Incentivizing Research & Innovation with Agrobiodiversity Conserved In Situ: Possibilities and Limitations of a Blockchain-Based Solution

Mrinalini Kochupillai*
Department of Aerospace and Geodesy
Technical University of Munich
Munich, Germany
m.kochupillai@tum.de

Ulrich Gallersdörfer
Department of Informatics
Technical University of Munich
Munich, Germany
ulrich.gallersdoerfer@tum.de

Julia Köninger
Department of Biology
Universidad de Vigo
Vigo, Spain
julia.koninger@uvigo.es

Roman Beck
Department of BusinessIT
IT University of Copenhagen
Copenhagen, Denmark
beck@itu.dk

***Abstract*—This article explores the use of blockchain for agrobiodiversity (B4A) with a specific focus on (i) providing an overview of the existing regulatory challenges when it comes to conserving agrobiodiversity, which results in a lack of research and innovation when it comes to agrobiodiversity conserved in situ, (ii) investigating how a blockchain-based solution may help overcome these challenges, and (iii) illustrating how incentive mechanisms can help to overcome existing intellectual property regimes that prevent effective conservation, research and innovation (CRI). Our research identifies (i) lack of incentives, (ii) lack of trust among stakeholders, and (iii) lack of traceability options as main hindering reasons for in situ CRI with agrobiodiversity. Further, We find that blockchain solutions may empower data providers, including small farmers, to collectively track, control and monetize the use of data and assets shared, while minimizing fraudulent activities. Transaction costs may also be lowered by removing complex and expensive interaction processes. However, further research and development is necessary to design an ethical and sustainable blockchain-based solution to incentivize in situ conservation, research and innovation with agrobiodiversity. Some future directions of research are recommended.**

***Index Terms*—Agrobiodiversity, Blockchain, Incentives, Sustainability, Benefits**

I. Introduction

Biodiversity is defined as "the variability among living organisms from all sources ... and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (CBD). The term biodiversity includes terrestrial and aquatic biodiversity, as well as agricultual biodiversity (agrobiodiversity) [1]. This article focuses on agrobiodiversity.

Agrobiodiversity comprises the biological diversity within the soil (the soil microbiome) as well as on the soil (genetic diversity contained in indigenous or local, non-uniform seeds, pollinators etc.). Efforts to conserve agrobiodiversity in its natural surroundings, such as through farming activities, is called in situ conservation.

Farming systems that utilize in and on soil agrobiodiversity are often more robust in the face of local biotic and abiotic stresses [2]. Agrobiodiversity, therefore, actively contributes to food and nutritional security in the face of rapid climate change [3]–[5].

International instruments, such as the Convention on Biological Diversity (CBD) [6] and the International Treaty on Plant Genetic Resources for Food and Agriculture ("the Seed Treaty") [7], emphasize the relevance of in situ agrobiodiversity conservation. They also require member states to adopt so called "Access and Benefit Sharing (ABS)" regimes. ABS regimes aim to facilitate research and innovation with agrobiodiversity on one hand, and grant monetary benefits (so called "benefit sharing"), to those granting access to their bio resources. However, due to several regulatory issues, the ABS system has failed to incentivize and promote in situ conservation, research and innovation (CRI) with agrobiodiversity [8, 9].

Since the 1900s, an estimated 75 per cent of crop genetic diversity has been lost [10] not at least due to expanding farm areas under commercially available uniform seeds. Additionally, as a consequence of the intense use of inorganic fertilizers and chemical plant protection measures, a significant loss of soil microbial (bacterial and fungal) diversity has been recorded as well [11]–[13].

Further, in most regions of Europe, legal regulations have (until recently) outlawed the sale of local agrobiodiversity contained in indigenous or local, non-uniform seeds. For decades, preference has been given to uniform, certified seeds that guarantee high yield, but rely on external support (in the form of chemical fertilizers and pesticides) for consistent performance [14]–[16].

With increasing environmental concerns, policy makers are facing growing consumer demand for organic and local food [17, 18]. Accordingly, regulators are seeking means of enhancing farmer migration to organic farming, particularly farming that uses local agrobiodiversity.

Responding to consumer demands and evolving scientific understanding of the importance of agrobiodiversity for sustainable agriculture, the new EU Organic Regulation (EU 848/2018) was adopted in May 2018. It seeks to promote the use of agrobiodiversity (referred to in the legislation as "heterogeneous materials"), in organic agriculture. The regulation permits such materials to be marketed without the need to pass cumbersome and costly seed certification requirements under existing laws. It also acknowledges that "there could be benefits of using such diverse material… to reduce spread of diseases, improve resilience and increase biodiversity."

Yet, decades of disengagement with local agrobiodiversity and associated farming practices has led to a situation where the mere permission to use and sell "heterogeneous materials" may not be adequate to trigger changes in farmers' choices. Concrete incentives, including economic incentives and re-education efforts may be needed to accomplish this goal [19]–[21].

Further, gaps in current scientific knowledge on best practices for profitable and sustainable use of agrobiodiversity [22, 23], make farmer migration to organic farming a risky endeavour. Current scientific understanding can profit greatly from on-the-ground experience of farmers (e.g., small farmers and indigenous communities) that are actively engaged in agriculture with local agrobiodiversity. However, an equitable, transparent and trustworthy means of incentivizing and facilitating farmer-sharing of local know-how and materials does not currently exist.

The present paper investigates whether, and the extent to which a blockchain-based solution could contribute to overcoming existing regulatory and practical hurdles and incentivize in situ CRI with agrobiodiversity.

Further, We find that blockchain technology may empower data providers, including small farmers, to collectively track, control and monetize the usage of data and assets shared, while minimizing illegal transactions. Transaction costs may also be lowered by removing complex and expensive interaction processes. However, blockchain solutions primarily deal with linear flows of data and information. In order to operationalize a B4A usecase in the real world, specific technological add-ons may be necessary that permit multiple entry and access points for data, know-how as well as associated materials (e.g., seeds). Further, unlike bitcoins that can be traded only once, farmers' knowhow (and materials) can be simultaneously traded with multiple "buyers" on the chain. Also, the B4A usecase is quite unlike a blockchain application for tracking agricultural supply chains, where the underlying materials are not significantly transformed post transfer from one stakeholder to the next. In the B4A usecase, the traded material (seed, soil samples, know-how) will get significantly transformed over time: This is desirable, but makes blockchain based traceability and benefit sharing challenging. Hurdles associated with physical materials transfers and stakeholder digital identities can be resolved by complementary development of biomarkers and by implementing trust checkpoints, respectively. However, further research and development is necessary to design an ethical and sustainable blockchain based solution to incentivize in situ conservation, research and innovation with agrobiodiversity. Some future directions of research are recommended. Index Terms—Agrobiodiversity, Blockchain, Incentives, Sustainability, Access and benefit sharing I. INTRODUCTION Biodiversity is defined as "the variability among living organisms from all sources . . . and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (CBD). The broad term biodiversityincludes terrestrial and aquatic biodiversity, as well as agricultual biodiversity (agrobiodiversity) [1]. This article focuses on agrobiodiversity. Agrobiodiversity comprises of diversity within the soil (the soil microbiome) and on the soil (genetic diversity contained in indigenous or local, non-uniform seeds, landraces, pollina- tors etc.). Efforts to conserve agrobiodiversity in its natural surroundings, such as through farming activities, is called in situ conservation. Emerging research reveals that farming systems that enhance agrobiodiversity are often more robust in the face of local biotic and abiotic stresses [2]. Agrobiodiversity, therefore, actively contributes to food and nutritional security in the face of rapid climate change [2]–[4]. International instruments, such as the Convention on Bi- ological Diversity (CBD) [5] and the International Treaty on Plant Genetic Resources for Food and Agriculture ("the Seed Treaty") [6], emphasize the relevance of in situ agro- biodiversity conservation. They also require member states to adopt so called "Access and Benefit Sharing (ABS)" regimes. ABS regimes aim to facilitate research and innovation with agrobiodiversity on one hand, and grant monetary benefits (so called "benefit sharing"), to those granting access to their bioresources. However, research reveals that due to several regulatory failures, the ABS system has failed to optimally incentivize and promote in situ conservation, research and innovation (CRI) with agrobiodiversity [8, 9]. Since the 1900s, an estimated 75 per cent of crop genetic diversity has been lost [7] due, inter alia, to expanding farm area under commercially available uniform seeds. As a consequence of the intense use of inorganic fertilizers and chemical plant protection measures, a significant loss of soil microbial (bacterial and fungal) diversity has also been recorded [8]–[10]. Further, in most regions of Europe, legal regulations have (until recently) outlawed the sale of local agrobiodiversity contained in indigenous or local, non-uniform seeds. For

