UNITED NATIONS DEVELOPMENT PROGRAMME

BLOCKCHAIN FOR AGRI-FOOD TRACEABILITY

Exploring the Technology's Potential for Sustainable Development

Blockchain for Agri-Food Traceability is a product of the UNDP Global Centre for Technology, Innovation and Sustainable Development, Singapore.

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FOREWORD

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Global agri-food systems need transformation. Almost 80 percent of the world's poor live in rural areas and mostly depend on agriculture for their livelihood. FAO estimated that as of 2018, agriculture directly contributed 17 percent of global greenhouse gas (GHG) emissions, thereby contributing significantly to climate change. Agriculture is also the major cause of environmental degradation and biodiversity loss globally.

Agri-food supply chains are complex and involve a large number of actors—from small-scale farmers, primary processors, and traders to product manufacturers, distributors, retailers, and consumers. This complexity limits farm-to-table traceability, which is key to identify sustainability-related issues in agri-food systems including extreme inequality and poverty, human rights violations, and environmental degradation.

Blockchain—the distributed ledger technology powering cryptocurrencies like bitcoin—is becoming a game-changer for supply chains. Its unique features make it a potent technology to reduce supply chain inefficiencies, enhance trust among diverse stakeholders, and contribute to cost savings. While blockchain's benefits for the private sector are perhaps clearer, its potential for addressing sustainability-related issues in the agri-food sector remains underexplored.

UNDP has been a pioneer in testing and demonstrating the feasibility of blockchain for advancing the Sustainable Development Goals (SDGs) in several agri-food value chains, such as cocoa, coffee, cashmere, and fisheries. To materialise its Strategic Plan 2022-2025, UNDP is invested in developing integrated solutions towards structural and inclusive transformation; blockchain technology is proving to be a key enabler for this objective.

Increased supply chain transparency enabled by blockchain and other digital solutions empowers stakeholders to spot and tackle the complex issues in agri-food sector. But the technology itself is only a piece of a larger puzzled—a common and thorough understanding of contexts, access to digital and stakeholder ownership are fundamental to long-term approaches to tackle inequality, so that no one is left behind.

I hope that this report sheds light on the potential of blockchain-enabled traceability can for value chains. We look forward to hearing your thoughts, ideas and embark together in the systemic transformation of agri-food supply chains to make them more resilient, fair, and inclusive.

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EXECUTIVE SUMMARY

Agri-food systems are under tremendous pressure. By 2050, the world's population is estimated to increase to about 9.7 billion. Feeding it will require increasing current food production by up to 98 percent. However, present agri-food supply chains—from 'farm to fork'—suffer from several inefficiencies and contribute to a number of socioeconomic and environmental problems.

The vast majority of small-scale producers, including smallholder farmers worldwide, often receive only a small fraction of the final market value of their produce. At their worst, inequities like these manifest as extreme poverty among farmers as well as human rights abuses at the farm-level in the form of slavery, child labour, and hazardous work environments.

Current agricultural practices also place undue pressures on the environment. Agri-food supply chains contribute 26 percent of anthropogenic release of greenhouse gases while using 50 percent of Earth's habitable land and 70 percent of freshwater. Moreover, agriculture is the largest contributor to the loss of biodiversity on Earth. In opaque supply chains comprised of a large number of suppliers, inequities and unsustainable practices at the first-mile are often masked.

The integrity of agri-food supply chains is often compromised through food safety incidents resulting from adulteration, dilution, tampering, or counterfeiting. Food fraud results in damages of up to $40 billion annually. Worse, the source of the problem is often not easily identifiable given the opacity of supply chains.

The above issues underline the common challenge of ensuring traceability and transparency in agri-food supply chains. There is growing global demand for sustainably sourced agri-food commodities (e.g., organic, slave free) among consumers, who are often willing to pay a premium for such products if they are convinced of the positive impact of their purchase. There is also growing interest among regulators and policymakers in traceability for ensuring a safe, sustainable, and resilient supply of food.

Blockchain—the technology at the heart of cryptocurrencies like bitcoin—is finding several applications in supply chain management. A blockchain is essentially a decentralised ledger distributed among all actors in the supply chain—unlike centralised databases and enterprise resource planning (ERP) systems controlled and operated by individual actors in siloes. In a blockchain, new transaction records and other relevant information is stored in the form of a 'block' which is cryptographically 'chained' to previous blocks. Once a record has been added to the ledger as a block, it cannot be secretly altered by any single actor. A blockchain is thus immutable and can act as a single source of truth with full data visibility possible for all stakeholders, thereby increasing supply chain efficiency, enhancing trust in the system, and reducing the likelihood of disputes.

These features make blockchain technology valuable for agri-food supply chains. Use of blockchain allows supply chain visibility till the farm-level, which can bring to light several inequities faced by small-scale producers. This visibility also enables upstream actors and policymakers to monitor for deforestation and other environmentally degrading farming activities. In case of detection of food contamination, blockchain-enabled traceability significantly improves the ease of identification and recall of the contaminated batches in the supply chain, immensely reducing costs from loss of sales and harm to human health.

Blockchain also enable 'smart contracts'—a self-executing mechanism embedded in the blockchain through which transactions can be automatically executed once pre-set conditions are met, removing the need for intermediaries. With smart contracts, disadvantaged stakeholders like smallholder farmers can benefit through regularly scheduled payments to support their livelihood. Additionally, transaction information can be securely and transparently shared among stakeholders who become aware of fair payments made to the farmers.

However, a number of important factors must be considered before opting a blockchain-powered supply chain traceability system. For instance, a traditional centralised database for recording transactions might be sufficient in case of relatively simple supply chains comprising of a limited number of actors or where there exist entities that trusted by all supply chain actors who can validate all transactions.

Moreover, implementing an end-to-end traceability system requires participation by all actors in a supply chain—from farmers, cooperatives, and processors to manufacturers, distributors, and retailers. This is often the harder part to manage than the technology itself as it requires careful assessment of the diverse incentives of all stakeholders for participating in a system that promotes transparency. Stakeholder engagement is crucial for aligning expectations and creating mechanisms of consensus building, data governance, and dispute resolution among parties.

Finally, when leveraging the technology for improving developmental outcomes, project managers should ensure that the most disadvantaged stakeholders—often the small-scale producers and smallholder farmers—do not get left behind. A traceability system requires the presence of basic digital infrastructure like internet connectivity and electricity at the first-mile, which might be a challenge in rural areas in developing countries. Also, literacy and digital skills of end-users must be taken into account when designing solutions.

1. TRANSFORMING AGRI-FOOD SYSTEMS

ISSUES WITH CURRENT AGRI-FOOD SYSTEMS

AGRICULTURE IS THE MAIN SOURCE OF INCOME FOR MOST OF THE WORLD'S POOREST PEOPLE, LIVING IN RURAL AREAS ON LESS THAN $1.25 DAILY.

With a projected world population of almost 10 billion in 2050, existing agri-food systems are unable to sustainably meet the nutritional demands of a burgeoning human civilisation.[1] Despite improving productivity in several commodities, the agricultural systems have not delivered in improving nutritional status globally. In order to achieve SDGs, it is imperative to look at agri-food systems holistically, from production, aggregation, and processing to distribution, consumption, and disposal. The sustainable expansion of agri-food systems is impeded by a number of challenges, including the inequity in benefits to small-scale producers, human rights issues, environmental degradation, and concerns on food integrity.

Inequity in the agri-food supply chain manifests in unfair compensation to small-scale producers, including smallholder farmers, at the origin of supply chains. For example, cocoa farmers on average receive only 3 percent of the market value of a chocolate bar.[2] Smallholder agriculture is the main source of income for 70 percent of the world's poor living in rural areas living on less than $1.25 daily.[3] With limited access to market, financing, and insurance opportunities, small-scale producers often rely on middlepersons who carve into their profits. Small-scale producers are also poorly protected against the risks of weather-dependent agricultural production.[4] More and more evidence points

1 Henri Leridon, "World population outlook: Explosion or implosion?" Population Societies 573, no. 1 (2020): 1–4, https://doi.org/10.3917/popsoc.573.0001.

2 Oliver Nieburg, "Paying the price of chocolate: Breaking cocoa farming's cycle of poverty," ConfectioneryNews, July 10, 2014, https://www.confectionerynews.com/Article/2014/07/10/Price-of-Chocolate-Breaking-poverty-cycle-in-cocoa-farming.

3 Nigel Poole, Smallholder agriculture and market participation (Rugby, UK: Practical Action Publishing, 2017), https://doi.org/10.3362/9781780449401.

4 Gerard Sylvester, ed., E-agriculture in action: Blockchain for agriculture (Bangkok: FAO and ITU, 2019), http://www.fao.org/publications/card/en/c/CA2906EN.

FOOD FRAUD RESULTS IN DAMAGES OF UP TO $40 BILLION ANNUALLY.

towards dependencies on markets for daily supply of food and nutritional security for a majority of small-scale producers. In opaque agri-food supply chains comprised of a large number of actors, inequities at the first mile are often masked.

At its worst, extreme inequity may manifest as human rights violations in the form of hazardous work environments and slavery. Children too often suffer from such violations. For instance, 25 percent of children aged 5 to 17 in Peru are being employed as child labour while 63 percent of working children in Philippines are being employed in hazardous conditions.[5] Such cases violate Article 11 of the International Covenant on Economic, Social and Cultural Rights (ICESCR), which protects the rights of everyone to a decent standard of living.[6] Unfortunately, such exploitative conditions remain concealed by the difficulty of monitoring labour conditions and the asymmetric power distribution between large agri-food actors (e.g., corporations) and small-scale producers.

Another problem with current agricultural practices is the undue pressure they place on the environment. The global agri-food supply chain contributes 26 percent of anthropogenic release of greenhouse gases while using 50 percent of Earth's habitable land and 70 percent of freshwater taken from ground or surface water sources such as rivers and lakes.[7] Moreover, agriculture is the largest contributor to the loss of biodiversity. A 2021 Chatham House report identified agriculture alone as the threat to 86 percent of all species at risk of extinction.[8]

With increasing consumer awareness about various environmental problems including the climate crisis, agri-food systems are increasingly under pressure to monitor and reduce their environmental impacts incurred during various supply chain operations. With growing concern on GHG footprint, it is important for agri-food systems to transition towards sustainable practices and tighter supply chains.

Finally, the integrity of agri-food supply chains is often compromised through food safety incidents. Stakeholders in the agri-food supply chain may intentionally or unintentionally alter the food distribution process—through adulteration, dilution, tampering, or counterfeiting—compromising the quality and safety of food. Food fraud results in damages of up to $40 billion annually.[9] Worse, the source of the problem is often not easily identifiable.

For instance, a foodborne outbreak caused by the Shiga toxin-producing E. coli was detected in Germany in 2011. Multiple lengthy investigations had to be conducted to determine the culprit—fenugreek seeds from Egypt. 50 people lost their lives and more than 4,000 fell ill. The incident caused the food industry in the European Union (EU) $1.3 billion. A ban on import of fenugreek seeds along with 15 other food products from Egypt cost the country about $4.2 billion.[10]

EXPLOITATIVE CONDITIONS REMAIN CONCEALED BY THE DIFFICULTY OF MONITORING LABOUR CONDITIONS AND THE ASYMMETRIC POWER DISTRIBUTION BETWEEN LARGE AGRI-FOOD ACTORS AND SMALL-SCALE PRODUCERS.

5 Vera Chiodi and Verónica Escudero, More is more. Livelihood interventions and child labor in the agricultural sector, ILO Working Paper 18 (Geneva: ILO, 2020), https://www.ilo.org/global/research/publications/working-papers/WCMS_764100/lang--en/index.htm.

6 Iman Prihandono and Fajri Hayu Relig, "International Certification as a Mechanism for Protecting the Human Rights of Indonesian Coffee Farmers," Environmental Policy and Law 49, no. 1 (2019): 49–54, https://doi.org/10.3233/epl-190125.

7 Joseph Poore and Thomas Nemecek, "Reducing food's environmental impacts through producers and consumers," Science 360, no. 6392 (2018): 987–992, https://doi.org/10.1126/science.aaq0216.

8 https://www.unep.org/news-and-stories/press-release/our-global-food-system-primary-driver-biodiversity-loss

9 Mischa Tripoli and Josef Schmidhuber, Emerging Opportunities for the Application of Blockchain in the Agri-food Industry, Revised version (Rome and Geneva: FAO and ICTSD, 2020), http://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1330492/.

10 Barakat Mahmoud, "The Most Common Food Safety Incidents Related to Developing Countries," Food Safety Magazine, August 20, 2019, https://www.food-safety.com/articles/6307-the-most-common-food-safety-incidents-related-to-developing-countries.

The inefficiencies in conducting traceback investigations reduces public trust in food safety. According to a study, merely 20 percent of global consumers placed complete trust in companies to ensure food safety.[11]

The need to raise awareness, manage unequal power distributions, meet sustainability standards, and enhance efficiency in agri-food supply chains drives the search for solutions. By monitoring the various stages of a supply chain, increased transparency enables companies and governments to readily trace information about an agri-food commodity across all stages.

AGRI-FOOD TRACEABILITY CHALLENGES

The above issues underline the common challenge of ensuring traceability in agri-food supply chains. Defined by the International Organization for Standardization (ISO) as "the ability to follow the movement of a feed or food through specified stage(s) of production, processing, and distribution",[12] traceability enables the efficient retrieval of key information on an agri-food commodity as it passes along the supply chain. Enhancing traceability can enable increased visibility on working conditions, monitoring of environmental impact of agri-food production, capability to track development outcomes, and improved public health outcomes. The importance of traceability is being recognised by diverse actors in agri-food supply chains, including regulators, corporations, and consumers.

Consumers are increasingly aware of the importance of environmental sustainability and labour standards during the production process of agri-food commodities. The number of American consumers who would switch brands to those that provide more in-depth product information, beyond what is on the physical label, nearly doubled from 39 percent in 2016 to 75 percent in 2018.[13] Additionally, over 71 percent of consumers around the world are willing to pay a premium for brands that provide transparent information. Where regulations are not in place to meet consumer demands, consumers can be a driver for change.

Complementing the rising consumer demand for traceability, voluntary third-party certification serves as a form of regulatory mechanism used by both public and private sectors in agri-food supply chains.[14] Demand from conscious consumers creates a market of certification standards which seek to reassure consumers by incorporating environmental, social, and food integrity considerations when evaluating supply chains. The adoption of third-party certification standards (e.g., Rainforest Alliance, Forest Stewardship Council, B Corporation) may demonstrate corporations' commitment towards responsible production. There also exist several third-party organisations certifying compliance with specific food production or management standards such as organic, kosher, or halal.

Despite the promises of third-party certifications, there are at least four distinct problems that limit its potential in enhancing traceability:

1. The proliferation of third-party certifications ironically reduces transparency in the certification sector. With over 400 certification systems for agricultural products in the EU alone, consumers may face decision paralysis in differentiating and evaluating the credibility of an individual certification.[15]
2. The legitimacy of certifications may itself be challenged. Companies may pursue 'greenwashing'[16] and use unverified certifications to present an environment-friendly image despite their unsustainable practices.[17] Together, these two challenges degrade consumer confidence in third-party certifications.
3. The enforcement of third-party certifications is dependent on audit processes which are fallible in their attempts to enhance traceability. Audit standards are most effective in addressing technical requirements but not

OVER 71% OF CONSUMERS AROUND THE WORLD ARE WILLING TO PAY A PREMIUM FOR BRANDS THAT PROVIDE TRANSPARENT INFORMATION.

