected by relevant licensing mechanisms is a critical consideration [50]. In the agro-food value chain, this decision often rests with Data Owners, who individually assess whether specific data sets should remain undisclosed due to the potential for unwanted exploitation for commercial or other purposes. This is particularly relevant for data related to Data Owners' proprietary "know-how" (data processing through algorithms or custom software), which are frequently regarded as trade secrets, and as such, is not made available to others. Consequently, data can be categorized as closed, shared, or open. Closed data are highly exclusive and often subject to trade secret protection, as they are not intended for sharing. Access to shared data is governed by contractual agreements, but this can result in increased operational costs due to the complexity of enforcing such agreements. While this direction may not entirely align with the data sharing objectives of an ADE, some Data Owners may prefer it because it affords them greater control over their data's use. On the other hand, open data form the bedrock of enhanced global decision making and transparency. Initiatives like the Open Ag Data Alliance (https://openag.io/, accessed on 28 July 2023) advocate for an open approach to data ownership and licensing, defining principles for data ownership that explicitly delineate rights and conditions governing data use. However, this approach raises questions about the appropriate licensing for data sets. A third option involves treating data as a hybrid between public and private goods, with Data Owners and specific Data Consumers establishing special data usage agreements to benefit both parties. Incentives, such as fair business models that facilitate value creation through various mechanisms (e.g., compensation), can encourage Data Owners to share their data. Ultimately, all ADE participants must be well-informed about the potential benefits and risks of data sharing, supported by well-defined contractual agreements to mitigate potential additional operational costs associated with licensing and establish clear data ownership mechanisms.

Farmers, in particular, require mechanisms that grant them data sovereignty [51], often involving local data management on farmers' premises to enhance their trust in the system. This challenge can be addressed through the blockchain-based self-sovereign identity (SSI) approach, which provides the means for decentralized data sharing to enhance data protection [52].

Table 2. An overview of identified studies discussing data ownership-related challenges.

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[48]	Insufficient farmers' understanding of access control policies and frameworks, the administrative burden of signing data sharing agreements, fear from data abuse and competitive advantage	-
[50]	Data sets handled as trade secrets for data protection	Open data-sharing system, suitable business models for fair data usage compensation, relevant contractual agreements
[51]	Ensuring data sovereignty to farmers	Local data processing and storage, transparent and easy-to-use controls for data disclosure

Table 2. *Cont.*

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[1]	Lack of a common understanding of data sovereignty, complex policy enforcement due to the sector's diversity	Development of regulatory frameworks for handling data and ensuring sustainability, new data sovereignty models for a fair value distribution
[20]	Varying degrees of intellectual property and privacy needs to be protected	Digital technologies with incorporated strict data security protocols
[49]	Willingness to share data due to fears of data abuse, liability or confidentiality and privacy of data	Innovative strategies to protect privacy and legal protection against data abuse
[52]	High protectiveness of data by Data Owners to prevent leading others to a competitive advantage	Technical solution based on federated learning that uses decentralized data to facilitate data sharing
[46]	Data ownership issues	-

3.4. Interoperability and Sustainability Challenges

In the realm of agro-food value chain analyses, gaining insights into the effects of various factors requires the synthesis of diverse data types, including management practices, food loss statistics, crop attributes, and socioeconomic details. Nonetheless, the integration of data from distinct value chain stages—ranging from pre-harvest to distribution—presents various challenges listed in Table 3 due to inconsistent data collection and description practices. These inconsistencies impede data comparison, analysis, interpretation, and the utilization of data in models and decision-support tools. To prevent an ADE from becoming merely another data integration solution, it is imperative to acknowledge the complexity of sustainably integrating data from multiple source systems through the facilitation of data discovery and description. Consequently, prioritizing interoperability becomes crucial in ADE development, which can be achieved at various levels, namely technical, semantic, and operational interoperability. Semantic interoperability, in particular, has been given significant attention, as it is fundamental for establishing a unified DE for the entire agricultural sector and enabling cross-sector interoperability. As outlined in [4,5], the key to fostering semantic interoperability in DEs lies in the utilization of shared metadata, which serves as the bridge between each data set within the ecosystem and existing reference models specific to the agricultural domain.