The paper is arranged as follows: Following this introduction, Section II provides a sketch of the background leading up to the research questions guiding this paper. More specifically, it summarizes the findings from extensive empirical research conducted with the aim of understanding (i) whether existing intellectual property rights regimes and associated policies incentivize in situ conservation of agrobiodiversity, and (ii) the needs of farmers currently engaged with in situ agrobiodiversity conservation and improvement. Section III then identifies the research questions that guide this paper. With the help of an exhaustive literature review, section IV identifies hurdles in international instruments contributing to sub-optimal in situ CRI with agrobiodiversity.

Previous work has recommended using blockchain technology to incentivize CRI with agrobiodiversity [21]. Section V summarizes the key features of blockchain technology with a view to providing an overview of reasons why B4A may be an appropriate blockchain usecase. Section VI goes deeper into this question: section VI A tabulates and categorizes the regulatory hurdles, lacunae and farmers' needs identified in sections II and IV, to determine which of them can, and which cannot, be addressed by blockchain technology. Section VI B focuses on the issue of incentives: emerging research suggests that on chain and off chain incentives can be combined to better accomplish real world results. Incentives that can be built in and off chain to support the cause of in situ CRI with agrobiodiversity are explored. Section VII concludes with recommendations for future lines of research that can support blockchain or Distributed Ledger Technology (DLT)[1] based incentivization of in situ conservation, innovation and research with agrobiodiversity by all stakeholders.

II. Background and Research Questions

A. Intellectual Property Protection Regimes, Inequitable Incentive Structures and Market Failures

This article builds on extensive legal and empirical research conducted to determine whether existing intellectual property protection laws and associated governmental policies are able to promote and incentivize CRI with agrobiodiversity conserved in situ [8, 9, 19]–[21, 24]. Arguably, conservation is not innovation. However, research conducted from multi-disciplinary, legal as well as ecological economics approaches have recommended that for 'sustainable innovations'[2] in 'plant varieties'[3], recognizing farmers' efforts as 'innovation', and not merely as 'conservation' is necessary and can support the cause of CRI with agrobiodiversity [20, 25]–[28]. Recognizing farmers' contributions as innovations can also help address issues of growing rural-urban migration (NO REFERENCE FOUND) and growing disinterest in agriculture among younger generations of farmers (NO REFERENCE FOUND).

In existing literature, seed sector innovators are broadly classified into two groups [29]: (i) formal innovators, i.e. plant breeders affiliated with Universities, research institutions or the seed industry, and (ii) informal innovators, i.e. farmers (particularly small and marginal farmers, who constitute almost 80 per cent of India's farming community).

A growing body of literature highlights the critical relevance of in situ conservation of seeds by farmers (the informal innovators). Particular relevance is placed on the saving of local, genetically variable seeds, that house diverse genetic materials necessary resisting pests and diseases, and ensuring food security in the face of climate change [30]–[32]. Agrobiodiversity conserved in situ, is also an important raw material necessary for downstream research and plant breeding by the formal sector.

Accordingly, researchers have argued that legal regimes that sub-optimally incentivize saving of local, genetically variable seeds, also undermine the continuation of plant breeding and seed improvement in the long run [19]. Kochupillai's legal and empirical research in India also identified several legal and policy hurdles that act as "perverse incentives", actively disincentivizing seed-saving.

Existing incentive structures have also been found to be either inadequate or inappropriate to incentivize CRI with agrobiodiversity. Intellectual property laws and associated governmental policies have also been found to inequitably skew the innovation landscape by (i) promoting only formal innovations using existing proprietary germplasm stores (e.g. in seed banks), and (ii) neglecting innovations that rely on and promote in situ agrobiodiversity conservation [19, 21], and CITE OTHERS).

B. Incentivizing Sustainable Seed Innovations: Challenges faced by Farmers

Past research has called for urgent legal and regulatory attention to level the seed-innovations landscape, and to promote sustainable innovations in plant varieties [**?**, 24]. Accomplishing this complex goal involves a rebalancing of incentives, roles and contributions among diverse stakeholders operating in a delicate ecosystem.

To find "means of incentivizing farmer-level innovations on and with seeds from often-neglected indigenous varieties in India", and, in particular, with the "greater role that public recognition for (small) farmers' seed innovation might play therein", a research grant was acquired from the UK Arts and Humanities Research Council (AHRC) in 2016-17.

The grant supported further empirical research and brought together experts and farmer-stakeholders to a one-day workshop designed to intensively debate and elicit diverse views on this topic. The workshop, hosted by the AHRC funded partner, the Art of Living Foundation, an international NGO working to revive traditional indigenous seeds, associated farming systems ("natural farming") and know-how, created 4 working groups. [4] All groups identified current challenges that either disincentivize or prevent active adoption of indigenous

[1] Blockchain is a subset of Distributed Ledger Technologies. For simplicity, we use the term *blockchain* but also include technologies that are not based on a block structure.

[2] Kochupillai, 2016 was perhaps the first to use and define the term "sustainable innovations" as innovations that: (i) Protect natural resources, inter alia, by supporting in situ conservation and improvement of agrobiodiversity. (ii) Facilitate both formal and informal (downstream) innovations to continue to take place in the generations to come. (iii) Equitably incentivize participation by all potential innovators in the process (life cycle) of innovation.

[3] Kochupillai's research deviated from the international legal understanding of the term 'plant variety'. The term "plant varieties" in Kochupillai's original work includes 'agrobiodiversity' as well as innovations on and with this diversity by breeders ("the formal sector") as well as farmers ("the informal sector"). This deviation was necessary because the Indian PPVFR Act, 2001, which was the main legislation Kochupillai's research focused on, includes not only breeders' varieties, but also so called "extant varieties" and "farmers' varieties" within its scope. Farmers' variety, has also been defined in the Indian legislation to include traditionally cultivated varieties, as well as wild relatives or landraces of a variety. Kochupillai's research focused on India for three reasons: India is a major (agro)biodiversity hotspot, almost 60 per cent of India's population relies on agriculture for its livelihood, and the Indian Protection of Plant Varieties and Farmers Rights Act, 2001 (PPVFR Act) is considered to be one of the most unique in the world as it purports to accomplish a complex three-fold goal: (i) promoting private sector innovations in plant varieties, (ii) protecting and promoting farmers' innovations in plant varieties, and (iii) rewarding farmers and farming communities engaged with conserving agrobiodiversity.

[4] The working groups focused on law, research, outreach and awareness and participatory plant breeding, Moderat by Sunita Sreedharan, Mrinalini Kochupillai, Shamika Mone and S.C. Tripathi respectively.

seeds (agrobiodiversity) by small and marginal farmers, and made recommendations for future actions to overcome these challenges.