11 Zebra Technologies, "Food Safety Supply Chain Vision Study," 2020, https://www.zebra.com/content/dam/zebra_new_ia/en-us/solutions-verticals/vertical-solutions/vision-study/food-safety-vision-study-2020-en-us.pdf.

12 Traceability in the feed and food chain — General principles and basic requirements for system design and implementation, ISO 22005:2007, 2016, https://www.iso.org/standard/36297.html.

13 Jessi Devenyns, "Report: Consumers want increased transparency from retailers and brands," Food Dive, September 21, 2018, https://www.fooddive.com/news/report-consumers-want-increased-transparency-from-retailers-and-brands/532723/.

14 Maki Hatanaka, Carmen Bain, and Lawrence Busch, "Third-party certification in the global agrifood system," Food Policy 30, no. 3 (2005): 354–369, https://doi.org/10.1016/j.foodpol.2005.05.006.

15 M. Ya. Bomba and N. Ya Susol, "Main requirements for food safety management systems under international standards: BRC, IFS, FSSC 22000, ISO 22000, Global GAP, SQF," Scientific Messenger of LNU of Veterinary Medicine and Biotechnologies. Series: Food Technologies 22, no. 93 (2020): 18–25, https://doi.org/10.32718/nvlvet-f9304.

16 Greenwashing, a term coined in the 1980s, refers to companies disseminating disinformation to present a false public image of being environmentally responsible.

17 Iñaki Heras-Saizarbitoria, Olivier Boiral, and Alberto Díaz de Junguitu, "Environmental management certification and environmental performance: Greening or greenwashing?" Business Strategy and the Environment 29, no. 6 (2020): 2829–2841, https://doi.org/10.1002/bse.2546.

WITH OVER 400 CERTIFICATION SYSTEMS FOR AGRICULTURAL PRODUCTS IN THE EU ALONE, CONSUMERS MAY FACE DECISION PARALYSIS IN DIFFERENTIATING AND EVALUATING THE CREDIBILITY OF AN INDIVIDUAL CERTIFICATION.

violations of social and environmental standards.[18] The subjective nature of the audit process may result in the use of audits as a deceptive tool to conjure positive business images (greenwashing). The growing demand for traceability is accompanied by a rise in audit fraud.[19] The increased demand for audits places immense pressure on auditors, leading to compromises in the accuracy of documentation. Moreover, even when audits identified non-conforming suppliers, they often go unpunished. Studies found that only about half of the firms surveyed imposed penalties on suppliers for social or environmental violations.20

4. Third-party certifications are expensive and may exclude smallholder farmers and small-scale producers from accessing markets in developed countries, where conscious consumers concentrate.

For some agri-food supply chains, these challenges translate to undetected human rights abuses. In the tea industry, for example, the Rainforest Alliance certification was awarded to tea estates who were suspected of degrading working conditions despite its supposedly strict criteria.[21] Such unfortunate reports degrade confidence among actors in third-party certifications and claims of traceability. Moreover, consumer demand might be an insufficient driver for change, serving at best as a motivating force for governments and businesses to take action to address the lack of transparency in agri-food supply chains.

In contrast, government regulations mandating traceability in agri-food supply chains may be more effective, provided that they are duly enforced and the market puts trust in the process. Regulatory requirements set minimum standards of compliance and attempt to address asymmetric information within supply chains. Regulations serve as formalised mechanisms that reward and punish firms participating in nations' agri-food markets.[22]

For instance, in Malaysia, the Malaysian Sustainable Palm Oil (MSPO) is a nationally mandated certification scheme supporting smallholder farmers and environmental protection. In contrast with the Roundtable on Sustainable Palm Oil (RSPO)—the global certification scheme which relies on voluntary participation—the MSPO draws lessons from the RSPO and tailors it to local communities, enhancing its effectiveness.

Consequently, leveraging the enforcement capacities of governments can accelerate the implementation of traceability solutions in the supply chain. Examples of existing regulations in different countries are highlighted in the following table.

18 Tannis Thorlakson, Jens Hainmueller, and Eric F. Lambin, "Improving environmental practices in agricultural supply chains: The role of company-led standards," Global Environmental Change 48 (2018): 32–42, https://doi.org/10.1016/j.gloenvcha.2017.10.006.

19 Muhammad Kamran Khalid, Mujtaba Hassan Agha, Syed Tasweer Hussain Shah, and Muhammad Naseer Akhtar, "Conceptualizing Audit Fatigue in the Context of Sustainable Supply Chains," Sustainability 12, no. 21 (2020): 9135, https://doi.org/10.3390/su12219135.

20 Thorlakson, Hainmueller, and Lambin, "Improving environmental practices in agricultural supply chains: The role of company-led standards."

21 Tansy Hoskins, "Supply Chain Audits Fail to Detect Abuses, Says Report," The Guardian, January 14, 2016, https://www.theguardian.com/sustainable-business/2016/jan/14/supply-chain-audits-failing-detect-abuses-report.

22 Peter Newton, Arun Agrawal, and Lini Wollenberg, "Enhancing the sustainability of commodity supply chains in tropical forest and agricultural landscapes," Global Environmental Change 23, no. 6 (2013): 1761–1772, https://doi.org/10.1016/j.gloenvcha.2013.08.004.

Table 1: Examples of existing traceability regulations in different countries

United States	China	Vietnam
Traceability standards were initially imposed under the Bioterrorism Act of 2002. The integrity of agri-food supply chains is observed by the Food and Drug Administration (FDA).[23] In 2020, section 204 (Enhancing Tracking and Tracing of Food and Recordkeeping) was proposed for inclusion in the Food Safety Modernisation Act (FSMA) to create a standardised approach for traceability mechanisms.[24]	The first Food Safety Law (FSL) was implemented in 2009. Various law enforcement departments have since implemented related laws and regulations.[25] In 2015, the FSL imposed stricter punishments for food safety violations, obliging sellers to be accountable for agri-food commodities sold to consumers.	Part of the Prime Minister's Decision 100 QD-TTg (Project 100), a national portal has been created to trace the provenance of agri-food commodities. All parties in the supply chain will be involved in the traceability system.[26] Currently, 48 localities have begun issuing plans for the implementation of the project, including workshops on traceability and preparation for necessary digital infrastructure.[27]

Another challenge with implementing traceability—whether as part of third-party certifications or regulations—concerns technology. Currently, recordkeeping in agri-food supply chains is largely manual and paper-based. The large number of actors each keep their own records on transactions. Even when digital records are kept using simple desktop software, they remain siloed and do not allow transparency within the supply chain.

Similar is the case with enterprise resource planning (ERP) systems used by most large corporations for the integrated management of business operations. ERP systems enable real-time updating and sharing of information after data entry.[28] In the agri-food industry, ERP systems are tailored for unique processes to reduce human error from traditional accounting methods. Unsurprisingly, most multinational corporations (MNCs) adopt ERP systems to manage the complex web of international supply chains. However, these centralised information storage systems contain opaque records of information which are subject to risk of false or inaccurate representation.[29] ERP systems are not an effective tool to address traceability concerns within the supply chain if there is trust deficiency among diverse stakeholders.

To overcome these challenges, existing traceability concepts in agri-food supply chains need revision. Currently, the concept of 'one-up, one-down' is the standard for recording information from direct suppliers and clients.[30] It tracks the immediate producer and receiver of the agri-food commodity to determine its provenance. However, this mechanism is inefficient and subject to manual records and slow communication between stakeholders. Supply chain-wide visibility is also limited, affecting the verification of supplier practices, provenance, and authenticity of agri-food commodities.

An end-to-end traceability system can address these limitations of the 'one-up, one-down' standard, tracking various characteristics of an agri-food commodity across different parts of the supply chain. Information recorded in such a system would include Key Data Elements (KDEs), which are physical characteristics of an agri-food commodity (e.g., weight, colour, shape),

23 Ali Demirci, Hao Feng, and Kathiravan Krishnamurthy, ed., Food Safety Engineering (Springer International Publishing, 2020), https://doi.org/10.1007/978-3-030-42660-6.

24 Frank Yiannas, "FDA Announces Key FSMA Rule to Advance Traceability of Foods, A Major Milestone in the New Era of Smarter Food Safety," FDA Statement, U.S. Food and Drug Administration (FDA), September 21, 2020, https://www.fda.gov/news-events/press-announcements/fda-announces-key-fsma-rule-advance-traceability-foods-major-milestone-new-era-smarter-food-safety.

25 Riccardo Berti and Mariagrazia Semprebon, "Food traceability in China," European Food and Feed Law Review 13, no. 6 (2018): 522–531, https://www.jstor.org/stable/26556927.

26 VNA, "Vietnam will have national portal on product traceability this year," Vietnam+, April 8, 2021, https://en.vietnamplus.vn/vietnam-will-have-national-portal-on-product-traceability-this-year/199801.vnp.

27 "Simultaneously deploying Project 100 on traceability in localities," Can Tho STnews, July 21, 2021, http://www.en.trithuckhoahoc.vn/Default.aspx?tabid=235&NDID=16783.

28 C. N. Verdouw, Robbert M. Robbemond, and J. Wolfert, "ERP in agriculture: Lessons learned from the Dutch horticulture," Computers and Electronics in Agriculture 114 (2015): 125–133, https://doi.org/10.1016/j.compag.2015.04.002.

29 Tian Feng, "An information System for Food Safety Monitoring in Supply Chains based on HACCP, Blockchain and Internet of Things," PhD dissertation, WU Vienna University of Economics and Business (2018), https://epub.wu.ac.at/id/eprint/6090.

30 United Nations Network of Experts for Paperless Trade in Asia and the Pacific (UNNExT), Information Management in Agrifood Chains: Towards an Integrated Paperless Framework for Agrifood Trade Facilitation (Bangkok: United Nations Economic and Social Commission for Asia and the Pacific, 2015), https://www.unescap.org/resources/information-management-agrifood-chains-towards-integrated-paperless-framework-agrifood.

and Critical Tracking Events (CTEs), which track the changes to a product during the transportation, transformation, and depletion process.[31]

To facilitate the accurate recording of information through the supply chain, a unique identifier is attached to each batch of agri-food commodity.

Use of various information and communications technologies (ICTs) can enable the following functionalities in an end-to-end traceability system:[32]

- Collection of information about characteristics of individual agri-food commodities through technology-enabled identifiers
- Continuous collection of information through the supply chain
- Data transfer and information sharing among stakeholders and certifying agencies
- Secure storage of information for internal and external uses
- Verification of information accuracy

The implementation of an end-to-end traceability system has been facilitated by the emergence of blockchain technology. In 2016, in one of the initial examples of the use of the emerging technology for agri-food traceability, retail giant Walmart and IBM demonstrated the use of blockchain to track the provenance of mangoes. The result was a spectacular improvement in the efficiency of provenance identification—from seven days to a mere 2.2 seconds.[33] Blockchain can complement existing ICT solutions to revolutionise agri-food supply chains.

WALMART AND IBM DEMONSTRATED THE USE OF BLOCKCHAIN TO TRACK THE PROVENANCE OF MANGOES. THE RESULT WAS A SPECTACULAR IMPROVEMENT IN THE EFFICIENCY OF PROVENANCE IDENTIFICATION—FROM SEVEN DAYS TO A MERE 2.2 SECONDS.

The following sections of this report will examine blockchain technology in greater detail and examine its applicability for agri-food supply chains. Section 2 will provide an overview of blockchain technology and its features which enable supply chain traceability. Section 3 will assess the feasibility of adopting blockchain and highlight key considerations for project managers. Section 4 will outline the limitations of blockchain technology. Overall, the report aims to serve as a guidebook for project managers for assessing the feasibility of a blockchain-enabled traceability system for agri-food supply chains and guiding its implementation.

31 Ali, Feng, and Krishnamurthy, ed., Food Safety Engineering.

32 Sununtar Setboonsarng, Jun Sakai, and Lucia Vancura, "Food safety and ICT traceability systems: Lessons from Japan for developing countries," ADBI Working Paper 139 (Tokyo: Asian Development Bank Institute, 2009), http://hdl.handle.net/11540/3727; Diana Kos and Sanneke Kloppenburg, "Digital technologies, hyper-transparency and smallholder farmer inclusion in global value chains," Current Opinion in Environmental Sustainability 41 (2019): 56–63, https://doi.org/10.1016/j.cosust.2019.10.011.

33 Reshma Kamath, "Food Traceability on Blockchain: Walmart's Pork and Mango Pilots with IBM," The Journal of the British Blockchain Association 1, no. 1 (2018): 1–12, https://doi.org/10.31585/jbba-1-1-(10)2018.


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2. BLOCKCHAIN TECHNOLOGY FOR AGRI-FOOD TRACEABILITY SYSTEMS

ORIGIN AND KEY FEATURES OF BLOCKCHAIN TECHNOLOGY

The development of blockchain technology happened unrelated to agri-food supply chains. In 2008, the creation of Bitcoin—the world's first digital cryptocurrency—by Satoshi Nakamoto spurred the rise of blockchain.[34] The innovative idea of a decentralised ledger was highly commended for its potential to provide transparency and accountability while protecting the privacy of stakeholders within a blockchain network.[35] Independent stakeholders of the network share the same set of data without directly interacting with each other, creating a system where users are not dependant on trusting one another—in other words, a 'trustless'[36] system that operates based on a consensus mechanism.[37] Soon, various industries garnered interest in the technology to catalyse its further development.

BLOCKCHAIN IS A DECENTRALISED LEDGER THAT IS CONSENSUS DRIVEN AND TAMPER-EVIDENT.

A blockchain-enabled system differs from the traditional data governance structure of a centralised database where a party or 'node' within the network is trusted by all other nodes and responsible for checking and distributing duplicate data to each actor. In many agri-food supply chains, it is difficult to pinpoint a single trusted party that can verify information on behalf of all stakeholders; hence the need for a decentralised traceability system.[38] To eliminate the need for a central and

34 Satoshi Nakamoto, "Bitcoin: A Peer-to-Peer Electronic Cash System," www.bitcoin.org (2008), https://bitcoin.org/bitcoin.pdf.

35 Daniel Tse et al., "Blockchain application in food supply information security," 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) (Singapore: IEEE, 2017): 1357–1361, https://doi.org/10.1109/IEEM.2017.8290114.

36 In a trustless system, trust is distributed evenly across the network. Participants do not need to trust each other but can conduct transactions through a previously agreed upon validation mechanism.

37 Dhruman Gohil and Shivangi Viral Thakker, "Blockchain-integrated technologies for solving supply chain challenges," Modern Supply Chain Research and Applications 3, no. 2 (2021): 78–97, https://doi.org/10.1108/MSCRA-10-2020-0028.