Standardized metadata for the agricultural sector can be made accessible as a reference ontology [26] to all interested parties, who can customize it to suit their specific requirements. This approach provides a more stable foundation for future data synthesis. Generally, such metadata ontologies encompass descriptions of data sources in terms of their inherent meanings and domain definitions [53]. In the long term, they establish a framework for harmonizing definitions of concepts across diverse data sets, thereby facilitating the integration of data from various sources throughout agro-food value chains. At present, the most advanced solution addressing interoperability challenges in agricultural data sharing has emerged from the DEMETER project [17], which introduced an overarching agricultural information model (AIM) and a reference architecture. These innovations offer a common basis for achieving interoperability objectives in agro-food value chains.

Table 3. An overview of identified studies discussing interoperability-related challenges.

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[26]	Semantic interoperability in agricultural data management	Semantics-based architecture and ontologies for agricultural data
[5,41]	Achieving interoperability between source systems	Developing a shared metadata repository and mechanism
[53]	Semantic interoperability between data sources	Data platform with a metadata ontology describing the contents of data sources and a common semantic model
[54]	Maintaining sustainable data aligned with Findability, Accessibility, Interoperability, Reuse (FAIR) principles in a global DE	A network of interoperable data and metadata resources to provide innovative solutions
[55]	Variety of input sources, the feasibility of building custom software to support decision making for small farms	-
[21]	Data and knowledge integration within agricultural landscapes	Syntax, semantic, organizational interoperability model based on a community-shared and reusable data reference model
[1]	Adaptation requirements of farmers, increased dependence on technology-providing (non-agricultural) companies	Extensive training of all actors across the value chain, diversity of data sources complicates data collection, storage, and processing
[20]	Interoperability of collected data, data models utilized, extensibility	Mapping source data to standardized ontologies and data models
[17]	Interoperability issues, identification of most suitable data sources and information models to be used	DEMETER information model built by reusing existing ontologies and models, a general reference architecture that integrates heterogeneous data sources
[46]	Interoperability issues make it costly and time-consuming to access and use agricultural data	-

However, practical experiences have shown that achieving semantic interoperability remains a challenging task. Due to the underdevelopment of the agricultural sector, existing projects had to create their own data-related standards, resulting in a plethora of project-specific information models. While it may seem intuitive for new projects to follow these established models to achieve semantic interoperability, the mapping between concepts, entities, and schemas can be quite demanding, and it may be challenging to identify a model that entirely fits the project's requirements. As a result, most projects opt to develop their own schemas, which further adds to the diversity of non-compatible schemas and metamodels. Consequently, instead of striving to achieve data interoperability among different projects within the agricultural sector, new schemas and metamodels only increase the variety of non-interoperable schemas, which hinders the usability of data at a global level. In the last few years, the need for the so-called "practical standardization" [41] has been advocated by practitioners and experts in the field, where a set of pre-defined building blocks would be specified based on the consensus of a wider community, thus accelerating data interoperability between different DEs. This approach is also followed by the IDSA, which presented a list of 12 sector-agnostic building blocks, with three of them focusing on data interoperability in terms of common data models, data exchange APIs, and traceability. Furthermore, the IDS data space reference architecture model [56]

also includes Vocabulary Hub, a data space infrastructure component dedicated to data discovery and metadata management.

3.5. Data Integration and Availability

In the context of collecting and integrating data from various source systems within agro-food value chains, harnessing new technological advancements is imperative to tackle the inherent complexity of this process [42]. Tracking the source of information within the ADE assumes significant importance as it significantly contributes to fostering trust in the quality of data supplied by Data Providers [5]. Data quality emerges as a critical factor in generating value within the ADE and plays a pivotal role in determining the reliability of extracted information. Ensuring high-quality data requires substantial investment from Data Providers in optimizing the data collection process over the long term, especially since a significant portion of agricultural data originates from farmers [41]. This entails the development of appropriate methods and tools for data collection, aimed at reducing inconsistencies in data entries and ensuring comprehensive documentation of each data set. However, our interactions with agro-food value chain participants have unveiled a notable reliance on manual data production and gathering processes, particularly prevalent among farmers. This heavy dependence on manual techniques adds burdens and costs to farmers, ultimately diminishing their enthusiasm to engage with the ADE. Furthermore, implementing an ADE entails considerable effort in accurately describing source data sets and transforming them into standardized models and formats, thereby enhancing the overall quality of agricultural data.

