EMPOWERING SMALLHOLDER FARMERS IN DATA-DRIVEN AGRICULTURE THROUGH BLOCKCHAIN TECHNOLOGY

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Over the past few decades, the integration of various forms of information and communication technology into agricultural practice has led to the emergence of new agricultural production modalities, characterized by increased agricultural output – a phenomenon commonly referred to as "data-driven agriculture." The existing literature acknowledges both the potential for data-driven agriculture to improve the livelihoods of smallholder farmers and the necessity for this new mode of agricultural production to incorporate elements of relatively new digital technologies, including machine learning, the Internet of Things, and blockchain technology. Although the blockchain has been identified as a key enabler for data-driven agriculture, the impact of integrating blockchain technology into data-driven agriculture applications on the livelihoods of smallholder farmers remains unresolved. This study aims to address this issue by examining how functionalities enabled by blockchain technology, such as the ability to immutably and reliably store information and blockchain's ability to reconfigure networks of actors, can be leveraged to improve the livelihoods of smallholder farmers. This may be achieved by either furthering product traceability along the supply chain, reducing transaction costs, or enabling data-driven yield optimization. To this end, three case studies of commercially active blockchain-enabled applications are analyzed. The study demonstrates that all three case studies have the potential to significantly reduce transaction costs. However, the degree to which supply chain traceability can be enhanced is heavily dependent on whether a given application is able to capture the totality of a given agricultural supply chain. None of the analyzed case studies provide insight into the means of enabling data-driven yield optimization practices for smallholders, as the examined systems do not collect relevant information to enable data-driven yield optimization. It is recommended that future research be directed towards the solution of this particular issue, as well as the implementation of a more granular approach to define the different functionalities enabled by blockchain technology to better understand its role in this context.

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AI	–	Artificial intelligence
dApps	–	Decentralized applications
IoT	–	Internet of Things
ICT	–	Information and communication technology
SCF	–	Supply chain finance
SLF	–	Sustainable livelihoods framework

1. Introduction

Over the last decades, the advent of new data processing and collection techniques has allowed for the successive improvement of value generation in different economic sectors such as finance, manufacturing, transportation, etc. Agriculture has not been excluded from these developments, and given the consequences of climate change, the role of data in the agricultural sector is expected to become ever more important over time (Rozenstein et al., 2024). Proponents of data-driven agriculture argue that data collection and processing would help farmers, governments, private corporations, and NGOs representing various interest groups to address issues ranging from reduced crop yield, climate change adaptation, prevention and treatment of plagues, to food security (Mehrabi et al., 2021). Generally, information about the physical conditions on the fields, the behavioral patterns of farmers, climatic conditions or soil degradation can be collected, operationalized, and processed, to generate insights for other stakeholders enabling them to develop new products, reallocate resources, enhance distribution channels of existing agricultural products, or even plan for policy intervention, which, in turn, allows for the optimization of agricultural production. Accordingly, the implementation of data-driven agriculture depends on the creation of a data ecosystem guaranteeing that relevant data is collected, generally on-site, and then transferred for processing to non-farmer stakeholders.

Furthermore, the last decade has also witnessed the advent of blockchain technology and its evolution from a mere peer-to-peer transaction network to a decentralized platform allowing for the development of decentralized applications (dApps) (Wu, 2019) and the collection of real-world data (Al-Breiki et al., 2020). More specifically, the advent of smart contracts, self-executing contracts with the terms of an agreement directly written into code, has allowed for an automatized manner to govern possible interactions between participants who do not know or trust each other in a decentralized network without having to rely on a centralized third party (Varfolomeev et al., 2021), and so-called oracles, services that provide external data to smart contracts enabling them to interact and operationalize information outside the blockchain, allow for the collection of real-world information and its storage on the blockchain. These technological developments have been praised for generating efficiency gains in sectors where recordkeeping must be tamper-proof and accessible such as in sustainable supply chain management (Saberi et al., 2019) and can effectively be leveraged to govern data collection, access to the collected data, and enable Internet of Things (IoT) interactions within a data ecosystem (Atlam et al., 2020). The literature shows that crop yields can benefit from blockchain-based systems by automating data collection through the use of IoT sensors and devices and making the collected data immutable and accessible to the relevant stakeholders to improve farming practices (Rehman et al., 2023). Consequently, it can be assumed that blockchain technology will be yet another important element together with artificial intelligence (AI) and IoT in the data architecture of sustainable farming.

Even though the value generated by implementing data-driven agriculture represents a Pareto improvement, as it improves the economic situation of some stakeholders without deterring the economic situation of others, the fairness aspects of data-driven agriculture have been subject to heavy criticism (Ferris & Rahman, 2017). The issue is that a substantial share of the food produced globally is grown by smallholder farmers (Ricciardi et al., 2018) i.e., farmers with plots of land smaller than two hectares. Smallholder farmers are generally poor, mostly located in the Global South, lack access to basic infrastructure, and most importantly, lack the necessary knowledge as to how the data they generate can be leveraged for data-driven agriculture, thus resulting in epistemic power differences between smallholder farmers and other value chain stakeholders, effectively putting them at a disadvantaged bargaining position (Leta et al., 2018). This poses a problem insofar as smallholder farmers are critical in their role as data generators for enabling data-driven agriculture but barely profit from the transition towards data-driven agriculture (Thatcher et al., 2016). Accordingly, the added value resulting from transitioning towards data-driven agricultural practices is captured by other actors along the value chain leaving little to the smallholder farmer. While the implementation of blockchain has been proven both to enhance crop yield and unleash the benefits of data-driven agriculture on an aggregate level and to present an alternative for fairer data markets (Khapre et al., 2021), little attention has been granted to how this technology can be deployed to improve the livelihoods of smallholder farmers in the context of data-driven agriculture. Thus, the central research question of this study arises:

RQ: How can blockchain technology be leveraged to improve the smallholder farmers' livelihoods in the context of data-driven agriculture?

By answering the research question, this study aims to provide an exploratory analysis as to how blockchain technology can be potentially deployed in the context of data-driven agriculture to guarantee that smallholder farmers benefit from the transition towards data-driven agriculture. Given the scope and nature of this analysis, the main objective is to provide exploratory advice to practitioners as to what structural aspects ought to be considered when integrating elements of blockchain technology into solutions for data-driven agriculture, so these would improve the livelihoods of smallholders. This study assumes that the efficiency gains generated by the implementation of data-driven agriculture alongside increasing demand for sustainable production will ultimately lead to more use of blockchain-based elements in the context of smallholder agriculture. Accordingly, it is expected that professionals aiming at developing data-driven sustainable agriculture projects in the future, could potentially benefit from the insights of this study.

It is important to note that the scope of this study is restricted to analyzing how the implementation of blockchain designs in sustainable data-driven agriculture could ultimately improve the livelihoods of smallholder farmers both in terms of technology and other domains, and not to exploring which external conditions are conducive to the implementation of such designs. This will ultimately limit the applicability of the insights produced throughout this study to settings, where external conditions i.e., structural issues, such as internet connectivity rates in rural areas or established socio-cultural practices conducive to the adoption of technological innovation, can be reasonably be assumed to be conducive to the integration of blockchain technology to data-driven agricultural practice.

Given the novelty of real-world blockchain applications, especially in agriculture, addressing the research question will contribute to the literature insofar as it would provide practitioners with design considerations that would allow them to facilitate data-driven agriculture in a manner improving the livelihoods of smallholder farmers. This is relevant because blockchain designs have beneficial attributes such as immutability, data consistency, and potential for the automatization of data collection (Liao et al., 2021), that together with other technologies will be fundamental to enable a data economy around agricultural practice (Kamble et al., 2020), and address sustainability issues (Rozenstein et al., 2024). The relevance of answering the research question derives from the fact, that smallholder farmers are the most vulnerable stakeholders in global agricultural value chains, and that the improvement of their living conditions in the Global South is considered one of the most pressing issues to be addressed when striving for sustainable development (Cohn et al., 2017). In theory, the initial exploratory analysis resulting from the research question could potentially pave the way for practitioners to develop blockchain-based solutions for sustainable data-driven agriculture that account for the most vulnerable stakeholders in global agricultural supply chains. Therefore, this research will highlight the importance of studying the development of blockchain-based solutions for data-driven agriculture while considering the perspective of smallholder farmers.

2. Data-driven agriculture, blockchain technology and smallholder farmers

2.1. Smallholder farmers and their livelihoods

In general, smallholder farmers, are any type of farmers relying on relatively small plots land (less than two hectares) for their subsistence (Kamara et al., 2019). Smallholders are a heterogenous group that spans across geographies, ethnicities, religions, and cultures. While smallholders in the Global North have more access to resources and are more productive than their counterparts in the Global South (Rauch & Brüntrup, 2021), smallholders in the Global South face a unique set of challenges that makes the one of the most vulnerable stakeholders in global agricultural supply chains (Vicol et al., 2018). These differences are reflected by the relevance of improving the livelihoods of smallholders in these different geographies to alleviate poverty and enhance food security (Raj et al., 2022). Regardless of this distinction, most smallholders are located in developing countries and form the backbone of agricultural production in these countries. (Rapsomanikis, 2015). Generally, smallholder farmers lack access to markets, rely on family labor to generate farm income, are poor, live in rural areas and are substantially less productive than types of farmers that utilize larger plots and deploy more capital-intensive farming techniques (Harvey et al., 2014). The livelihoods of smallholders are heavily constrained and improving their livelihoods is regarded as a precondition to eradicate hunger and poverty globally (Terlau et al., 2019). The need to improve the livelihoods of smallholder farmers results from the fact that most of all farms worldwide are owned by smallholders and that a very substantial share of the agricultural output of some regions e.g., Sub-Saharan Africa, is grown by smallholder farmers (Nyambo et al., 2019). Sustainable development is therefore not viable without making considerable efforts to improve the living conditions of smallholder farmers, especially in the Global South (Bagheramiri & Keshvarz Shaal, 2020).

