Ciência e Agrotecnologia
SCIENCE AND AGROTECHNOLOGY

Ciência e Agrotecnologia, 47:e0001R23, 2023
http://dx.doi.org/10.1590/1413-70542023470001R23

Review
eISSN 1981-1829

Rethinking plant breeding and seed systems in the era of exponential changes

Repensando o melhoramento de plantas e o sistemas de sementes na era de mudanças exponenciais

Mauricio Antonio Lopes[1*]

[1]Brazilian Agricultural Research Corporation, Embrapa Agroenergy, Brasilia, DF, Brazil
[*]Corresponding author: mauricio.lopes@embrapa.br
Received in July 19, 2023 and approved in September 29, 2023

ABSTRACT

The article stresses the need to reassess plant breeding and seed systems in our current era, characterized by rapidly shifting paradigms propelled by technological and scientific progress. It underscores the importance of incorporating cutting-edge technologies, fostering interdisciplinary collaboration, and implementing forward-looking policies to meet evolving societal and consumer demands while aligning with the Sustainable Development Goals (SDGs). Advancements in genetic editing, high-throughput technologies, precision breeding, and digital agriculture are transforming plant breeding, offering unprecedented capabilities to develop desirable traits, comprehend gene-environment interactions, and enhance crop efficiency. However, responsible innovation that considers ethical implications and regulatory frameworks remains essential in this context. Effective collaboration and engagement of stakeholders, including breeders, farmers, policymakers, and consumers, are vital for navigating the challenges and opportunities presented by this era of exponential change. Inclusive and multidisciplinary dialogues can harness diverse perspectives and experiences, contributing to a sustainable and resilient future for plant breeding and seed production. Ensuring access to diverse, high-quality seeds is crucial, especially in developing nations. Investments in seed infrastructure, capacity building, and farmer-centric approaches empower farmers and bolster seed security. In conclusion, the article underscores the significance of reimagining plant breeding and seed systems by embracing technology, promoting collaboration, and aligning strategies with the SDGs. By harnessing the potential of exponential changes, the envisioned future involves plant breeding and seed production that effectively address evolving societal and consumer needs, thereby contributing to agricultural resilience, global food security and sustainability.

Index terms: Technological advancements; sustainable development goals; SDGs.

RESUMO

O artigo enfatiza a necessidade de reavaliar o melhoramento de plantas e os sistemas de sementes neste tempo de mudanças de paradigmas impulsionadas por intenso avanço científico e tecnológico. Destaca-se a importância de incorporar tecnologias de ponta, fomentar a colaboração interdisciplinar e implementar políticas inovadoras para atender às demandas em constante evolução da sociedade, em consonância com os Objetivos de Desenvolvimento Sustentável (ODS). Os avanços na edição gênica, tecnologias de precisão e agricultura digital estão revolucionando o melhoramento de plantas, oferecendo capacidades sem precedentes para desenvolver características desejáveis, compreender interações gene-ambiente e aumentar a eficiência das lavouras. A inovação responsável, que contempla implicações éticas e estruturas regulatórias, permanece fundamental nesse contexto. A colaboração eficaz entre melhoristas, agricultores, formuladores de políticas e consumidores, é vital para o enfrentamento de desafios e para a busca de novas oportunidades. Assegurar o acesso a sementes diversas e de alta qualidade é essencial, especialmente em nações em desenvolvimento. Investimentos em infraestrutura, capacitação e abordagens centradas no agricultor são igualmente essenciais. Em síntese, o artigo destaca a importância de reimaginar o melhoramento de plantas e os sistemas de sementes através da inovação, de mais colaboração e alinhamento aos ODS. Ao aproveitar o potencial das mudanças, vislumbra-se um futuro onde o melhoramento de plantas e a produção de sementes abordem de forma eficaz as necessidades da sociedade e dos consumidores – discutidas em detalhe no texto, contribuindo para a resiliência da agricultura, a segurança alimentar global e um futuro sustentável para todos.

Termos para indexação: Avanços tecnológicos; objetivos de desenvolvimento sustentável; ODS.

