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Tokenizing circularity in agri-food systems: A conceptual framework and exploratory study

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ABSTRACT

This paper presents a conceptual framework that reflects the current state of thinking on tokenizing circularity in agri-food systems. The framework is built upon classifications of tokens and the key principles of circular economy and shows how tokenization can support circularity in agri-food systems through the flows of information and flows of value. Based on an integrative review of literature on tokenization, blockchain and the circular economy and multiple case studies in the agri-food domain, we show the relevance of tokenization to the circular economy in three ways: 1) enhancing traceability of physical and digital objects in supply chains; 2) improving transparency and credibility of circularity claims; 3) facilitating collaborative business ecosystems with incentives for more circular production and distribution. Based on the framework, we derive important research questions for future research agenda on tokenizing circularity in agri-food systems.

1. Introduction

The circular economy (CE), as opposed to the current linear economy, has been considered as a sustainable economic system in which resource depletion is maximally prevented (Kirchherr et al., 2017). CE is intrinsically linked to the concept of Cleaner Production as they both aim at preventing the production of waste, while increasing efficiencies in the uses of energy, water, resources, and human capital. In the past years, there has been a growing body of literature reviewing the principles and metrics of CE (see e.g., Corona et al., 2019; Ekins et al., 2020; Kouhizadeh et al., 2022b). In general, CE principles seek to add value to materials and products by maximising the length of their life cycle and regenerating them at their end-of-life. In most cases, transition to CE requires rethinking and redesigning of workflows, business models and governance arrangements in which digital technologies are expected to be enabler and catalyst (Bekrar et al., 2021; Hedberg and Šipka, 2021; Pagoropoulos et al., 2017; Upadhyay et al., 2021).

As CE is progressing, more and more products and processes are claimed to be circular. Globally, certification schemes for circular products are being developed.[1] For many parties in the supply chains, a pressing issue is, however, how to trust or verify such claims of circularity as it is not always visible where a product comes from and what it is made of. As circular supply chains are complex networks with closed loops of inputs, resources and outputs, the tracking and tracing of these highly interdependent flows is conceptually complex and operationally challenging.

An obvious approach to solving the verification problem may be to attach a label or an identifier to each product and process and then record and track these identifiers in a centralized database. This obvious solution is not necessarily the preferred one as most business operators are reluctant to share such data. It is also not the most effective one as a centralized database can, for example, be easily compromised and consequently constitute a *single point of failure* in a network of users. An alternative is to develop a distributed data ecosystem in which information can be verified and validated with reliable validation mechanisms. A distributed database secured with cryptographic methods is known to be able to keep shared, tamper-proof records. The technology is called distributed ledger technology (DLT), more commonly known as

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[1] See for example the Global Sustainable Enterprise System GSES®, more information at: https://certifications.controlunion.com/en/certification-programs/certification-programs/gses-circular-economy.

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blockchain technology, with the most known application in crypto-currencies such as the Bitcoin (Swan, 2015).

Started in the financial sector, DLT has now been widely recognized in many other sectors like healthcare, government, energy, mobility, and retail (see e.g., Bryatov and Borodinov, 2019; Hrga et al., 2020; Saari et al., 2022). In the agri-food domain, DLT and blockchain applications have gained significant popularity since 2017 (see e.g.,van Hilten et al., 2020; van Wassenaer et al., 2021). Agri-food chains are known to be fraught with problems related to transparency and traceability due to the complexity of the chains and inherent uncertainties in many natural processes involved (see e.g., Kramer et al., 2021). The rising number of publications on blockchain applications and CE in agri-food shows that there is an increasing appreciation of the potential utility of blockchain among the community of researchers and practitioners working on the circularity of agri-food systems (see e.g., Pakseresht et al., 2022b).

While there is a growing knowledge base on the general principles of blockchain applications, tokenization is still a novel topic that is in its infancy. There are some, mostly explorative studies and cases that mention the potential of tokens for circularity in agri-food systems (Kouhizadeh et al., 2022a; Patidar et al., 2021; Tarhini, 2021), but there is a lack of knowledge about how to use distinct types of tokens in the design of circular systems. Furthermore, to the best of our knowledge the application of blockchain tokens for circularity in agri-food systems has not yet been researched.

This paper contributes to filling this knowledge gap by answering the following two research questions: 1) Which types of tokens are relevant to CE in agri-food systems? 2) How can tokenization help improve circularity in agri-food systems? More specifically, our contributions are threefold: 1) a synthesis of the current state of thinking on tokenizing circularity; 2) a conceptual framework for understanding and analyzing token-based solutions for circularity in agri-food systems; and 3) an exploratory investigation of use cases on tokenizing circularity in agri-food systems based on the framework to identify the potential and directions for future research. Our research methodology consists of literature review and case studies which have resulted in the conceptual framework and the analysis of the use cases using the conceptual framework.

In the remainder of this paper, we first introduce the methodology used for developing the conceptual framework and then describe the background and related work on tokenizing circularity before introducing the conceptual framework. The applicability of the framework is then illustrated with a potential use case, followed by a discussion. We conclude the paper with a brief outlook on future research and development on this relatively new topic.

2. Research methodology

Our conceptual framework is built upon an integrative literature review on CE, supply chain management, and application of DLT or blockchain in agri-food chains. An integrative review method was considered suitable as the purpose of our study is to provide an overview of the knowledge base, combine insights and perspectives from different fields, and expand on the theoretical foundation of tokenizing circularity (Snyder, 2019). To identify relevant literature, our search strategy consists of a combination of ‘snowballing’ and ‘comprehensive pearl growing approach’ (Dekkers et al., 2022). This means initial studies (or ‘pearls’) that are known to be relevant are used for further search by tracking articles that cite these studies. This process is repeated in multiple waves until no new relevant articles are identified.

Initial pearls were identified in Scopus (24 references) with the search string (“Circular Economy”) AND (“Tokenization” OR “Tokenization”) AND (“Blockchain”). Articles were included and read by the researchers when their abstracts: (1) contained information about CE; (2) mentioned the application of blockchain; or (3) mentioned the use of digital ledger technology or DLT. Furthermore, we search Google Scholar using combinations of the following three keywords: 1) tokenization; 2) blockchain; 3) “circular economy”. Included articles were analyzed with the aim to identify frameworks and indicators for tokenizing or measuring circularity. Considering the novelty of the topic, we limited our literature search to those published in the last 5 years (i.e. from 2016 onwards) and also surveyed grey literature (e.g. popular articles published on technological websites) in the same period. In total, 345 articles were screened and 55 were studied in detail.