38 Feng, "An information System for Food Safety Monitoring in Supply Chains based on HACCP, Blockchain and Internet of Things."

trusted node, blockchain prevents data manipulation by continuously encrypting data into 'blocks' which are then added to a chain of existing blocks in an irreversible linear sequence.[39]

The encryption process of data involves hashing, which is a cryptography method that converts any form of data input into a unique string of text that can be stored on-chain. The process is one-way, meaning that participants may not decrypt and obtain the transactional information of other participants if they are not provided access to it. Since each new block is created using the hash of the previous block, whenever any on-chain data is changed, all subsequent blocks will reflect the change. As a result, blockchain fulfils the desired characteristics of a decentralised ledger that is consensus driven, yet secure and tamper-evident.[40]

In summary, blockchain consists of five defining features:

1. **Distributed ledger**. Blockchain is an open distributed ledger that can record transactions between two parties efficiently in a verifiable and permanent way by bundling them together in cryptographically linked blocks. The sequence of blocks differentiates a blockchain from conventional distributed ledgers, which act as a form of a database.
2. **Peer-to-peer (P2P) network**. Peer discovery and data sharing does not require a trusted and central middleperson. The distributed nature of the ledger makes it resilient as information remains accessible even if many peers are offline.
3. **Computational logic**. The use of cryptographic techniques enhances security and ensures that systematic protocols are in place. It strengthens confidence in the automation of work processes to enhance efficiency.
4. **Transparency and privacy**. Users can choose to remain anonymous or provide proof of their identity to others. During a transaction, encrypted information between blockchain addresses is exchanged, allowing the protection of users' identity.
5. **Immutability**. Once a record has been added to the ledger as a block, it cannot be secretly altered since all subsequent records will be linked to it. Any changes to past records must be validated via consensus amongst all network participants.

These features are highly valuable in agri-food supply chains. The blockchain acts as a single source of truth with full data visibility possible for all stakeholders. It can complement existing centralised ERP systems through a distributed system providing permanent and transparent records trusted by all actors.

FUNDAMENTAL FEATURES OF BLOCKCHAIN TECHNOLOGY

Public, Private, and Consortium Blockchains

Several types of blockchains exist, each with contrasting functionalities and permissions to meet the needs of diverse stakeholder relationships within the network.[41]

Public blockchain: A public blockchain is governed by democratic principles with no access restrictions. Anyone with access to the blockchain can send or validate transactions. These networks typically offer economic incentives for validators who operate through consensus mechanisms.

Private blockchain: A private blockchain is permissioned. One cannot join it unless invited by the network administrators. Participant and validator access is restricted. Under a permissioned blockchain, members of the network are usually known to each other, and consensus mechanisms are simpler. While private blockchain provides more privacy, scalability, and ease of governance, it may be less tamper-resistant.

Consortium blockchains: A consortium blockchain is semi-decentralised. It is also permissioned, but instead of a single organisation controlling it, multiple actors might each operate a node on such a network. The administrators of a consortium chain restrict users' reading rights as they see fit and only allow a limited set of trusted nodes to execute a consensus protocol.

THE BLOCKCHAIN ACTS AS A SINGLE SOURCE OF TRUTH WITH FULL DATA VISIBILITY POSSIBLE FOR ALL STAKEHOLDERS.

39 Michaela A. Balzarova and David A. Cohen, "The blockchain technology conundrum: Quis custodiet ipsos custodes?" Current Opinion in Environmental Sustainability 45 (2020): 42–48, https://doi.org/10.1016/j.cosust.2020.08.016.

40 Marco Iansiti and Karim R. Lakhani, "The Truth About Blockchain," Harvard Business Review 95, no. 1 (2017): 118–127, https://hbr.org/2017/01/the-truth-about-blockchain; Abderahman Rejeb, John G. Keogh, and Horst Treiblmaier, "Leveraging the Internet of Things and Blockchain Technology in Supply Chain Management," Future Internet 11, no. 7 (2019): 161, https://doi.org/10.3390/fi11070161.

41 Christine Leong, Tal Viskin, and Robyn Stewart, Tracing the Supply Chain: How Blockchain Can Enable Traceability in the Food Industry (Accenture, 2019), https://www.accenture.com/us-en/insights/blockchain/food-traceability; Gerard Sylvester, E-agriculture in action: Blockchain for agriculture: Challenges and opportunities (Bangkok: FAO, 2019), http://www.fao.org/publications/card/en/c/CA2906EN.

Businesses tend to opt for private or consortium blockchains to manage the read and/or write permissions of specified parties on the network.[42] Agri-food supply chains actors may also prefer permissioned blockchains to benefit from greater security and efficiency.

Table 2: Comparison between different types of blockchains

FEATURES	PUBLIC no centralised management	CONSORTIUM / PRIVATE multiple organisations / single organisations
Identity of Participants	Permissionless Anonymous Could be malicious	Permissioned read and/or write Identified Trusted
Speed of Processing Transactions	Can be set to open read and/or write Slow E.g., Bitcoin: Block Approval Frequency of 10 min. or more	Fast
Unique Value Proposition	Disruptive Disintermediation, removing the need for middlepersons and the corresponding cost for a large public system involving many trustless stakeholders Transparent to the public	Functional Can substantially reduce transaction costs Lower data redundancy Higher transaction frequency More transparency within the network

Additionally, a hybrid blockchain may be built by combining features of both private and public blockchains.[43] Organisations can control and customise the blockchain architecture to meet their needs. In a hybrid blockchain, the private system may protect users and disclose selected information to the public. The public anonymity of users can be maintained as identities are only released to another user during the transaction process. For example, customers may be able to publicly view the source of their products but may not be able to access restricted information such as a company's sales values.

Consensus Mechanism

A consensus mechanism is a predetermined set of rules that all parties follow to maintain the network. Consensus mechanisms govern the information added to a ledger. New blocks of data entries and transaction information are validated through a consensus algorithm before it is added to the existing blockchain.[44] The consensus mechanism bypasses the need for a central authority through a pre-existent agreement among different nodes to maintain a consistent record of information. Different types of blockchains may adopt different consensus mechanisms (see Appendix I for more information on consensus mechanisms).

Smart Contracts

Smart contracts replace traditional contracts by having terms of agreements directly written into lines of code, enabling a self-executing mechanism that can exist on a blockchain network. Stakeholders can predefine the rules of a business

42 Vector ITC, "Companies Prefer Private Blockchain for Security," Vector ITC, October 11, 2018, https://www.vectoritcgroup.com/en/tech-magazine-en/cybersecurity-en/companies-prefer-private-blockchain-for-security/.

43 Diego Geroni, "Hybrid Blockchain: The Best of Both Worlds," 101 Blockchains, January 28, 2021, https://101blockchains.com/hybrid-blockchain/.

44 Saikat Mondal et al., " Blockchain Inspired RFID-Based Information Architecture for Food Supply Chain," IEEE Internet of Things Journal 6, no. 3 (2019): 5803–5813, https://doi.org/10.1109/JIOT.2019.2907658.

relationship and codify the transaction protocol on a blockchain platform. Transactions can then be automatically executed once conditions are met, removing the need for intermediaries. Consequently, simple yet manual processes such as verification of information can be replaced, allowing transactions to proceed with greater efficiency.[45] Blockchain technology supports the use of smart contracts since the data stored is immutable and secure, allowing transactions to be conducted securely.

With smart contracts, farmers can benefit through regularly scheduled payments to support their livelihood.[46] Additionally, information collected is securely and transparently shared among stakeholders who become aware of fair payments made to these farmers. Problems of inequity and human rights violations can be better managed through direct engagements with farmers through smart contracts.

Notably, there are two main paradigms when discussing smart contracts:[47]

Figure 1: Code-only and ancillary smart contracts

Tokenisation

Tokenisation, in the context of blockchain technology, is "the process of converting something of value into a digital token that's usable on a blockchain application."[48] Physical agri-food commodities can be represented by digital tokens on a blockchain.

The primary benefit of tokenisation is fragmentised ownership. For example, a smallholder rancher might choose to tokenise their cattle if they are in the business of beef production and the cattle is one of their most valuable assets. They may then conduct transactions using these tokens. Essentially, instead of having to wait for the cattle to mature before they can sell it for a lump sum, the rancher can now transact a piece of ownership in advance and receive consistent revenue throughout the cattle's lifespan. This minimises seasonality effects and increases security for small-scale producers.

The tokenisation of agri-food products also has synergies with smart contracts as tokenisation can be used as an identification mechanism to track the characteristics of physical goods or batches of goods. Since each token is unique, the characteristics of the goods can be tracked individually and tracked changes may activate pre-defined smart contract clauses enabling autonomous transactions. For the same rancher in the example above, height and weight of the cattle could be measured to track its growth, and payments automatically sent to the rancher whenever certain pre-determined growth targets are met.

Ancillary Technologies

The viability of blockchain in agri-food supply chains is ascertained through ancillary technologies in the form of hardware and software oracles connected through the Internet of Things (IoT).[49] The IoT is an information network that connects sensors with

45 Wei Liu et al., "A systematic literature review on applications of information and communication technologies and blockchain technologies for precision agriculture development," Journal of Cleaner Production 298 (2021): 126763, https://doi.org/10.1016/j.jclepro.2021.126763.

46 Samuel Green, "Decentralized Agriculture: Applying Blockchain Technology in Agri-Food Markets," Unpublished master's project (Calgary, AB: University of Calgary, 2018), https://doi.org/10.11575/PRISM/34952.

47 Stuart D. Levi and Alex B. Lipton, "An Introduction to Smart Contracts and Their Potential and Inherent Limitations," Harvard Law School Forum on Corporate Governance, May 26, 2018, https://corpgov.law.harvard.edu/2018/05/26/an-introduction-to-smart-contracts-and-their-potential-and-inherent-limitations/.

48 Cryptopedia, "What Is Tokenization in Blockchain?" Gemini, August 12, 2021, https://www.gemini.com/cryptopedia/what-is-tokenization-definition-crypto-token.

49 Francisco Blaha and Kenneth Katafono, Blockchain application in seafood value chains, FAO Fisheries and Aquaculture Circular No. 1207 (Rome: FAO, 2020), https://doi.org/10.4060/ca8751en.

physical objects (things).[50] Many components of IoT serve as oracles—connections between the digital and physical worlds that can retrieve information for a blockchain to execute smart contracts.[51] A blockchain oracle acts as a secure middleware to collect and transfer information between blockchains.

A range of hardware and software oracles can be used alongside blockchains. Hardware oracles include quick response (QR) codes, radio frequency identifier (RFID) devices, and wireless sensors. Software oracles include web application programming interfaces (APIs). More information is attached in Appendix II for the interested reader.

These ancillary technologies support blockchains through the monitoring and verification of information in agri-food supply chains. For example, chemical and biological sensors can collect data on the usage of pesticides and fertilisers on farms. The immutability characteristic of a blockchain means the stored data is deemed secure and useful to verify sustainability certifications and ensure the integrity of agri-food commodities throughout the supply chain.

APPLYING BLOCKCHAIN IN AGRI-FOOD SUPPLY CHAINS

Popular Blockchains in the Agri-Food Space

Project managers considering incorporation of blockchain technology in agri-food supply chains might be interested in popular blockchains in the arena. Ethereum and Hyperledger Fabric remain integral in the discussion on the type of blockchain for organisational usage and serves as a baseline for comparison between different blockchain technologies.

Ethereum is an open software platform with permissionless blockchain network optimised for smart contracts that uses its own cryptocurrency called Ether.[52] It allows anyone to personalise their smart contracts that is connected to the Ethereum blockchain for validation by public nodes.

Hyperledger Fabric is an open-source project from the Linux Foundation supporting enterprise blockchain platforms.[53] It has advanced privacy controls for permissioned blockchains which shares data and participation rights with specified and authorised stakeholders only.

A 2021 study of 80 projects in agri-food supply chains found that 19 percent of blockchain projects adopted Ethereum while 10 percent used Hyperledger Fabric.[54] Noting that 47 percent of the projects did not reveal any information about their blockchain-based solutions, the finding is instructive of the dominance of these two blockchain architectures.

Between Ethereum and Hyperledger, project developers who hope to protect the private nature of transactional relationships may prefer Hyperledger. The 'channels' feature in Hyperledger Fabric allows for total transaction isolation, while the 'private data' feature keeps data private while sharing hashes as transaction evidence. Hyperledger Sawtooth, an alternative to Hyperledger Fabric, provides further specialised technologies tailored to different needs of enterprises.[55]

Blockchain-as-a-Service (BaaS)

Project managers in the agri-food sector may also be interested in readily available solutions and the future development trends in blockchain technology. Blockchain-as-a-solution (BaaS) is an increasingly popular service where companies can share existing blockchain infrastructure with monthly or annual service fees.[56] Currently, some ERP software companies like SAP and Oracle are moving up their value chain to develop the middleware technologies required to achieve synergy between existing ERP systems and blockchain networks.

Many ongoing BaaS trials focus on supply chain management and provenance checks. These solution providers have mostly adopted a model of offering blockchain services on cloud platforms to companies that want to employ blockchain but find it difficult due to high barriers to entry including high upfront costs and the unavailability of technical expertise. BaaS clients may also benefit from complementary consultation services offered by solution providers, ensuring the suitable employment of blockchain features to meet their needs. With rapid advances in multiple frontiers of the technology, new developments will be closely monitored by BaaS providers. The following table provides an objective and non-exhaustive comparison between existing BaaS providers. Appendix III provides technical details on future developments in blockchain technology.

50 Rejeb, Keogh, and Treiblmaier, "Leveraging the Internet of Things and Blockchain Technology in Supply Chain Management."

51 Giulio Caldarelli, "Understanding the Blockchain Oracle Problem: A Call for Action," Information 11, no. 11 (2020): 509, https://doi.org/10.3390/info11110509.

52 Petri Helo and A. H. M. Shamsuzzoha, "Real-time supply chain—A blockchain architecture for project deliveries," Robotics and Computer-Integrated Manufacturing 63 (2020): 101909, https://doi.org/10.1016/j.rcim.2019.101909.

53 Shishir Ranjan et al., "Network System Design using Hyperledger Fabric: Permissioned Blockchain Framework," 2019 Twelfth International Conference on Contemporary Computing (IC3) (IEEE, 2019): 1–6, https://doi.org/10.1109/IC3.2019.8844940.

54 Andreas Kamilaris, Ian R. Cole, and Francesc X. Prenafeta-Boldú, "Blockchain in agriculture," in Food Technology Disruptions, ed. Charis M. Galanakis (Academic Press, 2021), 247–284, https://doi.org/10.1016/C2019-0-02014-6.

55 Benjamin Ampel, Mark Patton, and Hsinchun Chen, "Performance Modeling of Hyperledger Sawtooth Blockchain," 2019 IEEE International Conference on Intelligence and Security Informatics (ISI) (Shenzhen, China: IEEE, 2019): 59–61, https://doi.org/10.1109/ISI.2019.8823238.

56 Arnad Banerjee, Integrating Blockchain with ERP for a Transparent Supply Chain, White paper (Infosys, 2018), https://www.infosys.com/oracle/white-papers/documents/integrating-blockchain-erp.pdf.

Table 3: Blockchain-as-a-service providers[57]

	SAP	ORACLE	aws	IBM
Hosting platforms	Hyperledger Fabric	Hyperledger Fabric	Hyperledger Fabric Ethereum Quorum Corda	Hyperledger Fabric
Blockchain type	Permissionless	Permissioned, Consortium	Permissioned	Permissioned
Authentication and authorisation services	–	Pay per use	Pay per use	Monthly subscription with free trial
Scalability	–	–	Provides API for quick node creation	IBM Smart Cloud only

The unique aspects of blockchain technology—particularly, transparency and immutability—can address issues related to income inequity, environmental degradation, human rights violations, and food safety in agri-food supply chains. By leveraging ancillary technologies, agri-food characteristics of interests can be tracked digitally through the supply chain, enabling quick identification and remedy of problems.

The promise of blockchain technology and the relative ease of its application may appeal to project managers working in the agri-food sector. Nonetheless, there are additional technical considerations for implementing a blockchain solution. In the next section of this report, project-related, operational, and technical considerations are highlighted for the reader to ponder over before adopting the technology.