There is an imperative to improve the livelihoods of smallholder farmers if sustainable development is to be pursued, however, what constitutes a livelihood, and improvements thereof need to be defined first. For assessing this issue, the United Nations has developed the sustainable livelihoods framework (SLF) (Elizondo et al., 2017). This analytical framework encompasses the capabilities and different types of capital used by individuals and communities to survive. Furthermore, it implies that communities and individuals have certain stocks of different types of capital and that interventions to promote human development, i.e. to improve the living conditions of those affected, should increase the stock of a particular type of capital without jeopardizing the other stocks of other types of capital. The types of capital examined in this framework are human capital, i.e. the abilities, skills and state of health;

social capital, i.e. the sum of horizontal and vertical relationships in a social group and their quality in terms of trust and reciprocity; natural capital, i.e. the total stock of available natural resources and their respective carrying capacity; physical capital, i.e. the available physical, man-made infrastructure; and financial capital, i.e. the financial resources available to carry out various economic activities. (Elizondo et al., 2017). This conceptualization of livelihood will be used throughout this study, and an improvement in the livelihoods of smallholder farmers will be understood, as increases in any of the capital stocks encompassed by the SLF that do not cause reductions in other types of capital stock.

2.2. The integration of data streams into agricultural practice

The integration of information technology into agricultural practice is generally possible over four different information streams (Maru et al., 2018), which can be typologized according to which type of information is collected, and where the processed information is deployed. First, there is the possibility to collect information on-site, process it and directly deploy it on the same plot where it was collected. An example of this practice would be to collect spatial and soil data to try to optimize yield using predictive models (Taylor & Amidy, 2020). Here farmers, either directly, or indirectly over an agent, own the collected data (Maru et al., 2018). Second, there is the possibility for farmers to use so-called imported data i.e., leveraging data streams that are generated off-site and are valuable to increase production on-site (Maru et al., 2018). An example thereof would be that a farmer leverages information collected elsewhere, such as climatic models to select which crops to plant, thus mitigating certain crop-specific risks. Accordingly, here farmers leverage data owned by others for the pursuit of their own interest, thus importing data. Third, data collected on-site can be deployed by other actors across the value chain to improve their internal processes (Maru et al., 2018) e.g., an insurance company could leverage information collected on-site to better assess underlying risks and more efficiently price a given insurance for a given plot, thus exporting data. Fourth, so-called ancillary data is generated off-site and utilized off-site to conduct activities indirectly affecting farmers (Maru et al., 2018). Here, other stakeholders, such as state-owned statistical agencies, could potentially collect information of the farms to develop policies, such as land-use plans, that indirectly influence the capacity of farmers to conduct their farming activities. Data-driven agriculture relies on the integration of these different types of information streams into agricultural practice and a single application aiming to enable data-driven agriculture can leverage one or more of these streams simultaneously to serve the interests of different actors across the value chain respectively (Rambhia et al., 2021).

2.3. *The opportunities of data-driven agriculture for smallholder farmers*

One of the most pressing issues that smallholder farmers face is their low productivity compared to more capital-intensive agricultural production modes (Harvey et al., 2014). This problem has become even more pressing in the last decade as changing climatic conditions have distorted weather patterns worldwide and exacerbated biotic stressors such as pests and diseases, further reducing the productivity of smallholder farmers in the Global South (Tabar et al., 2022). One of the most salient examples of how farmers in general, and smallholder farmers in particular, can utilize data-driven agriculture applications is by basing their planning on imported information to decide what to produce, when to produce it, how to better store it, and how to better deliver it to market (Maru et al., 2018). It is common for smallholders to plan their activities based on their intuition and traditions; however, it has been empirically proved, that a shift from this type of practice towards planning based on predictive models results in significantly higher productivity (Musshoff & Hirschauer, 2008). Accordingly, the generation, processing, and import of relevant information streams for agricultural planning promises to be an important feature of data-driven agriculture that could lead to an improvement in the livelihoods of smallholder farmers, provided this information is made available to them, as this would allow smallholders to increase productivity and mitigate risks through the implementation of yield optimizing farming practices.

The end-to-end traceability of food supply chains is another important structural feature of data-driven agriculture, as the optimization of agricultural production through predictive models and machine learning requires that information about the location, agricultural inputs, transport, and processing of agricultural products is recorded and operationalized (Kamble et al., 2020). Recording this information is not only necessary for the development of data-driven agricultural ecosystems, but also creates added value for consumers and a long-term competitive advantage for smallholder farmers participating in a given data-driven agricultural ecosystem (Babu & Devarajan, 2023). On the one hand, a certain traceability and transparency of the supply chain for agricultural commodities is necessary for smallholders in the Global South to gain access to more profitable export markets such as Japan, the United States, or the entire European Economic Area (Vanany et al., 2015). Improved access to such markets means a long-term advantage for smallholder farmers, as prices for their agricultural produce are generally higher in such markets. On the other hand, enhanced traceability of agricultural products offers a comparative advantage to smallholder farmers both domestically and abroad, as it increases product safety, for which consumers are generally willing to pay a higher price (Babu & Devarajan, 2023).

High transaction costs in the agricultural sector effectively translate into high market access barriers, which make it especially hard for smallholder farmers to commercialize their produce (Pingali et al., 2005). Transaction costs can be defined as the total of all heterogeneous costs incurred by an individual when transferring ownership of a good to another individual (Niehans, 1969). The existence of market transactions entails transaction costs for each market participant, such as transportation costs, customs duties, non-tariff barriers, information costs, price discovery costs, contract enforcement costs, etc. Neoclassical economic theory argues that market failure arises when the disutility resulting from transaction costs is higher than the utility gain resulting from transacting in the market (de Janvry et al., 1991). This type of market failure is reflected in the agricultural commodity markets in that buyers, in this case consumers of agricultural commodities, generally pay significantly higher prices than sellers i.e., producers of agricultural commodities, receive for the same good, thus explaining why a significant share of smallholder farmers decide to produce for self-subsistence instead of farming to sell their produce in the market (Cuevas, 2014). This price difference is generally captured by intermediaries i.e., rational economic actors mediating between sellers and buyers enabling the transactions in the first place, and leaving little to smallholders. In theory, devising mechanisms to reduce transaction costs in agricultural supply chains seems like a way forward to improve the livelihoods of smallholders. There is empirical evidence that integrating simple information and communication technology (ICT) into farming practices, such as cell phones, effectively lowers transaction costs for smallholder farmers by reducing various types of information costs, ultimately leading to a greater proportion of smallholder farmers accessing commodity markets (De Silva & Ratnadiwakara, 2008). Data-driven agriculture represents the natural evolution of this type of simple integration of ICT to improve connectivity within agricultural supply chains, and this improved connectivity between smallholder farmers and other actors has the potential to reduce transaction costs for smallholder farmers and ultimately open market access opportunities that would otherwise go unrealized. The literature argues that the main types of transaction costs incurred by smallholders result either from the use of resources to find suitable contract partners (in the form of travel costs, time and communication costs), from negotiating with potential contract partners, from setting contract terms, and from enforcing existing contractual relationships (Cuevas, 2014). Accordingly, applications of data-driven agriculture that effectively address these issues can safely be assumed to pose an opportunity to improve the livelihoods of smallholders, as they tackle the underlying issue of high transaction costs, ultimately enabling smallholders to engage in market exchange.

It seems that the situation of smallholder farmers in agricultural supply chains can be improved by the expansion of data-driven agriculture, provided that the concrete applications of data-driven agriculture either provide them with useful information that they can use for better planning, or structurally offer opportunities for transparency and traceability along the value chain, or lead to an effective reduction in transaction costs that enable smallholder farmers to access markets. Accordingly, these three dimensions offer a useful framework to assess the degree to which concrete data-driven agriculture applications benefit smallholder farmers.

2.4. The role of blockchain technology in data-driven agriculture

Blockchain technology, also known as distributed ledger technology, is a type of ICT that enables the creation of a decentralized chronological ledger that is managed and maintained collectively by its users, does not require a trusted central third party, and has a high level of tamper resistance (Bhatia et al., 2023). In a blockchain information is recorded in so-called blocks. Each block i.e., each unit of information, has three elements: an identifier, the identifier of the previous block in the blockchain, and the information stored in the block itself. All blocks are connected to each other, effectively leveraging these three elements, to form a chain, which guarantees that all information is recorded securely and chronologically (Menon & Jain, 2024). New blocks are added to the chain through a transparent consensus mechanism that distributes the existing chain among all network participants and guarantees that only new valid blocks are added to the blockchain by applying game theory (Bocek & Stiller, 2018). Participants conducting transactions on the blockchain span a network of actors who are collectively responsible for maintaining the infrastructure that makes distributed recording possible in the first place, and recording information on the blockchain requires coordination among actors so that the new information recorded on the blockchain is shared and trusted by all contributing actors. Participants who are willing to engage with other actors on the blockchain, i.e. initiate a transaction, pay a fee in the form of a token contained in the blockchain. The actors who add new information (new blocks) to the blockchain compete in a probabilistic manner for the right to do so. Once an actor has obtained the right to add a new block to the blockchain, they will only be rewarded with digital tokens if they have not tampered with the data already recorded. If they act maliciously and tamper with existing records to alter the state of the blockchain, they forgo all potential rewards and must bear the cost of attempting to add a new block to the blockchain (either in the form of electricity, other real-world inputs or a certain amount of locked digital tokens). This translates into a game-theoretic approach, where the Nash equilibrium lies in all actors cooperating for the correct maintenance of the blockchain (Qian & Ding, 2024).

This technological design effectively translates into a set of unique attributes of blockchain technology, such as decentralization, immutability, and transparency, which can be effectively leveraged for supply chain applications (Bhatia et al., 2023). Consequently, implementing blockchain solutions into existing or new digital ecosystems results in networks where different actors are interconnected through the blockchain i.e., the collective maintenance of the underlying ledger, where all actors can quickly and easily read all transactions recorded in the blockchain, and where actors can freely interact with each other without needing to rely on a trusted authority to guarantee trustworthy recordkeeping (Shin, 2019). Furthermore, the possibility to govern interactions between network participants through so-called smart contracts i.e., pieces of code that trigger a change of state in the blockchain once a given precondition has been fulfilled, allows to design and enforce different types of interactions within a given blockchain-based ecosystem, effectively facilitating the operationalization of this technology for a given business purpose (Khan et al., 2021). This represents a shift in the governance of interactions in a given ecosystem, in that the technology allows agreements between actors who do not know or trust each other to be automatically enforced by computers (Balcerzak et al., 2022), rather than relying on a trusted third party, such as government agencies.