2023 | Lavras | Editora UFLA | www.editora.ufla.br | www.scielo.br/cagro
All the contents of this journal, except where otherwise noted, is licensed under a Creative Commons Attribution BY.

INTRODUCTION

The agricultural landscape is undergoing a rapid and transformative evolution, fueled by exponential advancements in technology and scientific understanding (Schwab, 2016; Lin, 2021; Zani, 2023). In this era of unprecedented change, it is essential to reevaluate our approaches to plant breeding and seed production, unlocking the full potential of these fields to meet the challenges and opportunities that lie ahead (Van Vu et al., 2022). Traditional methods, which have served us well for centuries, now stand at the crossroads, beckoning us to embark on a journey of reimagining and reinventing our strategies (Kim; Kang; Kim, 2020).

Plant breeding, the intricate art and science of developing improved plant varieties, has long been the bedrock of agriculture (Duvick, 1984, 1996). Through meticulous selection, hybridization, and genetic improvement, plant breeders have successfully cultivated crops with enhanced yields, improved nutritional profiles, resistance to pests and diseases, and adaptability to diverse environmental conditions. However, the exponential growth of technological capabilities, alongside the pressing need to address global food security, sustainability, and resilience, demands that we explore new horizons in plant breeding and seed production (Ali et al., 2020; Ahmad, 2023; Stetkiewicz et al., 2023).

This review delves into the compelling need to rethink plant breeding and seed systems in the context of exponential changes, with an emphasis on embracing cutting-edge technologies, interdisciplinary collaboration, and forward-thinking policies (Lopes, 2021a). The transformative impact of emerging technologies on the industry and the challenges and opportunities they present will be explored. The aim is to inspire a paradigm shift in the collective approach to plant breeding and seed production, paving the way for a future where crops are precisely tailored to meet the diverse challenges of a rapidly changing world.

The rapid evolution of technology, encompassing areas such as genetic editing, high-throughput phenotyping, precision breeding, and digital agriculture, are revolutionizing the field of plant breeding (Crisp et al., 2022). These advancements offer unprecedented capabilities to accelerate the development of desirable traits, understand the complex interactions between genes and the environment, and enhance the efficiency and precision of crop improvement (Hickey et al., 2019; Varshney et al., 2020; Bohra et al., 2020; Steinwand; Ronald, 2020). Leveraging these tools effectively is crucial in an era characterized by dynamic climatic patterns, evolving consumer preferences, and emerging plant diseases and pests (Stetkiewicz et al., 2023).

However, as we embrace the potential of these technologies, we must also address the ethical considerations, regulatory frameworks, and potential risks associated with their use. Responsible innovation in plant breeding requires a thoughtful and inclusive approach that ensures transparency, safety, and equity. Additionally, as we navigate the complexities of exponential changes, it is essential to foster interdisciplinary collaboration and stakeholder engagement, including breeders, scientists, farmers, policymakers, and consumers. By fostering an inclusive and multidisciplinary dialogue, we can tap into diverse perspectives, expertise, and experiences to shape a sustainable and resilient future for plant breeding and seed production (Lopes, 2021a).

Furthermore, the challenges facing plant breeding and seed production are intricately intertwined with the broader global challenges outlined in the Sustainable Development Goals (SDGs) (Schwoob et al., 2018). Climate change, demographic changes, resource scarcity, biodiversity loss, and the need to achieve food security all necessitate a paradigm shift in our approach to agriculture. Plant breeders and seed producers play a pivotal role in addressing these challenges, as they are responsible for developing resilient, high-yielding, and climate-smart crop varieties (Lopes, 2021a).

Climate change poses one of the most pressing challenges for plant breeding and seed systems. Rising temperatures, changing rainfall patterns, and increased frequency of extreme weather events require the development of crop varieties that can withstand these adversities. Heat and drought-tolerant crops, as well as those resistant to pests and diseases that thrive under changing conditions, are crucial for ensuring food production in a changing climate (Ali et al., 2020; Ahmad, 2023; Stetkiewicz et al., 2023; Intergovernmental Panel on Climate Change - IPCC, 2019; IPCC, 2021).