57 Md Mehedi Hassan Onik and Mahdi H. Miraz, "Performance Analytical Comparison of Blockchain-as-a-Service (BaaS) Platforms," International Conference for Emerging Technologies in Computing (iCETiC 2019) (Springer, 2019): 3–18, https://doi.org/10.1007/978-3-030-23943-5_1.

3. IMPLEMENTING BLOCKCHAIN IN AGRI-FOOD SUPPLY CHAINS

GIVEN THE ADDITIONAL COMPLEXITIES OF DESIGNING AND DEPLOYING A BLOCKCHAIN SOLUTION, IT IS IMPORTANT TO ASCERTAIN WHETHER ONE IS TRULY REQUIRED.

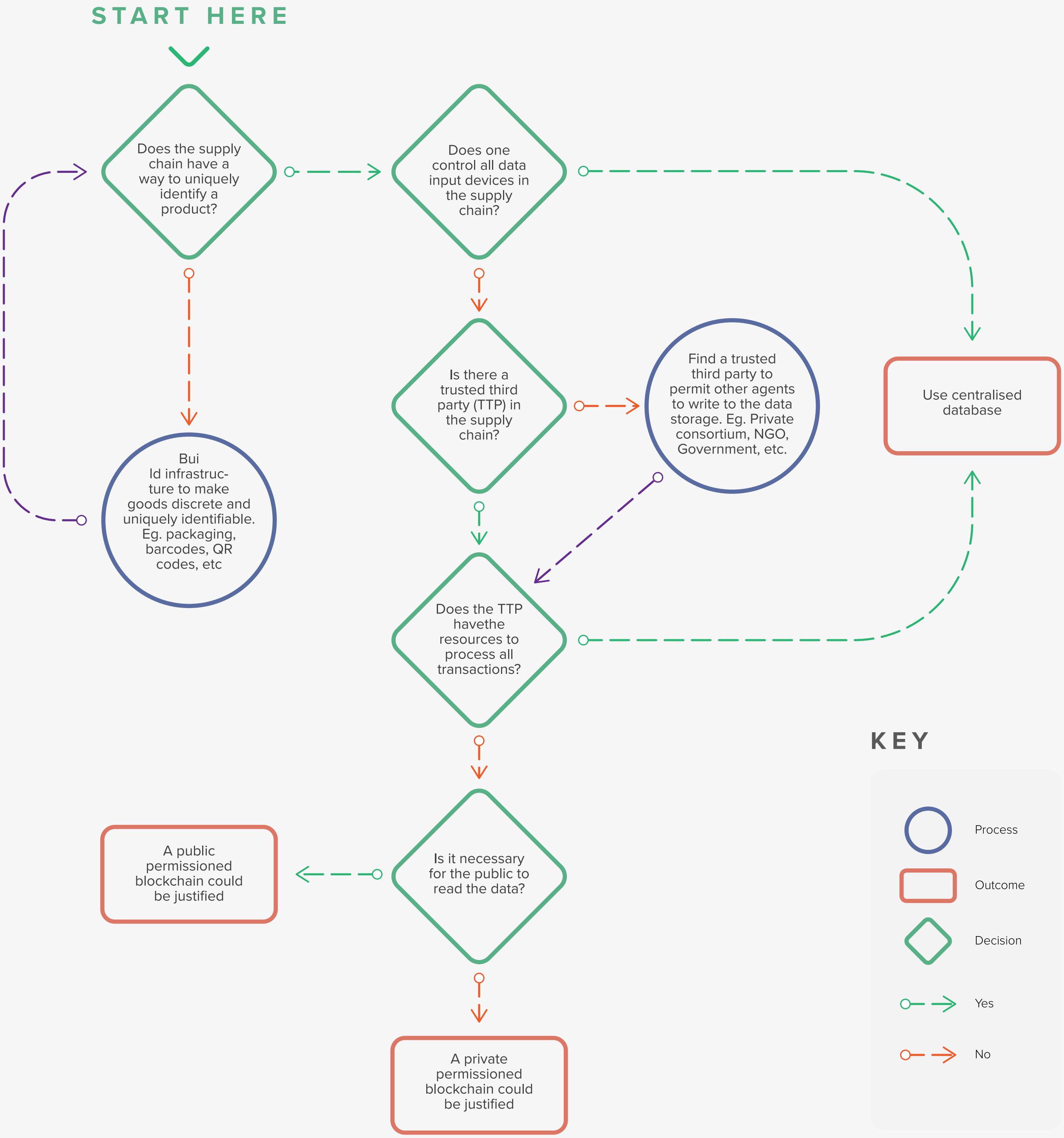
IS BLOCKCHAIN APPROPRIATE FOR A GIVEN SCENARIO?

There is presently a lot of hype around blockchain technology. Its unique features enable a wide variety of use-cases, including in the context of sustainable development. In addition to building efficient and sustainable supply chains, these range from improving access to energy to providing a legal digital identity for all.[58] However, not all supply chain traceability issues require a blockchain solution; in many cases a solution based on a centralised database should be sufficient. Given the additional complexities of designing and deploying a blockchain solution, it is important to ascertain whether one is truly required.

The following flowchart raises key questions that could help project designers ascertain whether blockchain would be suited to a given traceability system.

58 UNDP, "Beyond bitcoin," UNDP, https://feature.undp.org/beyond-bitcoin/.

Figure 2: Flowchart to ascertain whether blockchain may be suitable for a given traceability challenge



The first question highlights the need to have uniquely identifiable products, without which there cannot be traceability. For example, simply recording that a harvest of wheat happened on an immutable storage device does not allow subsequent tracking of its journey through the supply chain. The wheat will need to be packed into bales and registered with a unique identifier (e.g., a barcode) for each bale or lot to allow tracking through a supply chain—from its origin to consumption (or processing into another product like flour).

The next question checks whether a single entity has control over all or most stages of value addition in the supply chain as well as controls the devices that will be adding data onto the record. If it does (e.g., a tree-to-bar chocolate manufacturer having complete control over how their cacao was grown and processed), there is no need to use a blockchain. A centralised database using traditional SQL or NoSQL technologies will offer lower latency and reduced costs while still satisfying the requirements of traceability for the entity. If the entity seeks to make the data publicly verifiable, it can invite external auditors to access its data.

If there are multiple entities writing data into the traceability system's records—which is usually the case in complex agri-food supply chains—it is next important to know if there exists a trusted third party (TTP) that can verify the identities of all the supply chain's participants. This TTP will also need to issue unique identifiers to entities, locations, and products in this supply chain. If the TTP can process all transactions in the network (and is willing to do so), it would again be more economical to have a centralised database maintained by the TTP while still achieving a traceable supply chain.

However, if it is found that no single TTP has the resources to process and store all transaction records across the supply chain, it may be justified to use a permissioned blockchain. In case the supply chain has unknown actors, a public blockchain is more suited for traceability.

IDENTIFYING THE TRANSPARENCY/ TRACEABILITY GOAL

Once it is determined that a blockchain solution is appropriate for a given case, it is time to put the idea to paper and iron out the necessary details underlying the envisaged traceability system.

First, it is crucial to identify and clarify the developmental objectives for implementing a traceability system. As

TRACEABILITY IS AN ENABLER FOR THE BROADER GOAL OF ACHIEVING TRANSPARENCY THROUGHOUT THE SUPPLY CHAIN, THEREBY PROVIDING STAKEHOLDERS VISIBILITY OF ALL INFORMATION REGARDING THE PRODUCTS IN TRANSIT.

elaborated in Section 1, traceability and transparency should be the major theme behind the strategy to achieve specific developmental goals. These could include monitoring for deforestation or human rights abuses at the farm-level or ensuring food quality and safety standards across the supply chain.

It is also important to keep in mind the differences between traceability and transparency. Traceability recalls the history of a product in granular detail so that companies, suppliers, and consumers can correctly identify the origins of the product. Traceability is an enabler for the broader goal of achieving transparency throughout the supply chain, thereby providing stakeholders visibility of all information regarding the products in transit. This can power useful analytics that can result in more effective and efficient decisions towards the achieving the developmental objectives. With transparency, parties can expect fewer delays, waste, and other inefficiencies in supply chains which cause friction that cost time and money.[59] All relevant stakeholders in a supply chain can have open and transparent access to the data related to all transactions associated with the specific product or commodity. This makes the whole system accountable and easy to monitor and regulate real-time.

For sustainability certified products, traceability generally comes in three forms. Depending on the specific goals, objectives, and circumstances, one of the three different approaches can be selected to support the traceability initiative. The three forms are:[60]

1. **Product Segregation**: Certified materials and products are physically separated from non-certified materials and products at each step in the supply chain.
2. **Mass Balance**: Certified and non-certified products may be mixed; however, the exact volumes of certified materials are tracked such that an equivalent volume of the product can be sold as certified.
3. **Book and Claim**: A company can obtain sustainability certificates through a relevant standards body for

59 Deloitte, Using Blockchain to Drive Supply Chain Transparency and Innovation: Future trends in supply chain (Deloitte Development LLC, 2017), https://www2.deloitte.com/us/en/pages/operations/articles/blockchain-supply-chain-innovation.html.

60 Roundtable for Sustainable Palm Oil, RSPO Supply Chain Systems Overview (RSPO), https://www.rspo.org/files/docs/rspo_fact_sheets_systems_primer.pdf.

the volume of certified materials put into the system. The certificates can be bought and sold meaning that sustainability claims can be made via the existence of a certificate even though the actual product may not have been certified. An advantage of the book and claim approach is that it provides an opportunity to bypass long and complex supply chains, allowing a greater portion of the incentive payments to reach the producers, yielding greater adoption of sustainable practices.

If necessary, development of a traceability system can take place in a phase-wise manner, starting with a Book and Claim model as the minimum viable product (MVP) and transitioning into a Product Segregation model if required as the project progresses. There may be several reasons to consider adopting some elements of a Book and Claim system at least in the short-term. These may include a lengthy and complex supply chain as well as ensuring that pricing and incentives reach the upstream farmers quicker. If the objective is to increase the supply of sustainably produced commodities, a simpler Book and Claim based system may be put in place initially while a Product Segregation 'full-traceability' system is implemented in stages.

At this point, a vision and understanding of how greater transparency can solve the existing challenges within the supply chain under consideration should be developed and the benefits of using blockchain for relevant stakeholders should be thoroughly evaluated. Laying out the necessary details at the very beginning will eliminate any form of uncertainty and ensure that a singular direction for implementation and the corresponding impacts will be accurately brought forth to all stakeholders.

DEFINING THE PROJECT SCOPE

Introducing a blockchain solution into the existing technology ecosystem is a significant undertaking. Hence, it is good practice to define the scope of the project, specifying the segment of the supply chain that the blockchain solution will first be applied to. It could start with an MVP or proof of concept (POC) and expanded further through the development process.

The MVP can help prove a hypothesis about the blockchain solution and increase the likelihood of a sustainable and successful digital transformation of the supply chain. Furthermore, an architectural blueprint for future phases should also be drafted. The blueprint should encompass modernisation and integration with existing systems as well as major change components from both operational and cultural perspectives.[61] This can allow for smooth and strategic scaling up over the long-term.

Actors

Actors refer to the various individuals and organisations that participate in a supply chain, performing vital tasks such as creating a product, processing it from one form to another, transporting, auditing, and retailing it. In the agri-food sector, the actors can correspond to farmers or small-scale primary producers, cooperatives, processors, shippers, distributors and wholesalers, retailers, and others, who play a role in the chain of custody or ownership of a product in the supply chain.

To implement a traceability system, it is important to assign unique identifiers to each actor in the supply chain. The GS1 Global Traceability Standard[62] may be considered. In this standard, each entity is allocated a unique Global Location Number (GLN) and well-defined relationships (such as between a supplier and a recipient) are assigned Global Service Relation Numbers (GSRNs). A suitable nodal entity (e.g., project initiator, technology provider) can be tasked with issuing the identifiers.

Transactions Data

A blockchain-based traceability system employs transaction-based accounting, which stores richer data than a typical ledger-based accounting system.

A transaction can be defined as any significant interaction between actors in a supply chain, and can be associated with one or more of three types of flows:[63]

a. **Information flows**: transfer of information about the state of products or actors

b. **Inventory flows**: transfer of ownership / custodianship of products

c. **Financial flows**: transfer of cash or liquid assets

A BLOCKCHAIN-BASED TRACEABILITY SYSTEM EMPLOYS TRANSACTION-BASED ACCOUNTING, WHICH STORES RICHER DATA THAN A TYPICAL LEDGER-BASED ACCOUNTING SYSTEM.

61 Jose Arrieta et al., "Assessment," Blockchain Playbook Online - beta, 2018, https://blockchain-working-group.github.io/blockchain-playbook/phases/1/.

62 GS1 Global Traceability Standard, 2019, https://www.gs1.org/standards/gs1-global-traceability-standard#2-Traceability-and-the-importance-of-standards+2-3-The-need-for-traceability-data.

63 Vishal Gaur and Abhinav Gaiha, "Building a Transparent Supply Chain," Harvard Business Review, May 2020. https://hbr.org/2020/05/building-a-transparent-supply-chain.

Design an end-to-end traceability system would include tracing the path that a product takes from its origin (where it can be registered in the system) to the end consumer and noting the type of flow that occurs during each interaction between actors.

To decide what fields of each transaction needs to be added to the blockchain, it is useful to address the following questions:

a. Who will perform the transaction?

b. What product/service will be created/exchanged?

c. Where will the transaction occur?

d. When will the transaction occur?

e. Why will the transaction occur?

Let us examine a simple example of a transaction in a supply chain that uses the GS1 Global Traceability Standard. This example details the relevant fields when a product is processed into a new form that has a different unique identifier.

Table 4: Example of a supply chain transaction using GS1 Global Traceability Standard

Question	Relevant transaction fields
Who	GLN[64] of manufacturing firm
What	Input product • GTIN[65] of input product type • Lot number that the input product belongs to • Item-level identifier of input product (if applicable) New product created • GTIN of product type • Lot number that the product belongs to • Item-level identifier of input product (if applicable)
Where	GLN of factory/plant
When	Date-time stamp of completion
Why	Summary of interaction (e.g.: "Processed sugarcane into refined sugar")

Sources of Traceability Data

There are three main sources of traceability data:

1. **Master data** refers to the "single source of common business data used across all systems, applications, and processes for an entire organisation."[66] It can be subdivided into:
    - **Static data** which stores information (including company specific identifiers) about products, locations, and other parties and assets; and
    - **Relation data** which stores information about supply chain partners of an entity – suppliers and customers. This enables upstream and downstream queries by linking entities to each other. Additional information regarding certifications held by partners can also be stored, enabling insights into environmental, safety and ethical aspects of the supply chain;
2. **Transaction data** stores information about business transactions, comprising transfer of ownership and/or custody; and
3. **Visibility event data** involves records of completed business processes, which can be input manually or recorded automatically (e.g., location data of products, IoT sensors detecting loading of new products).

64 Unique GS1 Global Location Number

65 Unique GS1 Global Trade Item Number

66 GS1 Global Traceability Standard

ALIGNING STAKEHOLDER INTERESTS AND INCENTIVES

Upon defining the scope of the project, the next steps would involve engaging and building partnerships with relevant stakeholders. Once the specific stakeholders have been identified, it is important to consider their individual incentives and concerns for being a part of a traceability system. Time should be allocated in the project timeline to gather feedback, address concerns, and even incorporate suggestions from all relevant stakeholders.

