Navigating the Implications, principles and objectives of Digital Sequencing Information in agricultural crops

Abstract

Navigating the implications, principles, and objectives of digital sequencing information in agricultural crops is paramount in the contemporary agricultural landscape. Abstractly, it encapsulates the fusion of cutting-edge technology with age-old agricultural practices, ushering in a new era of precision farming. Digital sequencing information, derived from techniques like next-generation sequencing (NGS), enables a deeper understanding of crop genomes, empowering farmers and researchers alike with invaluable insights into crop traits, genetic variations, and evolutionary histories. This article realm intersects with real-world applications, driving objectives such as enhancing crop resilience to climate change, optimizing breeding programs for desired traits, and ensuring global food security. Principles of data integrity, accessibility, and ethical use underpin this digital revolution in agriculture, ensuring that the benefits are equitably distributed while safeguarding against potential risks. As we navigate this intricate landscape, the convergence of digital sequencing information and agriculture holds the promise of revolutionizing crop production, sustainability, and resilience in the face of evolving challenges.

Keywords: digital, principles, benefits, accessibility, landscape, digital

Introduction

PGRFA, which stands for the International Treaty on Plant Genetic Resources for Food and Agriculture, was drafted in the year 2000 with the intention of addressing the growing shortage of genetic resources, especially those that are associated with the breeding of new crops and the assurance of food security[89]. There are two international agreements that have an impact on the preservation and use of PGRFA. These are the Convention on Biodiversity (CBD) and the Seed Treaty on Seeds. On the other hand, the Seed Treaty is only applicable to a selection of species that are vital to agriculture and food security, while the CBD is in charge of both terrestrial genetic resources[78].

The ABS framework has many primary goals, the most important of which are to guarantee the preservation of biological variety, the sustainable exploitation of its constituent parts, and the fair distribution of benefits that result from the utilization of genetic resources with one another. The Seed Treaty was conceived as a sector-specific response to the CBD, taking into mind the need for a global commons in order to combat the loss of agricultural biodiversity and guarantee food security[54]. In addition to this, it intends to make it easier for farmers, conservationists, breeders, scientists, and educators to have access to plant genetic resources. A great effort has been made to establish a global commons around phytogenetic resources via the Seed Treaty. This treaty acknowledges the importance of farmers in the preservation and sustainable use of these resources. Access to plant genetic resources is intended to be made easier for farmers, conservationists, breeders, scientists, and educators via the implementation of this initiative[26]. It is crucial to note that the bounds of the common are severely regulated, since the multilateral system includes 64 of the species that are considered to be the most significant for agricultural purposes[15].

Eventually, the CBD and its Nagoya Protocol would be responsible for regulating any PGRFA that did not come within the purview of the Seed Treaty and was not governed by any other intellectual property system. The Nagoya protocol places a strong emphasis on the sovereignty of the nation of origin, and it requires that every single resource exchange be negotiated on an individual basis each and every time[7]. All species under the multilateral system are managed by a standard material

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transfer agreement (SMTA), whereas the Nagoya Protocol governs access to the resources based on bilateral agreements between nations utilizing prior informed consent and mutually agreed conditions (PIC/MAT). In conclusion, the Seed Treaty is a crucial step towards the creation of a global commons around phytogenetic resources. It acknowledges farmers as being vital for the protection and sustainable use of these resources[6].

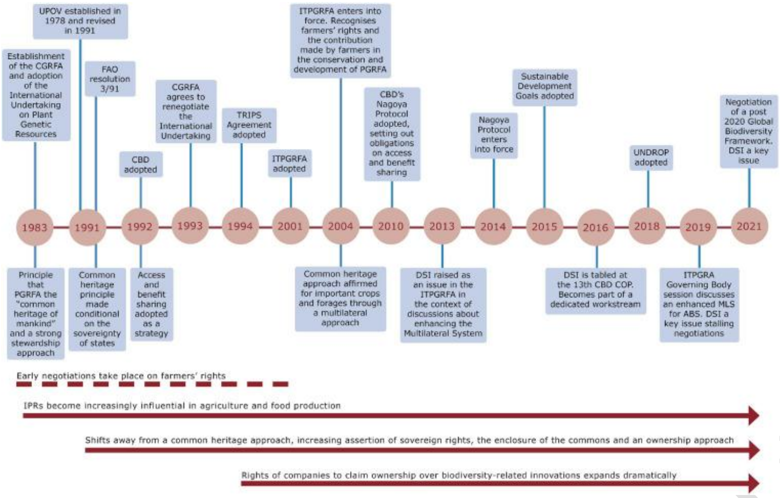

Fig 1. ABS framework

The Seed Treaty, much like the CBD, places an emphasis on physical genetic resources (PGRFA) since these resources are derived from plants and include both vegetative and reproductive propagation material. It is not obvious, however, if the responsibilities for digitally generated data (DSI) that are included in the benefit sharing requirements that are contained in the SMTA of the multilateral system also involve obligations[13]. When genetic resources are seen just as a material object, it is possible to make an incorrect assessment of contemporary activities that are associated with GRFA and the precise nature of what is being derived from them. Because of this, it is possible that these instruments will not be able to adapt to the current modalities of using PGRFA, which are largely mined to create enormous volumes of digital data as a consequence of different "omics" techniques[42].