The challenges and recommendations emerging from the workshop were divided into the following 10 broad categories (ι_i) [21]:

- ι_1 Inadequate attribution and recognition: As indigenous seeds are heterogenous and not uniform, once sold or exchanged, it can be difficult to identify the next generation of seeds as originating from a specific source. Farmer-sellers of high quality indigenous seeds, therefore, never get the recognition and attribution they deserve. This finding has also been confirmed by other researchers [24, 33, 34]. Farmers also emphasized the importance of giving unique names to seeds developed by farmers, and of acknowledging inventor-communities and persons engaged with farming using agrobiodiversity and traditional know-how. Recognition must also be given to those who make local improvements to indigenous seeds and know-how, especially when these improvements result in higher yields or better quality of produce.
- ι_2 Sub-optimal economic and other incentives: As a result of (i) inadequate (or no) attribution, (ii) low demand for indigenous seeds and associated know-how, and (iii) unavailable markets and government support in the form of a "minimum support price" for the produce resulting from unique local seeds and grains, innovative farmers who cultivate with and improve agrobiodiversity in situ, do not have optimal incentives to continue this work. While farmers (in India) are happy to share their materials and know-how with other farmers, such other farmers have no concrete incentive to migrate to farming systems that use indigenous, heterogeneous seeds and improve agrobiodiversity.
- ι_3 Traceability: There are currently no mechanisms in place that can track and trace the source of indigenous seeds and of associated know-how. This prevents the equatable and honest sharing of benefits on one hand, and the emergence of markets selling high quality indigenous seeds on the other.
- ι_4 Sub-optimal research and education: As farmers often do not have the know-how necessary to beneficially use indigenous seeds, research and education (formal and informal channels), including through community engagement is centrally relevant to promote adoption of farming techniques that utilize, conserve and improve agrobiodiversity in situ.
- ι_5 Reliable communication channels (e.g., to report problems, success stories etc.) are needed to facilitate communication between farmers and others engaged with agrobiodiversity.
- ι_6 Marketing channels and new markets are necessary to facilitate quick sales of produce and seeds resulting from using indigenous seeds.[5]
- ι_7 Means of ensuring and documenting quality of seeds/produces and accessibility of documentation.
- ι_8 Means of ensuring quantity, timely availability, and affordability of indigenous seeds and access to know-how on when and how to sow and cultivate them.
- ι_9 More Knowledge creation/verification, including through research in various disciplines and dissemination of research findings; currently there is sub-optimal research being conducted on characteristics and strengths of indigenous seeds and associated traditional agricultural systems.
- ι_{10} Revival/Maintenance of Traditional Ecological Knowledge (TEK) and local cultures associated with it.

C. Recommending a Three-Pronged Approach

With the aim of making more specific recommendations for concrete policy and regulatory action based on the key recommendations of the working groups, an impact acceleration grant was sought and acquired from the UK Global Challenges Research Fund (2019). The position paper for the Government of India, compiled using the GCRF grant, recommended a three pronged approach for incentivizing sustainable indigenous seed innovations [21, 35]:

1) Prong 1: Reviving Traditional Ecological Knowledge Systems, that contain rich knowledge on means of protecting and enriching in and on soil biodiversity
2) Prong 2: Re-designing Educational Curricula of Agricultural Universities and of Rural Agricultural Extension Services to incorporate extensive education and training in farming systems that incorporate this traditional ecological knowledge; and
3) Prong 3: Re-leveling the Incentives Landscape, inter alia, by adopting technical solutions such as blockchains to overcome hurdles that currently disincentivize research and in situ innovations with agrobiodiversity by farmers and researchers (i.e. formal and informal sectors).

This article focuses and builds on the third prong and is guided by the following research questions:

III. Research Questions and Methodology

A. Research Questions

- **RQ 1a.** Which major international regulatory regime(s) are responsible for promoting in situ agrobiodiversity conservation and its equitable access, use and benefit sharing?
- **RQ 1b.** Which shortcomings, if any, in these regimes, may be contributing to sub-optimal in situ conservation, research and innovation with agrobiodiversity?
- **RQ 2.** Is the promotion of research and innovation with agrobiodiversity conserved in situ an appropriate blockchain use case?

[5] it is necessary to note that some farmers' groups expressed opposition to the idea of seed "sales" and preferred to give away seeds and associated know-how for "free". However, all were interested in creation of appropriate channels for transfer of seeds and know, whether it be for free or for a charge

- **RQ 3.** How, and to what extent, can a blockchain-based solution help:
  - **RQ 3a.** address the identified shortcomings and challenges (RQ 1b.), and
  - **RQ 3b.** provide incentives for farmers to use, innovate with, and share traditional know-how and agrobiodiversity conserved in situ,

In relation to RQ 3a, the article looks into current capabilities and shortcomings of blockchain solutions that can help overcome challenges and implement recommendations identified by Kochupillai 2016, Kochupillai et al. 2019, and under RQ 1.

B. Methodology

This paper provides insights into the above research questions based on a comprehensive literature review. The search terms used for the literature review, as well as the outlines of the blockchain "Ecosystem and Conditions" are guided by the insights and recommendations gathered from the background research described in Part II above.

IV. The International Regulatory Regime for the Conservation and Equitable Use of Agrobiodiversity

A. Overview of the Major International Regulatory Regimes (RQ1a)

In the late 1980s, researchers found that biodiversity declined to "its lowest level since the end of the Mesozoic, 65 million years ago" [36]. With growing civil and political awareness about the rapid decline of global biodiversity, the need for an international legal instrument to protect both wild and domesticated diversity was voiced [37]. Eventually, the Earth summit of Rio in 1992 put the topic on the political agenda and collected signatures for the adoption of the Convention on Biodiversity (CBD) [6, 38].

The CBD has three main goals, namely (i) the conservation of biodiversity, (ii) the sustainable use of biodiversity and (iii) the fair and equitable sharing of benefits resulting from the use of biodiversity and associated plant genetic resources (PGRs) [39]. The exchange of PGR through the CBD is based on national bilateral "case-by-case negotiations" [40]–[42], whereby national rules govern the contracts [38, 43]. In spite of the stated goals, PGR were barely exchanged in the first twenty years of the CBD's implementation, suggesting a need to review and amend its provisions [44]. The CBD was extended in 2014 by a supplementary agreement, the Nagoya Protocol (NP) [45], which aimed, inter alia, to overcome shortcomings connected to the CBD's bilateral system. The NP aims to incentivize exchange of PGRs and consequently the promotion of in-situ conservation and engagement with PGRs. The NP clarified previous terminological ambiguities and added an article to facilitate access and benefit sharing (ABS) of PGRs.

In 2004, a further international regulation aimed at protecting agricultural biodiversity, was adopted. Titled the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), it was implemented by the Food and Agricultural Organization of the United Nations [46]. Also known as the Seed Treaty, the ITPGRFA aims to facilitate access to a wider range of PGRs (particularly those relevant for agriculture) through a central sharing point [44, 47, 48]. The Seed Treaty replaced bilateral negotiations with a multilateral system, which includes a Standard Material Transfer Agreement (SMTA) [49] for essential food and fodder crops [50]. The SMTA frames responsibilities and duties for providers and users of PGRs, including monetary and physical sharing in case of commercial usage of PGR ("benefit sharing") [38, 51]. The ITPGRFA is considered "the most sophisticated international benefit-sharing mechanism to date" [38].

Although the CBD and the ITPGRFA have been ratified by most countries, PGRs were barely exchanged [44, 47, 48]. In fact, studies find that the NP has complicated the access to PGRs, especially in biodiversity hotspots such as South Asia, East Africa, and South America [48, 52]. The limited use of PGR under the NP has also been linked to the small number of countries that facilitate access to PGRs through additional legal or administrative mechanisms which implement the CBD/NP.