2.5. The application of blockchain technology in data-driven agriculture

There are different manners in which blockchain technology can be integrated in the context of data-driven agriculture. Even though most applications do not pursue a single objective, identifying the main key objectives of the deployment of blockchain technology in applications in agriculture allows for understanding how this innovation plays out (Bhatia et al., 2023). The identification of two types of functionalities through which blockchain elements are integrated into digital services in data-driven agriculture enables the creation of a typology of agricultural blockchain applications that can be used to assess the impact of each type of blockchain-based solution on smallholder farmers' livelihoods.

2.5.1. Record-keeping functionality of blockchain

One of the most prominently examined use cases of blockchain technology in the literature is its usage for enhancing the traceability of agricultural products along the different stages of their respective value chains (Patelli & Mandrioli, 2020). In general, the use of blockchain technology to pursue this overarching goal leads to improved traceability in three domains: the distribution of agricultural goods, the origin and procurement of inputs, and quality assurance and safety (Menon & Jain, 2024). Firstly, all distribution-related activities such as transportation, storage, and relevant commercial transactions can be effectively recorded on the blockchain and are easily accessible to interested parties, increasing the transparency of distribution activities that an agricultural product goes throughout the supply chain (Bhat et al., 2022). Secondly, the implementation of blockchain as a record-keeping mechanism enables the transparent tracking of where a particular agricultural commodity is produced, what types of inputs are used for its production, such as the type of fertilizer used, and what other steps a particular commodity goes through in terms of processing (Patelli & Mandrioli, 2020). Thirdly, the integration of sensors and other IoT devices into blockchain-based traceability initiatives allows for monitoring external conditions, such as heat or humidity levels, that might have detrimental effects on the safety and quality of agricultural products (Xu et al., 2022). All the use cases described above for improving traceability leverage blockchain's record-keeping capability, combined with the easy accessibility of the underlying data, to develop agricultural solutions that create value for consumers by providing accurate and reliable information about the global value chain of a particular agricultural commodity.

2.5.2. Network functionality of blockchain

Alternative use cases of blockchain technology in agriculture take advantage of the fact that blockchains can be conceptualized as distributed networks of participants, that interact economically with each other without knowing or trusting each other or having to rely on third parties, i.e. intermediaries, to enable new modes of cooperation across the network (Zamani & Giaglis, 2018). Instead of generating value on the side of consumers by optimizing the traceability of agricultural value chains across different domains, this type of application generates value on the supply side by disintermediating different stages of the value chain, effectively reducing transaction costs across the value chain (Du et al., 2020). Good examples of how the network character of blockchains is harnessed to reduce transaction costs can be found in blockchain-based supply chain finance (SCF) initiatives in agriculture (Bhatia et al., 2023). Supply chain finance aims at optimizing financing within a given supply chain by optimizing cash and information flows between different stakeholders (Camerinelli, 2009). For instance, there are commercial ventures that use blockchain technology to optimize intermediation between farmers facing structural liquidity constraints and potential lenders, ultimately leading to better financial conditions for farmers and, thus, an increase in profitability (Bhatia et al., 2023). Accordingly, leveraging the nature of blockchains as networks interconnecting different types of actors in conjunction with the implementation of smart contracts to code different types of actions between these actors, presents an alternative functionality to record-keeping.

It is worth noting that the two functionalities described above are not necessarily mutually exclusive, as one can imagine that both the network and record-keeping functionalities of applications leveraging blockchain technology can be simultaneously utilized to enable and promote data-driven agriculture. Nonetheless, these two functionalities of blockchain elements in data-driven agriculture solutions represent two different ways to conceptualize how blockchain technology contributes to the creation of data-driven agricultural ecosystems and will be operationalized accordingly during the analysis.

2.6. Analytical framework

As mentioned above, elements of blockchain technology are employed in data-driven agriculture to perform two types of functions: either to leverage the record-keeping capabilities of blockchain technology to create a tamper-proof ledger of all possible transformations that a given agricultural commodity undergoes in the value chain, and/or to enable new types of interactions between a network of actors stabilized by the blockchain itself. In addition, improvements in three dimensions - reduced transaction costs, improved supply chain traceability and improved planning capabilities - have been identified in the literature as effective means of improving the livelihoods of smallholder farmers. This study will examine how the different functions identified impact smallholder farmers' livelihoods by qualitatively analyzing how each of these functions is used in the context of real-world data-driven agricultural applications and how it impacts the identified dimensions to assess how blockchain technology can potentially be used to improve the livelihoods of smallholder farmers more broadly. Analyzing real-life applications that have networking and/or record-keeping capabilities and their impact on farmers' livelihoods will shed light on how different ways of integrating blockchain technology into data-driven agriculture can be used to solve specific problems faced by smallholder farmers. The juxtaposition of these two dimensions provides an analytical framework for the analysis, which is illustrated in Table 1.

Table 1: Overview of the analytical framework for assessing the impact of blockchain on smallholders' livelihoods

Mechanisms for improving the livelihoods of smallholders	**Functionality of blockchain in data-driven agriculture applications**	
	Record-keeping	Spanning networks of actors
Reducing transaction costs	*To be analyzed by examining real-world applications*	*To be analyzed by examining real-world applications*
Enhancing traceability	*To be analyzed by examining real-world applications*	*To be analyzed by examining real-world applications*
Enabling yield optimization	*To be analyzed by examining real-world applications*	*To be analyzed by examining real-world applications*

3. Research methodology

This study will aim to answer the research question by pursuing a mostly constructivist qualitative approach. The nature of this study is purely exploratory and some overarching assumptions about what constitutes an improvement of the livelihoods of smallholder farmers are made. The exploratory scope of the study justifies this approach. It is assumed that improving the livelihoods of smallholder farmers is the result of implementing any design approach that provides an increase in any of the different capital stocks analyzed by the SLF for smallholder farmers, either individually or collectively, by enabling them to increase their yields through improved planning, reduce transaction costs so that selling their products on the market becomes economically viable, or improve traceability in the supply chain so that their products can potentially fetch a higher price, without jeopardizing the other capital stocks. Accordingly, data-driven agricultural applications that lead to improvements in these areas compared to the status quo are considered to improve the livelihoods of smallholder farmers, ceteris paribus.

To assess the extent to which data-driven agricultural applications related to blockchain can potentially improve smallholder farmers' livelihoods, a set (n=13) of real, commercially active applications were identified through desk research. Relevant cases were identified deploying a combination of desk research and snowball sampling, which is a common approach when conducting constructivist qualitative research (Noy, 2008). Initially, a series of search queries with keywords such as “blockchain”, “digital solutions for agriculture”, “digital applications in agriculture”, “precision agriculture”, “applications for small farmers”, “data-driven agriculture applications”, etc. were entered into publicly available search engines such as *google, SSRN, typset.io, web of science* and *google scholar*. This initial query yielded a significant number of websites, newspaper articles, white papers, policy documents, scientific articles and other types of documents. The sources and references used in these documents were further investigated to identify even more applications, leading to an iterative desk research process. All cases were related to the implementation of data-driven solutions for agriculture and contained elements of blockchain technology in their architecture.

The main selection criteria for including cases studies into the case study pool were that the applications in question were commercially active at the time of writing and that they included blockchain technology as a fundamental part of their underlying architecture. This has led to the exclusion of ventures that are still at an early stage of development or have ceased operations, as their impact is impossible to assess in practice, as well as other data-driven agricultural applications that do not utilize blockchain technology for their value proposition, or only to a limited extent.

As the main purpose of this study is to explore how the use of blockchain technology in the context of data-driven agriculture can impact the livelihoods of smallholder farmers, all applications studied were qualitatively categorized as either low, moderate or high, depending on the extent to which smallholder farmers are prevalent in the ecosystems studied. The prevalence of smallholders was assessed by examining how often smallholders were explicitly mentioned on the websites, in the documents and other publicly available sources of the case studies in question. Cases in which smallholders were not mentioned or only marginally mentioned were categorized as low, cases in which smallholders were mentioned alongside other types of farmers were categorized as moderate, and cases in which the value proposition was mainly directed at smallholders were categorized as high. All blockchain applications where the preeminence of smallholders to the overall ecosystem was considered moderate or low were not included in the analysis (n=9), as these can be considered applications of data-driven agriculture that focus on farmers in a broader sense rather than smallholders and are beyond the scope of this study.

The remaining cases (n=4) were then divided into different subsets. For this purpose, the network functionality, i.e. the extent to which the blockchain applications in question aim to connect actors in agricultural supply chains in new ways, and the record-keeping functionality, i.e. the extent to which the applications aim to capture information about the different stages of value creation in agricultural value chains, of the respective applications were qualitatively classified as either low, medium or high. This classification method resulted in three subsets: a first one where the applications have a high score for the network functionality (n=2) i.e., where the main function of the blockchain was to enable new types of interactions between different actors across the value chain; a second one where the ledger functionality of the applications has a high score (n=1) i.e., where the main function of the blockchain is to record processes taking place at different stages of the supply chain; and a third one where both functionalities were equally present (n=1). For the first subset, a selection procedure was implemented where the application with the lowest score on the ledger functionality of the application was selected for analysis. This is justified in that selecting the application with the lowest score for ledger functionality allows the study to better explore how the network nature of blockchain-based data-driven agriculture has the potential to improve the livelihoods of smallholder farmers. The selection and classification methods used provided the study with three different case studies to examine how applications that focus on either connecting supply chain actors with smallholder farmers in new constellations, capturing information about the different stages of value creation in the value chain, or a combination of both characteristics, impact the livelihoods of smallholder farmers in the real world.

