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Digital sequencing information in agricultural crops: A comprehensive review

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Abstract

Within the context of the modern agricultural environment, it is of the utmost importance to successfully navigate the consequences, principles, and aims of digital sequencing information in agricultural cultivation. In a general sense, it incorporates the combination of cutting-edge technology with time-honored agricultural traditions, so ushering in a new era during which precision farming emerged. The information obtained via digital sequencing, which is acquired from methods such as next-generation sequencing (NGS), makes it possible to get a more in-depth knowledge of agricultural genomes. This provides academics and farmers alike with essential insights on the characteristics of crops, genetic variants, and the evolutionary histories of crops. Increasing agricultural resistance to climate change, improving breeding programs for desirable characteristics, and guaranteeing global food security are some of the goals that are driven by this article's topic, which connects with real-world applications. This digital revolution in agriculture is based on the principles of data integrity, accessibility, and ethical usage. These principles ensure that the benefits are dispersed fairly while also protecting against any possible problems that may arise. The combination of digital sequencing information and agriculture has the potential of changing crop productivity, sustainability, and resilience in the face of developing difficulties. This is something that we are now navigating as we negotiate this complex environment.

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

Introduction

In the year 2000, the International Treaty on Plant Genetic Resources for Food and Agriculture, also referred to as PGRFA, was drafted with the intention of addressing the growing shortage of genetic resources, particularly those that are associated with the breeding of new crops and the assurance of food security [89]. The treaty was drafted with the intention of addressing the growing shortage of genetic resources. Specifically, the International Treaty on Plant Genetic Resources for Food and Agriculture is what is meant to be represented by the term PGRFA. To be more specific, there are two international treaties that have an impact on the preservation of PGRFA as well as its use. Institutions that fall under this category are the Convention on Biodiversity (CBD) and the Seed Treaty on Seeds, to name just two examples. Although the CBD is in charge of both terrestrial genetic resources, the Seed Treaty is only applicable to a limited number of species that are crucial to agriculture and food security [78]. This is even though the CBD is responsible for both of these resources. On the other hand, the CBD is accountable for both of these categories of resources inside the organization.

There are a number of fundamental purposes that are included in the ABS framework. The most important of these are to guarantee the preservation of biological diversity, the sustainable exploitation of its component elements, and the equitable distribution of benefits that result from the utilization of genetic resources when they are utilized in conjunction with one another. A sector-specific response to the CBD was developed in the form of the Seed Treaty, which was established with the need for a global commons project in mind. This was done with the purpose of ensuring that food security is maintained and at the same time avoiding the loss of agricultural biodiversity [54]. In addition to this, it is designed to make it easier for a larger variety of people to have access to plant genetic resources.

These persons include farmers, conservationists, breeders, scientists, and educators. The Seed Treaty has been responsible for a considerable portion of the work that has been done to establish a global commons that is centered on phytogenetic resources all over the globe. This agreement acknowledges the relevance of farmers in terms of the preservation of natural resources as well as the use of those resources in a form that is environmentally responsible. It is envisaged that the implementation of this initiative would make it easier for a wide range of persons to have access to plant genetic resources. These individuals include farmers, wildlife conservationists, breeders, scientists, and educators [26]. Taking into consideration the fact that the multilateral system includes 64 of the species that are considered to be the most significant for agricultural purposes [15], it is of the highest necessity to pay attention to the very rigorous laws that regulate the limits of the common habitat.

Any PGRFA that did not come within the jurisdiction of the Seed Treaty and was not governed by any other intellectual property regime would eventually be subject to regulation by the CBD and its Nagoya Protocol. This responsibility would be assigned to the CBD at some point in the future. In the end, this would turn out to be the case. The Nagoya protocol stipulates that each and every resource exchange must be negotiated on an individual basis each and every time [7]. This is a requirement that must be maintained. This is due to the fact that the Nagoya convention places a strong emphasis on the sovereignty of the nation of origin. The management of all of the species that are included in the multilateral system is accomplished via the use of a standard material transfer agreement (SMTA). The Nagoya Protocol, on the other hand, is responsible for managing access to the resources. This is accomplished by bilateral agreements between states that ensure the use of prior informed consent and conditions that are mutually agreed upon (PIC/MAT). In conclusion, the Seed Treaty represents a significant step toward the formation of a global commons that is focused on phytogenetic resources. This is an essential step. Specifically, it acknowledges the significance of farmers in maintaining the conservation of these resources and making use of them in a way that is environmentally responsible [6].