PGRs are accessed more frequently under the ITPGRFA, however, research institutes struggle with several barriers and bureaucratic hurdles when accessing PGRs [8, 9, 44]. The ITPGRFA aims to protect incentives for sharing,e.g., by not including intellectual property rights for PGRs in its treaty [53]. To better understand the specific strengths and shortcomings in the international regulatory regimes, the following literature review was conducted (RQ 1b, below).

B. Challenges and Shortcomings of International Regulatory Regimes (RQ1b)

To answer RQ1b, the current research on the topic was analysed through a systematic literature review and analysis of the relevant results. The literature review was conducted on the ISI Web of Knowledge database, particularly two subdatabases therein: (i) Current Contents Connect (=database 1, DB1) and (ii) Web of Science Core Collection (DB2). The search was carried out in September 2020 for publications in the English language from 1998 to 2020. The screening followed a three-step approach:

Step I: A broad keyword search was conducted. The keyword search in Step I looked for titles including the term "biodiversity", "access and benefit sharing" and "agriculture". *TS=((biodiversity AND Access and benefit sharing AND agriculture).*

The structured literature review yielded (i) 161 results in DB1 and (ii) 230 results in DB2. The topic of agrobiodiversity conservation and equitable access and benefit sharing is primarily covered under two international regulatory regimes (see section IVA above) [6, 38], namely, the CBD and its extension, the Nagoya Protocol (NP) and the (ii) International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA). As these regimes operate at the global level and almost all nations of the world are signatory to these [19] and the shortcomings of these regimes were the focus of RQ1b, for step II, papers were eliminated that did not mention at least any one of the two regimes.

Step II: Step 1 combined with *TS=(objectives AND Nagoya Protocol OR International Treaty on Plant Genetic Resources for Agriculture OR ITPGRFA)*

Step II yielded 38 papers in DB1 and 62 papers in DB 2 providing detailed information on the two regimes. We screened the papers to identify the key strengths of the two regimes. The findings are displayed in table I.

TABLE I
STRENGTHS OF EXISTING INTERNATIONAL BIODIVERSITY PROTECTION REGIMES (NAGOYA PROTOCOL (NP)/CONVENTION ON BIODIVERSITY (CBD) AND THE INTERNATIONAL TREATY FOR PLANT GENETIC RESOURCES FOR AGRICULTURE (ITPGRFA)) IDENTIFIED WITHIN LITERATURE

Strengths σ_i	**NP/CBD**	**ITPGRFA**
σ_1: Integration of ethical and legal principles in ownership and usage of PGR	[54, 55] [56, 58] [59]–[62]	[54, 56, 57]
σ_2: Objectives comprise indigenous knowledge	[59, 62]	[57, 61, 63]
σ_3: Following "noble objectives"	[62, 64]	[57, 58, 60]
σ_4: Ratified by most countries; inclusive	[65, 66]	[57]

Thereafter, these international treaties were scanned to extract and study the provisions that deal specifically with agrobiodiversity conservation, use, access or benefit sharing. Under various provisions, the treaties underscore the key role played by indigenous communities and their traditional knowledge in safeguarding and bringing forward (agro)biodiversity from generation to generation [67, 68]. Accordingly, these treaties emphasize and mandate benefit sharing with communities that grant access to their biodiversity, traditional knowledge and know-how for downstream use (including for use in research or for commercial purposes) (see Nagoya protocol Article 14-16; Article 10.2 of the ITPGRFA).

Beyond ensuring a "fair price" for these valuable resources, the goal of the benefit sharing regime is twofold: (i) to ensure that conservers of (agro)biodiversity, have the incentives and monetary means to continue their good work [54], and (ii) to give conservers of biodiversity concrete incentives to share (give access to) their resources and know-how with other stakeholders in the value or innovation chain [67, 68].

Indeed, agrobiodiversity and associated Plant Genetic Resources (PGRs) are actively sought by scientists engaged in sustainable agricultural research [22, 69]. However, due to the link between agrobiodiversity and exchanged PGRs, the effectiveness and the achievement of goals of agrobiodiversity regimes is validated best by analysing Access and Benefit Sharing (ABS) agreements [70]. Following different approaches, both regimes have only witnessed very minimal success in promoting equitable PGR access and benefit sharing. Under the Nagoya Protocol, on an average, 2.05 ABS agreements per year, per country have been signed [44, 50]. Under the ITPGRFA, from more than 3.3 million samples exchanged, no benefit-sharing occurred [70]. To find the shortcomings, hurdles, problems and weaknesses of existing regimes, in step 3 of the literature review, papers that discuss "shortcomings" of these regimes were extracted and analysed.

TABLE II
SHORTCOMINGS OF EXISTING INTERNATIONAL BIODIVERSITY PROTECTION REGIMES (NAGOYA PROTOCOL (NP)/CONVENTION ON BIODIVERSITY (CBD) AND THE INTERNATIONAL TREATY FOR PLANT GENETIC RESOURCES FOR AGRICULTURE (ITPGRFA)) IDENTIFIED WITHIN LITERATURE

Shortcomings	**NP/CBD**	**ITPGRFA**
ι_{11}:Lack of traceability of PGRs exchanged	[48, 73, 74]	[58]
ι_{12}:No access to PGRs due to		
- $\iota_{12.1}$: Lack of competences	[75]	[8]
- $\iota_{12.2}$:Delays and stoppages	[9, 70, 74, 76]	[8, 50, 58, 77]
- $\iota_{12.3}$:Incomplete catalogues of PGRs	[55, 78, 79]	[44]
- $\iota_{12.4}$:Legal uncertainties	[44, 59, 64, 78, 79]	[70]
- $\iota_{12.5}$:Usage of "irritating, vague terminology"	[62]	[72, 73, 79]
- $\iota_{12.6}$:High transaction costs	[9, 74, 80]	[62, 70]
- $\iota_{12.7}$:Lack of trust	[81, 82]	[70]
ι_{13}:No rules for sharing digital sequence information (DSI)	[44, 83]–[86]	[66, 87, 88]

Step III: Step 2 combined with *TS=(shortcomings OR problems OR hurdles OR limitations)*
Step III found 10 papers in DB1 and 11 papers in DB2 reporting that despite good intentions of international treaties, cumbersome bureaucratic and regulatory hurdles therein delay and disincentivize honest research practices. They thereby prevent equitable benefit sharing, creating an atmosphere of mistrust between providers and users of agrobiodiversity [71]. Lack of trust leads to sub-optimal accessibility and benefit sharing, triggering a vicious cycle where rampant biopiracy further reduces trust among stakeholders [72]. Table II lists shortcomings predominant in literature.

Current regimes are inadequate or unable to (i) trace PGRs to source, (ii) identify and penalize infringements, and (iii) incentivize access and benefit sharing. They thus fail to facilitate and incentivize legitimate and honest access to and research with PGRs. Further, they currently fail to integrate digital sequence information (DSI) associated with PGRs in their access and benefit regulations. Despite their significant role in research and development [89], DSI currently bypasses any ABS and obligations or values thereof [84]. Both the CBD/NP and the ITPGRFA have recently tried to include DSI, but describe the struggle to accomplish this as being a result of "pre-existing weakneeses" in their design [86].

The ongoing discussions on DSI also emphasize the need to rethink existing administrative and regulatory frameworks and to identify alternative or complementary solutions. Such solutions should facilitate the tracing and tracking of shared data to its source and to every downstream use [54]. It should also sufficiently protect and incentivize the maintenance of the source of PGRs and DSI [84, 86]. Externalising transaction costs associated with ABS and fostering interdisciplinary and cross-cultural research with PGRs are also worthwhile goals to pursue [44].