The analysis will rely on document analysis to assess the impact of each of the selected cases in relation to the identified dimensions that have been demonstrated to improve the livelihoods of the smallholder farmers involved, namely (i) enhanced supply chain traceability, (ii) provision of yield optimization information, and (iii) reduction of transaction costs. The analysis will also delve into the equipment and infrastructure requirements to assess the extent to which the examined blockchain applications can be potentially translated to other agricultural contexts involving smallholder farmers. An overview of the case studies selected for the subsequent analysis is found in Table 2.

Table 2: Overview of the case studies selected for analysis based on the function served by blockchain technology in the application

	Low network functionality	**High network functionality**
Low record-keeping functionality	*N/A*	*Hello Tractor*
High record-keeping functionality	*AgriUT*	*Agrikore*

4. Results of the case study analysis

4.1. Hello Tractor

Hello Tractor is a Kenyan company providing a platform for matchmaking between smallholders and mechanization service providers for the rental of tractors in a pay-per-use model. The company started operations in 2014 and its initial value proposition was to manufacture affordable low horsepower two-wheeled tractors with some monitoring equipment for Kenyan cooperatives and to provide a platform for cooperatives to serve smallholder farmers to amortize the initial cost of the machines (Cline & Emmanuel, 2019). In 2017, however, the company changed its strategic focus from improving on the tractor design per se and redirected most of its financial resources to further develop the tractor-sharing platform to reach even more smallholders (Chona, 2021). Currently, the Hello Tractor platform is used by over 250.000 smallholder farmers across five African countries and is expected to continue expanding (Cline & Emmanuel, 2019). Even though mechanical plowing has been proven to increase crop yield (Atidegla et al., 2017), smallholders generally do not rely on this technique because it is impossible for them to recover the cost of acquiring mechanical equipment such as tractors, simply because their plots are too small (Achoja & Aliber, 2021). Hello tractor effectively enables smallholder farmers to overcome this problem by implementing a sharing economy ecosystem in which smallholder farmers can mechanically plow their plots on a pay-per-use basis and wealthier actors, such as cooperatives, can amortize the cost of the machines by meeting smallholder farmers' demand for mechanical plowing. Hello Tractor has been praised for promoting the “Uberization of mechanical plowing” (Daum et al., 2021), a change of practice, where similar to scheduling transportation over Uber in dense areas, smallholders can schedule mechanical plowing services simply by leveraging an application over a smartphone. This model is highly beneficial to smallholder farmers, as it has been shown that replacing manual plowing with mechanical plowing leads to a significant increase in farm income through higher yields (Achoja & Aliber, 2021), thus significantly improving the financial capital base of smallholders.

4.1.1. Network functionality of Hello Tractor

Like other applications in the data-driven agriculture sector, Hello Tractor uses both IoT and blockchain technology to deliver its services. Through a series of sensors installed on the tractors in the network, the tractors collect real-world information about the use of the tractors, such as usage, the identity of the users, fuel consumption, ownership, relevant transactions, etc., which is automatically stored in a blockchain (Parmar & Shah, 2020). Accordingly, for Hello Tractor blockchain serves as the backbone for transparent and immutable information collection that is used to enhance trust and prevent fraud between actors in the Hello Tractor ecosystem, and it is the immutability of the data stored in the blockchain that comes into serves as a trust enhancing mechanism in the Hello Tractor ecosystem (Daum et al., 2021). From the tractor owners' perspective, the blockchain component of the Hello Tractor platform provides a robust ICT infrastructure that allows them to track their machines in real time and makes it difficult for malicious actors to steal the machines, as state changes in a blockchain are tamper-proof and immutable. From the smallholders’ perspective, the platform offers them with information about verified mechanization service providers, their geographical location, their track record and reviews from other smallholders, which smallholders can trust because the information stored in the blockchain cannot be easily tampered with (Hofmann et al., 2017) to defraud them. This becomes apparent when comparing similar ventures driving the “Uberization of tractors” that rely on cloud-based storage for data collection and storage instead of blockchain technology, as the risk of tampering with the information stored in such systems is significantly higher (Sharma & Kaur, 2023). Consequently, the implementation of blockchain technology in the context of Hello Tractor is not fundamentally necessary for the operation of the network but serves rather the purpose of assuring actors in this ecosystem that they will not be defrauded.

Given the context in which Hello Tractor operates, in rural communities in Africa, trust-enhancing measures are especially important for the acceptance and subsequent adoption of technological solutions as rural communities in these regions are especially distrustful of actors outside their respective communities (Daum et al., 2021). The main objective of the deployment of blockchain technology elements in the context of Hello Tractor is to enable new modes of cooperation between actors in the value chain through a technological solution that enables these very forms of cooperation. While the platform provides records as to the usage of mechanized plowing for growing agricultural goods, it fails to capture other stages of the value chain. Consequently, in the Hello Tractor ecosystem, the network functionality of blockchain technology dominates over its record-keeping functionality.

4.1.2. Effects on transaction costs

Hello Tractor has been acknowledged to effectively sink transaction costs for smallholder farmers willing to engage in mechanized plowing (Daum et al., 2021). To better understand how transaction costs are reduced through the implementation of Hello Tractor, the alternative for African smallholders willing to hire mechanized plowing services needs to be analyzed. Without the platform smallholders would find themselves in a situation where they would need to find other parties and negotiate the concrete terms for rental of tractors individually, thus incurring in high information and price discovery costs (Anidi et al., 2020). Furthermore, it has been acknowledged that adoption of tractor usage in smallholder communities across Africa has been low because of low levels of social trust, which result in increased default risk, which , in turn, further increases transaction costs for traditional tractor rental services (de Brauw & Bulte, 2021). Transaction cost theory predicts that a actors will not enter the market if the disutility of participating in the market is higher than the expected utility of engaging in market transactions due to high transaction costs (Cuevas, 2014). This is generally the case of tractor rental services in African countries, even though renting tractors would significantly increase their yield and thus their income, the transaction costs for renting them in such geographies has been generally too high for smallholders to engage in the tractor rental market (Anidi et al., 2020). Accordingly, the rapid expansion of Hello Tractor throughout several African nations can be understood as the consequence of a drastic reduction of transaction costs resulting in changes in farming practice, the substitution of manual plowing by mechanized plowing. Hello Tractor shows that transaction costs can be reduced by enabling new modes of collaboration between smallholder farmers and other value chain actors. This is one of the most pressing issues driving smallholder farmers to become self-sufficient instead of participating in market transactions, effectively hindering their economic development (Cuevas, 2014). In this case it is the network character of the underlying blockchain architecture that enables these new modes of cooperation through the implementation of trust-enhancing mechanisms ultimately leading to the reduction of transaction costs.

4.1.3. Effects on supply chain traceability

The Hello Tractor platform does not appear to have considerable effects on generating transparency regarding the processes the produce of smallholders undergo throughout the value chain. The use of the platform is restricted to a single stage of value generation in the whole value chain, preparing the plots for growing food. In terms enhancing supply chain transparency the benefits of deploying applications leveraging blockchain in the same manner as hello tractor gains in product traceability are limited. Accordingly, farmers are not expected to benefit from higher prices or access to better priced export markets through the mere usage of with a high network functionality and a limited ledger functionality such as Hello Tractor.

4.1.4. Potential for yield optimization

In terms of enhanced planning, the effects of Hello Tractor are moderate. On the one hand, the very purpose of the application is to allow smallholders to schedule mechanized plowing services, which represents planning efficiency gains compared to the status quo. On the other hand, the application does not provide farmers with relevant information on what to grow, how to grow it, and when to take appropriate measures to optimize yields - one of the most promising features of data-driven agriculture (Maru et al., 2018). Notwithstanding the restricted role of smallholders as data consumers in the Hello Tractor context, other actors in the supply chain might benefit from the collection and processing of data generated by smallholders, which in turn, might benefit smallholders in the form of better products and policies to support them (Maru et al., 2018). Hello tractor has partnered with IBM to integrate AI-based predictive models to its operation, which could potentially be used by banks and governments to optimize credit conditions and agricultural development policies, respectively (IBM, 2018). Consequently, smallholders would play a role as data producers in this context and benefit indirectly from the processing of this data, either by gaining access to better rental conditions for mechanized equipment or through the provision of public services such as road infrastructure.

4.1.5. Impact on smallholders' livelihoods

Even if the infrastructural requirements for using Hello Tractor's services seem negligible - a smartphone and access to mobile networks - access to such infrastructures is still an issue in many African rural regions (Okano et al., 2022), the geographies where Hello Tractor operates. Furthermore, the implementation of Hello Tractor does not radically change social practice. Even though a reduction of transaction costs and an uptake in the use of mechanized plowing equipment is observable, some smallholder communities still rely on booking agents that aggregate scheduling (Daum & Birner, 2020), which leaves space for further disintermediation (Onomu et al., 2020) and thus for further reduction of transaction costs. Accordingly, applications similar in nature to Hello Tractor need to also consider cultural and infrastructural issues, such as connectivity, to optimize their social impact. Notwithstanding the aforementioned structural problems, the services provided by Hello Tractor led to an increase in two different capital stocks, while not jeopardizing the rest, thus ceteris paribus enhancing the livelihoods of smallholder farmers who use Hello Tractor's services. First, improved yields due to the use of tractors for plowing lead to higher agricultural production and income from farming without significantly affecting the natural, physical, and human capital base of the smallholder farmers who use the services. Second, the social capital base of smallholder farmers is enhanced through the linking of the farmers to a greater proportion of mechanical plowing service providers due to the increase in the number of social relationships that the farmers can potentially engage in.