Furthermore, considering the conceptual framework as an artefact, we followed a design science paradigm to seek field testing through an extracting multiple case study (Aken, 2004; Yin, 2018). For this purpose, the designed framework is applied to six use cases of tokenization in the agri-food domain. First, a long list of in total 54 use cases was compiled based on desk research and previous reviews of Blockchain use cases in agri-food conducted by the researchers (Saurabh and Dey, 2021; van Wassenaer et al., 2021). The research team then selected 6 use case by checking the relevance to CE and the use of tokens. Other criteria for the selection of the use cases were the availability of use case experts for interview, the accessibility of use case documentation and geographic spread. Next, the data gathering of the selected cases was done by reviewing case documentation and expert interviews. The conceptual framework was then used to analyze the case findings and to systematically describe the usage of tokens for circularity in each use case.

3. Background and related work

3.1. Unpacking the concept of circular economy

The concept of CE has been defined and used differently by different researchers, covering a broad range of domains and dimensions. Kirchherr et al. (2017), for example, identified 114 definitions used in the literature. A number of seminal articles have influenced the development and evolution of the concept, for example, Geng and Doberstein (2008) defined CE as ‘the realization of [a] closed loop material flow in the whole economic system’. To make the concept of CE operational, the Ellen MacArthur foundation devised the well-known ‘6 R’ framework that outlines the main principles of CE as: *Reduce*, *Reuse*, *Recycle*, *Recover*, *Redesign*, and *Remanufacture* (Van Engelenhoven et al., 2021). These principles address different dimensions (e.g. use of resources, production methods, distribution and disposal of products) of CE as an economic system. More specifically, the *Reduce* principle refers to the reduction in the use of resources. The *Reuse* principle emphasizes using products or components once again for the original purpose for which they were conceived. Reuse inherently also causes reduction of the use of raw materials in ‘newer’ products and components. The *Recycle* principle refers to reprocessing waste materials into products, materials, or substances. This principle includes the reprocessing of organic material, but not energy recovery of the use of waste as fuels or as backfilling. The *Recover* principle is about collecting a product at the end of its use stage, which is then disassembled, sorted and cleaned for use in future product lifecycles—including for energy and backfilling. The *Redesign* principle refers to redesigning next generation products that use components, materials and resources recovered from the previous lifecycle, or previous generation of products. Finally, the *Remanufacture* principle refers to the restoration of an already used product to its original or upgraded state without losing functionality and keeping equivalent or new features.

The CE literature therefore suggests that the concept of circularity has bearing on products (including packaging) and processes. For all the principles, the possibility of tracking and tracing goods and the monitoring of manufacturing and distribution processes will be crucial.

3.2. Circularity in agri-food systems

Being heavy users of natural resources and suppliers of essential goods and services, agri-food systems play an intrinsic role in many of the societal challenges CE aims to address. Consequently, the concept of circularity has been an important theme in research on agri-food systems. In Table 1 we synthesize research on this topic by presenting an overview of the key themes and topics being addressed in the literature as well as the opportunities and challenges. The key references are indicated under the column ‘Main areas of focus’. Some specific references, when relevant, are also indicated under the columns ‘Opportunities’ and ‘Challenges’. A broader overview of research on agri-food supply chains can be found in the systematic literature review of Yadav et al. (2022) and Agnusdei and Coluccia (2022).

3.3. Tokenization and DLT

3.3.1. Tokenization in general

The notion of ’tokens’ is popularized by blockchain applications, however, the history of tokenization predates blockchain.[2] For example, physical tokens like casino chips have long been used to replace real money. In such cases, tokens are used to denote a legal right of ownership of the underlying currency. In the digital world, tokens were used to replace sensitive data (e.g. credit card information, social security numbers) with a non-sensitive digital equivalent (Díaz-Santiago et al., 2016). Tokenization in such context is the process of substituting a surrogate value (or ‘token’) for a sensitive data value in a data processing system.

Tokenization is often mentioned together with encryption as a means to secure information when it is being transmitted on the Internet (‘data in flight’) or stored (‘data at rest’) (Williams, 2010). While both are data obfuscation technologies, there are fundamental differences between tokenization and encryption. To start with, encryption is about mathematically transforming plain text into cipher text using an encryption algorithm and key (Bhanot and Hans, 2015). Tokenization is about randomly generating a token value for plain text and stores the mapping in a database (Stapleton and Poore, 2011). With encryption, the original data can leave the organization in encrypted forms. Tokenization makes it possible that original data never leave the organization, which is important in satisfying compliance regulations. The advantage of tokenization is that there is no mathematical relationship between tokens and the real data they represent. If tokens are breached, they have no meaning. The mapping from original data to a token uses methods that make it impossible to reverse to the original data without the tokenization system. This feature makes tokenization highly useful for data security in the Payment Card Industry (PCI).

Digital tokenization was first introduced by TrustCommerce in 2001[3] as a means to protect credit card information. The system that TrustCommerce developed replaced the primary account number (PAN) with a unique identifier known as a token, which is a reference (i.e. identifier) that maps back to the sensitive data through a tokenization system. The tokenization system maintains a secured vault database of tokens that are connected to the corresponding sensitive data. As described by Díaz-Santiago et al. (2016), the tokenization system, while derisking the merchant sites by being the intermediary between the merchant site and the card issuer site, still faces security risks as the vault database storing pairs of PANs and tokens can be breached. Alternative tokenization systems such as those using distributed ledger technology (DLT) can be used to circumvent this problem.

3.3.2. Tokenization and DLT

As suggested in Section 3.2.1, the security and power of tokenization as used in the PCI is limited to the management of the vault databases which is often centralized. When a token is issued and stored using DLT, the blockchain records the issuance and maintains a ledger of every movement of that token that is extremely difficult, if not impossible, to manipulate. This is due to the defining feature of DLT that the ledger is shared and synchronized across a set of DLT nodes through cryptographic methods (Sunyaev et al., 2021). DLT Tokenization becomes thus vastly more powerful as the distributed system can offer more security and resilience than a centralized one. Furthermore, as virtually all assets can be tokenized, tokenization can be applied to many more industries than the financial sector. For example, supply chains use digital tokens to manage the movement of goods (Sunny et al., 2020). The combination of tokenization and DLT offers unprecedented opportunity for improving traceability and transparency in virtually all industries.

There are many ways to describe DLT tokens using different token taxonomy frameworks (TTF) or classification frameworks. Freni et al. (2022), for example, studied eight token classification frameworks for the design of a morphological framework. A TTF breaks tokens down into basic reusable parts such as base token types, properties and behaviours which are then placed into a category by type and can support grouping. An example of such grouping can be found in Oliveira et al. (2018) where the choice parameters are classified into four categories: purpose (e.g. utility vs. security), governance (e.g. representation and incentives), functional (e.g. spendability and fungibility), and technical (e.g. blockchain native or blockchain non-native). This results in 8 archetypes as shown in Table 2. The heterogeneity of tokens means that tokenization can be applied in many different ways. It is unlikely that one token can fit all purposes of CE. This highlights the need for a framework with which tokenizing circularity can be considered with the plenitude of tokens.