Regulatory and bureaucratic delays result in researchers avoiding regulatory check posts [77, 79], blurring the origins of their data, or stopping research out of fear of allegations of biopiracy [44, 48, 59, 73]. As a result, international regulations that aim to protect, conserve and equitably regulate the access to (agro)biodiversity [85], currently limit the availability and access to valuable PGRs, and inadvertently disinentivize honest use of the systems established under these regulations (For the ITPGRFA: [42, 50]. For the NP/CBD: [8, 48, 52, 90]. Both regimes are currently looking for solutions [54, 66, 70, 84, 86].)

V. Blockchain Use Cases: Features and Conditions (RQ2)

A. Blockchain: Overview of Key Features

Blockchain as a technology was first applied in the decentralized cryptocurrency Bitcoin in 2008 [91]. As first application, Bitcoin is used for pseudonymous payments without the need to rely on a trusted third party. Since Bitcoin increased in popularity and communities understood that a blockchain network can be utilized for other purposes or use cases, applications outside the financial sector arose [92].

Most scientific literature [93]–[97] highlights four key advantages of blockchain that make it suitable for diverse use cases:

1) Trustlessness: Parties who do not fully trust each other are able to interact with each other. This absence of trust is the result of absolute transparency [98]. Each action of a user is visible to and verifiable by all other participants. Furthermore, it is non-repudiable, such that the acting user can never argue that a particular action did not happen.
2) Independence from third parties (or intermediaries): The trustlessness of the system comes with the fact that the parties do not need a trusted third party to run the system. Instead, the members of the network run the system together, without a single party being able to manipulate the state. Only if a specific threshold of accomplices is exceeded, manipulation is possible.
3) Automation and Execution: The maintenance of a consensus, especially about the evolution of a set of shared facts, is crucial. It allows the parties of the network to define rules to which everyone has to adhere; otherwise, participation is restricted, or the respective parties are punished for their malicious behavior. These rules are either a core part of the consensus mechanism or can be formulated in so-called Smart Contracts; little programs installed on the blockchain, running as autonomous services. With these Smart Contracts, these rulings can be extended to every aspect of the network, allowing participants to collectively define processes, responsibilities, roles, and outcomes.
4) Built-in incentive mechanisms: Incentives have been a key pillar in blockchain solutions. The incentive mechanisms existing in Bitcoin have lead to huge energy consumption and carbon footprint [99, 100], innovation in hardware and a market capitalization of over 280 billion USD in under 13 years of existence [101]. Further networks and applications have pulled many stakeholders into their ecosystems by proper incentive mechanisms. These incentive mechanisms usually have a two fold approach: a) reward good behavior and b) punish bad behavior.

Therefore, data platforms based on permissioned public or consortium blockchains with appropriate software architectures and governance models can help solve problems of (lack of) trust, traceability, and equitable data collection [102]. They empower data providers to collectively track, control and monetize the usage of their contributed data and assets. It also allows participants (farmers' groups, for example) to collectively decide the terms under which they will transfer materials, know-how and other data.

These features of blockchain appear to make it a useful technology for overcoming the identified challenges and shortcomings and incentivizing in situ conservation and use of agrobiodiversity. In the following sub-section we look more closely at whether and what extent, blockchain may be a good technological fit for this use case.

B. Blockchain for Agrobiodiversity (B4A): An appropriate Blockchain Use Case?

Blockchain applications in the agro-food sector are currently dominated by track and trace solutions [103, 104], aimed primarily at facilitating quality control and provenance checks [105]. Other applications permit direct sales from farmers to consumers [106], removing intermediaries [107], expediting payments with the help of smart contracts and enhancing farmers' profits from direct sales of products to consumers [108]. Emerging research on blockchain and incentives, however, suggests that features of blockchain technology, especially when used in combination with other emerging technologies, e.g., Internet of Things (IoT) [109, 110], make it potentially beneficial for applications that go beyond supply chain tracing and automated payments [106]. In particular, blockchain can be used to incentivize activities that existing regulations (e.g., due to regulatory and market failures), have been unable to incentivize [111].

Blockchain technology is particularly appropriate when one is dealing with

1) transactions, especially a chain of continuous, inter-linked transfers of valuable assets from one stakeholder (or buyer) to the next [112],
2) a use case that values or requires immutable record keeping [113]
3) a use case that has multiple stakeholders that do not trust each other [97],
4) a use case that requires "checkposts" that can check for data veracity or reconcile disparate data [114], and
5) a use case that values de-centralized rather than centralized management and monitoring of the system [115].

In the B4A use case, the features required to overcome the identified challenges correspond with all of the above points that indicate an appropriate blockchain use case. Specifically, as discussed in parts II C and III above, B4A requires

1) Corresponding with 1) above, facilitation and monitoring of transactions involving the transfer of agrobiodiversity in the form of heterogeneous seeds, soil samples, and associated know-how (e.g., know how on best practices to use/cultivate these seeds, or the specific characteristics of these seeds);
2) Corresponding with 2) above, immutable record keeping in order to be able to trace the original source from which these valuable materials and know-how started being transacted - this is necessary, inter alia, to permit attribution and benefit sharing;
3) Corresponding with 3) above, managing and incentivizing multiple stakeholders that do not trust one another or do not trust the existing centralized system
4) Corresponding with 4) above, "check-posts" (or nodes) that have incentive to research and verify the quality, characteristics (of materials) and authenticity (of know-how/information) transacted - this would incentivize research on and with agrobiodiversity (see Part II C above); and
5) Corresponding with 5) above, a distributed system, that would facilitate more "transactions" (or information sharing) without having to rely on a single/central authority, thereby creating more communication and marketing channels (see Part II C above) for heterogeneous seeds, and associated know-how and DSI (where applicable).

The following section VI discusses the current state of art in blockchain technology and the extent to which the technology can help overcome the challenges identified in sections II and IV by incorporating the above features.

VI. Blockchain for Agrobiodiversity: Possibilities and Limitations (RQ3)

A. Issues that Blockchain can and cannot help addressing

Research question 3a challenges us to analyze if blockchain helps us to address shortcomings and challenges identified in section II and IV. To understand whether, and to what extent, blockchain is an appropriate technological choice for incentivizing conservation, use and research with agrobiodiversity, we first outline the possible scenarios vis-a-vis impact of technological deployment. This has been done in terms of (possible) influence on any of the identified challenges and shortcomings in the existing systems. Specifically, four scenarios are possible:

- **Blockchain solves the problem (++):** An issue can be directly solved by blockchain. Depending on the complexity, blockchain might help by overcoming issues of communication, provenance or data integrity.
- **Blockchain supports other approaches in solving the issue (+):** Blockchain itself might not be the sole solution, but might enable other approaches which utilize the blockchain in solving the issue. This is often the case if blockchain and the data stored on it is used for other purposes, e.g., data analysis, research or education.
- **Blockchain has no impact on the problem (o):** Even if implemented, problems such as mindsets and systemic roadblocks will not (automatically) be solved or impacted by blockchain. In the face of such issues, it is irrelevant whether blockchain is implemented or not. However, resolving these issues (e.g. through education and prioritization under policy/regulation) can pave the way for a solutions based on blockchain.
- **Blockchain negatively impacts the problem(-):** Some problems might get elevated by a blockchain-specific implementation. Properties such as immutability and inability to delete data might conflict with other goals of a project, such as GDPR or data privacy, even putting lives of people/farmers at risk.