4.2. AgriUT

The AgriUT Foundation is the issuer of the AgriUT tokens and the enabler of the AgriUT token ecosystem. The AgriUT Foundation is a subsidiary of the Australian social startup AgUnity, which plays a role in the AgriUT ecosystem as the manufacturer of smartphones required to participate in the AgriUT ecosystem. The actors involved in the AgriUT ecosystem are individual smallholders, producer organizations, consumers and AgUnity subsidiaries. The ecosystem is supported smartphones sold by AgUnity to other actors in a given agricultural value chain, which are programmed to manage the distributed ledger system where all information is stored, the AgUnity SuperApp, which serves as an interface for integrating other actors in the value chain through the development of add-on applications, and AgUnity's digital marketplace, through which actors such as smallholder farmers and consumers can interact directly with each other (AgriUT, 2021). This system gives smallholder farmers a digital identity that allows them to create immutable and transparent records of what they produced, where they produced it, who it was sold to, and at what price. Other actors in the ecosystem can easily access this information and purchase the smallholder farmers' products through the marketplace, while tracking their origin and voluntarily giving the smallholder farmers behind the product an additional premium for agricultural practices that align with their own normative preferences (AgriUT, 2021). For example, a consumer who wants to buy coffee that has been grown under fair conditions can compare different types of coffee on the platform and see what price the smallholder farmers have been paid for their produce and, if they are willing, donate money to the smallholder farmer. Such donations are paid to the farmer in the form of AgriUT tokens, which can easily be exchanged by smallholders for fiat currency, thus resulting in increases in the financial capital base of the smallholder farmers in question.

4.2.1. *Record-keeping functionality of AgriUT*

In the case of the AgriUT network, blockchain technology is integrated into this ecosystem to create a transparent and trustworthy register of the farming conditions under which smallholder farmers produce and the economic conditions to which they are exposed (AgriUT, 2021). This system allows end consumers of agricultural products to follow who grew the product they are consuming, whether producer groups were involved in bringing together the produce of multiple smallholders, where and whether the product was further processed, e.g. by roasting, and which distributors were involved in the supply chain. It is precisely the creation of an unalterable, trustworthy and automated data record through the use of blockchain technology that creates added value for the consumer (AgriUT, 2021). To this end, AgriUT bases its blockchain infrastructure on a public blockchain, the *celo* blockchain, which in turn has technical features such as low transaction fees, high transaction capability, a strong focus on cell phones and low connectivity requirements (CLabs, n.d.) that are conducive to the integration of IoT sensors in rural areas. Accordingly, the main function of integrating blockchain technology into the AgriUT ecosystem is to enable more efficient record-keeping in global agricultural supply chains. While the AgriUT ecosystem utilizes blockchain technology primarily for record-keeping purposes, the implementation of this blockchain-based system also includes a marginal network functionality that allows end-users to directly reward smallholder farmers and cooperatives for agricultural practices that align with their own normative preferences (AgriUT, 2021). This represents a new mechanism for linking consumers and smallholders, as the technology allows them to donate money directly to smallholders, which is not necessarily possible when buying the same good through other channels. However, this feature does not necessarily change the relationships between smallholders and other actors in the value chain but replicates such connections on the blockchain. Furthermore, consumers' decision to donate money to smallholder farmers is not based on the ability to interact directly with smallholder farmers, but instead on access to information about the different stages of the value chain. Accordingly, the AgriUT ecosystem can be seen as one in which the record-keeping functionality of blockchain technology outweighs its ability to span networks of actors.

4.2.2. *Effects on transaction costs*

The use of blockchain technology in this data-driven agricultural application has a dual impact on transaction costs. Firstly, it significantly reduces the cost of donating money from consumers to smallholder farmers by enabling direct transfers between smallholder farmers and consumers that would otherwise have to be intermediated by other actors (AgriUT, 2021). While donations undoubtedly contribute to immediate economic relief for vulnerable communities such as smallholder farmers, for this type of intervention to contribute to sustainable development, i.e. to truly improve the livelihoods of the target groups, they must be accompanied by governance and capacity building measures (Barr et al., 2005), which is not a feature of the AgriUT ecosystem. Furthermore, it remains unclear whether philanthropy truly contributes to sustainable development of aid receivers as some critics argue that philanthropy further deepens dependency relationships between wealthy donors and less wealthy aid receivers (Pinho, 2014). Secondly, this ecosystem reduces the costs of information exchange between consumers and smallholders, which can be considered a reduction in transaction costs (Cuevas, 2014). However, this specific reduction in transaction costs does not directly affect existing relationships with other actors in the supply chain, such as distributors and retailers. Consequently, it remains unclear whether this form of transaction cost reduction has the potential to significantly alter the relationships between small farmers and other actors in the supply chain, enabling a significant proportion of smallholder farmers to sell their products on the market rather than relying on self-sufficiency (de Janvry et al., 1991). Overall, the AgriUT ecosystem appears to reduce specific transaction costs within its area of application. However, the impact of these reductions on smallholder farmers' livelihoods appears to be moderate at best, as they do not result in changes of smallholder farming practice.

4.2.3. Effects on supply chain traceability

The primary value proposition of the AgiUT platform is to facilitate consumer tracking of the origin of agricultural products consumed. The platform facilitates supply chain transparency by registering all stages of value generation and providing information about the share of the price paid by consumers that smallholders receive and how much of the price paid by consumers is captured by intermediaries e.g., distributors and retailers. Empirical evidence indicates that consumers committed to environmentally friendly and ethical consumption are willing to pay a price premium for products they trust to be produced under fair conditions, thus, explaining the success of certification schemes such as fair trade certifications (Sammer & Wüstenhagen, 2006). The efficacy of traditional fair trade certifications has been the subject of criticism, with the mechanism being deemed economically inefficient in fostering development among smallholder farmers in the long term (Dragusanu et al., 2014). This is due to the fact that the certifiers must at least cover the costs incurred through the certification process (Glasbergen, 2018), which results in them capturing a substantial portion of the price premium that consumers pay for certified agricultural products. In light of the aforementioned criticism, the integration of blockchain technology, as implemented in the AgriUT ecosystem, to record the economic conditions under which smallholder farmers exchange their products offers an alternative for consumers to be reassured that the products they are consuming have been exchanged under fair conditions. The establishment of an ICT system, such as the AgriUT ecosystem, records all relevant information and enables consumers to assess the extent to which the price paid for a particular agricultural product reaches small farmers. Concurrently, consumers can compare the performance of other comparable products recorded in the AgriUT ecosystem by scanning a QR code on their mobile devices and thus make a more informed decision regarding the purchase of a fairer product, ceteris paribus. This ultimately channels money to smallholders who benefit most from their purchase and further advances fairer conditions in agricultural supply chains. This system offers two advantages over traditional certification schemes. Firstly, it does not necessitate the involvement of third parties, who are frequently unaccountable and non-transparent regarding the certification process (Ruml & Qaim, 2021) and capture a significant proportion of the price premium resulting from certification. Secondly, it allows for better comparability for consumers when deciding on which products to purchase. This results from the fact that they can compare metrics, such as the share of the price that smallholders receive, instead of relying on certifications for this purpose. This ultimately translates into improvements in the financial capital base of smallholder farmers ceteris paribus, as it would theoretically them to capture a greater share of the value generated throughout the supply chain, thus improving their financial capital base without jeopardizing other capital stocks pursuant to the SLF.

4.2.4. Potential for yield optimization

The AgriUT ecosystem is a data-driven agriculture application in that it employs digital technology to collect data, which is then utilized to create more favorable economic conditions for smallholder farmers through enhanced transparency. The type of information recorded on the underlying blockchain primarily concerns economic exchanges along the supply chain and generates value for consumers, as it enables them to align their willingness to pay for goods produced by smallholders with their own normative preferences. In this context, smallholders act as data generators and are remunerated either directly, through donations, or indirectly, through capturing a higher share of the price paid by consumers, for their role as data generators. Nevertheless, the AgriUT ecosystem does not collect significant information pertaining to physical, chemical and climatic factors, which are crucial inputs for predictive yield optimization (Sakthi et al., 2023) models aimed at informing farmers about the most appropriate crops, methods of cultivation, and planting schedules. This type of planning is contingent upon other types of information that have a direct impact on the fields and not on the different stages of the value chain. Consequently, this application provides limited valuable information for smallholder farmers to optimize farm output along the lines of semi-automated decision-making.

4.2.5. Impact on smallholders' livelihoods

The AgriUT ecosystem has a positive impact on the livelihoods of farmers, primarily by improving their financial capital base. Firstly, the system allows ethically concerned and environmentally friendly consumers to purchase agricultural goods, thereby enabling them to be reassured that a substantial share of the price premium paid for fair supply chain practices reaches the smallholder farmer behind the product and is not captured by intermediaries and/or certifiers (AgriUT, 2021). Secondly, the system allows consumers to hold intermediaries accountable by providing reliable information about how much of the price premium paid for fair supply chain practices is reaching smallholder farmers. This allows consumers to make informed choices and to advocate for fairer practices in the agricultural supply chain. Furthermore, the platform allows consumers to make direct donations to smallholders, providing immediate economic relief. However, the long-term effects of these donations remain subject to academic discussion (Pinho, 2014).

Moreover, the platform's capacity to facilitate information exchange between consumers and smallholders has the potential to enhance the social capital base of smallholders. This is because it generates new horizontal linkages between them, which could indirectly lead to greater consumer awareness of the challenges smallholders face and, consequently, to more political pressure to address them. It is noteworthy that the technological design of the ecosystem addresses structural issues hindering the adoption of data-driven agriculture applications, such as low connectivity. The blockchain infrastructure is designed in a way that connectivity requirements for smallholder farmers willing to participate in the ecosystem are low, thus enabling more smallholders to become part of the ecosystem (AgriUT, 2021). This application does not appear to have other significant effects, either positive or negative, on the other stocks of capital smallholders need to have a sustainable livelihood.

4.3. Agrikore

Agrikore is a blockchain-based digital decentralized marketplace developed by Cellulant, a Nigerian mobile payments service provider, with the objective of digitalizing the interactions of various actors along agricultural supply chains. The objective of Agrikore is to provide a digital payment platform that facilitates transactions between various actors along the agricultural supply chain. These include smallholders, transporters, community aggregators, processors, traders, retailers, financial institutions, and de-risking agencies (Mastercard, 2022). The platform facilitates the creation of a comprehensive record of the different monetary transactions between various stages of the supply chain, thereby enabling a more transparent and efficient flow of goods. Furthermore, it facilitates the integration of smallholder farmers into the financial system through the issuance of digital money that is easily convertible to fiat money in rural areas (Quayson et al., 2021). This digital platform enables all actors within the agricultural supply chain to establish a digital identity through a blockchain-based wallet scheme. It records the full range of transactions between these parties, and the resulting data is publicly available to all stakeholders. Consequently, it provides a comprehensive overview of the value chain, allowing existing processes, such as direct sales from smallholder farmers to aggregators or processors, to be identified and explored. Additionally, it facilitates new direct interactions with other actors, including banks and insurance companies. The platform provides a means of facilitating the provision of financing opportunities to smallholders who would otherwise be unable to access such resources (Quayson et al., 2021). This is achieved by recording revenue streams generated by smallholders, which in turn allows financial institutions to model financial risk more accurately. The wallet scheme allows for the structuring of credits and payouts for smallholders without the requirement of a bank account (Arthur et al., 2024), as payouts can be handled in digital currency and delivered to the digital wallets of smallholders.