3.3.3. Token economy and economics of tokens

With the rising popularity of cryptographic tokens, the concept of ‘token economy’ has gained increased attention in research (Kim and Chung, 2019; Lee, 2019; Sunyaev et al., 2021). In our current context, the token economy is closely related to the concept of Web3 in which tokens form an atomic unit (Voshmgir, 2020). Web3 is an evolution of digital infrastructure notably enabled by DLT, whereby protocol facilitates the direct exchange of values between users, removing the need for trusted intermediaries.

The advent of Web3 has far-reaching implications for governance systems by providing a distributed ledger system that fundamentally differs from a centralized system. This also shows the relevance of tokenization to any economic system as all economic systems must rely on ledgers to enable economic exchanges to take place. More broadly, tokenization is considered to represent a paradigmatic shift in economic thinking with the intended creation of a self-governed (or algorithmically governed) economic system whose rules are programmed by the token designer (Freni et al., 2022).

3.4. Related work

As evidenced by the growing body of scientific and non-scientific literature on how to leverage blockchain technology for circularity (Kouhizadeh et al., 2019, 2022b; Narayan and Tidström, 2020; Pagoropoulos et al., 2017; Pakseresht et al., 2022a; Rehman Khan et al., 2021; Upadhyay et al., 2021; Weingärtner, 2019), the potential of DLT has certainly been noticed among the research community of CE. Blockchain is also, but to a lesser extent, addressed as a key enabler of circular agri-food systems. For example, the review of Pakseresht et al. (2022b) indicates Blockchain could accelerate CE in the agri-food sector by improving data utility, supply chain management efficacy, enhanced eco-efficiency, and superior traceability. The review of Dey and Shekhawat (2021) mentions the potential of tokens for sharing value in agri-food chains. The conceptual paper of Narayan and Tidström (2020) explores the use of tokens to manage partially convergent interests where cooperation and competition occur simultaneously, as is the case in CE. Kouhizadeh et al. (2020) argue that tokens could allow for incentivization of CE initiatives in particular to influence the recycling

[2] See also https://medium.com/coreledger/what-is-tokenization-everything-you-should-know-1b2403a50f0e.

[3] https://trustcommerce.com/blog/where-did-tokenization-come-from/.

Table 1
Overview of research on circularity in agri-food systems.

Theme	Main areas of focus	Opportunities	Challenges
Agri-food supply chains in general	- Agri-food supply chain management (see e.g., Barbosa, 2021; Brandenburg et al., 2014); - Technology and innovation (Testa et al., 2022); - Consumer behaviour and preferences (see e.g., Aschemann-Witzel and Stangherlin, 2021) - Food systems governance and policy (see e.g., Galli et al., 2020).	- Building resilience to climate change (see e.g., Stone and Rahimifard, 2018) - Digital innovation (see e.g., Kosior, 2018); - Blockchain (see e.g., Kramer et al., 2021; Rejeb et al., 2023); - Circular Economy (Chiaraluce et al., 2021; Esposito et al., 2020; Salimi, 2021).	- Complexity and interconnectedness of agri-food processes; - Data availability and quality; - Political and economic influences; - Interdisciplinary collaboration.
Understanding circularity in agri-food systems	- Modelling circular agri-food supply chains (see e.g., Stillitano et al., 2022); - Circular farming systems (see e.g., Tagarakis et al., 2021); - Food waste and food loss (see e.g., Mor et al., 2021; Tanveer et al., 2021).	- Resource use efficiency; - Food and nutrient security; - Substituting fossil fuel use; - Emission reduction; - Technological and social innovations.	- Complexity of agri-food processes; - Technological readiness; - Food safety laws and regulations; - Lack of market infrastructure; - Lack of data on impacts.
Measuring circularity in agri-food systems	- Indicators and metrics (see e.g., Falcone et al., 2022; Papangelou and Mathijs, 2021; Silvestri et al., 2022); - Life Cycle Assessment (LCA) (Notarnicola et al., 2017);	- End-to-end traceability; - Revers logistics; - Farm to fork optimization; - Big data and ICT, Internet of Things.	- Data availability and data quality; - Lack of integration of technology platforms; - Lack of harmonization and interoperability in data and models; - Standardization and validation of measurements.
Governance of circular agri-food systems	- Policy-making (Muscio and Sisto, 2020); - Circular business models (Centobelli et al., 2020); - Governance arrangements (see e.g., Miranda et al., 2021); - System transition (Jurgilevich et al., 2016).	- End-to-end transparency; - Collaborative ecosystem governance; - New business models; - Collaborative business models.	- Interdependencies; - Lack of value-sharing infrastructure; - Lack of collaboration and financing schemes;

behaviour of consumers. Wankmüller et al. (2023) demonstrate this application of tokens in a pilot of a plastic bottle supply chain.

Furthermore, although not explicitly addressing the application of blockchain or tokenization for circularity, we consider the substantial amount of work published on the digitalization of circularity in various supply chains highly relevant. This includes seminal work on digital twins of supply chains (Ivanov and Dolgui, 2020), industry 4.0 (Esmaeilian et al., 2020; Wamba and Queiroz, 2020) and digital traceability frameworks such as the Electronic Product Code Information Services (EPCIS) standard (Bruno and Viola, 2016).

4. Tokenizing circularity in agri-food systems: a conceptual framework

4.1. Linking circular economy and the token economy

Our conceptual framework aims at identifying the concepts that are central to tokenizing circularity, making them explicit and showing how those concepts are interlinked and what decisions are involved. Broadly speaking, these concepts fall into two categories: CE and token economy (see sections 3.1 and 3.3.3). The conceptual framework aims to help address two sets of questions: 1) how realizing CE can benefit from tokenization; and 2) which features of the token economy can effectively be applied to achieve the goals of CE.

The overall vision for tokenizing circularity is depicted in Fig. 1. Within CE, we distinguish three processes that collectively influence the status of circularity: physical, virtual, and governance. Physical processes are those that take place in the natural world with tangible or observable objects and effects. Virtual processes refer to processes that represent a virtualization of physical processes (Overby et al., 2010). Governance processes may involve both physical processes and virtual processes, but focus on verifying or stimulating the conformity of these processes to CE principles. Within the token economy, we consider three dimensions of the token economy, namely the mechanics, purpose, and governance of tokens. Our conceptual framework aims to highlight the central concepts and their relationships in relation to improving circularity in agri-food systems.

4.2. Tokenizing circularity in agri-food systems

In this section, we present the conceptual framework with circular agri-food systems as a case in point. The overall structure of the framework is visualized in Fig. 2. The points of departure in the framework are the six CE principles, as described in Section 3.1, that can be applied to agri-food systems to improve its circularity. The framework shows how circularity in agri-food systems is guided by these principles and supported by tokenization possibilities. The possibilities of tokenization are both supportive of and conditioned by the flows of information and flows of value in the CE. Understanding the interplays between CE principles and the flows of information and value through different tokenization possibilities is the key focus of this paper.