Demographic changes, including population growth, urbanization, and dietary shifts, also impact plant breeding and seed production. As the global population continues to grow, the demand for nutritious and diverse food increases. Plant breeders must respond to these changing dietary preferences by developing crops with improved nutritional profiles, enhanced flavors, and novel traits that cater to evolving consumer demands (FAO; IFAD; UNICEF; WFP; WHO, 2023).

Moreover, achieving the SDGs necessitates sustainable and responsible agricultural practices

(Schwoob et al., 2018). Plant breeders and seed producers have a vital role to play in developing crop varieties that promote sustainable intensification, reduce resource inputs, minimize environmental impacts, and enhance biodiversity. Integration of agroecological and sustainable intensification principles, such as intercropping, crop rotation, combination of crop-livestock-forest and ecological pest management, into breeding programs can contribute to the transition towards sustainable agricultural systems (Food and Agriculture Organization of the United Nations - FAO, 2020).

To address these challenges and ensure the availability of quality seeds, it is imperative to strengthen seed systems, particularly in developing countries. Access to diverse and high-quality seeds, along with appropriate policies and regulations, is crucial for smallholder farmers to adapt to changing conditions and improve their livelihoods. Investments in seed infrastructure, capacity building, and farmer-centered approaches are essential to empower farmers and enhance seed security (FAO, 2021).

In summary, the era of exponential changes demands a holistic and forward-thinking approach to plant breeding and seed production (FAO, 2021). Embracing technological advancements, fostering interdisciplinary collaboration, and aligning strategies with the SDGs will be instrumental in developing crops that are resilient, sustainable, and tailored to the needs of a rapidly changing world. By reimagining our approaches and leveraging the potential of plant breeding and seed production, we can contribute to global efforts towards achieving a sustainable and food-secure future for all.

RESHAPING AGRICULTURE IN THE ERA OF EXPONENTIAL CHANGE

In recent years, the world has witnessed an exponential growth in scientific and technological advancements, leading to profound changes in various aspects of our lives. Klaus Schwab, founder of the World Economic Forum, astutely noted that we find ourselves in a time of both great promise and great peril, as these rapid changes and disruptions reshape our economic, social, cultural, and human environments (Schwab, 2016). The emergence of mega-corporations wielding immense power, radical transformations in the world of work, and the impact of technology on human relationships are just a few examples of the risks we face (World Economic Forum -WEF, 2022).

Today, as we take the initial steps into the era of exponential technologies, the warning from Schwab becomes even more significant. Exponential progress, driven by groundbreaking technologies, stands in stark contrast to our incremental nature as humans (Harrington, 2018). This future, shaped by exponential changes, differs significantly from the gradual transformations of the past. One notable example of exponential advancement is Moore's Law, which accurately predicted in 1965 that the processing power of computers would double approximately every 18 months (Schaller, 1997). Since then, the rapid development of digital technologies has led to tremendous advancements in processes, competencies, and business models, with further leaps anticipated as artificial intelligence and quantum computing emerge (Ayoade; Rivas; Orduz, 2022; Choi; Oh; Kim, 2020).

The digital transformation has given rise to solutions that operate in synergy, facilitating "cross-fertilization" and accelerating the technological leaps we have witnessed in social media, e-commerce, the Internet of Things, artificial intelligence, robotics, and more (Schwab, 2016). These exponential innovations are poised to amplify their reach and impact with the impending explosion of connectivity (Langley et al., 2021). As of April 2023, there were 5.18 billion internet users worldwide, which amounted to 64.6 percent of the global population. Of this total, 4.8 billion, or 59.9 percent of the world's population, were social media users, most of them accessing the internet via mobile devices (Statista, 2023).

This context of radical changes not only foreshadows numerous advancements but also poses many dangers, as emphasized by Klaus Schwab (Schwab, 2016). As technology advances at an exponential rate, institutions, particularly public ones, struggle to adapt at the same pace (Hanna, 2018). How can we reconcile the capacity and urgency to respond to frontier challenges and the simultaneous need to safeguard the most basic rights of populations, such as housing, education, health, and security? Traditional government structures, characterized by limited coordination and synergy, may struggle to comprehend this emerging reality and offer effective solutions to the complex challenges that lie ahead (Mazzucato, 2013).