The data integration process presents its own set of challenges and potential pitfalls listed in Table 4 that could adversely affect the quality of data sets within the ADE if left unaddressed. A significant obstacle in this process pertains to non-standardized data formats, coupled with the storage and processing capacity required to derive meaningful insights from these data. Each source system on the Data Provider's side generates data in diverse formats and schemas, necessitating varying approaches to handle different data types (e.g., CSV files require different treatment than sensor data or satellite images). Moreover, data sets in the ADE originate from different sources (Data Providers), leading to incompatibilities related to data format, size, or the frequency of collection/generation [5]. Consequently, data integration solutions must be thoughtfully designed with interoperability, scalability, real-time data processing, end-to-end security and privacy, and standardized policy enforcement in mind [57]. Their operation also warrants vigilant monitoring using reliable tools and technologies to ensure accuracy at all times [58].

Another pressing challenge regarding data pertains to its availability, given that data serve as the fundamental resource within DEs. Unless the necessary input data are readily accessible, the potential for extracting valuable information for other DE participants remains constrained. Factors such as data volume and the frequency of data collection contribute to increased costs and complexity for Data Providers involved in the data collection process. Hence, data availability assumes paramount importance, particularly in the agricultural sector. As mentioned earlier, the agricultural sector lags behind in digitalization compared to other industries, resulting in many potential input data sets for ADEs still being prepared manually by farmers. This manual process is time-consuming and significantly impacts the efficiency of the DE, as limited value can be generated when data is scarce or dispersed across numerous "local" IT systems without clear information on its location. However, addressing the challenge of data availability can be substantially mitigated if national or local governments recognize the potential of data for ADEs and increase their investments in the digitalization of rural areas.

Table 4. An overview of identified studies discussing data integration-related challenges.

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[5]	Source data availability and quality, data integration of dispersed data	Metadata, data integrity mechanisms
[41]	Additional costs for Data Providers during data collection	-
[59]	Data integration in Farm Management Information Systems	Publish–subscribe-based system architecture for handling different data sources
[25]	Availability of technical components for data integration	
[20]	Data processing costs inflicted by data cleaning and analysis tools	-
[57]	Large diversity of agricultural data formats and meaning, lack of standardized practices for data and system integration	Platform design that considers seamless integration, processing, and use of farm data
[58]	Lack of extensive validation of developed technologies can comprise their reliability and accuracy in production settings	Suitable monitoring tools for smart agro-systems

3.6. Digital Infrastructure Availability and Access

The agricultural sector, being the least digitized economic sector, confronts a multitude of unique challenges when it comes to establishing an ADE [12]. These challenges encompass obstacles such as inadequate IT network infrastructure in rural areas, limited financial investments in digital transformation by stakeholders, insufficient digital skills among farmers, the involvement of numerous stakeholders within agro-food value chains, fragmented farming systems, and a high prevalence of manually generated data, among others listed in Table 5.

Effectively empowering small-scale farmers to make informed decisions necessitates the resolution of key challenges associated with digital technology utilization. Essential solutions include the development of user-friendly point-and-click interfaces, enabling farmers to easily select and customize tools on their desktops, potentially supported by cloud-based storage and processing [55]. Furthermore, the creation of a cohesive graphical user interface is imperative for presenting tailored, interconnected views of information, shifting away from isolated windows of unrelated data streams. These initiatives are pivotal in overcoming the unique hurdles posed by the agricultural sector's digital transformation journey.

Table 5. An overview of identified studies discussing digital infrastructure-related challenges.

Ref.	Challenge(s) Addressed	Proposed Solution(s)
[44]	Lack of efficient networking communication in rural areas, high cost of IoT devices.	Development of a network monitoring system, increased capital investments in agriculture
[55]	Difficult understanding of software and technical concepts for farmers	Graphical tools for farmers to ease the navigation when using tools
[1]	Unequal financial opportunities for investing in digital technologies, unequal access to broadband connections	-

4. Design Principles for ADS Implementation

As already mentioned, the primary goal of an ADE is to enable a secure and reliable exchange of agricultural data among stakeholders. Within this context, an ADS serves as a framework or platform designed to establish and uphold trust within an ADE, effectively resolving the data-sharing and exchange issues outlined in Section 3. At the moment, there are numerous uncertainties regarding the essential considerations for implementing an ADS and the specific design principles that should be adhered to in implementing an infrastructure capable of effectively addressing data-sharing challenges.