Some stakeholders may not be receptive to the idea of adopting blockchain in their operations due to various reasons. Blockchain technology is complicated and it would take time for some stakeholders to understand and agree to participate in the project. Also, some stakeholders might have concerns such as the possibility of leakage of sensitive information. Thus, to increase the likelihood of their participation, certain topics must be explained and concerns addressed when reaching out to these stakeholders. These include but are not limited to:

- Blockchain technology: Description, application in agri-food context, benefits, and Limitations;
- Specific incentives and concerns of stakeholders for adopting blockchain (details below); and

Roles and responsibilities of various stakeholders (refer to later sub-sections Key Entities in Blockchain Projects and Data Governance).

Farmers/Producers

Smallholder farmers and small-scale producers are stakeholders responsible for growing or harvesting the agri-food commodities. Incorporating traceability in the agri-food system would allow them to have visibility of the records of transactions and the actors involved in the supply chain, including processors and consumers. Their incentive for participating in blockchain projects is to gain access to global markets and attain a direct contact with consumers. Blockchain-enabled smart contracts can also help smallholder farmers reduce transaction costs by circumventing middlepersons and empowering the former to receive fairer prices for their produce.[67]

It should be taken into context that there is a growing trend of consumers demanding safe, sustainable, and ethical agricultural production. If this trend continues, farmers and producers might be forced to participate in voluntary sustainability certifications to maintain market access, which demands substantial paperwork and expenses to monitor and verify the sustainability of their practices.[68] Having blockchain to assist the collection of environmental performance indicators such as use of safe and sustainable inputs can facilitate the verification of sustainability standards by other entities in the supply chain, although it might not reduce the cost of the certification itself.

For projects aiming to improve smallholder farmers' access to agricultural insurance, farmers have an incentive to participate to benefit from the ability of blockchain-enabled smart contracts to verify insurance claims and accelerate pay-out processes.[69] For example, extreme weather events could trigger policies on the blockchain platform, facilitating insurance pay-outs during such events and enhancing the resilience of smallholder farmers to withstand shocks.

While smallholder farmers stand to benefit from blockchain, they may have hesitations in participating in projects due to several reasons. Farmers in rural areas may have limited mobile network coverage and other digital infrastructure. Ownership of smartphones—which may be required for recording farming activities—amounted to a mere 45 percent in 2018 in emerging economies.[70] Furthermore, only 24-37 percent of farms of less than a hectare in size have 3G or 4G connectivity.[71] Addressing farmers' concerns regarding the cost of smartphones and mobile data subscriptions would be important for facilitating their participation in blockchain projects. Additionally, lack of literacy and digital skills can deter farmers them from using technologies like mobile phones.

FARMERS IN RURAL AREAS MAY LACK MOBILE NETWORK COVERAGE AND OTHER DIGITAL INFRASTRUCTURE, LIMITING THE ADOPTION OF BLOCKCHAIN PLATFORMS.

67 Green, "Decentralized Agriculture: Applying Blockchain Technology in Agri-Food Markets."

68 Ibid.

69 Hang Xiong et al, " Blockchain Technology for Agriculture: Applications and Rationale," Frontiers in Blockchain 3, no. 7 (2020), https://doi.org/10.3389/fbloc.2020.00007.

70 Laura Silver, "Smartphone Ownership is Growing Rapidly Around the World, but Not Always Equally," Pew Research Center, February 5, 2019, https://www.pewresearch.org/global/2019/02/05/smartphone-ownership-is-growing-rapidly-around-the-world-but-not-always-equally/.

71 Zia Mehrabi et al., "The global divide in data-driven farming," Nature Sustainability 4, no. 2 (2021): 154–160, https://doi.org/10.1038/s41893-020-00631-0.

The role of farmer and producer cooperatives may be crucial in acting as the first node for recording information on farming activities, use of inputs, and sale of produce onto the blockchain. Cooperatives can also support the project by explaining the benefits of the technology and conducting relevant trainings for farmers.

Processors

Processors are involved in purchasing raw agri-food commodities from farmers or producers and converting them into a different product. Processors might be incentivised to participate in a blockchain project to improve their brand image and appeal to the conscious consumers who are inclined towards transparent brands that ensuring sustainable sourcing of agri-food commodities for processing. For instance, Cantina Volpone, an Italian winery, attracted the interest of national and international news publishers who dedicated articles to the winery's use of blockchain, thereby expanding the winery's reach to consumers across Europe and the United States.[72]

Despite the benefits of adopting blockchain, processors might be concerned about migrating their data from existing systems to the blockchain platform. This may require them to spend resources to ensure accurate migration of data. Additionally, processors might be concerned about the costs of incorporating the blockchain platform into their existing operations. Hence, it would be important to clarify financial and logistical expectations from them during the engagement phase.

Distributors

Distributors involved in transporting the finished products from processors to retailers would look forward to participating in blockchain projects to increase their brand value and image through the increased traceability of products. By tracking the characteristics and storage conditions of the final agri-food products (e.g., on ships, trains, trucks), downstream retailers can be confident of their quality. This may improve distributors' opportunities to gain more partnerships, market volume, and sales with retailers.

However, the need to input the characteristics and storage conditions of the agri-food products in their custody into the blockchain platform may require investment in technological resources such as sensors. Additionally, distributors would need to spend resources to migrate their data from existing systems or written documents into the blockchain platform.

Such economic concerns should be addressed during the engagement phase, where expectations with regards to financial and logistical resources are set.

Retailers

Aside from improving their brand image, retailers, who are responsible for selling the finished products to consumers, can look forward to improving their efficiency in tracing the origin of products if contamination is detected (e.g., through cases of food poisoning leading to hospitalisation), thereby improving food safety and quality outcomes. Blockchain can enhance the ease of identification of the contaminated batches already released in the market or still in the supply chain, thus increasing the efficiency in tracing and recalling the products. Removing these contaminated products from the supply chain before they reach the consumers can immensely reduce costs from loss of sales as well as harm to human health. More than 50 percent of international food companies surveyed in 2011 were affected by food-borne illness outbreaks in the last 5 years, where 18 percent of those affected lost $30-99 million of sales and 5 percent of those affected lost over $100 million of sales.[73]

Retailers would need to consider the funding and technological resources before deciding whether to adopt blockchain technology in their operations. They would also have to consider the need to migrate data from existing systems to the new blockchain platform, which would require manpower and resources.

Consumers

While consumers are unlikely to be engaged in the design and development of blockchain projects, their demand for ethical and sustainably sourced agri-food commodities is one of the main drivers for traceability in agri-food supply chains. The consumers' greater intention to purchase and willingness to pay a premium for products that have been sourced respecting certain environmental and social criteria (e.g., slave free, organic) serve as the basis for the success of blockchain projects in achieving development-related goals.[74]

The profile of consumers who are likely to pay a premium for products that are convincingly sustainably sourced may differ from market to market. For instance, a study to validate the value proposition of UNDP-supported 'The Other Bar'[75] chocolate bar showed that young consumers (18-25 years), who are also more likely to know about blockchain technology, responded better to impact messaging such as 'slave free'.[76]

72 Matteo Pio Prencipe, "Blockchain based traceability as a solution for traceability issues in the agri-food sector: The Placido Volpone winery case study," Master's Degree Thesis (2020), https://doi.org/10.13140/RG.2.2.14520.57606.

73 Beth Kowitt, "Why Our Food Keeps Making Us Sick," Fortune, May 7, 2016, https://fortune.com/longform/food-contamination/.

74 Nir Kshetri, "Blockchain and sustainable supply chain management in developing countries," International Journal of Information Management 60 (2021): 102376, https://doi.org/10.1016/j.ijinfomgt.2021.102376.

75 'The Other Bar' is the world's first blockchain shared value chocolate bar which was launched in 2019 with support from UNDP, Amsterdam-based FairChain Foundation, and APEOSAE (an association of over 165 organic cacao farmers in the Ecuadorian Amazon). See: https://undp.medium.com/how-blockchain-has-transformed-the-lives-of-ecuadorean-cocoa-farmers-1c89941f549c.

76 FairChain Foundation, Validating the "The Other bar" value proposition, White paper (FairChain Foundation, 2021).

On the other hand, consumers might not be willing to pay a premium for the traceability aspect of sustainably sourced products for a variety of reasons including limited purchasing power, time, and/or critical thinking abilities when purchasing these products. Because of the latter, the additional information about sustainability and health elements might not be seen as a need or an incentive for this group of consumers.[77] Price, however, remains the dominant factor defines a purchasing decision.

Government Agencies

Currently, government agencies find difficulties in managing food-borne illness outbreaks due to the lack of transparency and traceability in agri-food supply chains. Hence, one food-borne illness incident can lead to nation-wide or company-wide recalls, international bans on imports, and total shutdown of production.[78] Government agencies can increase their preventive measures for healthcare by implementing blockchain technology to quickly trace the origin of the contaminated products. This would help reduce the likelihood of these products reaching the consumers and thereby reduce monetary costs, time, and loss of human lives. Furthermore, transparency and traceability enabled by blockchain can help government agencies to monitor and verify companies' compliance to regulations and export market requirements, thereby further protecting citizens from potentially harmful practices or products from firms. Also, needless to say, developmental issues such as inequity of benefits to small-scale producers, environmental degradation, and human rights violations—which are likely to be a priority for governments—can be monitored and assessed with the implementation of blockchain in the agri-food sector.

While most blockchain projects in agri-food supply chains have been funded and initiated by private sector players, government agencies have been playing the supporting role through grants, awards, and supporting services.[79] However, one of the major concerns for government agencies to be involved in blockchain projects is the collection of sufficient evidence and funding to back such projects, especially due to the complexity of the technology and the involvement of multiple stakeholders both domestically and internationally. To this end, research may be conducted to justify the investments required for blockchain-powered traceability projects.

Aside from this, regulatory uncertainty at the global level with regard to blockchain technology might make it difficult for governments to adopt it. Government agencies would be expected to set up new regulatory frameworks for data governance for blockchain.[80] This would require new competencies through training and recruitment of subject matter experts to ensure that they are able to keep up with and regulate the developments in blockchain technology. For leveraging the full potential of the technology, governments need to establish a national mechanism or a nodal institution that can provide consultancy, capacity building, and serve as an incubation centre for diverse POC blockchain solutions. Such a mechanism will help governments to build trust and move towards large-scale blockchain deployments with confidence.

KEY OPERATIONAL CONSIDERATIONS

Digital Landscape

Most smallholder farmers live in rural areas in developing countries, where there is a lack of internet connectivity, other supporting digital infrastructure, and digital literacy. Hence, an important operational consideration for the implementation of blockchain projects would be the digital landscape.

a. Internet connectivity

Internet broadband coverage in rural areas in developing countries remains limited, with only a third of the population living in these areas having at least 3G network coverage.[81] Since data is manually or automatically entered onto the blockchain through the internet and ancillary technologies such as RFID and sensors, all stakeholders having operations in rural areas would need to consider the strength and coverage of internet in these locations.

b. Digital literacy

Since only a third of the population living in rural areas in developing countries has 3G network coverage[82] and only 45 percent of people living in emerging economies own smartphones,[83] lack of necessary digital skills might be a major barrier. Ensuring that farmers possess or learn the required skills for participating in the traceability system should therefore be an important consideration for project managers.

77 Green, "Decentralized Agriculture: Applying Blockchain Technology in Agri-Food Markets."

78 Ibid.

79 Lan van Wassenaer, Mireille van Hilten, and Marcel van Asseldonk, Applying blockchain for climate action in agriculture: state of play and outlook (Rome: FAO, 2021), https://doi.org/10.4060/cb3495en.

80 Ibid.

81 Trendov, Varas, and Zeng, Digital Technologies in Agriculture and Rural Areas: Briefing Paper.

82 Trendov, Varas, and Zeng, Digital Technologies in Agriculture and Rural Areas: Briefing Paper.

83 Silver, "Smartphone Ownership is Growing Rapidly Around the World, but Not Always Equally."

c. Other digital infrastructure

For blockchain technology to be implemented, data needs to be entered into the traceability system using digital devices. The increasing ownership of smartphones—possible devices for data entry—in developing countries is creating enabling conditions for blockchain projects.[84] However, compared to developed countries, the penetration of smartphones is still limited. Thus, considering stakeholders' ownership of digital devices would still be important.

In scenarios where stakeholders are unable to afford such digital devices, resources would need to be allocated to provide these tools to them. Given the complexity and costs involved, it would be recommended to prioritise the implementation of blockchain projects for higher value agri-food commodities as it would justify the high costs of implementation.[85] The challenge however lies in the lack of incentives for farmers to collect data. A missing element currently is the need for business models for data collection in a way where back-office support and technology are included so that they can be viable. This is key to ensure sustainability of the model for smallholder farmers.

Another consideration would be the availability of local expertise for setting up and maintenance of software and hardware for blockchain systems. For instance, WWF's blockchain traceability project for tuna in Fiji faced difficulties in finding local expertise to install RFID equipment.[86] It would be important to identify the digital infrastructure required, and thereby the expertise needed for setting it up and troubleshooting in case of any technical issues. Another important aspect to consider would be the recurring annual costs associated with maintenance of blockchain platforms including the hosting fees and the business model that will make the whole system fully sustainable in the long run.

Key Entities in Blockchain Projects

Designing a successful blockchain project would entail the identification of all the key stakeholders beyond the supply chain actors. This includes the project initiators, funders, and technology providers. These key players would be involved in leading the project and managing the costs and logistics required to implement the project.

a. Initiators

Initiators act as anchors of projects and usually convene various stakeholders and facilitate engagement and collaboration among them. Blockchain projects in the agri-food supply chains have commonly been initiated by private sectors firms with a focus of using blockchain as a profit-driven solution for tackling environmental and social issues in supply chains. However, the scope of such projects is usually limited and do not involve a wide range and number of stakeholders. With increasing attention and awareness about blockchain as a traceability solution for address developmental issues in the agri-food systems, initiators for blockchain projects can also be development-focused organisations such as government agencies, international development organisations, and non-governmental organisations (NGOs).

b. Funders

Existing pilot blockchain projects in the agri-food sector are mainly funded by large multinational corporations (MNCs). Their aims of investing in blockchain-enabled traceability in their operations include the desire to monitor and report their impact to consumers, which could be a result of consumer demand and preference for transparent brands. However, for blockchain projects where there is no dominant player interested in implementing such a project, attracting funding can be a challenge.

Some of the costs include the software development of the blockchain system or subscription to an existing blockchain service. Digital infrastructure such as sensors and RFID equipment may also be required for automatising the tracking and input of data into the system. Aside from this, training programmes may be necessary for various actors, which would add to the overall cost of the project. Other costs may include maintenance of the infrastructure and the blockchain system and scaling up as necessary.

One of the key operational considerations would be to demonstrate quantifiable benefits of a blockchain project to investors. Agri-food MNCs might consider investing a portion of their sustainability budget or even their marketing budget for blockchain projects to communicate their positive impact and influence consumers. Research findings from the UNDP's The Other Bar pilot in Ecuador showed that incorporating traceability through blockchain increased consumers' purchase intentions.[87] Highlighting consumer preference for traceability and development impact through their purchase of agri-food products could potentially attract investments from large agri-food MNCs.

Alternatively, even though public sector players and NGOs have been playing the supportive role of providing grants and awards, public-private partnerships can be considered as one of the ways moving forward, particularly as a solution that

84 Ibid.

85 Kshetri, "Blockchain and sustainable supply chain management in developing countries."

86 Bubba Cook, Blockchain: Transforming the Seafood Supply Chain (WWF, 2018), https://www.wwf.org.nz/?15961/Blockchain-Transforming-Seafood-Supply-Chain-Traceability.