Because these resources are derived from plants and include both vegetative and reproductive propagation material, the Seed Treaty places a particular emphasis on physical genetic resources (PGRFA), much as the CBD does. This is owing to the fact that these resources are generated from plants. It is not immediately clear whether or not the responsibilities for digitally created data (DSI) that are included in the benefit sharing criteria that are included in the SMTA of the multilateral system also include obligations [13]. Whether or not they do involve duties is not something that is immediately evident. When genetic resources are seen as nothing more than a material object from the very beginning, it is simple to make an erroneous appraisal of current activities that are associated with genetic resources for agricultural uses (GRFA) and the precise nature of what is being derived from them. As a consequence of this, it is very expected that these instruments will not be able to adjust to the current methods of using PGRFA. These methods are primarily exploited to generate enormous amounts of digital data as a result of a variety of "omics" techniques [42]. Specifically, this is due to the fact that PGRFA are mined to a significant extent.

The intellectual property of the PGRFA is organized according to a complex collection of international papers that are legally enforceable and partly overlap with one another. These documents serve as the basis for the intellectual property resources of the PGRFA. Behind the surface of each of these technologies are a variety of ideas and goals that are distinct from one another [51]. Major instruments that are pertinent to the PGRFA include patents, breeder's rights, copyright, and the sovereign right over generic resources. These are the instruments that are important. The right to copyright is one of the examples of other instruments. The safeguarding of commercial secrets is yet another device that is of great significance. There is a possibility that under such regimes, either one of the physical things (seeds) or both of the informational entities (genomic sequences) may be privatized [76]. This is a feasible scenario. It is possible that this will take place in its whole or in part. A single PGRFA might be privatized for a variety of reasons and criteria, depending on whether its informational or physical components are being analyzed, as well as the regime that is being reviewed. In principle, this could happen for a number of different reasons and criteria. This is something that would be the case regardless of whether or not the PGRFA is being taken into account. The hybrid character of PGRFA, which is both a physical and informational commodity, makes it difficult to construct a regulatory framework that can be accommodated within this "regime complex" in order to ensure access to and distribution of the potential advantages [96]. This challenges the process of ensuring that the potential benefits are distributed. PGRFA is a commodity that has both physical and informational properties, which is the reason for this finding. As of the year 2016, discussions about the present situation of DSI have become more prominent in a number of international forums. There are a number of examples of settings that are included in this category [68]. Some of these settings 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.

Principles

The principles of Digital Sequencing Information (DSI) revolve around the generation, storage, analysis, and use of genetic sequence data. Here are the key principles:

1. Sequencing Technology

- **DNA/RNA Sequencing:** The core principle of DSI is the sequencing of DNA or RNA to obtain the genetic code (i.e., the sequence of nucleotides). This can be achieved through various sequencing technologies such as Sanger sequencing, next-generation sequencing (NGS), and third-generation sequencing methods like PacBio and Oxford Nanopore.
- **High-Throughput Sequencing:** Modern sequencing technologies allow for high-throughput sequencing, enabling the rapid generation of large amounts of genetic data from multiple organisms.

2. Data Generation and Quality Control

- **Accurate Data Capture:** The quality of DSI relies on the accuracy of the sequencing process. High-fidelity sequencing techniques and thorough quality control measures are employed to ensure that the sequence data

accurately represents the genetic material of the organism.
- **Error Correction:** Sequencing processes can introduce errors, so algorithms and techniques are applied to correct these errors and produce reliable data.

3. Data Storage and Management
- **Digital Storage:** Once genetic sequences are obtained, they are converted into digital formats (e.g., FASTA, FASTQ) and stored in databases. These digital records can be shared, analyzed, and reused without the need for physical samples.
- **Databases and Repositories:** DSI is stored in various public and private databases, such as GenBank, EMBL-EBI, and DDBJ, which facilitate access to and the sharing of genetic information.