The intellectual assets of PGRFA are framed by a convoluted collection of international legally enforceable documents that partly overlap with one another. These instruments have separate underlying ideas and goals[51]. Patents, breeder's rights, copyright, and the sovereign right over generic resources are the primary instruments that are applicable to the PGRFA. Trade secret protection is another important instrument. Under such regimes, it is possible that either one or both of the physical things (seeds) and informational entities (genomic sequences) might be privatized[76]. In principle, a single PGRFA might be privatized based on a variety of criteria and reasons, depending on whether its informational or physical components are being evaluated, as well as the regime that is being reviewed. It is difficult to establish a regulatory framework that may fit inside this "regime complex" in order to assure access and distribution of the potential advantages because of the hybrid character of PGRFA, which is both a physical and informational commodity[96]. Since 2016, discussions regarding the status of DSI have become increasingly prominent in a number of international contexts. These contexts include the ABS framework, the Seed Treaty, the CBD, the Convention on International Trade of Endangered Species, the Pandemic Influenza Preparedness Framework of the World Health Organization, and the United Nations Convention on the Law of the Sea[68].

Another facet of "Big Data" is the information presented in digital sequences.

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Within the realm of biological science, the term "Digital Signature Information" (DSI) has become more popular. Genomic research alone is responsible for the generation of petabases of data each year. Because of this fast expansion, there is an urgent need for a worldwide standardized infrastructure that can preserve data for an extended period of time[65]. By exhibiting the majority of the characteristics of other digital artefacts that have been generated in other domains, where alternative governance models have previously been effectively applied, DSI might be deemed to be presenting these characteristics[23]. These projects, such as DivSeek for crop genomics data and GODAN for phenotypic data, have been made possible as a result of research on PGRFA, which has led to the opening of possibilities for DSI management on a worldwide scale. PGRFA conservation often involves increasing quantities of DSI, such as in the DNA barcoding of life project or the sequencing of genomes of a whole botanical garden. This is because of the growing importance of PGRFA[20].

In the field of biological research, the prevalence of large amounts of "omics" data has posed a challenge to the method in which science is conducted and disseminated, as well as to the philosophy that underpins it[47]. Around time, the field of biology has steadily advocated extending access to public research data and findings, a perspective that has lately solidified in a variety of policy recommendations all around the globe. With that being said, it is still necessary to take into consideration the "digital divide" that is intrinsic to the current usage of information and communication technology. The Seed Treaty, which is currently designed in a somewhat libertarian manner, should not be stretched further by inequalities in data access, infrastructures, and specialists[36].

In the field of synthetic biology, there is a controversy that concerns information that is only available in digital form and originates from genomics databases. In order to control the interchange of DNA "parts," other intellectual property models have arisen[35]. One of these models is a two-tier approach that differentiates non-commercial technology from high-potential output. This strategy is aimed to optimize the sharing of biomaterials and related data. It is necessary to do more research in order to reveal the degree to which it may be applicable to PGRFA and the breeding setting in general[48].

The Seed Treaty has set itself the lofty objective of enabling the protection and sustainable use of PGRFA, as well as the fair and equal distribution of the advantages that result from their use for the purpose of ensuring food security and in promoting sustainable agriculture. Nevertheless, in order to accomplish these objectives, it is necessary to have a deeper and more thorough understanding of the ways in which digitization has altered activities[71]. Care should be given to ensure that clear mechanisms of access and exchange of data are provided while developing the governance structure for the PGRFA. Additionally, the capacities of each stakeholder engaged should be taken into consideration[83].

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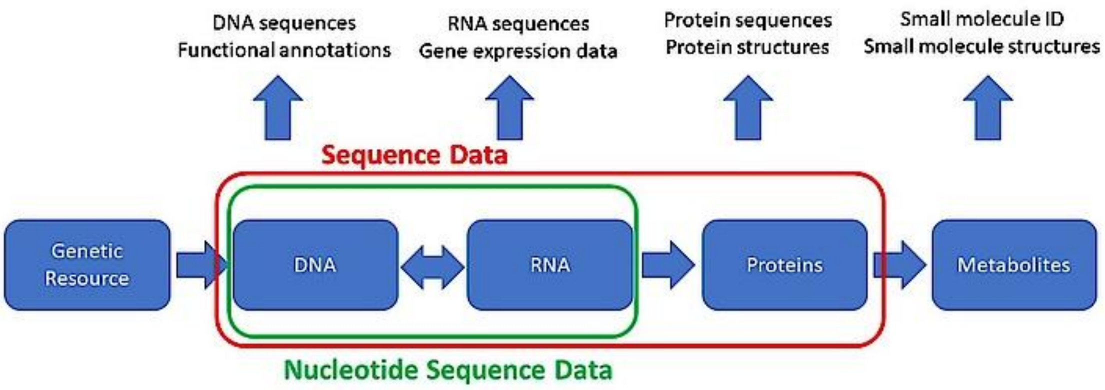

Fig 2. Sequence data

A New International Organization

The issues that have arisen as a result of the fact that research methodologies may now replace the use of physical biological material with DSI have been the subject of international talks since the year 2016[91].