87 Fairchain Foundation, Validating the "The Other bar" value proposition.

covers smallholder farmers. An example of a model could be a joint venture between a private sector entity and a farmer cooperative with equal ownership of stock to establish a division of labour. The private sector entity could deal with the mid- and last mile of the supply chain and farmers with the first mile. Another key element in such a model should be to add as much value as possible at the origin to generate a more equal sharing of profits and positive spill-over effects in suppliers' countries.

c. Technology providers

Referring to Section 2, there is a range of blockchain frameworks (e.g., Hyperledger, Ethereum) and types (public, private, consortium). An important consideration would be to decide the type and framework of blockchain that would suit the scope of the project while taking into account the considerations of stakeholders involved. Upon doing so, the next step would be to explore the various BaaS providers and infrastructure suppliers offering relevant hardware like RFID equipment, if necessary.

A centralised blockchain network consist of parties with known identities. Hence, it is easy to validate the transactions based on the credibility of the participants who can post to the ledger. In a decentralised network, anyone can participate and transact on the ledger and hence, the system must account for vulnerabilities that may result from this format. Especially in projects where there is a scope for a blockchain solution to transition into a fully decentralised system from a centralised system, all the above factors need to be accounted for and a clear roadmap put in place during the POC stage itself.

Data Governance

The permanency of data stored on a blockchain makes it crucial to put in place a data governance system and strong data practices prior to actual implementation. Formalising various data practices and roles would help ensure the accuracy of the data, which would thereby determine the effectiveness of using blockchain for traceability.

Prior to beginning the project, the initiator can assemble a team of personnel representing each stakeholder to be the overseeing body of the project and data flows. Gathering individuals from different parts of the supply chain would facilitate discussions and negotiations based on their individual organisations' perspectives, concerns, and desired outcomes from the project.

The overseeing body can then consider the following questions and formalise roles for the stakeholders involved:[88]

Who makes decisions with regard to rules, access of data, process for members to join and leave, and number of nodes given to each stakeholder?

a. Who enforces the rules?

b. Who manages the blockchain platform?

c. Who makes decisions to update the platform?

d. Who has access to the data?

e. Who can input data?

Who is responsible for resolving issues that arise, including technological collapse, contractual default, and misconducts?

To evaluate and monitor the effectiveness of the blockchain system, internal audits can be implemented. Audits identify any problems or tampered inputs in the system,[89] which is crucial for ensuring that no stakeholder is taking undue advantage of the system. Furthermore, the immutability of data input into the blockchain platform can assist the verification and assessment of ESG indicators. By conducting continuous audits, the progress of the blockchain project can also be evaluated against the specific developmental goals set out at the beginning.

Privacy Concerns

As seen in Aligning Stakeholder Interests and Incentives, privacy concerns may be a major deterrent for private sector players like traders, processors, distributors, and retailers to participate in blockchain projects. The actors in an agri-food supply chain may be in competitive relationships with each other and would not value a traceability system that might threaten their competitive edge in the industry.[90]

Privacy concerns regarding cybersecurity and hacking risks would be covered later in Regulation and Cyber Security. Here, we focus mainly on the management of stakeholder expectations with regard to the preservation of their competitive edge. One solution is to minimise sensitive and confidential information being uploaded into the system by inputting digital fingerprints of data or references to where the information can be found instead.[91]

Since the adoption of blockchain technology in agri-food supply chains is still in its infancy, more research and technological advancements are required to understand

88 Eric Piscini et al., Taking blockchain live: The 20 questions that must be answered to move beyond proofs of concept (Deloitte, 2017), https://www2.deloitte.com/us/en/pages/consulting/articles/taking-blockchain-live.html; Vedat Akgiray, Blockchain Technology and Corporate Governance: Technology, Markets, Regulation and Corporate Governance, OECD Corporate Governance Working Papers No. 21 (OECD, 2018), https://doi.org/10.1787/22230939.

89 Hugh Rooney, Brian Aiken, and Megan Rooney, "Q&A. Is Internal Audit Ready for Blockchain?" Technology Innovation Management Review 7, no. 10 (2017): 41–44, http://doi.org/10.22215/timreview/1113.

90 Wei Liu et al., "A systematic literature review on applications of information and communication technologies and blockchain technologies for precision agriculture development."

91 IBM, Storage Needs for Blockchain Technology - Point of View (IBM Corporation, 2018), https://www.ibm.com/downloads/cas/LA8XBQGR.

how to keep data involving multi-party transactions private to protect the business interests of various stakeholders.[92]

Dispute Resolution

Disputes resolution consists of three steps: an examination of the ground truth; a judgement on the winning party; and finally, enforcement. Any traceability model must spell out a dispute resolution scheme within its agreement to be signed by all parties that join.

A conventional, centralised system of dispute resolution would see two disputing parties take their case to the governing authority (traditionally a court) for resolution. In such a case, evidence in the form of a data query can be made using the traceability data for each transaction to understand the ground truth. The governing authority can then issue a ruling on which party is aggrieved and may allocate relief accordingly.

It must be noted that blockchain is still a nascent technology and is not a recognised form of evidence in courts in most countries. Nonetheless, it is rapidly gaining traction. In 2018, the Supreme People's Court of China announced[93] new binding provisions that confirmed that internet courts in China can rely on blockchain evidence, due to its distributed, tamper-free, and traceable nature. Several US states, including Vermont, Arizona, Ohio, and Delaware, have introduced legislation to formalise blockchain's use as admissible evidence, while in other states, blockchain data would merely be treated on par with other records kept by businesses.[94] It is thus important to seek legal advice within the relevant jurisdictions on their legal systems' recognition of blockchain evidence.

While this centralised model is simple to set up, it suffers from some challenges. It demands the maintenance of a governing authority, either an existing legal authority or a new one funded by private entities or the government. It may also not be scalable as more parties are added to the traceability network, with network growth exceeding growth in capacity to handle complaints.

Blockchain technology also allows a decentralised model of dispute resolution.[95] The broad steps are:

1. Funds from the receiving party are allocated to a smart contract (like an escrow account)
2. If the receiving party is satisfied, the money is transferred
3. If a dispute occurs, online jurors are randomly selected from the network
4. The jurors hear the arguments from the parties, and are incentivised to adjudicate wisely, with a monetary reward for those who vote with the majority

While this decentralised framework is more affordable, timely, and scalable, it adds new challenges too. Complex disputes may be difficult to adjudicate due the lack of legal training of randomised jurors. Outcomes also tend to be binary, lacking legal nuance. These complex cases may need to be escalated to a centralised authority, like judicial courts.

KEY TECHNICAL CONSIDERATIONS

Registering a New Product

A key tenet of a traceability system is the consistent use of unique identifiers to track a product's movement through a supply chain. To make this possible, when a product is introduced into the supply chain, a unique token must be issued on the blockchain to represent it.

The first major decision to be made is on the desired precision of the traceability data. Using the GS1 Standard as a reference, three broad levels of precision are possible for representing products:

a. **Class Level** (using GTINs in GS1): Identifies only the type of product

b. **Lot Level** (represented using GTIN + Batch/Lot Number in GS1): Identifies each batch of products (e.g., one batch of cans made from the same raw materials)

c. **Instance Level** (GTIN + Serial ID): Every individual item produced is given a unique serial ID

A greater level of precision affords better traceability but is also more expensive to implement and may also reduce productivity and profitability by making compliance burdensome. For example, tracing every single can with a unique serial ID may be infeasible for small firms, which may only have the human resource and tools to handle such tasks per batch.

The second major decision to be made is at which stage to register a product on the system. Network infrastructure may be sparse in remote regions, meaning that the first available point of registering a product may be upstream from the farm or source of original production. It is also relevant to note whether the additional cost of packaging the harvested

92 Wei Liu et al., "A systematic literature review on applications of information and communication technologies and blockchain technologies for precision agriculture development."

93 Laney Zhang, "China: Supreme Court Issues Rules on Internet Courts, Allowing for Blockchain Evidence," Library of Congress, https://www.loc.gov/item/global-legal-monitor/2018-09-21/china-supreme-court-issues-rules-on-internet-courts-allowing-for-blockchain-evidence/.

94 Concord Law School, "The Admissibility of Blockchain as Digital Evidence," Concord Law School, April 23, 2019, https://www.concordlawschool.edu/blog/news/admissibility-blockchain-digital-evidence/.

95 Alexandra Miller, "Blockchain: a new frontier for dispute resolution?" Kennedys Law, November 25, 2020, https://kennedyslaw.com/thought-leadership/article/blockchain-a-new-frontier-for-dispute-resolution/.

goods into batches and boxes with unique identifiers would disincentivise the actor from participating in the system.

Issuing Unique Identifiers

Apart from labelling products uniquely, a centralised authority will also need to issue recognisable and unique identities to locations, organisations, transactions, and documents. An existing standard like the GS1 may be adopted (for a fee), or a new one may be created for a given supply chain. A summary of the identifiers in GS1 are shown below:

Table 5: Issuing unique identifiers using GS1 Standard

Theme	Entity	GS1 Identifier
Traceable objects	Products at any packaging level (class-level)	Global Trade Item Number (GTIN), can be augmented with batch number / serial number
	Physical documents like invoices and tax forms	Global Document Type Identifier (GDTI)
	Logistical units packed together	Serial Shipping Container Code (SSCC)
Traceability parties	Trading partners	Global Location Number (GLN)
	Relationships (provider and receiver)	Global Service Relation Number (GSRN)
Traceability locations	Physical locations	Global Location Number (GLN) + Extension for different sites

Establishing a Standard Data Model

Data is the lifeblood of any digital technology system, including blockchain. Referencing the important characteristics of big data, the following factors should be carefully considered: volume, variety, velocity, value, and veracity of the data in the blockchain.[96] To ensure that an ever-increasing volume of data can flow seamlessly between all parties in the supply chain, a standard data model should be established at the earliest possible stage. This will prevent multiple silos of data from forming, which can obstruct useful interpretation and analysis at the big picture-level. Moreover, it will be at this stage that the differences between the existing legacy data systems of every participant become apparent. Hence, it will be important for communication and collaboration among the parties to discuss and converge on a common language going forward.[97]

In addition, it is important to determine the compatibility of existing data sources and understand the data access privileges among parties. It is also not necessary for all supply chain data to be accessible to all actors. Multiple blockchains can work together to filter out the relevant data for relevant stakeholders. Hence, parties should agree on a data model that can share required traceability data and protect sensitive product data on the blockchain[98]—a balancing act between maintaining private versus public facing information.

Key considerations in making a unified data model work include:[99]

a. **Extracting and importing data**
This covers how data will first be extracted from its original sources or imported onto a central platform that will be accessible for further processing.

Several existing technologies are expected to interface with blockchain solutions:

- ERP systems
- Electronic ordering and payment systems
- Invoicing systems
- Logistics systems
- Order management systems
- Traceability systems

b. **Data conversion and storage**
This covers how data which are incompatible or unstructured will be processed into a standard structure through processes such as deduplication, restructuring, and more, to make it useable for the blockchain system.

c. **Data reporting and analysis**
Finally, the collected data should connect with an analytical system to derive insights.

96 BBVA, "The five V's of big data," BBVA, May 26, 2017, https://www.bbva.com/en/five-vs-big-data/.

97 OECD, Is There a Role for Blockchain in Responsible Supply Chains? (OECD, 2019), https://www.oecd.org/fr/gouvernemententreprise/is-there-a-role-for-blockchain-in-responsible-supply-chains.htm.

98 Leong, Viskin, and Stewart, Tracing the Supply Chain: How Blockchain Can Enable Traceability in the Food Industry.

99 Ace Elliott, "What Is a Unified Data Model?" Mixpanel, November 12, 2019. https://mixpanel.com/blog/unified-data-model/.

This flow of data from existing systems onto the blockchain are continuous processes. Therefore, a future-proofing strategy should also be created, detailing clear steps for expanding the model to support future integrations and scalability measures.

With regard to the actual data model standard, GS1 is a common standard that enterprises like IBM and Microsoft have adopted thus far.[100] They have past collaborations with GS1, the global business communications standards organisation, to leverage its standards in their enterprise blockchain applications for supply chain clients.

According to GS1, a complete traceability system will include components that manage:[101]

a. Identification, marking, and attribution of traceable objects, parties, and locations
b. Automatic capture (through a scan or read) of the movements or events involving an object
c. Recording and sharing of the traceability data, either internally or with parties in a supply chain, so as to provide visibility to what has occurred

Regulation and Cyber Security

When it comes to security, there are three main areas to examine, following the CIA security triad model: Confidentiality, Integrity, and Availability.[102] Authentication, Authorisation, and Audit (AAA), and Non-Repudiation, are also fundamental security aspects that are analysed for protecting information and designing/managing new systems and networks.

When it comes to personal data specifically, government bodies might maintain strict regulatory oversight. A public facing blockchain solution will need a fine balance between privacy and identification. One way to address laws and regulations is to avoid putting any form of personally identifiable information on the blockchain. Given that there are broad definitions of personal data across different regimes, great care should be taken to avoid falling into their scope. Some of the well-known personal data laws include the EU's General Data Protection Regulation (GDPR), and we will be referencing it as our primary example.

Use cases particularly suited to avoiding data capable of directly or indirectly identifying an individual include:[103]

a. Financial settlement systems that do not involve natural persons
b. Supply chain management
c. Managing distributed IoT non-personal sensor data
d. Other applications that do not handle information on natural persons

For use cases that involve personal data, organisations should consider using more privacy-friendly blockchain techniques, such as those that combine on-chain and off-chain storage to:

a. Avoid storing personal data as a payload on the blockchain;
b. Store an encrypted version of personal information, where the encrypted keys can be deleted upon request to prevent future attempts to decipher the information stored;[104] and
c. Allow blockchain transactions to serve as mere pointers or other access control.

Moreover, there is a fundamental contradiction in blockchain's value and the enforcement of laws, such as the GDPR, to allow the erasure of personal data. With regard to data immutability, it is important to consider how blockchains will be compatible with data privacy laws. How to implement the right to be forgotten in a technology that guarantees that nothing will be erased is an interesting challenge for which, fortunately, there are multiple solutions. One is to encrypt the personal information written in the system, to ensure that, when the time comes, forgetting the decryption keys will ensure that sensitive information is no longer accessible. Another solution is to focus on the value of blockchain to provide unalterable evidence of facts by writing the hash of transactions to it, while the transactions themselves are stored outside of the system. This maintains the integrity of transactions, while enabling the ability to erase the transactions, leaving only vestigial traces of forgotten information on the blockchain.

Finally, another point of conflict is the emphasis on the roles of data controllers in regulations such as the GDPR. In a blockchain network however, nodes replace the positions of data controllers. Blockchain democratises the power of the data controllers among a network of nodes, which when taken individually, are unable to influence the network in compliance with GDPR requirements.

100 Jennifer Zaino, "The Blockchain Intersection with Supply Chain Data," DATAVERSITY, October 12, 2017, https://www.dataversity.net/blockchain-intersection-supply-chain-data/.

101 GS1 Global Traceability Standard.

102 Eric Piscini and Lory Kehoe, Blockchain & Cyber Security. Let's Discuss (Deloitte, 2017), https://www2.deloitte.com/tr/en/pages/technology-media-and-telecommunications/articles/blockchain-and-cyber.html.

103 Pritesh Shah et al., Blockchain Technology: Data Privacy Issues and Potential Mitigation Strategies (Thomson Reuters, 2019), https://www.davispolk.com/insights/articles-books/blockchain-technology-data-privacy-issues-and-potential-mitigation.