Central to our conceptual framework is the recognition and characterization of a circular agri-food systems as a collaborative business ecosystem in which physical processes are managed by various business management processes and supported by the ecosystem structure. To have impact on the physical processes in such a business ecosystem, the circularity principles must be adopted in business management processes and supported by the business ecosystem structure. The term 'business ecosystem' was introduced by Moore (1993) as "*an economic community* supported *by a foundation of interacting organizations and individuals - the organisms of the business world. This economic community produces goods and services of value to customers, who themselves are members of the ecosystem*". In the context of supply chain management, the concept of business ecosystem can be related to the view of 'chain network'. According to the often-cited conceptual framework of Lambert and Cooper (2000), a chain network comprises three closely interrelated elements: *the network structure*, the *business processes*, and the *management components*. The network structure consists of the

Table 2
Token archetypes, modified from Oliveira et al. (2018).

Archetype	Class	Main purposes	Description
Cryptocurrency	Currency	Currency	A token with the ambition to become a widespread digital form of currency
Equity Token	Tokenized security	Earnings, store of wealth	A token which confers its holder a right to equity-related earnings, such as profit-sharing, application rents or platform fees.
Funding Token	Tokenized security	Store of wealth, Funding	A token which is perceived as a long-term investment from the holder's perspective, and as a financing vehicle for the projects team and/or the community.
Consensus Token	Utility token	Validation, Rewards, Store-of-wealth	A token which is used as a reward to nodes which ensure data validation and consensus.
Work Token	Utility token	Work, Reward	A token which is used as reward to users who complete certain actions or exhibit certain behaviour.
Voting Token	Utility token	Voting right	A token which confers a voting right to its holder.
Asset Token	Utility token	Voting right, asset ownership	A token which represents asset ownership
Payment Token	Utility token	Payment	A token which is used as internal payment method in the application.

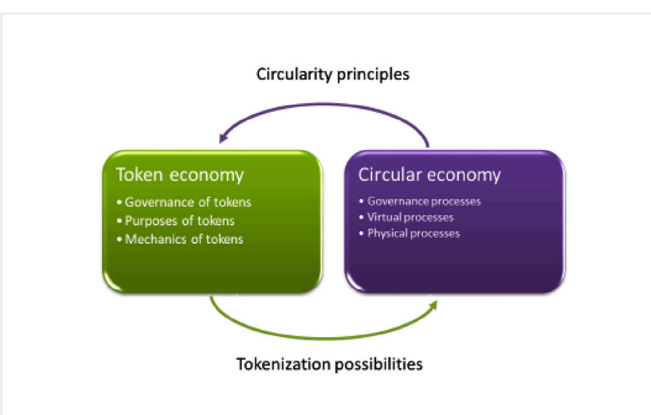

Fig. 1. Overall vision for tokenizing circularity.

member organizations and their linkages. Business processes are the activities that produce a specific output of value to the customer and the management components are the managerial variables by which the business processes are integrated and managed across the network.

The chain network view represented one of the paradigm shifts of modern business management that individual businesses no longer compete as solely autonomous entities, but rather as supply chains. The business ecosystem conceptualization furthers this shift by emphasizing the community aspect and collaboration in the business environment. As noted by Adner (2017), the rising popularity of the term 'ecosystem' goes hand in hand with increasing interest and concerns with interdependence across organizations and activities. The fast developments of the information and communications technologies (ICT) have accelerated the development of collaborative business ecosystems by allowing the development of advanced collaboration platforms and networks. It is now widely recognized that a healthy collaborative business ecosystem leads to economic and social value creation (Graça and Camarinha-Matos, 2017). Based on Lambert and Cooper (2000), we distinguish the physical processes in agri-food systems as farming, input supply for farming, logistics, food processing, retail, and the final consumption. The business management processes include activities that plan, monitor, control and organize the physical processes. The business processes across the chain networks are integrated and managed through the business ecosystem structure.

To show how tokenization influences the flows of information and flows of value in the circular agri-food systems, we consider two interacting systems in the token economy, i.e. the ledger system and the governance system (both will be elaborated in the next section). Both systems are enabled by DLT. Given the heterogeneity of the tokens and the multidimensionality of the concept circularity, the question of tokenization in CE is no longer simply 'to token or not to token', but rather how to apply tokens effectively in a specific context. This effectively entails a mapping between different types of tokens and different processes in a circular business ecosystem. In the next section, we therefore also elaborate on the mapping between the right two columns in the framework.

4.3. Paths to tokenizing circularity

Built upon insights from the literature (e.g., Freni et al., 2022; van Wassenaer et al., 2021), we recognize that the business processes in circular agri-food systems can be supported by two interacting systems in the token economy, i.e. the ledger system and the governance system. Fig. 3 presents an overview of tokenization possibilities mapped to the ledger system and the governance system and related tokenizable objects as introduced before.

With the ledger system we refer to systems that register and keep track of objects (both physical and virtual) and the transactions that they undergo. As now widely known, blockchain is essentially a type of distributed ledger in which a series of data blocks are linked (or 'chained') to each other using cryptographic hashing functions. Tokens are part of blockchain-enabled distributed ledger systems with a type of database that is shared, replicated and synchronized among the members of a decentralized network (Walport, 2016). Ledger systems enable the traceability of the physical flows of assets, including input material, products, waste, by-products, and the resources used. Ledger systems can also record the transactions or events that are conducted on the assets, including the processing, distribution and transfer of assets between the participants of a circular food system. As a consequence, accurate, reliable and timely ledger systems are of crucial importance to determine the circularity assets in a circular food system based on the 6-R principles.

With the governance system we refer to systems that design and enforce the roles and rules of actors and their interactions. In decentralized systems like the blockchain, a consensus mechanism is required to ensure data consistency between different nodes. The design and choice of consensus mechanism is an important aspect in the governance system of the token economy (Lee, 2019; Swan, 2015; van Wassenaer et al., 2021). In supporting the governance system, a consensus token can, for example, be used as a reward to nodes which ensure data validation and consensus.

As noted by many writers, CE requires new governance perspectives and arrangements centered on collaboration (Cramer, 2022; Miranda et al., 2021). When studying governance in business ecosystems, three

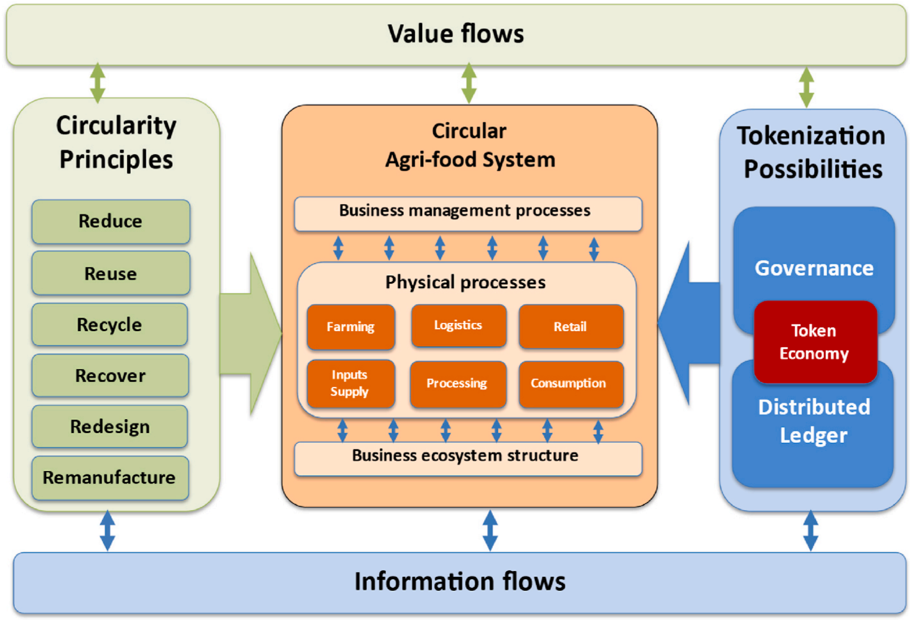

Fig. 2. Conceptual framework for tokenizing circularity in agri-food systems.