TABLE III
Categorization of Issues and Shortcomings

Issue/Shortcoming/Problem	**BC Impact**
Farmer Challenges	
ι_1 Importance of attribution	++
ι_2 Economic and other incentives, royalty and rewards	++
ι_3 Traceability of source of seeds and know-how	++
ι_4 Research and education	+
ι_5 Communication channels	+
ι_6 Marketing channels for sales of produce and seeds	+
ι_7 Means of ensuring and documenting quality of seeds	++
ι_8 Means ensuring quantity, availability and affordability	++
ι_9 Knowledge creation and verification	++
ι_{10} Perpetuation of traditional ecological knowledge	+
Shortcomings identified in Literature Review	
ι_{11} Lack of traceability of PGRs exchanged	++
ι_{12} No access to PGRs due to	
- $\iota_{12.1}$ Lack of competencies	+
- $\iota_{12.2}$ Delays and stoppages	+
- $\iota_{12.3}$ Incomplete catalogues of PGRs	++
- $\iota_{12.4}$ Legal uncertainties	o
- $\iota_{12.5}$ Usage of "irritating, vague terminology"	o
- $\iota_{12.6}$ High transaction costs	++
- $\iota_{12.7}$ Lack of trust	++
ι_{13} No rules for sharing digital sequence information	++
ι_{14} Political pressures	o
ι_{15} Policy-based imperatives	o
ι_{16} Inequality, powerbalances changing at community level	-

We sort aforementioned issues, shortcomings and problems from the literature and attribute them a category (++, +, o or -). All items are depicted in Table III. This allows us to focus on the issues that can be solved by blockchain and evaluate whether the current state of blockchain is sufficient to address these problems. As the issues of incentives is one that is particularly complex in the B4A usecase, we discuss it separately in the following sub-section.

1) Issues that may be supported by Blockchain: From Table III it becomes clear that issues or categories of issues that relate to communication and knowledge transfer and preparation, e.g., research and education (ι_4), communication channels (ι_5), marketing channels for sales (ι_6) or perpetuation of traditional ecological knowledge (ι_{10}), can benefit from the ecosystem created by a blockchain network. Within this ecosystem, additional services can be created (e.g. in the form of distributed apps) that serve diverse purposes of the stakeholders (especially farmers) in the network, without directly relying on blockchain technology. It is imaginable, for example, that other stakeholders (e.g., research institutes) offer specialized data analysis or research based verification based on the data, or know-how available on-chain.

In fact, the compilation of data and know-how from diverse sources via the B4A system would facilitate and enhance research on and with agrobiodiversity. B4A could facilitate the identification of relevant material, if, for example, search functions supported by AI or ML models are built on it. B4A would also support speedy and traceable transactions of the material and associated know-how. However, it is noteworthy that blockchain cannot help identify materials once they are removed from tamper proof packaging and are transformed. Therefore, blockchain technology will need support from other technologies such as biomarker technology to support tracking and tracing throughout the seed innovation lifecycle.

2) Issues that may be aggravated by Blockchain: Some issues are not affected, or are negatively affected by blockchain: Especially in the relationship with the government and the larger society, problems might be elevated. Managing data or incentive structures over a blockchain network that requires governmental or legislative action ($\iota_{12.4}$) for proper functioning, might lead to delayed or competing actions. Approaches to reduce inequality or re-balance economic power structures at a community level might lead to counter-movements or, in the worse cases, to violence and civil unrest (ι_{16}).

3) Issues that may be addressable by Blockchain: We divide the issues that may be addressable by blockchain, into three distinct categories: ν_1) Identity, attribution and non-repudiation, ν_2) provenance, tracking, and information verification ν_3) disintermediation and cost reduction (See table IV).

Although a blockchain solution can potentially provide these features, there are important limitations resulting from the complexity of the B4A use case, including the number of stakeholders involved, the need for diverse smart-contract terms from each participating farming-community/ contributor of materials and know-how, as well as the diversity of materials and data that needs to be transacted. Accordingly, in the following sub-section, for each of the categories, we describe a) the state of the research and b) the current limitations that need to be overcome in the context of B4A as well as recommendations to approach the issues.

B. Possibilities and Limitations under the Current State of Blockchain Art

1) ν_1: Identity, attribution and non-repudiation: The reliable creation and management of identities is highly relevant in every blockchain application [116]. A decentralized identity management allows the creation of arbitrary amounts of identities without requiring a third party. Furthermore, messages that are signed with these identities are tamper-proof and non-rebuttable.

The creation of such identities relies on asymmetric cryptography [117]. Often, key-derivation algorithms are used to generate private and public keys generated randomly by the computer. However, in the context of B4A-use case with real-world attribution, two key challenges remain:

- How is an identity that exists in the blockchain linked to a real-world entity, e.g. a farmer or institution? As our use case includes multiple stakeholders with different roles and responsibilities within the system, we need to be able to connect real-world entities with on-chain identities. Otherwise, we cannot distribute respective rights and roles to the stakeholders in the system.
- How can we prevent Sybil-attacks (multiple creations of identities)? As regular blockchain solutions allow the creation of an arbitrary amount of digital identities, we need to ensure that only one real-world identity controls one on-chain identity with respective rights. Otherwise, one party could create multiple accounts acting on behalf of many.

The complexity of this problem is further increased as several of our key stakeholders a) are not in possession of standardized forms of digital identities and b) can be legal or natural persons, requiring diverse approaches for establishing identities.

Current technology permits three different strategies for enabling identities within the B4A system. These methodologies result in different costs and effort, and are not fully decentralized. The entities responsible for the system will need to select an appropriate technology depending on attributes of the to-be identified party.

(A) For maintainers of the network, entities are preselected (by a trusted network partner, e.g., an NGO or local University) and introduced to the system [118]. With that, they will receive an on-chain identity which grants them the respective role in the network. As this process is expensive, only core maintainers of the network are onboarded with this approach.

(B) For legal entities such as companies or research institutions which want to interact with the network, we recommend the party to create an identity which is linked to their domain. To enable a secure communication between users and websites, web servers usually have digital certificates, which allows the user to verify the correctness of the website[6]. We recommend an approach [120] that allows us to endorse on-chain identities with respective website certificates. This a) establishes a secure binding to a real-world identity and b) prevents the creation of multiple identities. This process can be further supervised by the maintainers of the network, e.g., that only research institutions can be registered providing a domain with a .edu Top Level Domain (TLD).

[6]These certificates are so-called TLS/SSL-certificates issued by Certificate Authorities. These certificate authorities ensure that only the website owner has access to this certificate. The existence of a certificate is shown by the "lock"-sign in the URL-bar in all modern browsers. These systems are used on over 90% of all websites according to Google [119]

TABLE IV
FEATURES OF BLOCKCHAIN

Key Blockchain Feature	Issues and Downsides
ν_1 Identity, attribution and non-repudiation	ι_1 Importance of attribution $\iota_{12.7}$ Lack of trust
ν_2 Provenance, tracking, and information verification	ι_3 Traceability of source of seeds and know how ι_{11} Lack of traceability of PGRs exchanged ι_7 Means of ensuring and documenting quality of seeds ι_8 Means ensuring quantity, availability and affordability ι_9 Knowledge creation and verification
ν_3 Disintermediation and cost reduction	$\iota_{12.6}$ High transaction costs

(C) For farmers' collectives or for informal groups of farmers[7] collectively making contributions to the system, it may be necessary to work through a trusted local NGO, local government body or local trusted University. In countries like India, for example, several recent movements aimed at reviving traditional ecological knowledge systems and farming techniques (such as Natural Farming) that help revive and improve agrobiodiversity, are pioneered by non-governmental organizations. These NGOs can then be the trusted third party through which legitimate data entries can be made into the B4A system. Novel systems such as Self-sovereign identities can be leveraged to issue such identities and onboard respective parties [121].

(D) For private or natural persons (e.g., farmers and consumers), a KYC ("Know your Customer") process can be established. This is the most complex and costly approach, as the natural person who wants to interact with the system has to contact one of the maintainers of the network to get accredited for the network [122]. The maintainers need to ensure that the information about the natural person a) is correct and b) no duplicate entry exists. These maintainers are best placed near the location of the respective natural persons and comprise NGOs and other non-profit organisations.

(E) If an entity (e.g., a farmer) has not the technical capabilities to participate in the network, other stakeholders need to act as a trustworthy intermediary between the entity and the network. With this approach the entity is entirely dependent on the intermediary, requiring that party to be trustworthy towards the original entity as well as towards the network.