4. Data Analysis and Interpretation
- **Bioinformatics:** Advanced computational tools and bioinformatics methods are used to analyze DSI. This includes sequence alignment, phylogenetic analysis, gene prediction, and functional annotation.
- **Comparative Genomics:** DSI enables the comparison of genetic sequences across different species or individuals, providing insights into evolutionary relationships, genetic variation, and functional genomics.

5. Ethical and Legal Considerations
- **Access and Benefit Sharing (ABS):** The use and sharing of DSI must comply with international agreements and national laws regarding the fair and equitable sharing of benefits derived from genetic resources, such as the Nagoya Protocol.
- **Intellectual Property:** DSI raises questions about intellectual property rights, especially concerning the patenting of genetic sequences and the use of digital data without the transfer of physical genetic material.

6. Applications and Utilization
- **Agriculture:** In agriculture, DSI is used for crop improvement, conservation of genetic diversity, and the development of disease-resistant varieties.
- **Medicine:** DSI plays a crucial role in medical research, including the identification of disease-associated genes and the development of personalized medicine.
- **Environmental Monitoring:** DSI is also used for monitoring biodiversity, tracking invasive species, and studying ecological interactions.

7. Data Sharing and Open Science
- **Global Collaboration:** The principle of open science encourages the sharing of DSI to foster global collaboration in research and development, making genetic data accessible to scientists and breeders worldwide.
- **Interoperability:** Standards and protocols are established to ensure that DSI from different sources can be integrated and analyzed together, facilitating collaborative research and innovation.

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

When discussing the subject of biological research, the term "Digital Signature Information" (DSI) is becoming more prevalent as a result of its increasing prevalence. The area of genomic research is entirely responsible for the accumulation of petabases of data on an annual basis. As a consequence of this fast expansion, there is an urgent need for an infrastructure that is standardized on a worldwide scale and is able to store data for an extended period of time [65]. Because DSI displays the majority of the characteristics of other digital artifacts that have been generated in other domains, where various governance models have been effectively applied in the past, it is probable that these characteristics are being shown by DSI [23]. This hypothesis is supported by the fact that DSI displays these characteristics. Certain initiatives, such as DivSeek for crop genomics data and GODAN for phenotypic data, have been viable as a result of research on PGRFA, which has led to the opening of possibilities for DSI management on a worldwide scale. These possibilities have been presented as a consequence of the research that has been conducted on PGRFA. Information on crop genomes may be obtained via DivSeek, whilst phenotypic data can be obtained through GODAN. PGRFA conservation often involves increasing the quantity of DSI that is utilized. This is the case with projects such as the DNA barcoding of life project or the sequencing of the genomes of a whole botanical garden plant collection. The reason for this is because PGRFA is gaining greater significance, which is the reason for this [20].

The approach that is utilized to conduct and convey scientific research in the field of biological research has been confronted with a problem as a result of the widespread availability of enormous amounts of data pertaining to "omics" [47]. In addition, this challenge has been raised to the theoretical framework that underpins the scientific investigation process. Over the course of a considerable amount of time, the field of biology has persistently advocated for the broadening of access to public research data and findings to a greater extent. Quite lately, this point of view has been firmly entrenched in a variety of policy ideas all across the globe. On the other hand, in spite of this, it is still very important to take into consideration the "digital divide" that is intrinsic to the way that information and communication technology is now being used. The Seed Treaty, which is already constructed in a manner that is largely libertarian, should not be subjected to further pressure as a result of inequalities in data access, infrastructures, and specialists [36].

In the field of synthetic biology, there is a dispute going on about information that can only be accessed in digital form and that originates from genomics databases. Information is the primary topic of discussion in this argument. The objective of the proliferation of new forms of intellectual property is to enable the exercise of control over the interchange of DNA "parts," as stated in reference [35]. For instance, one of these ways is a two-tier strategy that differentiates high-potential output from non-commercial innovations. This is an example of one of these approaches. With the use of this technology, the goal is to achieve the greatest possible interchange of biomaterials and the data that is linked with them. It is essential to do more research in order to ascertain the degree to which it could be relevant to PGRFA and the breeding environment in general [48].