It is now permissible to obtain and utilize DSI from plants that are subject to international treaties without any benefit-sharing responsibilities being triggered. This is the case, with the exception of situations in which national laws demand differently. This absence of benefit-sharing is unacceptable to a great number of people and has been the subject of intense controversy[73]. There are fears that it may reduce or abolish open access to DSI, which is what supports research and innovation. This is despite the fact that support for openness and benefit sharing is typically strong. For instance, DSI was used in the process of designing diagnostic kits and vaccinations that were essential in preventing the loss of millions of lives during the COVID-19 pandemic[47]. Taxonomy, the identification and mitigation of dangers to vulnerable species, the monitoring of illicit trade, the identification of the geographical origin of goods, and the planning of conservation management are three other areas in which it has played a significant role[10]. It is highly probable that, in the absence of a global consensus on DSI, an increasing number of nations will develop their very own regulations concerning access and benefit-sharing. This will result in the creation of a complicated environment for researchers and actors from the private sector to navigate, and it may also restrict the positive effects that DSI could potentially have[30]. In addition, an excessive number of distinct national laws may cause consumers to seek out DSI from nations that have the least restrictive arrangements, which may result in a "race to the bottom" and also prevent many individuals from participating in benefit sharing[76].

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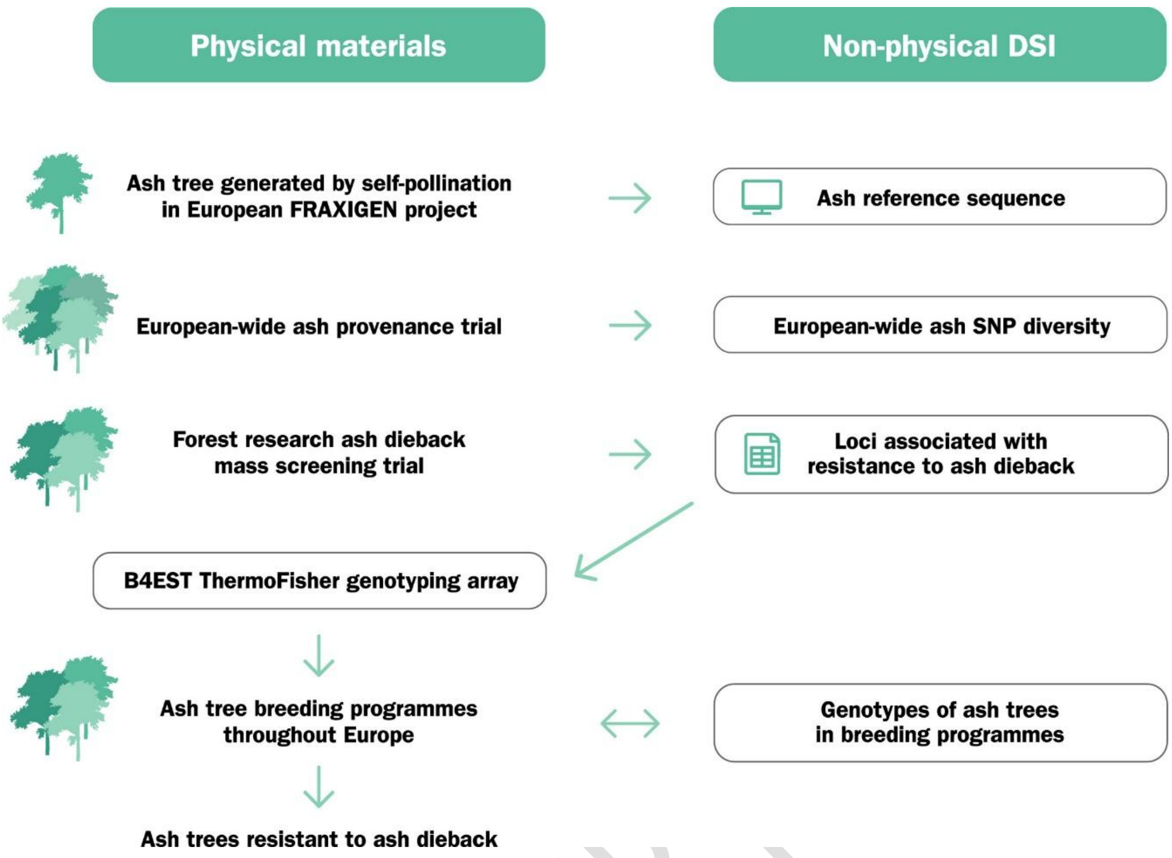

Fig 3.New International Organization

Speciality ofDigital Sequencing Information

Access to genetic information (DSI), which may be either genotypic or phenotypic data, is particularly important for the purposes of plant research and crop improvement. The Seed Treaty recognizes that the sharing of information is a benefit that does not include monetary compensation; nevertheless, it is not obvious how much this information exchange is taken into consideration in day-to-day operations[93]. When it comes to current breeding, the multifaceted idea of PGRFA is often disregarded when DSI is used. This particular kind of cultural commons is really one of a kind, since it involves a large number of participants and is connected to a wide range of socioeconomic principles[33]. In most cases, the use of PGRFA in a breeding program does not result in the depletion of the resource (non-rivalry), but rather strengthens its inherent worth and has the potential to rekindle interest in its preservation[50].