Moreover, as science and technology continue to rapidly evolve, disruptive innovations will emerge, potentially widening the gaps between different societies and regions. Information and knowledge has become more accessible to citizens through digital media, leading to a more enlightened, engaged, and demanding population. New business standards will emerge, incorporating concepts, tools, and practices of management and governance, placing greater demands on governments in terms of executive functions, structuring roles, and formulation of effective public policies (Mazzucato, 2013; Stiglitz; Greenwold, 2014).

Merely acknowledging that an era of exponential advances necessitates governments capable of incorporating exponential technologies and work models, with adjustments in skills, infrastructure, and coordination, is insufficient (Hanna, 2018). A new, agile workforce capable of adapting to continuous change must be cultivated (Bongomin et al., 2020). Engaging citizens and communities will be imperative for capturing signals, fostering cooperation, and validating government actions. The cost and rapid obsolescence of infrastructure will pose significant challenges. Therefore, eliminating redundancies, establishing data standards and platforms, and fostering shared planning and projects will be crucial changes (Hanna, 2018; Mazzucato, 2013).

In the face of these changes and challenges, the implications for food systems are profound, as they intersect with food security, nutrition, human health, ecosystem viability, climate change, and social justice (Caron et al., 2018). To address these food, environmental, and social challenges in the era of rapid technological changes and disruptions, countries must integrate data and information from both public and private domains. Predictive and contextual analyses should guide policy decisions, and performance goals and metrics should be defined. Such advances can only be achieved through radical changes in structures, leadership, and coordination.

While agricultural research and innovation have achieved significant success over the past century, current and emerging problems and crises will inevitably drive the reinvention of agricultural systems (Rockström et al., 2020). This challenge will benefit from the abundant scientific advances already available. Sustainable pathways can be facilitated in increasingly intensified, high-performance agriculture by incorporating knowledge and technologies to manage operations that are more complex (Herrero et al., 2020). This includes the rotation of different crops, a wider range of species and varieties, diverse methods of soil, water, and fertility management, and sophisticated risk management, among other challenges that foster sustainable farming.

The progressive automation of agriculture holds immense potential to empower site-specific management methods and practices, enhancing precision and efficiency in the use of inputs and pest control. Agronomic research will need to account for an increasing number of factors, necessitating closer interaction with producers whose fields will become practical laboratories. With advancements in information and communication technologies, agronomists will have real-time access to and processing capabilities for multiple combinations, enabling them to identify economically, environmentally, and socially suitable approaches within specific production realities, whether in large, medium, or small-scale farming ventures (Jararweh et al., 2023; Newman et al., 2023; Zhao; Liu; Huang, 2023).

Another significant challenge facing agronomy and rural areas is the need to embrace multifunctionality, aligning with the 2030 Agenda and the Sustainable Development Goals (SDGs) (United Nations, 2015). In addition to food and fiber production, agriculture can contribute as a provider of renewable energy and biomass feedstocks, enabling cost-effective strategies to decarbonize industries dependent on non-renewable fossil sources for energy, chemicals, and materials. Furthermore, consumer demand for new flavors, aromas, and unique culinary experiences provides significant potential for social inclusion and wealth generation in rural areas (Lopes, 2017; 2023).

Amidst these changes and challenges, industries and businesses must evolve, integrating capacities and domains of knowledge to empower agricultural systems and rural areas in the face of various forces and factors shaping the future of agriculture and food systems (Schwoob et al., 2018). The seed industry, given its enormous impact over the past century, holds particular importance in this context. Many successes in modern agriculture can be attributed to the numerous biological innovations embodied in seeds. However, the seed industry now faces a new set of standards, requirements, and expectations to provide solutions that accelerate the transition of agriculture and food systems toward a sustainable future (Lopes, 2021a; FAO, 2021).