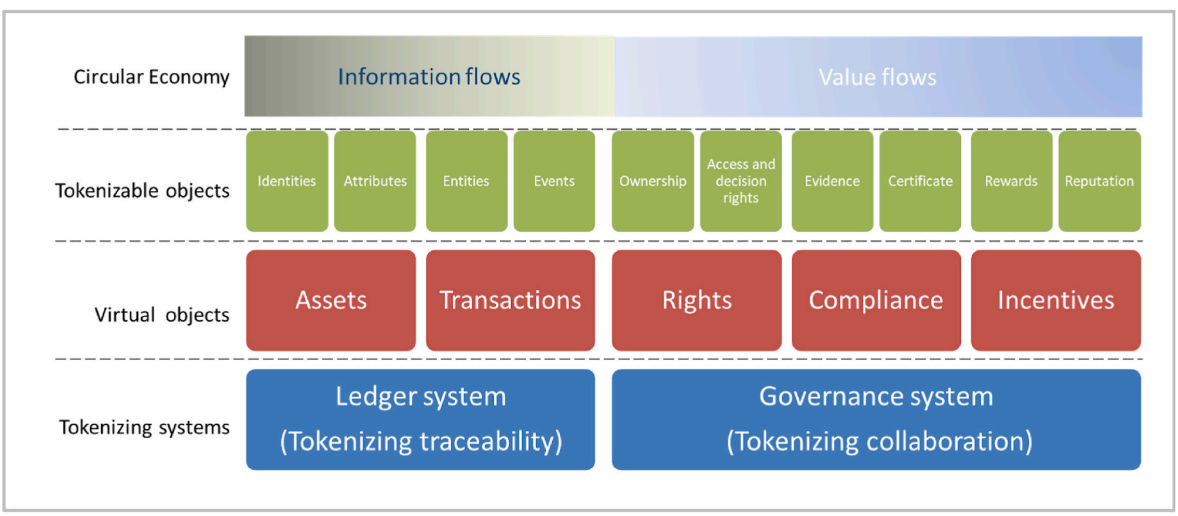

Fig. 3. Paths to tokenizing circularity.

main dimensions should be identified: 1) the allocation of property and decision rights, in other words who is the owner of assets and who has the authority to take decisions within the ecosystem, 2) the rules and systems for compliance with regulations and norms of authorities and certification bodies, and 3) the interorganizational incentive mechanisms aiming at rewarding desirable behaviour and discouraging undesirable behaviour. For all three dimensions, data validation and consensus are key aspects for good governance and can be supported by tokenization. Rights, compliance and incentives represent therefore the three main paths to tokenization through the governance system.

The tokenization layer contains various tokenizable objects to which specific types or values can be assigned following, for example, the archetypes in Table 2. For the ledger system, four tokenizable objects are identified: identities of assets, attributes of assets, entities and events involving different entities. In order to be tracked, each virtual object (or batch of objects) must have a unique identity that can be tokenized. For this purpose, non-fungible tokens (NFTs) are suitable as they are unique digital identifiers that cannot be copied, substituted, or subdivided. NFTs are not only used for virtualizing physical objects, but also for identities of digital objects, for example a digital certificate. Asset identity tokens can be used to track any physical flow, including end products, input material, resources used, waste/scrap, by-products, and emissions. As such, they can be applied to all CE principles. However, traceability of all flows in a circular food system is complex and implementation can be costly. For this reason, asset identity tokens will usually be applied to particular well-scoped parts of a circular agri-food system. Furthermore, the perishability of some agri-food products may limit the use of asset identity tokens.

Attributes of assets can include the state or characteristics of objects such as volumes, quality features, or the number of times an object is used. For this purpose, both NFTs and fungible tokens can be used, depending on the CE principles to be used. Just as asset identity tokens, this type of tokenization can in theory also be applied to all CE principles, but unique identification is not required. This makes these tokens useful for mass balance approaches of aggregated information. Furthermore, asset attribute tokenization can also be used in combination with identity tokenization to provide more detailed information. Transactions in a circular business ecosystem can be tokenized through, for example, the parties involved (entities) or the goods and services traded, or the conditions of the trade (events). An event takes place at a specific time (time slot) and place and under specific circumstances and can be considered as a virtual object that has a set of identities, time, space, and a set of conditions as object properties. For tokenizing transaction, multiple types of tokens can be used.

Tokenizable objects in the governance system related to rights include ownership and decision rights. Compliance can be tokenized through the underlying evidences (e.g. audit reports, test results by designated labs) or the resulting qualifications (e.g. certificate). Incentives in a circular business ecosystem can be material (e.g. currencies) or immaterial (e.g. reputation). Different types of tokens can therefore be used to represent different types of incentives.

Following Figs. 2 and 3, Table 3 illustrates the mapping between token economy and CE through different paths. It describes the potential use of tokens for circularity principles per application scenario of the framework. These are applicable for food chains although defined on a generic level of abstraction (products/resources) since the agri-food is a very diverse domain, including different types of production, e.g. livestock farming, arable farming and greenhouse cultivation, and numerous types of products and resources.

5. Applying the conceptual framework

Our framework has outlined the categories of both physical goods and digital artefacts in agri-food systems that can be tokenized. In this section we show the utility of the framework through retrospective case study of use cases in the agri-food domain and the design of a new 'Circularity Coin'.

5.1. Mapping existing tokenization cases in agri-food systems

The aim of our retrospective case study is to assess the compatibility of tokens used in practice with the CE principles and paths to tokenizing circularity. In particular, we use the case study to identify issues with the design or communication of the existing tokenization applications. We applied the framework to six different blockchain use cases related to CE by mapping the elements of these cases with the elements in our framework. The tokenization use cases we considered were Bext360,[4] Circularise,[5] GreenToken,[6] NatureCoin,[7] Nori,[8] and OriginTrail.[9] A brief description of these use cases can be found in the Appendix. Table 4 shows the main features of these use cases as mapped to the conceptual framework.