DSI from PGRFA is distinct from traditional perspectives on natural resources or cultural commodities in at least two primary ways: an optimal breeding value is achieved during genomic selection by merging pre-breeding data of multiple accessions, which makes it difficult to determine the exact contribution of each and every "accession" that is used. The development of synthetic biology has caused a disruption in the connection between the material (germplasm) and the products that are created from it. As a result, it is now impossible to determine the precise contribution of each and every "accession" that is employed[16].

The non-static, broadly diffused, non-rivalrous, and often non-exclusionary characteristics of DSI from PGRFA are not well accommodated by the policy framework that is currently in place[18]. There are significant distinctions between resources, which are to be extracted, natural genetic resources, which are to be extracted and valued, and PGRFA, which are to be largely mixed or crossed in order to enhance diversity and chosen throughout the breeding process. When working to

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strengthen coherence across the global governance of DSI-PGRFA, it is necessary to highlight the specificities that are under consideration[30].
On a regular basis, the characterization and sequencing of PGRFA is carried out on cultivars, landraces, farmer's breeds, and even crop wild cousins. In general, this results in a significant volume of digital data and seeks to establish a connection between phenotype and genotype [43]. The objective is to make it possible to anticipate phenotypes based on the whole of the genome's variability, which is referred to as "genomic selection." Genome-wide association studies (GWAS) can be used to identify relevant traits, such as fragrance in rice, underlying genetics responsible for pearl millet drought resistance, or loci encoding morphological diversity in barley. These traits can be identified by using pan-genomes, genomes, transcriptomes, metabolomics, and phenotypic data[1]. The genetic variety that has already been gathered and is easily accessible via gene banks is being mined by an increasing number of research projects. This allows for improved identification of key features, as well as enhanced breeding prediction and efficiency[59]. This contributes to the maintenance of high levels of food security by ensuring that the PGRFA is used in a sustainable manner to supply locally adapted, adaptable, and resilient to a variety of biotic and abiotic challenges while also being essential[84]. Notable is the fact that the discovery and characterisation of unique features have been made feasible via the combination of many hundreds of accessions from across the world[90]. Exploiting the existing variety that has been gathered in gene banks, on the other hand, does not necessarily appreciate the effort that breeders and farmers have done in the past over the course of agricultural history[2]. The vast majority of breeding programs have been fashioned by the continuous flow of genetic material, and these programs themselves adhere to self-established decentralized principles that are distinctive to each crop[58]. There is a lack of clarity about the manner in which the propagation and dissemination of genomic data may interact with the structures that are currently in place, the impact that these structures may have on the connection between big and small breeders, and the ways in which an expanding quantity of data that is publicly accessible may have an effect on practices[11].

Current status of DSI

The Green Revolution has seen seed as an important medium for the transmission of technology, both directly embedded in seeds and offered as a set together with better kinds. This has occurred both before and after the revolution[3]. The Fourth Industrial Revolution, often known as Industry 4.0, has seen the emergence of big data as a new product. Food and seed systems have not been immune to this trend[95]. The decrease in cost of gene sequencing technologies is enabling for technical breakthroughs that enable the replication of seeds' DNA in virtual format, which is referred to as DSI, hence creating large PGRFA data sets. These developments are built on genetic editing and CRISPR-Cas9Footnote1 procedures[70].
This has resulted in a debate over the governance standards that need to manage access to DSI as well as the fair and equal distribution of benefits that result from their consumption, as stipulated in the third aim of the CBD[9]. It is of the utmost importance to find a solution to this debate as soon as possible, given that it is anticipated that the cost of genome sequencing will continue to decrease, which will result in an increase in the availability of reference genomes of a higher quality[23].
It was in 2015 that the intense worldwide policy discussion began, and it has been escalating ever since. The issue centres on whether the definition of the word "genetic resource" in the existing legal framework includes DSI or simply physical PGRFA[29]. Under the Convention on Biological Diversity (CBD), the Nagoya Protocol (NP), and the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), which are the three primary international legal frameworks that govern access and benefits resulting from biodiversity and PGRFA, there is no exact definition for DSI[77].
In the interim, programs such as DivSeek, which was initiated in 2012, have been sequencing plant

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genetic material that is stored in national and international gene banks. This material was first acquired from communities of farmers with the premise that it would stay in the public domain[52]. There is no indication of access or benefit sharing in the description of DivSeek, which is a cooperation between 69 institutional and corporate members. This collaboration contributes to the corporatization of this huge data[39].

A growing quantity of literature is documenting all aspects of this issue, with academics from a variety of fields putting up arguments for the inclusion or exclusion of DSI in the ABS framework of the CBD. This body of literature is developing[68]. Countries that are engaged in DSI research and have high incomes say that it is vital to retain a conceptual and definitional separation between physical genetic material and data connected with that material. They contend that the generation of the latter needs researchers to add resources and skills to their arsenal[92]. Those who hold the opposing viewpoint consider DSI to be an integral component of PGRFA. They believe that its worth stems from a historical stewardship of resources and that it represents a call to put an end to the long-standing colonial heritage of copyright infringement[50].