With the purpose of preserving food security and promoting sustainable agriculture, the Seed Treaty has set a lofty objective for itself: to make it possible to preserve and make sustainable use of PGRFA, as well as to ensure that the advantages that result from their use are distributed in a fair and equitable manner. One of the goals that the Seed Treaty has set for itself is to achieve this ambitious goal. However, in order to accomplish these objectives, it is necessary to have a more in-depth and all-encompassing understanding of the ways in which activities have been altered as a consequence of the proliferation of electronic communication [71]. It is essential to take measures in order to ensure that transparent mechanisms for data access and exchange are offered at the same time that the governance structure for the PGRFA is being built. Taken together, these safeguards are essential. In addition to this, it is essential to take into consideration the competencies of each and every stakeholder that is engaged [83].

A New International Organization

Since the year 2016, people have been attending worldwide conferences to talk about the issues that have arisen as a result of the fact that research methods may now replace the usage of physical biological material with DSI. [91] These issues have been the subject of debate at these conferences.

DSI may now be received and used from plants that are subject to international treaties without any benefit-sharing obligations being triggered. This opportunity was previously unavailable. A new and better policy has been implemented. Generally speaking, this is the case; nonetheless, there are rare instances in which national laws compel something else to be done. There are a big number of people who find this lack of benefit-sharing to be unacceptable, and it has been the subject of a great amount of discussion [73]. Concerns have been voiced over the prospect that it might limit or abolish free access to DSI, which is responsible for supporting research and innovation. They have expressed their concern about this possibility. The fact that there is often a significant amount of support for benefit sharing and transparency does not alter the fact that this is the situation. As an example, in the case of the COVID-19 pandemic, DSI was used in the process of manufacturing diagnostic kits and vaccines, both of which were essential in preventing the loss of millions of lives [47]. Taxonomy, the identification and mitigation of dangers to sensitive species, the monitoring of illicit trade, the identification of the geographical origin of commodities, and the formulation of conservation management strategies are three other areas in which it has played a significant role [10]. The administration of conservation management is yet another domain in which it has been actively involved and played a key role. It is highly possible that a rising number of nations will develop their very own laws governing access and benefit-sharing in the absence of a global agreement on DSI. This is something that is extremely realistic. This is due to the fact that DSI need the consent of all nations throughout the world. Furthermore, it is possible that this may impede the positive effects that DSI has the potential to have [30]. The result of this will be the formation of a complicated environment that academics and actors from the business sector will have to manage. Furthermore, customers may be compelled to seek out DSI from nations that have the least restrictive arrangements due to the overwhelming number of various national regulations that are in place. It is possible that this will lead to a "race to the bottom" and will also prevent a large number of people from participating in benefit sharing [76]. The results of each of these scenarios are bad.

Speciality of Digital Sequencing Information

When it comes to the goals of plant research and crop development, having access to genetic information (DSI), which may be represented by either genotypic or phenotypic data, is of the utmost value. This is because DSI can be used to generate new crops. The Seed Treaty acknowledges that the sharing of information is a benefit that does not entail monetary remuneration; nevertheless, it is not obvious how much this information exchange is taken into account in day-to-day operations [93]. This is despite the fact that the Seed Treaty recognizes that the exchange of information is a benefit. When the concept of DSI is applied to the context of contemporary breeding environments, it is common practice to neglect the difficult notion of PGRFA. This is a common way of doing activities. This one-of-a-kind type of cultural commons is genuinely one of a kind [33], due to the fact that it is connected to a broad variety of socioeconomic concepts and has a large number of people involved in its entirety. The application of PGRFA in a breeding program does not, in the majority of instances, result in the depletion of the resource (non-rivalry), but rather enhances the resource's intrinsic value and has the potential to renew interest in the preservation of the resource [50].