4.3.1. Hybrid functionalities of Agrikore

Blockchain technology serves as the technical foundation of Agrikore. In this context, the technology serves two primary functions: as an immutable record of the provenance of agricultural commodities and as an interface for different actors to structure agreements and automatically execute them through the usage of smart contracts (Kumarathunga et al., 2022). Moreover, the digital identity scheme through wallets is a function of the cryptographic properties of the technology and ultimately serves to facilitate the generation of new cooperation modes throughout the supply chain. This is achieved through the reliable identification of the different actors participating in the ecosystem. The blockchain records information regarding the inputs, practices, output, and stages of the value chain that agricultural commodities undergo before reaching the final retailer. This record-keeping functionality is simultaneously critical for enabling a digital currency for digital payments. The usage of blockchain technology for recording transactions effectively overcomes the double spending problem, a precondition for establishing a reliable digital currency, where the issuer cannot default on the actors involved in the ecosystem. This, in conjunction with the blockchain-enabled capability to regulate interactions via smart contracts (Kumarathunga et al., 2022), opens the possibility for smallholder farmers to engage in modes of cooperation with other actors in the supply chain, such as financing agreements, that would otherwise not be possible without the deployment of blockchain technology. Consequently, both robust network and record-keeping functionalities are present within the Agrikore ecosystem.

4.3.2. Effects on transaction costs

There are several mechanisms by which the Agrikore platform reduces transaction costs for smallholder farmers (Quayson et al., 2021). Traditionally, farmers in structurally disadvantaged areas have to find buyers for their produce in order to sell it to the market. This results in a number of transaction costs, such as travel costs (Kyaw et al., 2018), search and negotiation costs (Haile et al., 2022), and contracting costs, which generally lead to market failure in agricultural supply chains. These types of cost are disproportionately high for smallholder farmers in rural and structurally disadvantaged regions of the Global South due to a persistent lack of infrastructure and long distances between potential contracting parties (de Brauw & Bulte, 2021). One of the problems that the Agrikore platform solves is connecting smallholder farmers with potential buyers by integrating them into a digital network of different actors in the supply chain in a way that is more time efficient and less costly for smallholders (Andeme Bikoro, 2022), instead of having to travel long distances to negotiate prices for their produce. The platform provides all stakeholders with an overview of potential contract partners and allows smallholders to connect with potential buyers without having to leave their farms. This is a dramatic change from the status quo, allowing smallholders to reach more potential buyers, compare a wider range of terms and conditions for selling their produce, and choose the best buyer for their produce. In addition, other types of transaction costs associated with default risk and contract execution costs (Cuevas, 2014) are significantly reduced because interactions between parties on the platform are moderated via smart contracts. Because smart contracts are self-executing pieces of code that trigger a transaction on the blockchain once a set of pre-agreed conditions are met, smallholder farmers can be assured that they will not be shortchanged when they ship their produce to a seller, and sellers can be assured that they will receive the agricultural products under the terms agreed upon by both parties. Accordingly, this type of blockchain-enabled interaction not only reduces traditional transaction costs, but also increases trust between smallholders and other supply chain stakeholders, which could lead to a greater willingness of potential buyers to purchase agricultural commodities from smallholders. In addition to significant reductions within the supply chain, the Agrikore platform facilitates greater access to public or private financing opportunities (Yang et al., 2021). The platform provides smallholder farmers with a digital wallet that can be used to send and receive payments in a digital currency that is exchangeable one-to-one with fiat currency, which can be used to enter into microfinance contracts and receive government subsidies and development aid (Yang et al., 2021). This represents an improvement in the livelihoods of farmers, as one of the most pressing issues in the pursuit of sustainable development is to improve access to finance for smallholder farmers (Acclassato Houensou et al., 2021).

4.3.3. Effects on supply chain traceability

The Agrikore system effectively records all transactions that take place within the ecosystem, while collecting information on the origin and conditions under which the agricultural commodities were produced and exchanged. In a manner analogous to the AgriUT system, the platform could potentially be used for consumers to track all stages of the value creation of agricultural commodities across the entire value chain (Arthur et al., 2024). This is because all transactions related to these processes are recorded on the underlying blockchain and are accessible to interested parties. Despite the fact that relevant information for the traceability of agricultural commodities is recorded on the platform, the realization of this potential remains unrealized due to two factors. Firstly, there are no user-friendly interfaces that allow relatively effortless access, so traceability for the ordinary consumer is limited. Secondly, supply chains are very complex and often span multiple countries and currency areas. This limits the platform's ability to enable supply chain traceability, as transactions that take place outside the platform are not captured by Agrikore. Overall, Agrikore is a blockchain-based interface that enables transactions between actors in agricultural supply chains and captures information that can potentially be used to improve the traceability of products. However, specific interfaces still need to be developed to realize this potential and improve the livelihoods of smallholder farmers by providing them with access to markets with better prices.

4.3.4. Potential for yield optimization

The type of information recorded in the underlying blockchain primarily concerns economic exchanges along the supply chain, thereby creating added value for smallholder farmers. This is achieved by facilitating the search for new business partners to bring their products to market. Nevertheless, this type of information is only applicable to a limited extent in terms of yield optimization, as the data required to utilize predictive models to assist farmers in optimizing cultivation practices is not collected. Nevertheless, the platform's intermediation function towards potential financiers facilitates financing opportunities for smallholder farmers. This is crucial for enhancing agricultural productivity (Basu, 2006), as it could facilitate the modernization of farming practices, provide access to training, and offer contingency planning opportunities, such as access to insurance opportunities, to smallholder farmers.

4.3.5. Impact on smallholders' livelihoods

Agrikore has a positive impact on the livelihoods of smallholder farmers by reducing transaction costs in the agricultural supply chain through two main mechanisms. Firstly, it reduces the transaction costs associated with certain interactions between the various stages of value creation within the supply chain, such as price discovery, contract enforcement and information costs (Cuevas, 2014). This is achieved by establishing a network of supply chain actors in which the actors involved become visible to each other. Secondly, it facilitates access to finance, which is considered a prerequisite for traditional economic development in smallholder communities (Basu, 2006). This is achieved by reducing the cost for smallholder farmers to access the financial system. These two factors lead to an improvement in the financial capital base of smallholders without, in all other respects, preventing them from accessing other capital stocks. This, in turn, has the effect of improving the livelihoods of smallholders. Furthermore, the platform facilitates the expansion of smallholders' social capital base, which encompasses their vertical and horizontal relationships with other actors based on trust and reciprocity. This is due to the fact that the platform increases the number of potential actors with whom smallholders can interact. Concurrently, the utilization of smart contracts serves to reinforce trust within the Agrikore ecosystem.

4.4. Findings

Overall, the various case studies show that the integration of blockchain technology into data-driven agricultural applications has the potential to improve the livelihoods of smallholder farmers, either by creating mechanisms that incentivize fairer commercial exchange terms for smallholder farmers along the supply chain, or by reducing transaction costs such that a change in agricultural practice becomes economically viable, ultimately leading to higher productivity for smallholder farmers. Interestingly, the integration of blockchain elements into the various applications does not appear to have a significant impact on yield optimization planning. However, blockchain elements do appear to enable more efficient planning opportunities, but not in a way that leverages digital technology for smallholder farmers to know what they are growing, how they are growing it, and when they are growing it. A summary of the key findings is presented in Table 3.

The analysis shows that by capturing all relevant transactions and transfer prices, transparency about the economic conditions under which transactions take place between smallholder farmers and their buyers is increased. This has the potential to address equity issues where a lion's share of value creation in global agricultural supply chains is captured by intermediaries. Comparing the AgriUT case with the Agrikore case, it is clear that the development of user-friendly interfaces for consumers to effortlessly access the information stored on the blockchain is a critical factor in enabling consumer pressure for smallholder farmers to capture a greater share of the value generated throughout the supply chain. In addition, the Hello Tractor case demonstrates that smallholder farmers can only reap the benefits of blockchain-enabled supply chain traceability to the extent that information about all stages of value creation is captured and stored by the underlying infrastructure.

Interestingly, all cases show that the integration of blockchain technology into data-driven agriculture, regardless of whether a dominant network functionality is present, leads to reductions in transaction costs that can be critical for smallholder farmers to access markets. These types of cost reductions can be achieved either by focusing on a single stage of the value chain, such as plowing in the case of Hello

Tractor, or by attempting to encompass the entire value chain and enable new forms of collaboration between stakeholders. Although blockchain has the potential to reconfigure the way stakeholders work together, simply replicating these relationships on a digital platform allows for a relevant reduction in transaction costs from a smallholder perspective, as discovering potential business partners becomes much cheaper for smallholder farmers. This, combined with the facilitation of new forms of collaboration, appears to be conducive to increasing the financial capital base of smallholder farmers. In addition, the use of other elements of blockchain technology, such as smart contracts to govern potential interactions between stakeholders and digital identity management through digital wallet systems, appears to reinforce this effect.

All of the case studies analyzed fail to deliver on the promise of providing platforms for farmers to optimize yields through predictive modeling and automated decision making. This is because the applications in question do not capture relevant information about the physical conditions that enable this type of decision making in the first place. Nevertheless, marginal efficiency gains in terms of traditional planning can be observed in some of the applications, simply because the platforms provide smallholders with information that allows them to plan their activities in the first place, either through scheduling, more transparent discovery of potential business partners, or access to finance. It appears that for blockchain-enabled data-driven agricultural applications to deliver on the promise of yield optimization, they must be designed to capture information about physical conditions on the ground, and data collection must be designed to capture all stages of the value chain. Overall, the two cases that aim to cover the entire supply chain could benefit from collecting more information on the deterministic factors that enable data-driven decision making for smallholder farmers in the first place.