The research stream known as the "Parts Agenda" in the field of synthetic biology is opposed to the incorporation of DSI into the ABS. This is due to the fact that it breaks down genetic resources into their most fundamental functional elements in order to produce standardized and interchangeable "bioparts" [4]. In spite of the fact that biobricks are the most widely used bioparts, their unrestricted access has resulted in issues and regulations. Legal obligations to share benefits with countries of origin can apply to bioparts that are synthesized in the laboratory using genetic sequence data that has been downloaded, as well as multiple fragmented bioparts that have been spliced together with elements from other genetic resources[5]. These bioparts originate from different countries, each of which has its own set of distinct regulations regarding DSI. It has been argued by a number of academics that this strategy may result in traceability issues in a single synthetic product, especially in systems that include many biological devices[8].

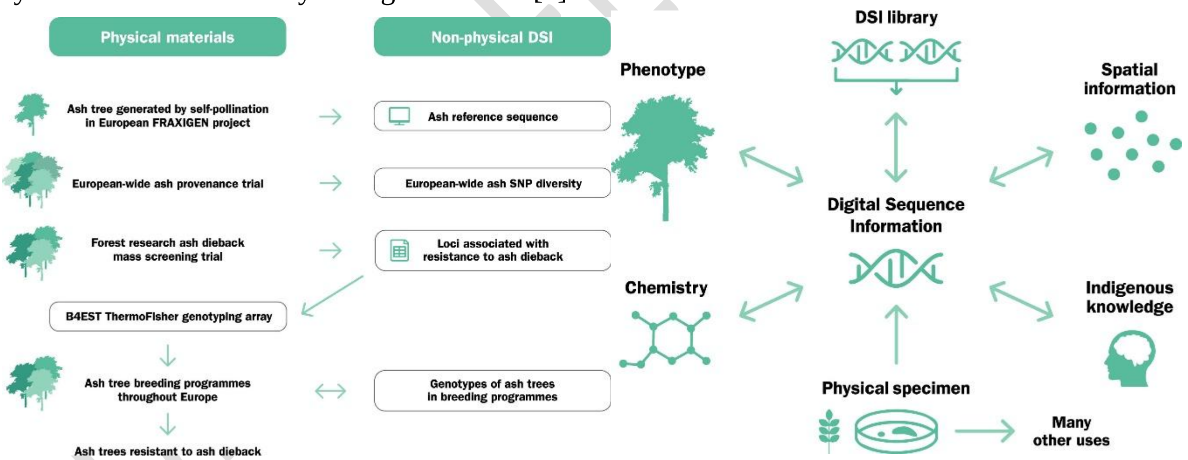

Fig 4. Current status of DSI

Plants that have been used as model organisms for a long time and produced in the laboratory for many generations before to the coming into effect of the CBD, Plant Treaty, or the NP are the source of many popular bioparts that are utilized in plant synthetic biology. This is another argument that may be made against the inclusion of DSI[12]. In light of the fact that the foundation of novel biological devices was appropriated at some point in time prior to the existence of the existing benefit-sharing framework, it is possible that a request for retroactive rules will be necessary[14]. The existing legal regulation of DSI at the national level on a bilateral basis has been analysed by Bagley and colleagues, bringing to light a policy international policy arena that is both complicated and uneven[17].

It is impossible to halt the expansion of DSI, which now consists of over 1500 biological databases that are open to the public. One of these databases is the International Nucleotide Sequence Database Collaboration (INSDC), which has 1.5 billion genetic sequences[19]. On the other hand, developments in genomics and molecular biology are anticipated to improve the characterization and assessment of wild genetic resources and landraces, which will ultimately lead to an increase in the amount of DSI that is accessible to the general population[21, 22]. A significant number of these DSI databases are now stored in open-access forms; however, there is currently no legislative protection in place to prohibit mining and private profiteering, nor is there any further enclosure of new goods that have been generated based on the contents of these databases[24, 25].

Instead of engaging with authorised providers of physical genetic resources to enter into an ABS agreement with the provider's prior informed consent, the failure to include DSI within the scope of the CBD, NP, and Plant Treaty presents an intolerable "digital loophole" for countries that provide PGRFA[27]. This lack of inclusion allows users to circumvent benefit-sharing obligations by synthesising genes and elements of interest through the generation and utilization of genetic sequence data that is accessible to the public. The existing enclosing of DSI inside the sovereign realm of the nation state poses a danger to the open-access ideals that are declared to be a part of contemporary science and creates a barrier to the most recent research in synthetic biology[28, 29].

Analysis of seed enclosure evolution: appropriations and substitutions

The agricultural sector of the economy has always been one that has placed a strong emphasis on the automation of labour in order to achieve uniformity, control over natural elements, and processing conditions that optimize homogeneity and cost savings[31]. Instead of attempting to reform the agri-food system as a whole, industrial capital has been intervening at certain areas within the system. Industrial capital has been attempting to transform the system as a whole. Both appropriations and substitutions were the two categories that Goodman and colleagues proposed for these interventions in their theory[32]. Appropriations capitals concentrated on the production and basic transformation processes of fruits and vegetables, while substitutions was originally used in the phases of food manufacturing that occurred beyond the farm gate[34].