To establish trust within data spaces, several fundamental design pillars need to be addressed to establish trust and secure data sharing in complex ecosystems, encompassing challenges related to Data, Governance, People, Organizations, and Technology, as illustrated in Figure 3. Nevertheless, upon performing extensive research on data-sharing challenges within agro-food value chains, it becomes evident that not all these principles hold equal relevance across different sectors. For instance, data availability is already effectively managed in the manufacturing sector, where data are automatically collected from machines, unlike the agricultural sector. This discrepancy stems from the unique and diverse challenges inherent to each sector. The agricultural sector, characterized by its lower level of digitalization and predominant manual data collection from farmers, presents particularly distinctive challenges. In light of these observations, we introduce a set of design principles tailored to the specific challenges of agricultural data sharing, identified through our analysis. These design principles aim to address each group of challenges and lay the groundwork for a comprehensive trust framework suitable for the context of an ADE.

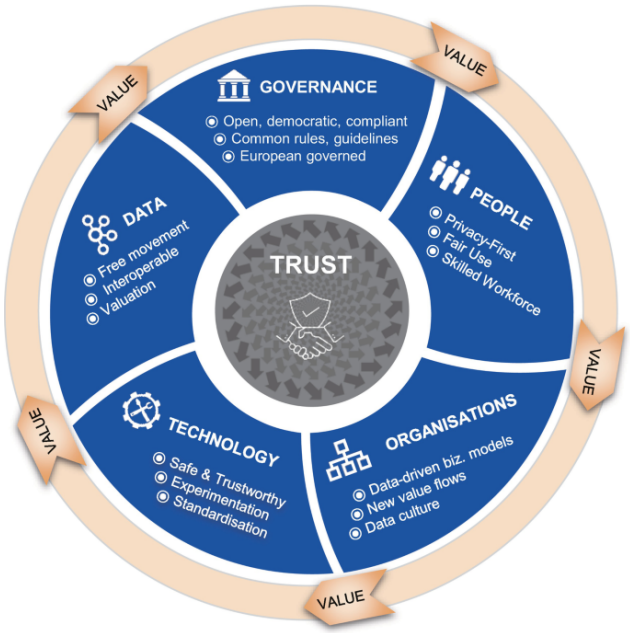

Figure 3. The data-sharing wheel representing core pillars of data spaces [10].

In our proposal, the design principles are divided into four pillars (Data, Governance, Technology, and Participants), as depicted in Figure 4. As the basic asset of ADS, the "Data" pillar includes principles related to ensuring the adequate quality, semantic interoperability and availability of enough data for the ADS. In terms of trust, the design principles under this pillar imply developing mechanisms for data provenance and transparency for each data set offered in the ADS. An important design principle under this pillar is also the data generation and collection, which has been repeatedly mentioned as a significant challenge in the agricultural sector due to the sector's low digitalization level and (still) a large portion of those processes being done manually. In this regard, data and metadata curation are also important design principles to follow, as manually prepared data by Data Owners

might potentially include erroneous data and, therefore, negatively impact the data quality. Data integration is closely related to principles listed under the "Technology" pillar, which focuses on establishing a common and secure infrastructure, standards, and technical components to achieve interoperability within ADS (between source systems and infrastructure components). On a more organizational level, the "Governance" and "Participants" pillars address the socioeconomic aspect of ADEs, which is a far more challenging task with many unknowns at the moment. The trust framework provided by the ADS heavily relies on the data governance framework that defines the principles and agreements on data sharing between ADS participants. The design principles listed under this pillar need to establish clear conditions and data ownership definitions for all participants in the data exchange process, i.e., all data value chain participants (from Data Owners to Data Users). Also, suitable mechanisms are needed to ensure the data sovereignty of all participants.

Figure 4. Design principles for ADS implementation divided into four pillars.