With these processes in place, the aforementioned digital identity issues can be mitigated and digital identity can be securely used within the application.

2) ν_2: Provenance, tracking and information verification: The append-only data structure of a blockchain creates a log of all activities in the network, such as trade between parties or the report of a new type of seed. A node within this network needs to evaluate all logs to get the current state of the network (e.g., what seeds are available). This allows the tracking and proof of provenance of data and values, as every action is transparent to the network. This also relates to the property of identity and non-repudiation, as a once created transaction that is logged in the network can never be removed from this log again. The main issue for tracking and provenance proofs in blockchain is the connection between on-chain data to their real-world counterpart, as properties of goods need to be measured, stored and potentially updated in the blockchain, requiring a) standardized methods of measurements and b) ways to ensure the trustworthiness of data respectively the entity that uploads the data [123]. This is often referred to as the Oracle problem [124].

The current research in blockchains focuses on either the establishment of digital twins for blockchain networks or secure oracles [124]–[126]. Trust in the data and the third party providing it can be achieved by:

- **Trust establishment as a form of consensus:** Multiple entities which are able to observe the same phenomenon are able to "vote" about the state of the phenomenon. This could be the case when multiple research institutes report the same types of quality for one specific seed. This consensus-driven approach can also work after-the-fact, as e.g, seed quality can be later on evaluated by multiple third parties which can then coordinate on the validity of previously submitted data [127].
- **Trust establishment due to tamper-proof hardware:** An alternative form of trust establishment requires the usage of certified hardware. This hardware is specifically designed for the use case and includes mechanisms to connect to the blockchain and submit collected data. For example, hardware that measures the temperature of shipped goods can be used to prove the cold chain. However, this approach leads to a centralization, as the hardware manufacturer controls the hardware and potentially can manipulate it, while also the hardware itself could be manipulated, depending on the complexity of the hardware (e.g., instead of cooling the seeds itself, only the sensor of the hardware could be cooled). Multiple hardware vendors can complicate attack vectors, providing for a more secure network [128].
- **Establishment of a trusted third party:** A trusted third party with the sole purpose of measuring real-world phenomena and providing this information on-chain is

[7]In all cases involving individual farmers or farmers collectives, the existence of banks well connected to the international banking network would be beneficial, if not crucial. Farmers who own bank accounts can then obtain direct payments into their accounts through the operation of smart contracts, on mutually agreed terms. This would reduce corruption and transaction costs.

also a viable way to go if parties exist within the network that are more trusted than others. A local research institute would be able to obtain reliable information about seeds, such that it can be directly put on the blockchain. Obviously, this also leads to some form of centralization, however the third party could still be blamed after the fact as all the submitted information is recorded [129].

This issue of trustworthy third party data is under research and even own networks like Chainlink [126] have been created to address aforementioned issues.

To resolve challenges within our use case, we recommend the adoption of a public permissioned blockchain and designing processes for coordination between multiple parties on the validity of data. In the proposed use case, multiple stakeholders exist which fulfill different roles in the system. As some parties might be more trustworthy than others (based on the role or on previous experience), a hierarchy can be established for determining the validity of data. For example, farmers should be able to claim properties of their seeds. However, other farmers as well as research institutions that have legitimately acquired a sample of the specific seeds should be able to verify or reject these properties, while also adding new, previously unknown features based on research (by research institutions or corporations) or observation (by farmers or consumers). Over time, an amazon like rating mechanism may have to be evolved with weights/ranking attributed to the rating based on track record - for example, the rating by a new end-consumer may be weighted/ranked lower than the rating by an established independent research institution. Proper management of roles and ratings can ensure validity of data and know-how entered into the system, or of materials transacted via the system.

3) ν_3: Disintermediation and cost reduction: A blockchain as a decentralized network replaces centralized entities that charge fees for using their infrastructure. Removing third party intermediaries can, therefore, reduce costs [130]. However, this replacement comes with some caveats:

- The cost of removal is replaced with the cost to incentivize other parties to join and maintain the overall network, either by monetary incentives in public permissionless networks (e.g., Bitcoin) or through secondary incentives (being able to use the platform itself, caring for a social purpose or others) in permissioned networks. In the B4A use case, entities who run the network incur the costs of setting up and maintaining servers. Accordingly, these costs are not entirely removed but distributed among the participating parties. This could lead to reduced overall costs, especially in the long run when set up costs are recuperated.
- Not all activities of an intermediary can be replaced by a decentralized network. If the intermediary serves specific roles in the network e.g., as arbitrator, other trusted third parties have to be established or complex voting schemes have to be created to allow this feature in a decentralized network [131]. This is especially the case if we need to decide about the data validity of given inputs. For that case, we need to establish means as mentioned in ν_2.
- A true disintermediation is often only possible in use cases that permit or call for public permissionless networks. In permissioned networks such as B4A, some form of trusted intermediary is needed to establish, maintain and extend the quality and practical utility/value of the network over time. In some cases, such as in cases of farmers working via NGOs, the intermediary may also have control over the distribution of funds received in the network, as it makes the rules in the network and maintains it (for a specific group or regions, for example). In our case, the proposers and designers of this system need to involve all (local) stakeholders to find valid rules.
- The decentralization often comes with a limitation of throughput in the network. Public permissionless networks often face some technical barrier (e.g. 7 transactions per second in Bitcoin), while permissioned networks are only limited by the hardware and internet connection to other parties, as well as the complexity involved in verifying the quality of data/materials/know-how, at least to some extent, at the entry point [132].

For the B4A use case, the fair distribution of rights and responsibilities is important. We assume that due to the stakeholders of the network, no additional fees will occur e.g. on the level of farmers. They should be able to use the network without fees, as they provide key material to sustain and continuously add real value to the network.

VII. RQ3B - Building Incentives into B4A

A. Why Incentives?

A blockchain-based sustainable agrobiodiversity conservation system constitutes an institution for all involved stakeholders. Institutions provide the economic incentive structure that are expressed by informal constraints and formal rules [133]. Informal constraints such as sanctions or a certain code of conduct, as well we formal rules such as constitutions or law set the stage for how institutions and their incentive structures evolve. Thus, incentives provided in blockchain-based systems play an important role also for B4A and decide whether a system growth or stagnates. As we have seen, the traditional system was not able to align incentives, which led to a low agrodiversity conversation rate due to uncooperative incentive structures or even opportunistic behavior. Blockchain systems not only provide transparency, but also the certainty that agreed upon processes, payments, and actions will be executed. In other words, farmers can be certain that they gain the rewards that were agreed upon, which increases the trust in the system, and decreases the appearance of opportunistic behavior [134]. Thus, a blockchain-based B4A system allows for re-engineering not only the supply chain, but also incentive structure and payoff matrix for stakeholders such as farmers involved [135]. Therfore, it is plausible to assume that the existing inadequate intellectual property protection regimes that are not able to incentivize sustainable innovations can also be remodeled and rewards can be guaranteed once the system is blockchain-based.

Incentives can have different forms, ranging from assurance of compliance to user-functionalities or economic incentives such as personal benefits. Incentives can also nudge people to behave in a certain, intended way. In other words, blockchain systems can discourage people from actions which may adversely impact the sustainability of the overall system. As incentive mechanisms are part of the blockchain protocol, they reside in code on-chain to guarantee that given a certain behaviour is achieved, the agent, for example farmers and downstream researchers, can be certain that they receive the reward or any other benefit that has been promised. blockchain-based systems, supported by smart contracts and remote sensing algorithms, have been evaluated, for example, for reinforcing payments for ecosystem services in Namibia [136]. On-chain blockchain incentive mechanisms manifest incentives into blockchain systems using specific blockchain constructs, including game theoretical economic incentives, e.g., in form of validation rewards.