Food production is "freed" from the unpredictability and irregularities of natural processes, which impede the economic prospects of many agricultural commodities. This is made possible by the growing use of industrial techniques and factory-like technologies[37]. These days, appropriations and substitutions techniques are carried out in both the primary and production phases. One example of this is the use of LED technology in underground hydroponic systems, which allows for perfect control over the growth conditions[38]. It is not only a reflection of the appropriation of natural cycles by industrial techniques and circumstances that the expansion of closed-loop aquaponics systems in urban areas is a reflection of, but it also provides an example of substitutions processes via the replacement of soil with liquid solutions. An additional kind of laboratory appropriation is the expanding tendency of in vitro culture of animal cells for the purpose of producing meat[40]. This phenomenon totally replaces the use of animals and activities that take place outside.

The physical processes of enclosure initially took place, with land enclosures being the first to take place [41, 44, 45]. This was the beginning of the control and appropriation of aspects of natural settings that were designated as resources, such as forests, land, and water, all of which were essential to the production of sustenance. As early as the late eighteenth century, people were forced off the farm and into factories as a result of private enclosures of common land by the nobility. This was compounded by the need of the First and Second Industrial Revolutions for inexpensive labour[46, 53]. Kloppenburg (Citation1998) and Montenegro de Wit (Citation2016) have meticulously recorded and analysed historical and more current processes of seed privatization of both cultivated crops and crop wild cousins via the Marxist lens of primitive accumulation. This research has been conducted in

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the world of seed. A continuing historical trend that has developed in tandem with the technological advancements of various IRs is the replacement of farms and workers in the agricultural sector who do not have access to land[55, 56,57].

The notion of enclosure has been the foundation for the development of five interconnected kinds of seed enclosures throughout the course of the past century. These seed enclosures are listed as follows: logistical, technical, legal, financial, and social. There has been an increase in the possibility for excluding logistical enclosures, which means that it is now simpler to limit access to these enclosures[60]. Samples are often provided by national gene banks to researchers and breeders who make a request for them; however, these gene banks typically do not send samples directly to farmers. The majority of the time, private businesses do not make any of their holdings accessible to the general public. It is also necessary to take into consideration the potential practical limitations that may be imposed on access to in situ PGRFA[61]. This is because in situ PGRFA diversity frequently exists in marginal farmlands or "in the wild" (in crop wild relatives), and it is most practically possible for foreign scientists to gather this information through formal collecting missions. In order to locate the plant populations that are of concern, it is necessary to rely on the expertise of national scientists or local farmers[62]. In the absence of collaboration between national and local authorities as well as farmers, the availability of such resources may be restricted in terms of their actual availability. The loss of seed and the illegality of seed-saving traditions and abilities that date back hundreds of years have been brought about by the privatization of seed[63]. It was not until the 1960s that international law began to take an interest in plant genetic resources. This was at the time when the Green Revolution was spreading its new methods and techniques. UPOV, which stands for the International Union for the Protection of New Varieties of Plants, has become the official international entity for the purpose of managing the Plant Genetic Resources and Conservation Association (PGRFA). This organization has, ever since it was established, been working solely and expressly toward the privatization of seeds all over the globe by imposing intellectual property rights on different plant kinds from the beginning[64].

Fig 5. DNA helix

The International Undertaking on PGRFA was established by the FAO Council in 1983. This undertaking is not legally enforceable, but it does declare PGRFA as a legacy of humanity that should be provided without limitation whenever possible[66]. On the other hand, nations that advocate for the private appropriation of subsets of PGRFA via the implementation of plant variety protection legislation declined to support the International Undertaking effort. In 1989, the Food and Agriculture Organization of the United Nations acknowledged that the rule protecting plant varieties was more important than the notion of common heritage[67]. The talks that took place during the Uruguay Round of the General Agreement on Tariffs and Trade (GATT) in 1991 resulted in a new resolution being passed by the FAO Council. This resolution acknowledged the sovereign rights that states have over their genetic resources[69]. When the CBD was ratified in 1993, these national rights were further expanded upon[72]. After that, in 2010, the National Policy on Genetic Resources (NP) was

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enacted, which included the adoption of obligations for monitoring, reporting, and enforcing access and benefit-sharing agreements[74].