104 Carlo R. W. De Meijer, "Blockchain versus GDPR and who should adjust most," Finextra, October 9, 2018, https://www.finextra.com/blogposting/16102/blockchain-versus-gdpr-and-who-should-adjust-most.

For cross-border transactions particularly, separate organisations will have to work with the respective authorities to develop new regulations and standards that potentially did not exist before such a blockchain system was implemented. By creating a global “regulatory sandbox”, promising use cases can then be safely tested and refined.[105]

SUSTAINABILITY OF THE BLOCKCHAIN ECOSYSTEM

Lastly, a blockchain solution is only as good as the parties it links and the extent to which they are willing to collaborate to maintain the entire system. The blockchain solution will initially be set up to be focused on just a segment of the end-to-end supply chain. Developing the solution beyond the pilot test is an incremental and iterative process.[106]

Long-Term Stakeholder Engagement

To ensure the long-term sustainability of a blockchain solution, stakeholder engagement should be maintained by establishing a clear communication channel for parties to raise concerns to expedite a recalibration of the model over time. As discussed earlier, there will be numerous phases and iterative improvements to build out the solution over time. Clear checkpoints should be set up to assess the progress of the solution along its development journey. Parties will hence have the option to exit or continue in the initiative with minimal risk. It is therefore likely that goals and requirements will shift, and the appropriate governance processes should be well defined to manage this possibility and sustain cooperation throughout the initiative.[107] A clear directive should also be put in place to delineate ways to recalibrate the parameters based on new ecosystem changes.

Initiating a blockchain project that involves numerous parties in the supply chain may incur a significant capital investment. Juggling the alignment of incentives of the stakeholders, fair allocation of benefits from the platform as well as the allocation of costs for developing a shared ledger may be a larger issue for supply chains that typically involve huge imbalances in economic power between participants (e.g., smallholder farmers at the first mile and much more powerful MNCs downstream in the supply chain). Without strong multi-stakeholder participation, many of the benefits of the technology are likely to not be realised.

Scalability and Inclusivity

The blockchain solution should be built in a way that is scalable and potentially accessible to all stakeholders in the supply chain. When the blockchain solution has been proven to achieve its intermediate goals, parties should take the successes to key ecosystem partners to grow the network and encourage further participation. This way, the blockchain project can garner additional investment progressively to create a greater impact.

There are a variety of mechanisms today to improve the scalability of blockchain. Enterprise solutions like Hyperledger and Corda have their own methods to increase possible transactions per second and latency. It is important to have a good estimate of the number of actors in the supply chain and expected volume and velocity of transactions to ensure that the blockchain system being built can support them. Referencing the implementation methodology of FairChain—a project aimed at distributing value fairly across global supply chains—they highlight the need for a continuous evaluation process to unlock value for all participants over the longer term.[108]

It is also worth noting that certain supply chain actors may have been left out at the early adoption stages due to a technological divide or a lack of incentives. Informal actors or other vulnerable groups who stand to benefit the most from a blockchain solution are usually also the ones who lack access to sufficient resources to participate. Hence, the infrastructure and technology for the solution need to be carefully selected with consideration of the limitations of the upstream actors of the supply chain to avoid creating de-facto barriers to entry. Greater attention can be given to such actors who might require assistance to participate in the future expansion of the blockchain network.

105 Mischa Tripoli and Josef Schmidhuber, Emerging opportunities for the application of blockchain in the agri-food industry, Revised version (Rome: FAO, 2020), http://www.fao.org/documents/card/en/c/ca9934en/.

106 Leong, Viskin, and Stewart, Tracing the Supply Chain: How Blockchain Can Enable Traceability in the Food Industry.

107 OECD, Is There a Role for Blockchain in Responsible Supply Chains?

108 FairChain Foundation, “The Methodology,” FairChain Foundation, https://fairchain.org/our-methodology/.

4. LIMITATIONS OF BLOCKCHAIN TECHNOLOGY

THIS SECTION DESCRIBES SOME OF THE CURRENT LIMITATIONS OF BLOCKCHAIN TECHNOLOGY IN GENERAL AND PARTICULARLY WITH REGARD TO THEIR APPLICATION IN AGRI-FOOD SUPPLY CHAINS. SOME OF THE LIMITATIONS HAVE NO CLEAR-CUT SOLUTION AND HENCE REQUIRES A CONSIDERATION OF EXISTING BEST PRACTICES TO BALANCE THE TRADE-OFFS INVOLVED.

LIMITED INTEROPERABILITY

There is currently little support for enabling interoperability between different blockchains. A unified technology standard for blockchain should be established among the working parties. This is an important consideration given that different blockchain systems built by different companies may not be interoperable. In the context of the agri-food sector, the larger players may need to guide the smaller supply chain actors, making careful selections about the type of blockchains to be used to minimise interoperability issues from arising in the future.

RISK OF ERRONEOUS DATA ENTRY

While the blockchain itself may be trustless and secure, some of the underlying operations surrounding its use are still error prone. The blockchain does not have a verification mechanism to ascertain whether the raw data inputted are correct. This makes it necessary to have an intermediate layer to facilitate the verification and validation of data. Data integrity lies in the hands of the data collectors and needs a system of validation to avoid data tampering. Having a unified system with definitive standards and regulations is essential. An unreliable system to record information can cause major issues, especially since alterations cannot be made on the blockchain to correct past erroneous entries.

Organisations developing a blockchain solution from scratch may begin with manual input of data, giving rise to the possibility of error. Companies like Raw Seafoods, that have trialled a blockchain solution, have put in place verification mechanisms among the parties before a block is allowed to be added to the blockchain. This allows them to spot any suspicious data entry that does not match with historical data at the point of block production.[109] Data can also be validated by corroborating it with the geographical location of data entry gathered via Global Positioning System (GPS) devices or Internet Protocol (IP) address of the computing device used to submit the data to be entered onto the blockchain. However, even these can possibly be forged. Nonetheless, there exists a risk that a seemingly innocuous data entry might make its way onto the blockchain, and it would then require additional resources and effort to rectify the data history.

RISK OF PHYSICAL ASSET SECURITY

While the information about an agri-food asset (e.g., a crate of mangoes) may be made accurately entered onto the blockchain, the blockchain itself is not capable of ensuring the security of the physical asset in transit. For example, the label used to track an asset and carrying accurate information about it may be forged and used with a counterfeit by a corrupt actor. The asset itself may be adulterated in transit. Hence, it is important to find ways to manage the security of physical assets in the supply chain. Since the blockchain by itself has no way to identify such occurrences, other technologies should be leveraged to address such issue.

Organisations today are addressing these risks in three ways:[110]

1. Conducting stringent physical audits when products first enter the supply chain to ensure that shipments match blockchain records;

2. Building distributed applications, called dApps, that track products throughout the supply chain, check data integrity, and communicate with the blockchain to prevent errors and deception. If a counterfeit or an error is detected, it can be traced to its source using the blockchain trail of the transactions for that asset; and

3. Making the blockchain more robust by using IoT to automatically scan products and add records to the blockchain without human intervention;

Another solution could be the use of tamper evident physical food packaging. For example, the QR code on a product may be placed behind a seal on the product. If the QR code were to be tampered with, the seal will be broken, and the consumer can recognise that the product integrity has potentially been compromised. VeChain, a blockchain application platform, has innovated a variety of Near Field Communication (NFC) chip labels that are "unpacked and destroyed, disposable, and splash proof",[111] meaning that the labels are tamper proof once labelled properly onto the product.

ISSUES WITH BLOCKCHAIN-IOT INTEGRATION

To eliminate the element of human error, companies have integrated IoT with blockchain for real-time data collection and update. Having IoT sensors feed data directly to the blockchain can minimise mistakes in data entry.

However, blockchain-IoT integration faces persistent technical issues that are yet to be resolved with effective solutions. Current IoT systems have a dependency on a centralised client-server models managed by a central authority, which make them susceptible to a single point of failure. Blockchain integration helps address this problem by decentralising decision making to a consensus-based shared network of devices.[112]

Yet, there exist other issues yet to be fully overcome:

- **Reliability:** The reliability of IoT sensors could potentially be undermined due to a physical malfunction or tampering. Additional measures should be in place to ensure the integrity of IoT devices such that they cannot be altered by external interventions. Multiple IoT sensors can potentially be used for redundancy, maintaining the benefits of distributed systems.
- **Storage and scalability:** IoT systems generate enormous volumes of data. A clear and coherent data model must be established to lower latencies and transaction processing speeds. Compared to centralised systems, blockchain suffers from potentially lower speeds or high latency when processing transactions.[113] IoT devices can

109 IBM Blockchain, "IBM Food Trust: Blockchain for Seafood," YouTube video, 59:00, August 26, 2020, https://youtu.be/24sU7T4jQbM.

110 Gaur and Gaiha, "Building a Transparent Supply Chain."

111 VeChain, "Chips," VeChain ToolChain™ Help Center, March 3, 2020, https://docs.vetoolchain.com/hc/en-us/articles/360040322671-Chips.

112 Deloitte, "Can blockchain accelerate Internet of Things (IoT) adoption?" Deloitte Switzerland, June 22, 2018, https://www2.deloitte.com/ch/en/pages/innovation/articles/blockchain-accelerate-iot-adoption.html.

113 Md. Ashraf Uddin et al., "A Survey on the Adoption of Blockchain in IoT: Challenges and Solutions," Blockchain: Research and Applications, no. 100006 (2021), https://doi.org/10.1016/j.bcra.2021.100006.

easily generate gigabytes (GB) of data in real-time. This presents a barrier for integration with blockchain, which is not designed to store large amounts of data. Different techniques are being researched to filter, normalise, and compress IoT data to lighten transmission. An appropriate consensus protocol must also be chosen to increase bandwidth and decrease the latency of transactions.[114]

LIMITED CAPABILITY OF SMART CONTRACTS

Smart contracts can be used to automate certain transactions that take place between parties in the supply chain. However, they currently have limited capability to support the complexities of real-world contractual agreements and the business realities. In most states, a 'contract' is legally binding and enforceable in a court of law. There are certain constraints limiting the widespread adoption of smart contracts:[115]

a. There is a necessary reliance on a technical expert who writes the software code of the smart contract. While the parties draft a legal contract, they also need to create a supporting document that lays out the functionality required of the smart contract for the technical expert.

b. There is usually a reliance on external data sources such as an oracle. For a smart contract to execute based on input data, the external data received through the oracle should be accurate and synchronised among the different nodes in the blockchain. However, there is usually latency that may result in varying data inputs. For more sensitive data inputs, fluctuations can be disastrous. An oracle acts as a common data input source that pushes the necessary data to all nodes at predetermined times. Yet, concerns have been raised that such oracles can themselves become points of failure.

c. Smart contracts posted on the immutable blockchain results in a problem when there is little recourse to altering or terminating the contract in an atypical situation. The costs incurred to make changes are likely higher than for traditional textual contracts. Business realities reflect that totally immutable smart contracts may not always be desirable.

d. There are limits in the ability of software code to replicate real-world terms and conditions. The ambiguity that may exist in certain contractual conditions may not be possible to represent using the exacting standards of software code. This restricts the use of smart contracts to a select number of uses cases.

e. There are potential workarounds that prevent the logic of smart contracts from executing. For instance, the wallet that the contract is supposed to withdraw from might be empty at the time of execution, thereby preventing the code from executing properly. While terms can be set such that the amount of required capital be locked in the contract as escrow, actual business practices involve liquid capital movement that may not support the case for capital lockup. Hence, more advanced agreements might need to be made to resolve such situations.

It is good to note that while technical experts can help to audit and reduce the risk of smart contract misbehaviour, parties should expect a scenario where bugs can slip through. Given the close linkages between different smart contracts, one misbehaviour can cause repercussions that are difficult to fix. For example, the failure of even just one oracle can invalidate the quality of a batch of records made during a certain period of the traceability process.

In context of the highlighted issues with smart contracts currently, the following best practices have been suggested:[116]

a. Parties entering any type of contractual arrangement would be best served using a hybrid approach that combines text and code. Given the constraints of code in representing business realities and nuances of real contract terms, the text-based contract can act as a backup.

b. The text should clearly describe the behaviour of the contract and give full visibility into content such as variables and event triggers.

c. Both parties should decide on a clear method of resolution upon contract failure or misbehaviour.

d. Third-party technical experts and insurers can be engaged to check for errors and reduce the risks involved.

LIMITATIONS OF ORACLES

Blockchain oracles are used to solve the 'oracle problem'[117] that exists when implementing smart contracts on the blockchain. On a decentralised platform like the blockchain, nodes need a way to accurately verify that a physical asset has been transferred to its rightful owner following the transfer of the digital token of the asset. The digital world needs to 'know' about the physical world and oracles were created to solve this problem. However, several issues regarding oracles are still being resolved.

114 Ana Reyna et al., " On blockchain and its integration with IoT. Challenges and opportunities," Future Generation Computer Systems 88 (2018): 173–190, https://doi.org/10.1016/j.future.2018.05.046.

115 Levi and Lipton, "An Introduction to Smart Contracts and Their Potential and Inherent Limitations."

116 Ibid.

117 Jimmy Song, "The Truth about Smart Contracts," Medium, June 11, 2018, https://jimmysong.medium.com/the-truth-about-smart-contracts-ae825271811f.

One major concern is ensuring the quality of data when not every node has the same access to data. It is resource-intensive to manage and enforce quality control for off-chain data submitted by the blockchain nodes. Different nodes will have equal opportunity to submit data, yet there may be little incentive for the majority to invest in obtaining data of the highest quality.

Furthermore, the process of adding new oracles to the blockchain network involves a slew of social governance coordination and nodes of the blockchain to install upgrades each time. This can result in increased friction which slows the development of the blockchain. Hence, oracle networks usually operate separately from the base layer of the blockchain, eliminating any potential dependencies and related risks.

Moreover, a decentralised oracle system should be preferred over a centralised version. A centralised system depends on a single oracle operator which reintroduces a plethora of potential vulnerabilities that are tough to defend against. Issues regarding a single point of failure and the necessity to trust in correct behaviour of an entity are reintroduced. Entities with heavy responsibilities can come under pressure once the value of the contract scales, and are vulnerable to other risks such as bribes, intimidation, and regulatory pressures.

There is yet to be a fool-proof solution to solve the trust liability brought about by introducing oracles to the blockchain network. However, there are projects today that are making impressive advancements to minimise the risk of malicious behaviour.

Provable is the leading oracle service for smart contracts and blockchain applications, serving thousands of requests every day on platforms like Ethereum, R3 Corda, Hyperledger Fabric, and EOS. Instead of utilising a decentralised oracle model to ensure data accuracy, Provable (Oraclize) uses a unique approach to demonstrate that the data fetched from the original source is genuine and untampered. This is accomplished by accompanying the returned data together with a document called an authenticity proof. The authenticity proof opens the opportunity for anybody to verify themselves whether the data (or result) delivered is in fact authentic.[118] Another prominent oracle solution provider that is otherwise focused on the track of a decentralised oracle system today is Chainlink. They have developed a decentralised oracle network that can provide a multitude of different guarantees that can be used in any combination to provide customised oracle solutions to any use case.[119]

118 Abdeljalil Beniiche, "A Study of Blockchain Oracles," arXiv (2020), https://arxiv.org/abs/2004.07140v2.

119 Chainlink, "What Is the Blockchain Oracle Problem?" Chainlink, August 27, 2020, https://blog.chain.link/what-is-the-blockchain-oracle-problem/.