The 6 use cases illustrate different paths to tokenization for CE in practice, with four cases through the ledger system and two mainly through the governance system. Traceability and transparency of products and suppliers were the most mentioned management objectives in the ledger system. Two cases (i.e. Circularise and Nori) were more focussed on the governance system by providing incentives to the users to adopt circularity principles. In the case of OriginTrail, the distinction of ledger system and governance system is not clear-cut as the token TRAC both supports traceability (ledger system) and the governance system (used for powering the operations of the system). Except for NatureCoin, all use cases aim to support more than one circularity principles through traceability or transparency. This suggests that the mapping to specific CE principles, while conceptually important, may be less relevant in practice.

[4] https://www.bext360.com/, accessed on 10 December 2022.
[5] https://www.circularise.com/, accessed on 10 December 2022.
[6] https://www.green-token.io/, accessed on 10 December 2022.
[7] https://nature-coin.io/, accessed on 10 December 2022.
[8] https://nori.com/, accessed on 10 December 2022.
[9] https://origintrail.io/, accessed on 10 December 2022.

Table 3
Examples of different paths to tokenization for circularity in agri-food systems.

Systems in the token economy		Application scenario (tokenizable objects)	CE Principles	Description (use of the token) (References containing example applications in agri-food or other sectors)
Ledger system	Assets	Identities	Reduce	Track used resources (inputs), e.g. a single or batch of products (Rusinek et al., 2018)
			Reuse	Track particular products and track its reuse (Wankmüller et al., 2023)
			Recycle	Track if products or batches of waste are recycled (Tarhini, 2021)
		Attributes	Reduce	Track amount of inputs used or waste produced (Felipe Munoz et al., 2021)
			Reuse	Track number of times a resource is used; capacity utilization
			Recycle	Register mass balance created versus recycled waste
			Recover	Track energy content at end-of-life
			Redesign	Track new features of products
			Remanufacture	Track lifespan of resources
	Trans-actions	Entities	Reuse	Track different owners of the same products or packaging (entities) (Sunny et al., 2020)
			Recycle	Track different owners or users of the same products (Toyoda et al., 2017)
			Redesign	Track different attributes of the same item by different owners (entities)
		Events	Recover	Evidence showing the recovered content of a product at the

(continued on next page)

Table 3 (*continued*)

Systems in the token economy		Application scenario (tokenizable objects)	CE Principles	Description (use of the token) (References containing example applications in agri-food or other sectors)
				end-of-life stage (Xie and Tan, 2021)
			Remanufacture	Evidence showing new combination of ingredients for the same product or process (Zhou et al., 2019).
Governance system	Rights	Ownership	Recycle	Product changing ownership (being used by another user)
		Access and decision rights	Reuse	Assigning use rights to different user (Eshghie et al., 2022)
			Redesign	Assigning rights to decide or use alternative products or processes
			Remanufacture	Assigning rights to decide or use alternative products or processes
	Compliance	Evidence	Reduce	Use of inputs, e.g. pesticides, water, fertilizers, energy (Kim et al., 2018)
		Certificates	Redesign	Certificates for using circular processes (Dos Santos et al., 2021)
	Incentives	Rewards	Reuse	Circularity points for reusing products at lower costs, e.g. packaging materials (Tarhini, 2021).
			Recycle	Circularity points for use of recycled inputs (Eshghie et al., 2022)
			Redesign	Tokens for premium prices for circular producers (Rusinek et al., 2018)
			Remanufacture	Circularity points for extending lifecycle of resources, e.g. biodiversity score or soil system robustness (Howson, 2020)
		Reputation	Reduce	Qualifications, ranking or ratings based on emissions (Golding et al., 2022)
			Recover	Circularity token (NFT) for using inputs from recovered resources, e.g. agricultural equipment (Heim and Hopper, 2022)
			Redesign	NFT for most circular products or producers (Heim and Hopper, 2022).
			Remanufacture	Circularity token (NFT) for extending lifecycle of resources, e.g. biodiversity score or soil system robustness

5.2. Designing a circularity token

The multiple case study in Section 5.1 illustrated how our conceptual framework can help understand existing use cases. In this section we proceed to illustrate how our conceptual framework can be used for new tokenization initiatives using a potential use case called the Circularity Coin[10]. This use case is triggered by the question whether it is possible to use DLT to keep track of materials and products in circular supply chains and how to design the appropriate incentives and governance arrangements for the DLT system to be adopted by the circular business ecosystem.

To achieve this purpose, we first examined the organization of a supply chain in agri-food systems to see how circularity principles may be applied to make the supply chain circular. Fig. 4 shows a high-level description of the structure of the supply chain for potted plants on the left and on the right how the supply chain becomes a *supply community* when following circularity principles. All stages in the supply chain, from plant breeding to recycling of end products, are included to enable the assessment of circularity. The token system is designed to keep record of the balance and mutation of the circularity tokens at each stage through the token register.

Following the paths to tokenizing circularity of Fig. 3 and Table 3, the identities, events or other aspects of the supply chain can be

[10] See more information at: https://www.wur.nl/nl/Onderzoek-Resultaten/Onderzoeksprojecten-LNV/Expertisegebieden/kennisonline/Tokenizing-Circularity.htm.

Table 4
Examples of tokenization for circularity in the agri-food domain.

Blockchain solution	Circular agri-food systems			Paths to tokenization			CE Principles
	Main business management objectives	Physical process	Ecosystem structure	Ledger/ Governance	Virtual objects	Tokenized objects	(Most relevant)
Bext360	Proof of origin, traceability of assets	Farming, processing, retail	Farmers, supply chain partners	Ledger	Assets	Identities of commodities (e.g. coffee, cacao)	Reduce, Redesign
Circularise	Provenance	All chain	Supply chain	Governance	Compliance, incentives	Certificate, reward through the token CIRCOIN	Recycle, reuse, remanufacture
GreenToken	Supplier transparency, provenance	Whole supply chain	Farmers, input suppliers	Ledger	Assets	Identities (raw material) and attributes (child labour, recycle status)	Reduce, Reuse, Recycle, Remanufacture
NatureCoin	Incentives	Retail, Consumption	Citizens, logistics	Governance	Incentives	Rewards through the token NatureCoin	Recycle
Nori	Accountability, transparency in carbon removal	Farming	Farmers, business partners, general public	ledger	Attribute (certified CO_2 removal)	Removed CO_2 as represented by the token NRT	Reduce, Redesign
OriginTrial	Traceability	Logistics	Supply chain	Ledger/ Governance	Transactions, rights	Utility token TRAC for operations of the system (tracking and tracing entities and events)	Reduce, Reuse, Recycle, Remanufacture