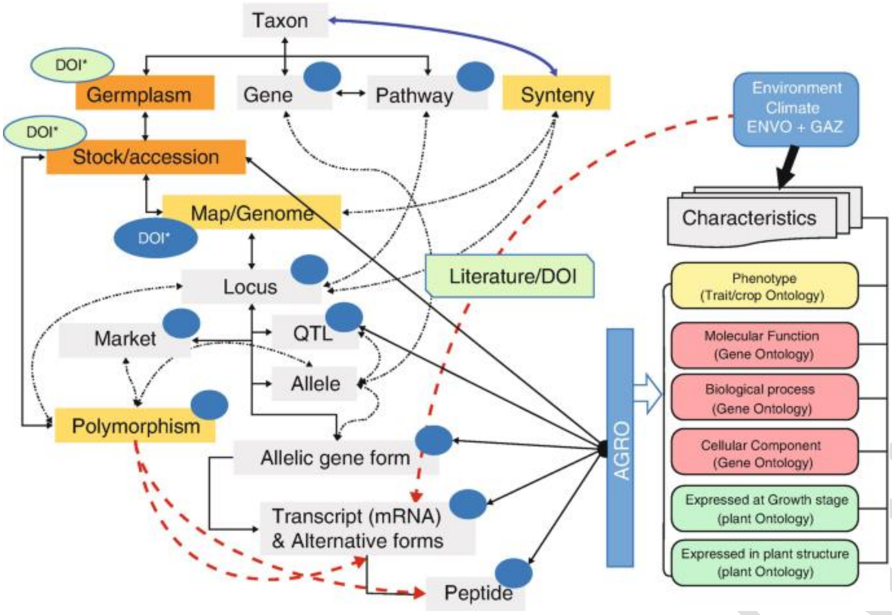

Fig 6. Seed enclosure evolution

Both the ITPGRFA and its MLS became operational in the agricultural sector in the year 2004. Patent regulations, plant variety protection laws, contractual limitations accompanying seed sales, and bilaterally oriented access and benefit-sharing rules are only some of the examples of the convoluted nature of the expansion of national and regional intellectual property laws that restrict seed rights everywhere in the globe[75]. By the middle of June 2022, the Plant Treaty had already implemented a Standard Material Transfer Agreement (SMTA), which had been used to send more than 6.3 million samples. This was done in order to circumvent some of the cumbersome contractual arrangements that were needed by the CBD and NP[79, 80]. In the United Nations Declaration on the Rights of Peasants (UNDROP), which aims to grant individual and collective rights to local communities for land, seed, and natural resources, as well as for research priorities to be defined and implemented by farmers, the recognition of farmers' contributions to diversity and seeds as a shared heritage of humanity that must be preserved was included. This recognition was included in the UNDORP[81, 82].

The privatization of seed has also resulted in the formation of financial enclosures. This is because the investment required to get access to hybrid seeds and patented varieties is generated inside capital enclosures, which are restricted to only those actors who possess the finances necessary to participate. There are still just a few of participants in the agri food sector that have the financial means to afford gene editing technologies and gene sequencing technology[85].

The intellectual property architecture to which proprietary seeds belong and biodiversity are polar opposites, which is another reason why proprietary seeds have a significant impact on the reduction of biodiversity. A buffer against illnesses or changes in the environment may be provided by cultivated variety; however, the legal mandate that farmers are required to use registered seeds not only promotes dependency on multinational corporations but also homogenizes crops throughout the world[86]. Monocultures of mono varieties are becoming an increasingly dangerous menace, particularly in light of the fact that access to a large number of variations has been limited, so diminishing the variety of crops and diets. The seed business is responsible for about seven billion euros' worth of commerce in Europe alone, and the market-driven pressures that are responsible for seed selection are not always aligned with the demands of local agricultural communities[87].

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Farmers often have little or no access to gene banks, and their linkages to more widespread, national, and international forms of PGRFA-related innovation are either non-existent or very limited. The identity of the farmer from whose material is gathered is often not included in the data that collectors and gene banks keep about the materials that are in their collections. This is because there is a mechanism that erases their unique contributions[88]. By the time that they are officially included in the collections of a gene bank, the relationship that was previously established with the farmer from whom the PGRFA was first acquired has been fully severed. In addition to this, the historical gender implications of seed stewardship should be taken into consideration[92]. Over the course of history, women have been responsible for carrying out and managing the process of seed preservation, and this is the case in many nations even now. There are significant differences in the worldviews, knowledge systems, and methods of knowing that farmers and scientists have about agrobiodiversity. Farmers are deemed to be acting in an impolite or unlawful manner if they do not comply with the legal framework[94]. With the advent of technology developments like as synthetic biology and DNA sequencing, technological enclosures have advanced into the digital dimension of the Fourth Industrial Revolution (IR). Seeds have also entered the digital arena because to these improvements. In silico, which refers to the modelling, simulation, and visualization of biological processes in computers, is now being considered a novel approach of seed conservation that is comparable to the physical in situ and ex situ modes of seed conservation[97]. The publication of new academic publications devoted to in silico plants is now taking place. Transversal mechanisms are instances of mechanisms that transport multiple enclosures, such as legal, financial, and technical ones. Other features of seed control, such as certificates and the distinct, consistent, and stable criteria necessary to register varieties in official registers, are examples of these mechanisms[98]. Dematerialization and fragmentation of genetic materials are two new domino consequences of Fourth Industrial Revolution technologies that are producing new sorts of digital enclosures in the case of seed. This is causing severe global governance issues for the Plant Genetic Resources Foundation of America (PGRFA)[99].