The impact on smallholder livelihoods resulting from the adoption of data-driven agricultural applications in their farming practices appears to have a positive impact on smallholder livelihoods along two dimensions. First, the applications improve the financial situation of smallholder farmers, which, given that smallholder farmers are arguably the most vulnerable actors in global agricultural supply chains, seems to be an essential step towards achieving sustainable development among smallholder farmers. Second, the observed reduction in transaction costs seems to have a positive impact on improving the social capital base among smallholder farmers. After all, the technology enables new forms of cooperation that smallholders can trust due to its technological design and enhances trust in existing linkages with other actors through the inclusion of blockchain-based elements such as smart contracts and digital wallets.

Table 3: Overview of the main findings of the case study analysis.

Type of blockchain functionality	**Case study**	**Effects on supply chain traceability**	**Effects on data-driven yield optimization**	**Effects on transaction costs**	**Potential impact of smallholders' livelihoods**
Dominant network functionality	Hello Tractor	*The system is constrained to a single stage of value generation (plowing), which precludes the ability to provide end-to-end supply chain traceability.*	*Does not capture the information needed to enable data-driven yield optimization approaches* *However, the platform provides classic planning capabilities for mechanized plowing, such as scheduling, which could lead to marginal efficiency gains.*	*Platform radically reduces transaction costs, making it possible to change farming practices* *Further reduction of transaction costs could be achieved through complementary policies such as increasing connectivity in rural areas.*	*Results in significant improvements in the financial capital base of smallholders* *Results in marginal improvements in the social capital base by enabling new forms of cooperation, where trust and reciprocity is enabled by the system.*
Dominant ledger functionality	AgriUT	*Information about origin and transfer prices between actors in the supply chain is operationalized in the ecosystem, allowing consumers to purchase goods that have been exchanged under fair conditions.* *User interface appears to be a critical factor in enabling traceability, as it is transparency for the consumer that enables*	*The information collected in this ecosystem is relevant to planning in that smallholders can more easily identify better buyers.* *However, improvements in planning are reduced to a commercial dimension unless information about field conditions is operationalized.*	*The impact on transaction costs for smallholders is limited because the application merely replicates existing supply chain relationships rather than reconfiguring the way stakeholders interact.* *Effective reductions in transaction costs are limited to donation schemes, and it remains questionable to what extent such schemes*	*Results in an improvement of the financial capital base, as the platform enables consumers to exert pressure for fairer commercial conditions for smallholders.* *Marginal effects on social capital can be expected, but it remains questionable whether these are conducive to real improvements in the long run.*

		structural change		*can achieve sustainable development in the long term.*	
Hybrid network and ledger functionalities	Agrikore	*Due to Cellulant's legacy as a mobile payment service provider, the scope of record keeping is limited to payments within the supply chain, thus creating transparency into the business conditions faced by smallholders.* *Lack of interfaces for consumers to easily access the recorded information limits the impact of creating supply chain transparency from a smallholder perspective.*	*The information collected in this ecosystem is relevant to planning in that smallholders can more easily identify better buyers.* *However, improvements in planning are reduced to a commercial dimension, as information on field conditions is not operationalized.* *Marginal gains in terms of better, but not data-driven, planning are achieved through access to finance.*	*The Agrikore ecosystem leads to a significant reduction in transaction costs, both in terms of existing supply chain relationships and access to finance.* *Moderation of supply chain interactions through smart contracts increases trust and reciprocity between stakeholders.*	*Improves the financial capital base of smallholder farmers by enabling them to sell their produce on the market instead of relying on subsistence farming.* *Improves the financial capital base of smallholders by providing access to finance* *Improves the social capital base of smallholders by creating new relationships of trust between different supply chain stakeholders.*

5. Discussion

The objective of this study is to examine the potential of blockchain technology in the context of data-driven agriculture to enhance the livelihoods of smallholder farmers. To this end, this study first identified two common functionalities of blockchain technology in data-driven agriculture applications and three different factors that need to be improved in order to improve the livelihoods of smallholder farmers. It also identified relevant case studies where blockchain technology has been integrated into data-driven applications for the benefit of smallholder farmers. These were analyzed to examine how the identified functionalities of blockchain technology lead to improvements in transaction costs, supply chain traceability, and yield optimization opportunities, the three relevant factors that the literature argues need to be addressed in order to improve the livelihoods of smallholder farmers were also considered.

Upon examination of the research question posed by this study, the case studies analyzed demonstrate that one of the most pressing issues that the integration of blockchain technology addresses in the context of data-driven agriculture is the high transaction costs associated with global agricultural supply chains. This is significant because a substantial proportion of smallholders do not sell their produce to the market, primarily because the cost of doing so is higher than the utility they would receive from doing so (Cuevas, 2014). This is important for the improvement of the livelihoods of smallholders, as improving their capacity to sell their produce to efficient markets is expected to result in an improvement of their income (Alobo Loison, 2015). Moreover, it seems that the integration of blockchain technology results in reductions of transaction costs for smallholders, regardless of whether the network functionality of the application in question is dominant and of whether the blockchain infrastructure captures information about a single or more stages of value generation across the supply chain. Consequently, the implementation of blockchain technology to digitally connect networks of supply appears to be a relatively straightforward method for enhancing smallholders' access to agricultural commodity markets, without necessarily accounting for the complexity of the entire supply chain. Upon examination of the matter of traceability throughout the supply chain, it appears that the potential effects of integrating blockchain technology into data-driven agricultural applications is more limited. Establishing a system where all transactions within the supply chain take place on a common platform provides consumers with a means to assess whether an agricultural commodity has been exchanged under fair commercial conditions. This allows ethically conscious consumers to avoid purchasing products that are highly intermediated, thereby exerting consumer pressure on intermediaries that engage in predatory commercial practices, or at least enabling higher prices for the products of fair smallholder agriculture. (Sammer & Wüstenhagen, 2006). However, the case studies analyzed did not design their data collection in a manner that would enable consumers to ascertain the agricultural inputs used to grow the commodities traded over the platforms. Integrating such information about the provenance and the local conditions under which agricultural products are grown remains an unsolved issue. Solving this could potentially result in even higher income levels among smallholders, as it would enable transparency and allow them to address a market segment of consumers willing to pay a higher price for their produce (Kremen et al., 2007). It is notable that applications designed to enhance product traceability must consider the entirety of the supply chain, which renders their implementation more challenging than that of data-driven applications aimed at modifying individual stages of value generation. Consequently, enhancing traceability across supply chains appears to be a more intricate issue than merely reducing transaction costs, which is in line with best practice for enabling product traceability through the implementation of blockchain technology (Yang et al., 2023). The integration of blockchain technology into data-driven agricultural applications to enable yield optimization through the deployment of predictive models appears to present the most significant challenge to overcome. The results of the case studies analyzed do not indicate any significant improvements in this field. To achieve this objective, it is necessary to utilize the blockchain in a manner that enables the collection and operationalization of all relevant data, including real-world information about the physical conditions on the fields (Sakthi et al., 2023). This data can then be utilized to facilitate data-driven yield optimization, which is not evident in any of the case studies analyzed. This represents a valuable consideration for developers of data-driven agriculture applications, as it enables the implementation of this farming practice for smallholder farmers. The current focus of both AgriUT and Agrikore is on economic aspects of the supply chain, rather than on the collection of real-world information, such as physical factors, that are necessary for assisting smallholders in optimizing their yields (Sakthi et al., 2023). In order for such applications to assist smallholders in their pursuit of better yields, a radical shift in information collection is required.

To ascertain the most effective manner in which blockchain technology can be deployed in the context of data-driven agricultural applications to the advantage of smallholder farmers, it is first necessary to define whether the application in question is designed to address individual stages of value generation within the supply chain, or whether it aims to capture the entire supply chain. For the former, it appears that the establishment of networks of stakeholders with the objective of reducing transaction costs for smallholders represents a relatively straightforward and effective means of improving their livelihoods. The cases demonstrate that this effect can be maximized by concurrently leveraging other aspects of blockchain technology, such as identity management schemes (Subramaniyan & Prabhu, 2023) and smart contracts (Feng et al., 2019), which further reinforce trust and potentially enable interactions with new stakeholders. This ultimately results in improvements regarding both the financial and social capital base of smallholder farmers. For the latter, simply reconfiguring how supply chain stakeholders interact with each other, with the sole objective of reducing transaction costs, appears to leave unrealized some attributes of blockchain technology that are conducive to the improvement of the livelihoods of smallholder farmers. For such applications, it is necessary to consider improvements in product traceability. Moreover, to achieve optimal supply chain traceability, it is essential to integrate not only commercial conditions but also information regarding agricultural practices and physical field conditions into the system (Yang et al., 2023). This integration would maximize the benefits of enhanced produce traceability for smallholder farmers in contexts comparable to the ones analyzed and would allow consumers to discover new information about the provenance of the products they consume stretching beyond the commercial transactions smallholder farmers engage in, thus potentially increasing income for smallholder farmers (Sammer & Wüstenhagen, 2006).

The application of predictive models and automated decision-making techniques has the potential to enhance the livelihoods of smallholders by improving their income and optimizing their utilization of resources (Ndimbo et al., 2023). This potential, however, appears to remain unrealized due to a lack of information collection regarding the physical conditions on the fields, which are crucial for enabling this mode of agricultural production (Yang et al., 2023). It is recommended that future research be directed towards this issue, particularly as optimizing yield through digital technology is the promise data-driven agriculture is praised to be conducive to and integrating smallholders into superior modes of agricultural production is in line with improving their livelihoods.