As the final pillar of trust, we merged the People and Organizations pillar depicted in Figure 3 into a single "Participants" pillar. This decision stems from the similarity of design principles referring to people and organizations taking part in the ADS. Namely, a significant challenge but also a pre-condition to ADS success is to develop sustainable mechanisms for incentivizing agro-food value chain participants to become members of the ADS. The ADS design should clearly describe the supported business models that allow its participants to achieve their objectives and gain additional value either through altruistic or value-oriented activities. Moreover, this task becomes ever more important in the agricultural sector, where most data are created by farmers and other individuals, and the lack of an appropriate infrastructure or resources to prepare data for use in ADS implies that they need to invest additional efforts in data preparation with (often) no obvious benefit. Hence, when designing an ADS, we must consider this fact and employ various measures and mechanisms, such as rewards, transparency of activities and similar, to motivate people and organizations to become participants in the ADS and help achieve its objectives.

Trust can also be addressed by the "Participants" pillar, where we want to focus on developing clear and suitable data ownership strategies that meet the needs of data providers as well as mechanisms for their enforcement. Participation incentives and customized business models not only build participants' trust in data sharing, but also increase

their willingness to actively participate in the process, thus resolving the insufficient data availability challenge.

Once we have established trust and familiarized participants with the benefits of sharing their data, we must employ design principles from the "Data" pillar, which will ensure the high quality and usability of data. As already mentioned, IDSA and other projects already provide some technical building blocks and metamodels for seamless data integration to ultimately achieve interoperability. This is a prerequisite for extracting valuable insights from data sets available in the ADE and increasing the participant's satisfaction with the overall infrastructure.

Finally, we also propose a few design principles aimed at addressing the limited availability of a proper digital infrastructure, which is especially relevant for the agricultural sector. Even though this group of challenges heavily relies on national digitalization strategies, we propose to employ design principles from the *Technology* pillar to facilitate this process and reuse existing standardized technical components and solutions to achieve the desired results with minimal investments.

To summarize, we provide an overview of our contributions in Figure 5, illustrating how we align the identified data-sharing challenges with design principles in ADS, which can help reduce or remove their negative impact on data sharing in agro-food value chains. Our four proposed pillars can address one or multiple groups of challenges at once. For instance, trust between participants can be established by employing all four design principles to some extent. In this context, the design principles from the "Governance" pillar address this challenge by reducing the unknowns for participants. The data governance framework must be established as a single source of truth for any questions or doubts regarding participants' roles, assets, data access and protection mechanisms, etc.