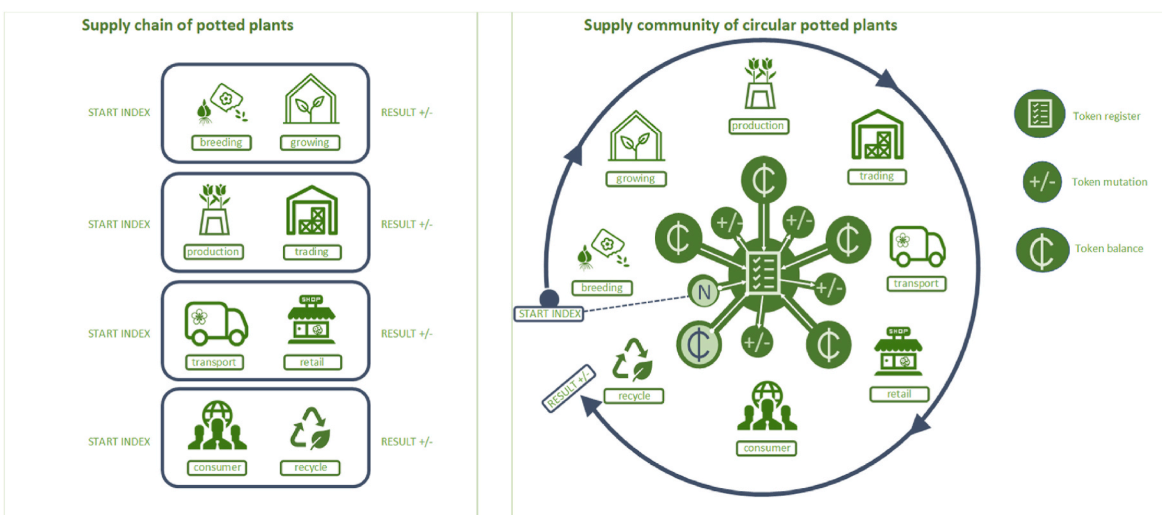

Fig. 4. Key processes in the supply community of potted plants.

tokenized. In order to keep track of the objects of interest and their states in the chain, it is necessary to create a digital identity to represent each object. With the supply chain digitalized, a circularity token registry can then be developed for each product or semi-product in its lifecycle to track its circularity status using the Circularity Coin. The Circularity Coin is designed as a fungible token that can be uniquely linked to a product or an object. The value of the token is accredited or deducted (shown as token mutation) based on how the process fulfils the 6 R principles (Fig. 5). Fig. 5 illustrates how a Circularity Coins is accredited to or deducted from the initial balance based on the circularity check using the 6 R principles. The circularity check first distinguishes durable parts from non-durable parts to assess the possibility of recycling. Furthermore, the product and packaging are assessed separately as different circularity principles may apply. Following this system, the more Circularity Coins are circulating in the supply chain of a product, the more circular the supply chain is.

With the Circularity Coin being created as a fungible token, it can be traded with other ERC20 tokens or fiat currencies in different cryptocurrency ecosystems. The coins can also be used to raise funds through token sales whose proceeds can be used to finance the operations of the token system for the specific supply chain. In this way, a circular business ecosystem can be created that facilitates the transition towards CE.

6. Discussion

6.1. Contribution and limitations of this study

To our knowledge, there has been no academic study that has focussed on the mapping between CE and the token economy, especially in the agri-food domain. This paper has contributed to theory

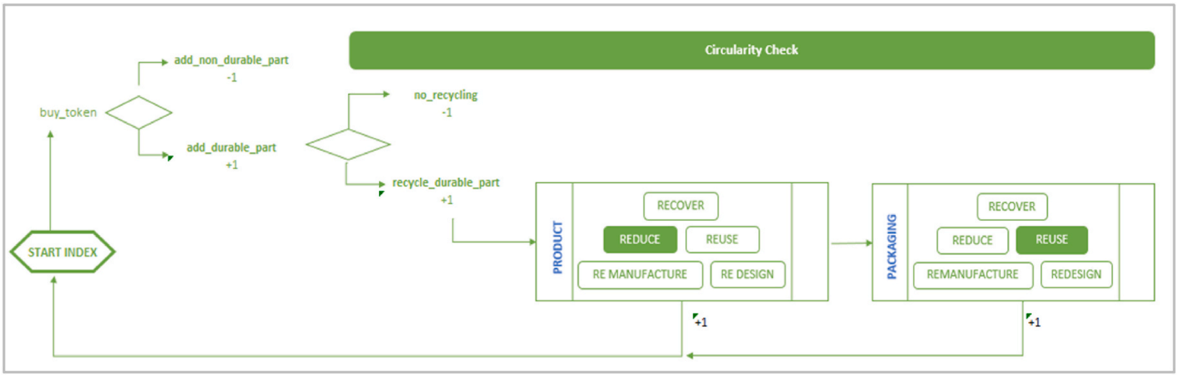

Fig. 5. Accrediting the Circularity Coin in the supply community.

development by synthesizing the current literature and presenting a conceptual framework illustrating the paths to tokenization. Although the paper is to a large extent conceptual, a number of practical implications could be derived using the findings from the case studies. Understanding these implications may give directions for future research.

While closing part of the knowledge gap, this study has several limitations. The first limitation is related to the novelty and rapid development of the topic. Although we have attempted to include as many use cases as possible, some of the potential use cases may still have been overlooked. Secondly, the potential drawbacks of using blockchain-based systems may need more explanation than what is currently mentioned. In many situations, it might not be desirable to tokenize circularity as there are still many unresolved issues and tensions regarding the application of blockchain technology (Kouhizadeh et al., 2020). Finally, the design of the circularity token is described at a high level of abstraction and mainly focused on the settlement of the coins. Other social, economic considerations have not been included.

6.2. Practical implications of tokenizing circularity

Towards practical implementation, it is important to consider the feasibility and desirability in the design phase. Our conceptual framework shows that tokenization is an advanced form of digitalization or virtualization which entails a cyber-physical ecosystem of objects, actors and organizations. It entails transformative changes in business and governance processes reflected in the flows of information and flows of value in a digital ecosystem. A sufficient level of digital infrastructure is needed to be able to create, share and manage the digital ecosystem. This means the feasibility of tokenization will to a large extent depend on the availability and quality of digital infrastructure. Furthermore, effective tokenization requires a level of digital capabilities (i.e., skills, knowledge, and attitudes) among the users sufficient to understand and make use of the digital systems. During the design process, a quick assessment should therefore be made on the suitability of the digital infrastructure and the digital capabilities of the intended users.

At the current state of developments, tokenization is applicable both for the ledger system and for the governance system. For different CE principle, the feasibility may further depend on the availability of data and the clarity of the compliance rules. This applies not only to tokenizing circularity, but also to other aspects of sustainability.

7. Concluding remarks

In this paper we have presented a conceptual framework that shows the relevance of tokenization to the circular economy (CE), with specific focus on circular agri-food systems. By capturing the relationships among well understood concepts of CE with the new and less known concepts in the token economy, we have provided a framework and a model that will help position the existing body of knowledge on circular agri-food systems and blockchain applications.