From the point of view of conventional viewpoints on natural resources or cultural commodities, there are at the very least two essential characteristics that differentiate DSI from PGRFA. A list of them is as follows: An ideal breeding value is produced during the process of genomic selection by combining the pre-breeding data of a number of distinct accessions. This is done in order to obtain the optimal breeding value. As a result of the characteristics of this process, it is not possible to ascertain the precise contribution that each and every "accession" that is used contributes. The expansion of synthetic biology has resulted in a disruption in the interaction that takes place between the material (germplasm) and the products that are formed from it. This disruption has occurred as a consequence of the rise of synthetic biology. At this point in time, it is tough to ascertain the specific contribution that each and every "accession" that is employed [16]. In light of the fact that something has taken place, this is the consequence.

[18] The non-static, globally distributed, non-rivalry, and often non-exclusionary qualities of DSI from PGRFA are not successfully accommodated by the legal framework that is now in place. This is due to the fact that the framework does not provide sufficient accommodations for these traits. When it comes to the vast majority of cases, these characteristics do not preclude anybody. PGRFA, which are to be significantly mixed or crossed in order to promote variety and selected during the breeding process, are to be distinguished from resources, which are to be extracted, natural genetic resources, which are to be extracted and valued, and resources, which are to be extracted. PGRFA are to be chosen during the breeding process. The selection of PGRFA is going to take place throughout the breeding procedure. There are a number of key ways in which these three types of resources are considered to be unique from one another. In the process of working toward the objective of developing coherence throughout the global governance of DSI-PGRFA, it is very vital to lay a focus on the particulars that are being taken into account [30]. The particulars are being taken into account, which is the reason why this decision has been reached.

Continuously, the characterisation and sequencing of PGRFA are performed on cultivars, landraces, farmer's breeds, and even crop wild relatives. This is done in order to ensure accurate results. The reason for this is to guarantee that the findings will be correct. To ensure that the PGRFA is recognized in a precise way, this activity is conducted in order to assure this recognition. As a consequence of this, a substantial amount of digital data is produced as a result of this, and the purpose of this endeavor is to build a relationship between the phenotype and the genotype [43]. The purpose of this endeavor is to make it feasible to predict phenotypes based on the diversity of the whole genome, which is a process that is known as "genomic selection." The objective of this endeavor is to make it possible to do so. With the use of genome-wide association studies, also known as GWAS, it is feasible to uncover a number of significant features that come from a range of different sources. The scent that is present in rice is one example of these qualities. Other examples include the underlying genetics that are responsible for pearl millet exhibiting enhanced tolerance to drought, and loci that encode structural variation in barley. The discovery of these characteristics may be performed by a number of methods, such as the use of pan-genomes, genomes, transcriptomes, metabolomics, and phenotypic data [1].

There are a great number of research initiatives that are taking use of the genetic diversity that has been accumulated in the past and is now freely available via gene banks. It is anticipated that this pattern will continue. To add insult to injury, as a result of this, it is possible to increase the identification of significant characteristics, as well as to boost the accuracy of breeding predictions and the effectiveness of breeding [59]. Because of this, high levels of food security are maintained by ensuring that the PGRFA is used in a sustainable way to produce solutions that are locally adapted, adaptive, and resistant to a range of biotic and abiotic problems while also being important [84]. This is done in order to maintain high levels of food security. This helps to guarantee that high levels of food security are maintained regardless of the circumstance that may be occurring. One thing that is noteworthy is the fact that the combination of many hundreds of accessions from all over the globe has made it possible to discover and characterize certain characteristics [90]. This is an accomplishment of great significance. There is a significant deal of importance attached to this achievement. By using the existing diversity that has been accumulated in gene banks, on the other hand, it is possible that it does not necessarily reflect a respect for the efforts that breeders and farmers have made in the past over the course of agricultural history [2]. It is the continual flow of genetic material that has been responsible for the establishment of the overwhelming majority of breeding programs, and these programs themselves adhere to self-established decentralized regulations that are particular to each crop [58]. 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 large and small breeders, and the ways in which an increasing quantity of data that is publicly accessible may have an effect on practices are not well understood [11]. There is a lack of clarity with regard to certain specific characteristics.