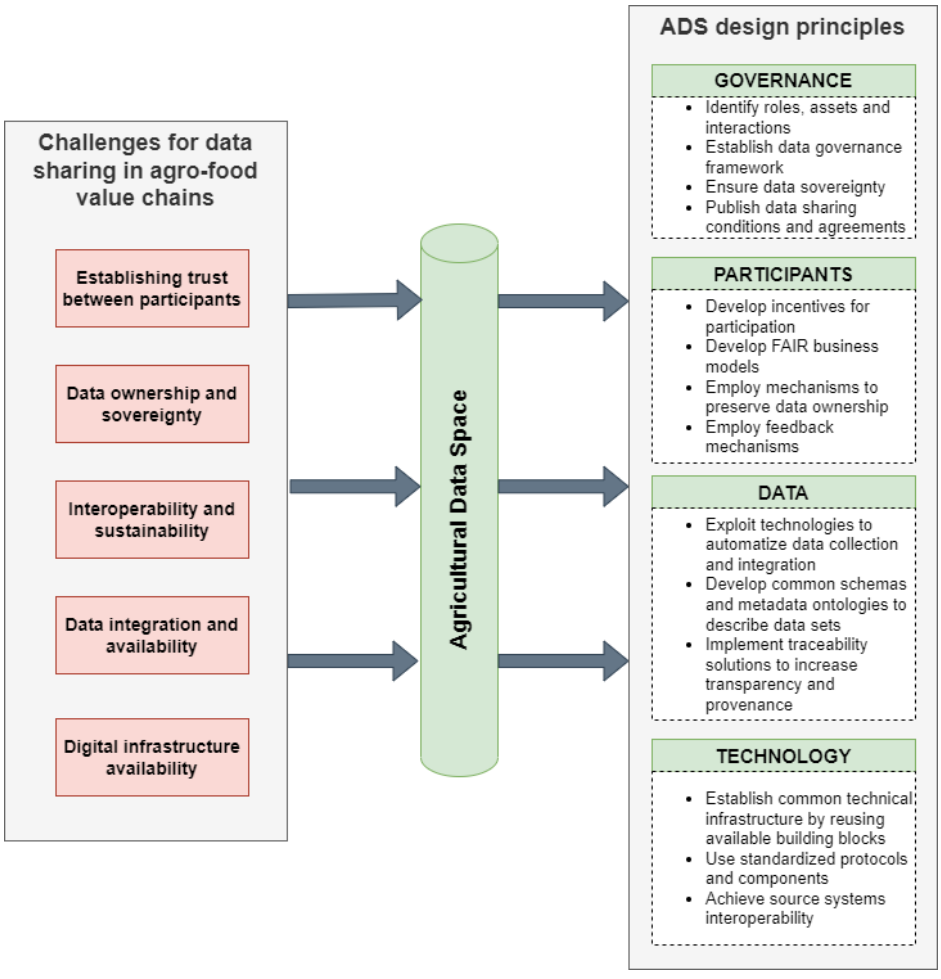

Figure 5. Summary of data-sharing challenges and ADS design principles to address them.

5. Conclusions

This study investigates the importance of ADE and ADS infrastructures in facilitating agricultural data sharing and exchange while maintaining data sovereignty and privacy. By leveraging collected data, an ADE has the potential to transform the agricultural sector and provide valuable insights to improve various areas such as smart farming, food loss prevention, and food production optimization. However, establishing an ADE is complex and still in its early stages. It requires addressing different social and technical challenges to ensure active participation from stakeholders and prevent creating yet another data integration solution with the limited value generated from scarce data. Our findings based on our research methodology reveal that (1) challenges and barriers to data sharing in agro-food value chains can be classified into five groups (establishing trust between stakeholders, data ownership and sovereignty, interoperability and sustainability, data integration and availability, and the availability of digital infrastructure); (2) an ADS represents a crucial cornerstone for building a trust framework within an ADE, which provides means to ensure secure data exchange, interoperability and reusability of data models and components, comprehensive data governance and usage policy enforcement mechanisms; and (3) a more specific set of design principles tailored to the agricultural sector is needed to implement such an infrastructure.

Specifically, our extensive literature review of data-sharing challenges revealed difficulties in establishing trust among stakeholders in the data-sharing process, adequacy of data ownership and sovereignty mechanisms, achieving interoperability (most often, semantic), the complexity of data integration and data availability, and the general availability of the required digital infrastructure. The primary concern of farmers and agro-food businesses (i.e., Data Owners and Providers) is unclear data ownership and usage rights, which could prevent potential data abuse and unallowed data monetization to gain a competitive advantage in the market. Furthermore, insufficient trust in the data-sharing and exchange process is a strong inhibitor for Data Providers to become part of the ADE, which also affects the availability of useful data that could be used for advancing the value chain. On a technological level, sharing and exchanging agricultural data relies on the interaction between diverse source systems with different data formats and models. Hence, achieving interoperability between these systems whilst maintaining data quality for accurate decision making is an important prerequisite for the success of the entire ADE initiative. Our design principles for ADS implementation proposed in this study represent our initial contribution toward addressing data-sharing challenges in agro-food value chains. We aim to ease the ADS design process by providing design principles that consider different aspects of the trust framework—data, technology, governance, people and organizations (i.e., participants). As part of our future work, we plan to dive deeper into the data governance challenges and develop an ADS data governance framework to be evaluated in the Slovenian agro-food value chain.

Author Contributions: Conceptualization, M.Š. and D.C.; methodology, M.Š.; validation, M.Š. and D.C.; writing—original draft preparation, M.Š.; writing—review and editing, M.Š. and D.C.; project administration, M.Š. and D.C.; funding acquisition, M.Š. and D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Slovenian Research Agency (research core funding No. P2-0057), and also in part by European Union funding for Research and Innovation—Horizon H2020 Projects ZeroW (Grant No. 1001036388) and Data4Food2030 (Grant No. 101059473).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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