As the framework suggests and confirmed by the exploratory study, there are many paths to tokenizing circularity in different contexts of agri-food systems. We therefore expect to see a proliferation of new tokens emerging in the coming years. In addition to studying existing use cases, the framework can also support the design of new use cases in agri-food systems. Considering the ongoing discussion on the goals and strategies of CE, it is important to set priorities and develop a decision support framework for assessing its feasibility and effectiveness. To that end, our framework can be used as a basis for formulating hypotheses and gathering further empirical evidence to test them. One such hypothesis is that tokenization of assets can improve efficiency in circular agri-food chains with a high level of re-use and recycling by identifying patterns in inventory and distribution data. Another hypothesis is that tokenization of incentives can improve the understanding of consumer preferences for circular products. A token such as the 'Circularity Token' can for example be used to identify key factors influencing consumer preferences for recycled or re-manufactured products.

Potential future research includes user acceptance and scalability of token-based systems for circularity. Literature and our own experiences have shown that any new form of 'economy' (e.g. bio-based economy or digital economy) is enabled not only by technologies, but also by novel business models among the actors and effective governance arrangements. The interests and roles of different actors in the ecosystem need to be well understood and coordinated in order to achieve CE. When the transition to a new economic system involves new technologies, user acceptance and scalability are known to be crucial. In the case of the Circularity Coin, we consider the acceptance by consumers of the Circularity Coin to be a key success factor for tokenization. It can be expected that active use of the token will trigger more adoption of circular products and processes by producers and supply chain partners. Whether this is the case remains to be seen in practice. It is therefore highly recommended to start with small pilots to test the acceptance and scalability.

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CRediT authorship contribution statement

All authors have made substantial, direct and intellectual contribution to the work and approved it for publication. LvW: Conceptualization, literature review, funding acquisition, writing, review & editing; CV and AK: Conceptualization, methodology, writing & review; MvH: Conceptualization, cases, writing & review. KvM: Conceptualization, visualization, writing & review; BT: Conceptualization, methodology, writing & review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix. Brief description of the use cases studied

1. Bext360

Bext360 is one of the early blockchain initiatives in the domain of agri-food that has covered critical supply chains like coffee, cocoa, cotton, palm oil, and recyclables. According to its own description, "… the SaaS platform provides blockchain traceability and quantifiable measurements for sustainability". The sustainability measurements Bext360 tracks include worker pay, carbon, water, and electricity, from farm to retail. Furthermore, Bext360 uses blockchain to provide reliable data and secure transactions in the supply chains of, for instance, coffee, cotton and palm oil. Both physical assets and virtual objects (e.g. data) in the supply chain are represented as tokens which are stored in the blockchain to facilitate payments, yield smart contracts and track assets through the whole supply chain.

2. Circularise

Circularise is a blockchain solution offered by a dedicated company and team of developers. The company characterizes itself as a supply chain transparency start-up and its product as a solution for "traceable supply chains for a circular economy". Its aim is to "help companies to trace materials and products and verify the origins, certificates, CO_2 footprint and other material data on blockchain". It aims to achieve that by tracing materials from source to end-product. Circularise utilises a combination of blockchain, peer-to-peer technology and cryptographic techniques like Zero-Knowledge Proofs (ZKPs) to build a decentralized information storage and communication platform. To make Circularise a self-sustaining system, the company built a payment system in the platform based on its own cryptocurrency, CIRCOIN, that should be exchangeable with fiat currencies. CIRCOINS would be spent to fuel blockchain operations.[11] The fundamental idea is that the upkeep will have to be supported by the users. In the case of Ethereum, transaction costs have to be paid by parties every time on-chain operations (not read-only) are executed. Some of the actions that parties can perform on Circularise are going to have a small cost to be paid in CIRCOIN.

3. GreenToken

GreenToken is provided by a well-established technology company, SAP. Unlike Nori and Bext360, GreenToken is not focussed on a specific product or a group of producers. Instead, GreenToen is concerned with the fact that many businesses do not know who the suppliers are of their suppliers, and thus cannot provide their customer with full information about their products. The motto of GreenToken is 'enable supplier *transparency*'. Like Bext360, GreenToken is not concerned with compliance, incentives, or rights, it is about the ability to identify (identities) across the transaction chain. GreenToken aims to show that provenance information up to the raw materials. In addition, GreenToken includes attributes such as sustainable sourcing, child labour-free production and ethical trading. The circularity principles used are broad, including reduce (of certain types of sources, or eliminate the use of child labour), recycle, reuse, and remanufacture.

4. NatureCoin

NatureCoin is an initiative to address the major problem of plastic pollution. NatureCoin uses smart bins for recycling in cities. The NatureCoin app will analyze waste and calculate a reward which is provided in the form of the "NatureCoin" cryptocurrency. Tourists can then exchange the coins for goods or services, e.g. transport or souvenirs. NatureCoin uses the ERC223 token standard, based on the Proof-Of-stake (POS) consensus mechanism, thus requiring no energy-consuming mining process for the coins. The providers of NatureCoin state that "it is designed to provide everyone with a rewarding recycling experience". The coin offers incentive for people to track their carbon footprint and earn money every time they scan the product they present for recycling.

5. Nori

Nori is a blockchain-based trading platform that the providers call a "carbon removal marketplace". Nori implements a token called NRT (Nori Carbon Removal Tonnes). One NRT represents one tonne of removed CO_2 stored for 10 years or more. This is realized by farming practices that enable the storage of carbon dioxide in soils. Any business or interested member of the public can buy a Nori certificate of carbon removal by buying NRT tokens. The tokens are transferred to farmers who implement sustainable farming practices that are verified by independent third-party auditors. The token is used as a certificate of contribution to sustainability for the buyer, and evidence of sustainable practice for the farmer. The farmers implement a circularity practice that falls into a *reduce* and *redesign* circularity principles as they reduce or eliminate tillage or redesign their farming practices.

6. OriginTrail

OriginTrail is a Decentralized Knowledge Graph (DKG) based on an open blockchain information sharing platform. OriginTrail is also the name of the platform and the company. The company presents itself as specializing in tracking and tracing, and in that context uses Electronic Product Code Information Service (EPCIS) for product identifications and data sharing. EPCIS is a standard of GS1, a global standardization with chapter organization in almost every country of the world. OriginTrail is used to discover, manage, and store data for everything from supply chain tracking to verifying art, diplomas, and business certifications. OriginTrail uses an Ethereum token TRAC to power its operations. TRAC token is used to pay for data processing and storage on the network. OriginTrail presents use cases involving standards and certifications (safeguard the validity of issued certificates, etc.), integrity of systems (security audits, safety of trains, etc.), traceability (food, apparel, etc.), interoperability of data, and financial transactions. Therefore, OriginTrail is not product specific, and the custom solutions built with it can cover the entire supply chain. OriginTrail is used for tracking and tracing with no direct reference to CE principles. However, tracking and tracing make it possible to quantify the reduce, reuse, and recycle principles.

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