Blockchain systems are by nature distributed and have to align interests and incentives among the involved stakeholders. Alignment with the goals of the blockchain system occur when participants are incentivised to behave. In permissioned public blockchain systems, participants are pre-defined, which means that incentives can usually be created through traditional means (e.g., legal contracts, creating efficiencies and business revenue) [136].

B. Incentives necessary in B4A

In B4A, incentives are necessary for farmers to change their behavior toward a more biodiversity and soil sustaining farming. In blockchain systems supporting research and innovation with agrobiodiversity, a system-wide alignment of existing incentives or re-engineering of non-existing or contradictory incentives is required. In other words, every entity in the system should have as dominant strategy, to behave within the incentive structure engineered in the blockchain-based reorganized market. Incentive alignment has been achieved "when the system's embedded features induce users to employ the system consistent with the design objective" [137]. A blockchain-based agrobiodiversity system that aligns incentives across all entities involved allows agents to freely choose their own actions but uses incentives to make them inclined to choose actions that coincide with goals of the system's design. In such a blockchain system, a conscious and mindful incentive alignment is mission critical. Unless incentives are properly aligned, the nodes of the blockchain system will not contribute to form consensus.

Following the conclusions of [138], it appears that in B4A, blockchain can be used to

- incentivise farmers, researchers and other stakeholders to positively behave and interact in the system whilst simultaneously disincentivizing illicit behavior. This would, for example, incentivize proper declaration of source/origin and automate equitable benefit sharing with farmers;
- identifying (new) participants, making digital identity available and usable whilst ensuring that information once attributed cannot be repudiated, thereby reducing the chances of disputes resulting from dishonest behavior. This would, for example, ensure that any new user/stakeholder entering the system can be given a proper digital identity and all materials and know-how originating from her can be either be appropriately compensated/rewarded, or sent back/black listed (e.g., due to consistent low quality or false claims);
- maintaining an immutable record of transactions/transfers (e.g., record of agrobiodiversity and know-how transfers from farmers to various categories of end users[8]); this would, for example, ensure that in case of downstream research resulting in new products (e.g., improved, uniform seeds), royalties can be paid to farmer-originators.
- independently verify data entries to determine whether information submitted to the blockchain is correct in B4A. Instead of a proof of work based verification of transactions, it may be necessary to use other approaches such as "proof of authority".
- remove intermediaries in complex interaction processes and reduce overall transaction and communication costs. In B4A, while several regulatory intermediaries can be reduced, a trusted third party would still be necessary to check and confirm the quality and veracity of materials and know-how shared by various stakeholders. This entry gateway of corruption cannot be completely eliminated even when using blockchain. However, appropriate incentives written into smart contracts [136] can transform trusted third parties into stakeholders that can be rewarded for honest work.

VIII. Conclusions and Recommendations for Future Research

This paper identifies (i) concrete hurdles and loopholes in international regulations designed to protect and promote (in situ) agrobiodiversity conservation, (ii) practical hurdles faced by farmers engaged with farming using agrobiodiversity, and (iii) looks into into the extent to which blockchain technology may help in resolving the identified shortcomings and hurdles [19, 20].

Based on a review of the existing state of art, it appears that a blockchain based solutions can help overcome several of the hurdles in the current international regulations, and the resulting practical problems of (lack of) trust, traceability, and equitable data collection. For this, an appropriate software architecture needs to be implemented, including asymmetric cryptography, key-derivation algorithms and decentralised identity management. While high transaction costs currently

[8]A large number of stakeholders and end-users would potentially (need to) be involved in B4A, including farmers who are currently engaged in agriculture using agrobiodiversity; farmers who want to migrate to such agriculture; research institutes interested in conducting research or breeding with agrobiodiversity; corporations, including the seed industry; governmental regulators; seed and organic certification agencies and international regulatory authorities under the CBD and the Seed Treaty

prevent the equitable sharing of agrobiodiversity and associated know-how, blockchain solutions could lower costs by removing complex and expensive interaction processes. If complemented with biomarker technology, blockchain may allow equitable integration of digital sequence information in biodiversity regulations and thus facilitate implementation of more streamlined and transparent values and obligations for access and benefit sharing [89].

This feature, in fact, points to one of the crucial features of a blockchain based solution for the B4A usecase, namely, its ability to actually incentivize sharing of information, knowhow and materials. Since on-chain blockchain incentives mechanisms can guarantee rewards or other benefits for data or material shared, in a blockchain solution, incentives could empower data providers (e.g., farmers) to collectively track, control and monetize the usage of data and assets shared. The digital identity of stakeholders allows appropriate compensation and ensures the security and quality of information (maintaining an immutable record of transactions and verifying data entries). Challenges in relation to digital identity of stakeholders could be overcome, for example, by implementing pre-selected maintainers of the network, on-chain identities or "Know-your-customer" processes.

Blockchain based solutions, can, therefore, increase the number of legitimate transactios, minimize black-market or illegal transactions involving agrobiodiversity, and enhance incentives for research and innovation with agrobiodiversity conserved in situ. However, several current challenges cannot be addressed by blockchain (alone) and several issues may be aggravated by implementing a blockchain solution.

While in this paper we lay out the key features (in the form of challenges and shortcomings in existing systems) that have to inform such an application and it's ecosystem, as well as the possibilities and limitations of blockchain technology, a lot still needs to be done. This includes the definition of the software architecture, the exact roles and responsibilities of various "nodes" and stakeholders in the system, the concrete incentive mechanisms and the manner in which they can be implemented to keep all parties on board. Future work is, accordingly, aimed at close collaboration with all stakeholders to align interests with incentives and design concrete mechanisms to implement a blockchain for biodiversity.

In terms of real-world effects, technical solutions like blockchain for agrobiodiversity can help ensure that legal regimes and policies do not inequitably favor one direction of scientific research and innovation to the exclusion of others. Particularly, such solutions can incentivize research and innovation linked to long ignored Traditional Ecological Knowledge (TEK) systems that support sustainable in situ innovations with agrobiodivdrsity by both formal and informal sectors. Blockchain can, therefore, help diversify the directions of knowledge and value flows and create multiple options for successful farmer-migration to sustainable agriculture using local agrobiodiversity.

However, blockchain based solutions can also create new legal and ethical issues. Ethical issues linked to trustworthiness and integrity of codes and privacy concerns must be adequately addressed at an early stage of development. These issues are particularly significant with disruptive technologies like blockchain that can destabalize existing socio-economic power structures, including in rural and remote areas. Moving into a world ruled by code, one must also ensure that smart contracts that execute code are designed fairly, taking all stakeholders' interests equitably into account, i.e., they should be inclusive and free from bias. Empirical research may be necessary to identify what is considered 'fair and inclusive' by contributors (farming communities). With the emergence of "code" based governance, it would also be necessary to conduct extensive legal research to determine how issues of liability would be reconciled.

Further, in order to make the DLT or blockchain-based solutions more immediately usable in practical terms, smooth interaction between the developed system and existing governance structures and regulations is necessary. This would ensure a sustainable transition that secures meaningful and continuing interaction between human and autonomous actors. This goes also for the used currency in such a system. Instead of a cryptocurrency-based incentive mechanism, it may be necessary to adopt a "Biodiversity points" based reward system - similar to systems adopted in carbon trading. In countries like India, where a biodiversity fund exists under the Biodiversity Act, these points could then be exchanged for cash by farmers and other stakeholders. The details of such a system, however, require more research in the future.

In a blockchain for biodiversity world, all stakeholders, farming systems and sectors could have a fair(er) chance of surviving and flourishing equitably. Most importantly, all stakeholders could be incentivized to partake in research and sustainable innovations that enhance agrobiodiversity in situ. Concerted, multi-disciplinary and translational research is needed to accomplish this.

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