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

The idea of genetic resource, often known as GSI, has been the topic of debate in the field of agricultural research. On the basis of the gathering and exchange of physical material, both the Nagoya Protocol and the International Trade Protocol on Genetic Resources and Foods (ITPGRFA) were formed. Both of these protocols were named after the Nagoya Protocol. On the other hand, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) has adopted a proactive approach by emphasizing the inclusion of relevant information in some parts [100]. As stated in the Nagoya Protocol, the definition of digital assets (DSI) is now the subject of a discussion and controversy across the world. This is because digital assets are accessible, valued, managed, and employed in different ways compared to physical items. This is owing to the fact that digital assets are more easily available. The framework for the usage of genetic resources is established by the Nagoya Protocol and the Multilateral System (MLS) of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA). Both of these documents are responsible for building the framework. As a foundation, this concept is predicated on the notion that consumers and suppliers participate in agreements and trade tangible commodities that have clearly defined origins, ownership, and value [101]. Because of the extensive alteration that DSI has made to these principles, which are often beneficial in their whole, traceability has been rendered irrelevant. MLS acknowledges the difficulties that are associated with determining the value of small-scale innovation. These difficulties include the verification of the origin of PGRFA (Plant Genetic Resources for Food and Agriculture) and the monitoring of the transfer of genetic resources across a range of distribution channels. Additionally, it recognizes the mutual dependency of nations on Plant Genetic Resources for Food and Agriculture (PGRFA) and the worldwide accessibility of Digital Sequence Information (DSI) via open source databases or public open access databases [102].

It is possible that the subscription model that was proposed by the Governing Body of the ITPGRFA, which involves users making payments to the MLS, could effectively align with proposals to impose levies or membership fees for the utilization of DSI as a method of sharing monetary benefits that more accurately reflect user behaviour for DSI. This assertion is based on the fact that the MLS is the entity that is responsible for the subscription model. It is important to make considerable reforms to the legal systems that are in existence all over the globe [103]. In conclusion, the link between DSI and farmers' rights is a complicated one, and it is vital to acknowledge this complexity.

Implication of digital sequencing

Digital Sequencing Information (DSI) has significant implications in agricultural crops, influencing various aspects of crop breeding, conservation, and global food security. Here are some key implications:

1. Enhanced Crop Breeding

- **Precision Breeding:** DSI allows for the precise identification of genetic traits related to yield, disease resistance, drought tolerance, and other agronomically important characteristics. This accelerates the development of new crop varieties with desirable traits.
- **Genome Editing:** Technologies like CRISPR-Cas9, informed by DSI, enable targeted modifications of specific genes, allowing breeders to introduce or knock out traits with high precision.

2. Conservation of Genetic Resources

- **Digital Repositories:** DSI helps in creating digital repositories of genetic sequences from diverse crop varieties, including wild relatives. This is crucial for conserving genetic diversity, which can be tapped into for future breeding efforts.
- **Access and Benefit Sharing (ABS):** The use of DSI in breeding programs raises questions about fair and equitable sharing of benefits arising from the use of genetic resources, especially when the physical transfer of biological material is not necessary.

3. Global Food Security

- **Adaptation to Climate Change:** By leveraging DSI, crops can be bred to withstand extreme conditions like salinity, drought, and extreme temperatures, ensuring stable food production in the face of climate change.
- **Pest and Disease Resistance:** DSI enables the identification of genetic factors that contribute to pest and disease resistance, which is critical for reducing crop losses and maintaining food supply.

4. Regulatory and Ethical Considerations

- **Intellectual Property:** The use of DSI raises questions about ownership and patents, especially when it comes to gene sequences that could be crucial for future crop development.
- **Biodiversity and Sovereignty:** There is ongoing debate about the use of DSI from plants in one region by entities in another, particularly concerning the sovereignty of countries over their genetic resources.

5. Data-Driven Agriculture

- **Integration with AI and Big Data:** DSI can be combined with AI and big data analytics to predict crop performance, optimize breeding strategies, and make informed decisions in agriculture.
- **Precision Agriculture:** DSI can also contribute to precision agriculture by providing insights at the genetic level, helping farmers make decisions about crop management practices that align with the genetic potential of their crops.

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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