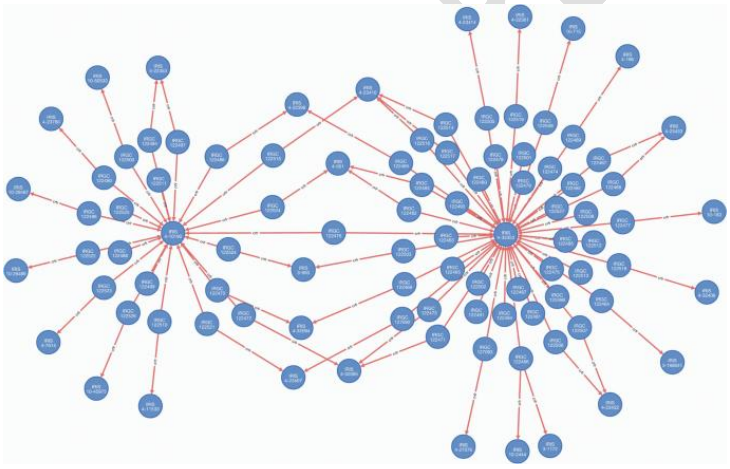

Fig 7.Plant Genetic Resources Foundation

DSI's Emergence and Intersection with Nagoya Protocol and ITPGRFA MLS

The idea of genetic resource (GSI) in agricultural research has been a topic of discussion, with the Nagoya Protocol and ITPGRFA being founded on the gathering and interchange of tangible material. However, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) has adopted a proactive stance by including relevant information into some clauses[100]. The definition of DSI according to the Nagoya Protocol is now a subject of dispute, since it is accessible,

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valued, controlled, and used in distinct ways compared to physical items. The genetic resource utilization framework established by the Nagoya Protocol and the Multilateral System (MLS) of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) relies on the premise that suppliers and users engage in negotiations and exchange physical materials that possess well-defined origins, ownership, and worth[101]. DSI completely alters these principles, rendering traceability insignificant and DSI generally useful as a whole. The MLS acknowledges the difficulties in assessing the value of small-scale innovation, determining the origin of PGRFA (Plant Genetic Resources for Food and Agriculture), and monitoring the transfer of genetic resources across various distribution channels. It also recognizes the mutual reliance of nations on Plant Genetic Resources for Food and Agriculture (PGRFA) and the worldwide accessibility of Digital Sequence Information (DSI) via public open access or open source databases[102].
The subscription model suggested by the Governing Body of the ITPGRFA, which involves users making payments to the MLS, could align effectively with proposals to impose levies or membership fees for the utilization of DSI as a method of sharing monetary benefits that better reflect user behaviour for DSI. Ultimately, the connection between farmers' rights and DSI is intricate and necessitates substantial modifications to global legal structures[103].

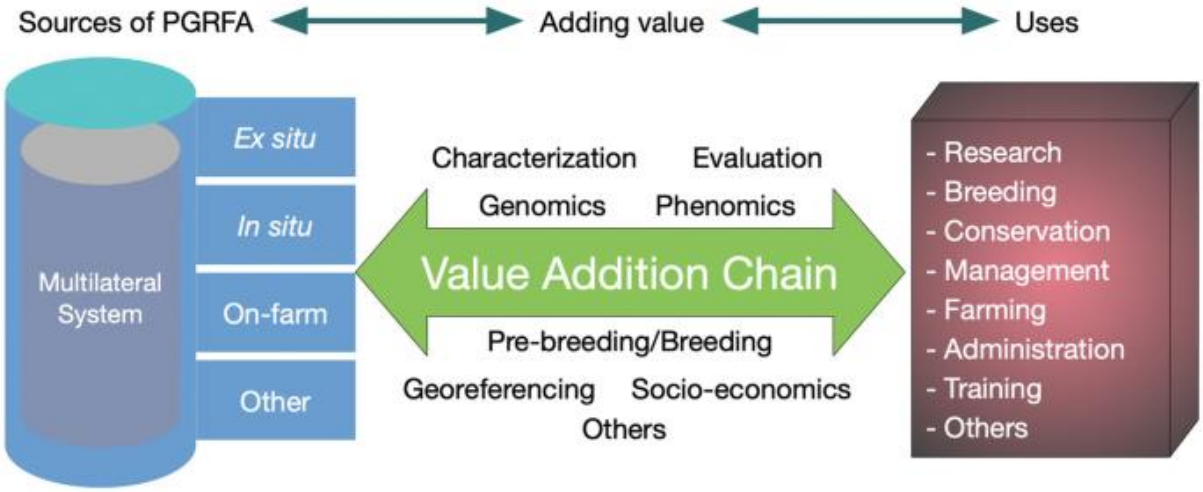

Fig 8.DSI's Emergence and Intersection with Nagoya Protocol and ITPGRFA MLS

Conclusion

In conclusion, the integration of digital sequencing information in agricultural crops represents a transformative leap forward in the quest for sustainable and resilient farming practices. By leveraging advanced genomic insights, stakeholders across the agricultural spectrum—from researchers to farmers—can make more informed decisions, optimize breeding strategies, and enhance crop resilience against environmental stresses. The principles of data integrity, accessibility, and ethical use are critical in ensuring that this technological advancement benefits a broad spectrum of society, promoting food security and equitable resource distribution. As we continue to navigate the complexities of this digital revolution, it becomes clear that the careful application and management of sequencing information will play a pivotal role in shaping the future of agriculture, driving innovation, and ensuring the stability of food systems in the face of global challenges.

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