CONCLUSION

This report has introduced the emerging blockchain technology and its progressively important role in improving traceability and transparency in the agri-food industry to achieve sustainable development. Beneath the hype, a blockchain solution has numerous facets to be considered—both from technical and operational perspectives—given that its application would involve most stakeholders in a supply chain. Therefore, it is important to ensure that a blockchain system is indeed the best solution for a given developmental problem, compared to alternatives like traditional database technology which may be cheaper and easier to implement.

After a solution is initially deployed, consistent efforts are required for ensuring its sustainability. This will involve continuously engaging with stakeholders and revising and improving processes as more and more actors and stakeholders are onboarded and the solution scales in both size and scope. With rapid advances in the core and ancillary technologies, several of the current limitations preventing the wide-scale adoption of blockchain in agri-food supply chains promise to be addressed in the near future.

There are several benefits of blockchain's application in supply chains—from enhancing operational efficiencies to reducing the likelihood of disputes and enhancing trust among supply chain actors. The challenge lies not in convincing the private sector about these benefits but to leverage the use of the technology to include more people—including smallholder farmers—and to ensure that no one gets left behind. This is where UNDP can play a critical role, by working with diverse stakeholders—including the public and private sectors and the civil society—and fostering the design and development of inclusive solutions that benefit stakeholders at the first mile.

Whether it's gender inequality, income inequity, deforestation, or human rights abuse, the challenges faced by current agri-food systems are complex and interlinked, requiring integrated solutions—something UNDP is best placed to deliver. The UNDP Strategic Plan 2022-2025 underlines the importance of integrated development solutions driven by country priorities towards achieving structural and inclusive transformation. Moreover, digitalisation is envisaged as a key enabler for maximising development impact. Blockchain technology, which intrinsically requires an integrated approach for deployment through stakeholder engagement and consensus building, can be a gamechanger for transforming global agri-food systems.

APPENDIX

APPENDIX I: CONSENSUS MECHANISMS

Consensus mechanisms enable a decentralised network to take over the duty of a centralised authority in ensuring a single source of truth and in making certain decisions, such as the verification of information before adding it to the blockchain.

The most well-known mechanism is Proof of Work (PoW) which is used in Bitcoin.[120] PoW requires nodes, also known as miners, to solve difficult computation tasks before validating transactions to be added to the blockchain. All active miners will be expending computational power and electricity in a bid to obtain a block hash that is below the target, yet only one miner can be successful. The difficulty also automatically adjusts to the competition such that the frequency of a successful mining is kept relatively constant. As a result, PoW often leads to high levels of computational power and energy consumption which are environmentally undesirable.

An alternative approach is the ‘Proof of Stake’ (PoS) protocol. Unlike PoW, no computational power is required and not everyone can join the network. Participating nodes of the network act as ‘validators’ to validate transactions and earn transaction fees. The chance of getting chosen as the validator for the next block varies depending on the amount of stake they have on the network. As such, PoS may lead to undesired monopolisation where nodes with the highest percentage of ownership are prioritised.

Other consensus mechanisms for consideration include Proof of Elapsed Time (PoET),[121] Simplified Byzantine Fault Tolerance (SBFT),[122] and Proof of Authority (PoA)[123] that could better suit different network dynamics and stakeholder relationships. Below is a non-exhaustive list of other consensus mechanisms:[124]

120 B. Sriman, S. Ganesh Kumar, and P. Shamili, “Blockchain Technology: Consensus Protocol Proof of Work and Proof of Stake,” Intelligent Computing and Applications (Singapore: Springer, 2021): 395–406, https://doi.org/10.1007/978-981-15-5566-4_34.

121 Mic Bowman et al., “On Elapsed Time Consensus Protocols,” IACR Cryptology ePrint Archive 2021 (2021): 86, https://eprint.iacr.org/2021/086.

122 Guy Golan Gueta et al., “SBFT: a Scalable and Decentralized Trust Infrastructure,” arXiv (2019), https://arxiv.org/abs/1804.01626v3.

123 An Cong An et al., “Building a Product Origins Tracking System Based on Blockchain and PoA Consensus Protocol,” 2019 International Conference on Advanced Computing and Applications (ACOMP) (IEEE, 2019): 27–33, https://doi.org/10.1109/ACOMP.2019.00012.

124 Tien Tuan Anh Dinh et al., “Untangling Blockchain: A Data Processing View of Blockchain Systems,” IEEE Transactions on Knowledge and Data Engineering 30, no. 7 (2018): 1366–1385, https://doi.org/10.1109/TKDE.2017.2781227.

Table 6: Additional consensus mechanisms

Consensus protocol	Network setting	Description
Practical Byzantine Fault Tolerance (PBFT)-based	Private	Used by Hyperledger, PBFT assumes that some nodes might be corrupt or malicious. Hence it multicasts information to multiple nodes to ensure that the minority of unreliable nodes are identified and do not prevent consensus from being achieved.
Stellar	Federated	Nodes form intersecting groups (federates). Consensus is agreed in each group, then propagated to the rest of the network.
Ripple	Federated	A variant of PBFT where the nodes belong to intersecting groups, and in each group there is a large majority of non-Byzantine nodes.
Threshold Relay	Public	Nodes form random group based on a public verifiable random function, then nodes in the group create a new block by signing it with a threshold signature.
Proof-of-Authority (PoA)	Private	Some pre-defined nodes are set as trusted authorities that can propose the subsequent blocks. Every authority node will then be assigned a time window during which it can propose blocks in a round-robin fashion.
Proof-of-Burn (PoB)	Public	A node destroys some base currencies it owns in another blockchain in exchange for a chance of proposing a new block.
Proof-of-Elapsed Time (PoET)	Private	Each node runs a trusted hardware that generates random timers. The first node whose timer has expired can propose the next block.

APPENDIX II: ORACLES AS ANCILLARY TECHNOLOGIES

Hardware Oracles

Various IoT tools act as hardware oracles to support traceability and the collection of information.

a. Quick Response (QR) codes and barcodes

QR codes and barcodes are machine-readable, optical labels that store information about an item or product. The QR code is a two-dimensional optical visualisation of information and is actively replacing barcodes by providing greater information capacity. Both solutions are convenient, cost friendly and accessible given the proliferation of scanning devices like mobile phones with integrated cameras. For example, FoodSQRBlock is a proposed blockchain-based solution that improves information accessibility for consumers and producers.[125] However, QR codes and barcodes are vulnerable against forgery, may present cybersecurity risks, and require the need for visual contact through a line of sight.[126] For instance, QR codes can be cloned and reused to authenticate counterfeit agri-food products for distribution.[127] Hence, radio-frequency identification (RFID) tags may be more preferable for traceability in a supply chain.

125 Somdip Dey et al., "FoodSQRBlock: Digitizing Food Production and the Supply Chain with Blockchain and QR Code in the Cloud," Sustainability 13, no. 6 (2021): 3486, https://doi.org/10.3390/su13063486.

126 Aleksandr Lanko, Nickolay Vatin, and Arturas Kaklauskas, "Application of RFID combined with blockchain technology in logistics of construction materials," MATEC Web of Conferences 170, no. 1 (2018): 03032, https://doi.org/10.1051/matecconf/201817003032.

127 Shundao Xie and Hong-Zhou Tan, "An Anti-Counterfeiting Architecture for Traceability System Based on Modified Two-Level Quick Response Codes," Electronics 10, no. 3 (2021): 320, https://doi.org/10.3390/electronics10030320.

b. Radio-frequency identification (RFID)

RFID is a communication technology that identifies stored information transmitted wirelessly through radio signals. Electronic chips are inserted into tags, enabling detection based on the frequency of radio waves emitted.[128] Active RFID tags contain a battery and are capable of transmitting information independently. They are suitable for mobile operations that involve writing data inputs, while passive RFID tags only read information and identify characteristics of other physical objects with tags.[129] Due to the use of radio waves, RFID tags do not require a line of sight between the reader and the tags, allowing greater efficiency and higher read accuracy to be achieved. Nonetheless, cost considerations may limit the application areas of RFID tags to pallets and containers instead of single product tracking.[130] Moreover, RFID tags may be subject to security breaches and heterogenous RFID standards. Nonetheless, solutions such as biometric access enhances security,[131] allowing RFID tags to be a popular tool to record smart contracts in the implementation of blockchain solutions in agri-food supply chains.

c. Wireless sensor network (WSN)

WSN is a spatially distributed autonomous network of sensors to collect and monitor real time data of physical and environmental conditions through a mobile network.[132] Specific technologies under WSN include near-field communication (NFC), Bluetooth Low Energy (BLE), and ultra-wideband (UWB).

NFC is used for wireless short-range communication for RFID tags.[133] The technology is likely to remain prominent with an increasing number of NFC enabled devices such as smartphones. NFC solutions can be used at each stage of the food supply chain and by end consumers to acquire traceability information.

BLE provides a secure means of wireless communication while utilising less power than prior Bluetooth standards.[134] It is useful for applications that periodically exchange small amounts of data and could prove useful within agri-food supply chains where there may be limited connectivity in sparse areas. Additionally. UWB utilises radio waves at high frequency to precisely determine one's location with high security while utilising little power. UWB presents an inexpensive approach to securely identify the location of agri-food commodities, reducing potential fraud in the exchange of positioning information.[135]

These technologies may be useful to manage differing granularity of information between agri-food commodities. Since NFC, BLE, and UWB are increasingly integrated into mobile devices and are more efficient than QR codes, they allow easy management of data for all stakeholders.[136]

d. Smartphones

Smartphones are integrated devices that house powerful processors, wireless capabilities, digital cameras, NFC devices, and software tools.[137] Smartphones are capable of reading data through NFC, scanning QR codes and barcodes, and can utilise their GPS antennae to communicate location information. In the near future, smartphones may replace sensor technologies such as barcode scanners. This could benefit many agri-food supply chains by reducing digitisation costs.

Software Oracles

Software oracles retrieve data from third-party sources such as web APIs that allow access to real-time information like weather data and satellite imagery, or online databases containing key agri-food information such as crop protection, seed costs, and cropping methods.

a. Weather

Weather changes such as humidity and temperature can have a significant influence on crop yields. For example, although tropical crops such as banana, sugarcane,

128 Feng Tian, "An agri-food supply chain traceability system for China based on RFID & blockchain technology," 2016 13th International Conference on Service Systems and Service Management (ICSSSM) (2016): 1–6, https://doi.org/10.1109/ICSSSM.2016.7538424.

129 Lukáš Kubáč, "RFID Technology and Blockchain in Supply Chain," Transactions of the VŠB – Technical University of Ostrava, Mechanical Series 64, no. 1 (2018): 35–44, https://doi.org/10.22223/tr.2018-1/2042.

130 Tian, "An agri-food supply chain traceability system for China based on RFID & blockchain technology."

131 Mohamed El Beqqal and Mostafa Azizi, "Review on security issues in RFID systems," Advances in Science, Technology and Engineering Systems Journal (ASTESJ) 2, no. 6 (2017): 194–202, https://doi.org/10.25046/aj020624.

132 Rejeb, Keogh, and Treiblmaier, "Leveraging the Internet of Things and Blockchain Technology in Supply Chain Management."

133 S. P. Srinivasan, D. Sorna Shanthi, and Aashish V. Anand, "Inventory transparency for agricultural produce through IOT," IOP Conference Series: Materials Science and Engineering 211, no. 012009 (2017), https://doi.org/10.1088/1757-899X/211/1/012009.

134 Marc Jayson Baucas and Petros Spachos, "Permissioned Blockchain-Driven Internet of Things Gateway Using Bluetooth Low Energy," ICC 2020 - 2020 IEEE International Conference on Communications (ICC) (2020): 1–6, https://doi.org/10.1109/ICC40277.2020.9149142.

135 Mridula Singh et al., " UWB-ED: Distance Enlargement Attack Detection in Ultra-Wideband," 28th USENIX Security Symposium (2019): 73–88, https://www.usenix.org/conference/usenixsecurity19/presentation/singh.

136 Danny Pigini and Massimo Conti, "NFC-Based Traceability in the Food Chain," Sustainability 9, no. 10 (2017): 1910, https://doi.org/10.3390/su9101910.

137 Joonkoo Lee and Gary Gereffi, "Innovation, upgrading, and governance in cross-sectoral global value chains: the case of smartphones," Industrial and Corporate Change 30, no. 1 (2021): 215–231, https://doi.org/10.1093/icc/dtaa062.

cocoa, and coffee thrive in highly humid environments, excess humidity leads to unwanted bacterial growth and rotting of crops.[138] Software oracles on the blockchain can grant smallholder farmers access to time and location-specific weather data and analysis[139] which can enable precision agriculture. As a result, farmers may be able to allocate scarce resources more strategically and potentially improve yields.[140]

b. Satellite imagery

The agri-food supply chain can leverage satellite imagery to monitor farms to optimise agricultural inputs such as fertilisers and pesticides. Satellite imagery serves as an objective monitoring tool for consumers or corporations down the value chain who wish to analyse phases of crop production. Additionally, smallholder farmers benefit by utilising satellite imagery as proof of land ownership against land demarcation conflicts.

c. Crop protection, seed costs, and cropping methods

Besides real-time data, software oracles have access to databases containing reliable historical data. Existing crop protection databases store plant protection chemical datasets such as pesticide, herbicide and fungicide manufacturer labels.[141] Access to the open database promotes transparency between stakeholders. Other databases of an agri-food supply chain may provide information on seed costs and cropping methods which can empower smallholder farmers against information asymmetry.

APPENDIX III: FUTURE OF BLOCKCHAIN

The rapid development in the area of blockchain technology has fostered numerous communities innovating in different aspects of the technology including scalability, processing speed, and computational capacity. Readers interested in future developments in blockchain can utilise the following keywords for further research. They are categorised under four potential developmental fronts: Layer 1 solutions (On-chain); Layer 2 solutions (Off-chain); Consensus mechanisms; and distributed ledger design.[142]

LAYER 1 SOLUTIONS (ON-CHAIN)	LAYER 2 SOLUTIONS (OFF-CHAIN)	CONSENSUS MECHANISMS	DISTRIBUTED LEDGER DESIGNS
Sharding	Roll-ups	Byzantine Fault Tolerance (BFT)	Tangle
Hard Forks	Plasma	Proof of Authority	Directed Acyclic Graphs
	Channels	Delegated Proof of Stake	Hashgraphs
	Sidechains	Others	

138 B. Leuenberger, "Tropical Crops," Freie Universität Berlin, https://www.bgbm.org/en/greenhouses/tropical-crops.

139 Gareth Goh, "How to Optimize Crop Growth Using Weather Data to Track Humidity," Tomorrow.io, April 26, 2021, https://www.tomorrow.io/blog/how-to-optimize-crop-growth-using-weather-data-to-track-humidity/.

140 Sara Spaventa, "The Power of Satellite Imagery In Agriculture & Farming," FarmTogether, May 6, 2021, https://farmtogether.com/learn/blog/the-power-of-satellite-imagery-in-agriculture.

141 Joy Culbertson, "10 Popular Agriculture APIs," ProgrammableWeb, November 15, 2020, https://www.programmableweb.com/news/10-popular-agriculture-apis/brief/2020/11/15.

142 Aziz, "Blockchain Scalability Solutions: Overview of Crypto Scaling Solutions," Master The Crypto, https://masterthecrypto.com/blockchain-scalability-solutions-crypto-scaling-solutions/.

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