The results of this study may be subject to some degree of selection bias due to the sheer size of the overall pool of available case studies. Consequently, the case studies analyzed may not be representative of the way blockchain is integrated into data-driven agriculture applications, thereby reducing the generalizability of the obtained results. Nevertheless, the specific issues addressed by the case studies are reflective of the realities of smallholder farmers in specific contexts. Moreover, the income levels of farmers in each specific case appear to have benefited from the introduction of the analyzed applications, resulting in improvements of their livelihoods. These improvements were largely due to an increase in their financial capital base. By comparing the different functionalities blockchain technology enables against established mechanisms for improving the livelihoods of smallholder farmers, it is possible to construct a useful framework for assessing how the technology has the potential to improve the livelihoods of its users. This study assumes that structural conditions allowing for the adoption of technological solutions are given. However, in reality, structural issues such as limited mobile network coverage in rural areas (Mapiye et al., 2023), low digital literacy in smallholder communities (Magesa et al., 2023), low levels of trust towards outside actors (Ruml & Qaim, 2021), or particular socio-cultural practices might effectively hinder the adoption of new technological solutions. Accordingly, it is recommended that further research is directed to this issue to maximize the impact of digital applications in enabling smallholder farmers to transition towards more data-driven agricultural practices.

Methodologically, the proposed framework proved useful in addressing the research question. However, the differentiation between the various functionalities of blockchain technology in the context of data-driven agriculture proved to be inadequate during the course of the analysis. In fact, other features enabled by blockchain technology, such as automated enforcement of agreements through smart contracts or digital identity management through digital wallets, appear to be relevant for designing solutions aimed at enabling data-driven agriculture through the implementation of blockchain technology in a way that is beneficial for smallholder farmers. It is recommended that for future research that a more granular distinction of the functionalities enabled by blockchain technology be operationalized so that the impact of these features on the livelihoods of smallholder farmers can be more fully understood. It is recommended that when comparing the functionalities a given technological artifact enables against other dimensions, a more categorical differentiation of the analyzed functionalities is undertaken. Furthermore, future research should examine the potential for further improvements to the livelihoods of smallholder farmers, beyond increasing their financial capital stock. Other factors should be considered, as a more holistic approach (Mazibuko, 2013) to assess the extent to which blockchain technology could be leveraged for the purpose of sustainable development may yield more fruitful results. Nonetheless, this study manages to deliver insights that are in line with the literature insofar as systems leveraging the attributes of blockchain technology generally result in reductions of transaction costs, and thus disintermediation (Schmidt & Wagner, 2019). Furthermore, the results are in line with the literature in that enabling transparent record-keeping of the interactions taking place in a given ecosystem through distributed ledger technology results in better traceability of the interactions taking place in that system (Sunny et al., 2020).

This study demonstrates that the analyzed applications fail to fulfill the promise of data-driven yield optimization due to a lack of capture of relevant information for this purpose. Consequently, it is recommended that future research address the issue of what relevant data should be collected and how it should be operationalized to enable yield optimization through predictive models for smallholder farmers (Sakthi et al., 2023). To further examine this issue, it is recommended that researchers adopt a perspective that includes the role of blockchain technology in data-driven agriculture, as well as how it interacts with other technologies that the literature establishes as critical to enable data-driven yield optimization practices among smallholder farmers.

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Appendix A: Overview of the initial case study selection

Name	Scope	Goods and/or Services Provided
arbol	Recording and modelling of climate data to generate climatic models that can be leveraged either by farmers, for enhanced planning , by insurence to better assess climatic risk, or by other actors relying on climatic predictions for their planning	Raw climatic data for develpers of climatic forecast developers Climatic forecasts from climatic forecast developers using raw data Marketplace both for data exchange and for comparing climatic forecasts
AgriUT	Provision of information about the last mile to consumers while allowing consumers to directly "tip" smallholders for sustainable farming practice	Creation of records about the "last mile" of agricultural smallholder production Sale of low-cost smarphones serving as data sensors for the creation of records (Through AgriUnity - parent company)
Trace (FairFood)	Provision of SAS for first mile tracking for distributors of food products	Whitelabel Interface (comissioned by a distributor) between consumers and producers to track the supply chain of aggricultural goods
bext360	Provision of SAS for end-to-end tracking for distributors of food products	Whitelabel Interface (comissioned by a distributor) between consumers and producers to track the supply chain of aggricultural goods Additionally environmental and social issues such as labor conditions are included in the data collected
Moyee Cofee (Krypc)	Provision of end-to-end information about the different value stages of coffee in addition of carbon footprint assessments at each stage	End-to-end information about coffe (origin, roasteries, packing and logistics)
FairChain Farming	Creating producer surplus for smallholders in the coffee market through quality differentiation	Immutable registry of all transactions farm-to-fork Price discovery by quality of the beans produced through AI powered engines Training programs are offered to smallholders Force smallholders to establish commercial relationships to entities "controlled by them" at higher stages of value generation
Hello Tractor	Matchmaking between smallholders and mechanization service providers, for the rental of tractors in a pay-per-use model	Platform for matchmaking between smallholders and tractor owners Recordkeeping of the usage of tractors for mechanization service providers to optimize offering and enable a pay-per-use model Facilitation of payments between stages of value generation through stablecoins
Provenance	Provision of SAS for end-to-end tracking for distributors of food products with a focus on sustainability measures	Whitelabel Interface (comissioned by a distributor) between consumers and producers to track the supply chain of goods. Sustainability measures for brands and consumers to assess the sustainability impact of all stages of value generation
Open Harvest (Heifer Labs)	Improving farmers credit score both by providing them with best practice advice and recording the degree of attainment to these advices in Malawi	Providing farmers recommendations for planning based on AI generated climate models Generation and recording of Farmers' credit scores based on the degree they engage in best practice Intermediation with banks for accessing credit
Agrichain	Disintermediation of traditional supply chains through the usage of a digital platform	Marketplace for interactions with different actors across the value chain Tools for inventory management
AgriDigital	Disintermediation of traditional supply chains through the usage of a digital platform	Marketplace for interactions with different actors across the value chain Tools for inventory management Tools for harvesting management
Arc-Net	Provision of SAS for end-to-end tracking for brands of different types of goods throughout the value Chain	End-to-end traceability of different kinds of goods Tracking of on-site conditions for agricultural produce Certification of product autenticity Collection of data inputs for planning advice and precision agriculture
Agrikore (Cellulant)	Operating a digital market place connecting financial actors and agri supply chain actors	Offering of Financial services to rual populations in Africa through its digital marketplace Linking actors across agricultural supply chains Provision of infrastructure for blockchain-based digital payments

Appendix B: Declaration of originality master's thesis

By signing this statement, I hereby acknowledge the submitted Master's thesis titled

"Empowering smallholder farmers in data-driven agriculture through blockchain technology"

to be produced independently by me, without external help.

Wherever I paraphrase or cite literally, a reference to the original source (journal, book, report,internet, etc.) is provided.

I declare to also have finalized the SDG statement for this thesis (available in the MSc. thesis documentfolder on the Intranet).

By signing this statement, I explicitly declare that I am aware of the fraud sanctions as stated in theEducation and Examination Regulations (MSc-EER 2023-2024) of SBE, Maastricht University.

Place: Maastricht

Date: June 21st 2024

First and last name: Daniel Acosta Stasiukynas

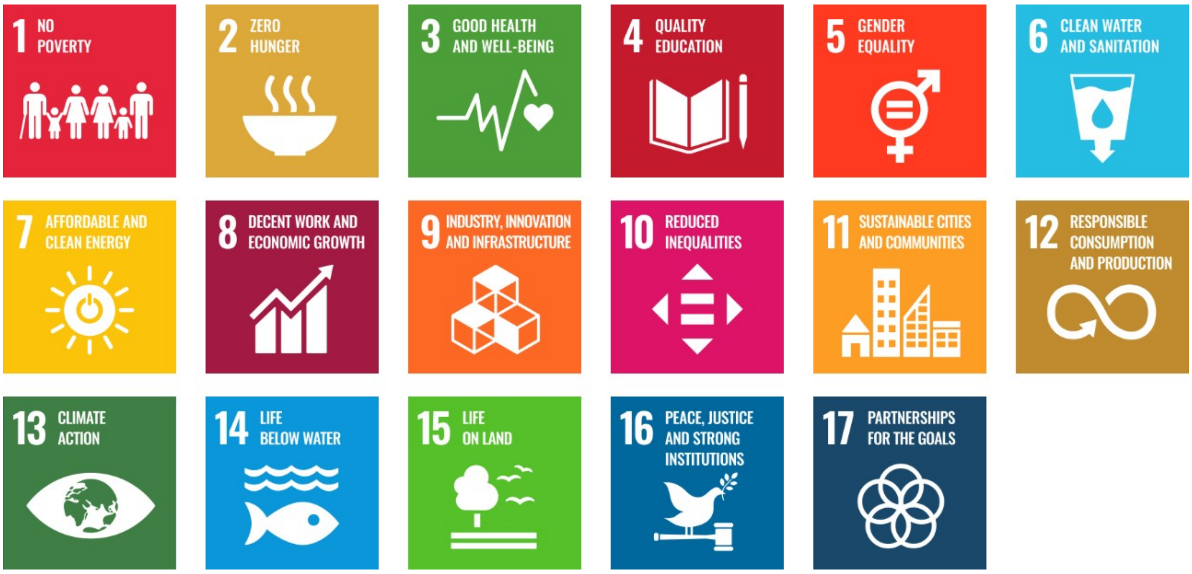
Study programme: Sustainability Science, Society, and Policy

ID number: 6368752

Signature: ....

Appendix C: Sustainable development goals (SDG) statement

Through the research conducted for this Master's thesis, I seek to contribute to one or more of the 17 SDG(s) set forth by the United Nations (https://www.undp.org/sustainable-development-goals). Specifically:



SDG Code(s): 1 and 2

Explanation (max. 300 words):

This master thesis contributes to the advancement of SDGs 1 and 2 as it aims to explore how the integration of blockchain technology to data-driven agriculture might improve the livelihoods of smallholder farmers. As farmers are the most vulnerable and poor actors in global agricultural changes improvements in their livelihoods are expected to result in poverty reduction. Furthermore, smallholder farmers build the backbone of food production in many geographies. This study explores how the integration of blockchain technology in data-driven agriculture might result in productivity gains for smallholders, thus also contributing to the eradication of hunger.