The era of exponential changes demands a comprehensive reassessment of our approaches to plant breeding and seed production. The rapid evolution of technologies, coupled with the pressing global challenges of food security, sustainability, and resilience, necessitates embracing cutting-edge tools and methodologies. It calls for interdisciplinary collaboration, stakeholder engagement, and forward-thinking policies. By harnessing the power of exponential changes, we can shape a future where plant breeding and seed production are pivotal in addressing the complex and interrelated challenges of our rapidly changing world.

Unlocking the potential of nature-inspired agriculture

The term “sustainability” is increasingly prevalent, yet few can precisely define it. As society becomes more aware of the finite resources on our planet and the need to use them wisely and sparingly, sustainability has taken on multiple meanings and interpretations. One interpretation that resonates strongly describes sustainability as a process of reconciling human systems with nature, particularly with regard to the atmosphere, water resources, biomes, and the diverse living beings that inhabit them (Pan, 2021).

One of the key obstacles to achieving this reconciliation is the widespread use of fossil fuels and the resulting global greenhouse gas emissions, which have increased by two-thirds since international negotiations on climate change began three decades ago. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to a prudent threshold of 1.5°C will require a 45% reduction in carbon dioxide emissions based on 2010 levels by 2030 and 100% reduction by 2050 (IPCC, 2021; Frank et al., 2017). This presents an enormous challenge that applies collectively to countries, companies, and individuals, who must come together around an agenda of decarbonization in nearly all sectors of society, including energy, agriculture, transportation, infrastructure, and industrial systems.

Agriculture and the food system lie at the heart of this challenge, as they are significant users of natural resources and remain heavily carbon-intensive sectors, often seen as contributors to the climate crisis. While humans have historically observed and made interventions in natural systems to adapt plants, animals, and ecosystems to their needs (Herrero et al., 2020), these interventions have at times disregarded critical balances refined over millions of years of trial and error, which have ensured resilience and durability in nature. Disrupting these balances solely for short-term human benefits jeopardizes the planet's health and, ultimately, the viability of society itself (The World in - TWI2050, 2018; Rockström et al., 2020).

This is why agriculture and food systems are under pressure to realign with principles that have been perfected over millions of years and are encoded within living beings and natural systems, predating human evolution, agriculture, industries, trade, or any modern artifact. Hence, there is an urgent need to mimic nature's capacity to integrate complex systems, using resources efficiently, incorporating waste into useful processes and products, conserving soil and water, sequestering more carbon than emitting, and maximizing energy efficiency, all guided by the principles of the circular economy: reduce, reuse, and recycle (Herrero et al., 2020; Lopes, 2022).

Such advancements would facilitate our journey toward the long-desired reconciliation between human systems and nature. For agriculture, this reconciliation depends on redefining the concept of performance, traditionally associated with the quantity of food or raw materials produced in a given space and translated into economic gains. The world's growing demand for sustainability requires agriculture to adopt more sophisticated measures of performance that focus not only on physical production and profitability but also on eco-efficiency, social benefits, and ethically acceptable management practices, all embedded in its operations, processes, and products (Lopes, 2022; Philippi; Andreoli, 2021).

Since efficient management requires effective measurement, there is a growing interest in metrics that indicate a company's or business's commitment to eco-efficiency, clean renewable processes, people development, transparency, and other values cherished by society. To address these challenges, it is essential to mimic nature's ability to integrate complex systems, efficiently utilize resources, minimize waste, conserve soil and water, and prioritize carbon sequestration. The agricultural sector, as a major user of natural resources, needs to redefine performance metrics beyond mere production and profitability, incorporating eco-efficiency, social benefits, and ethical management practices (Lopes, 2021a).

Furthermore, the challenge of reinventing agricultural systems to mimic natural systems as much as possible is central to achieving sustainability. By observing and learning from the intricate balances and processes perfected by nature over millions of years, we can develop agricultural practices that are not only productive but also regenerative and in harmony with the environment (Lopes, 2021a).

The transition towards mimicking natural systems requires a shift from conventional, input-intensive agriculture to agroecological approaches that prioritize biodiversity, soil health, water conservation, and carbon sequestration. Agroecology seeks to create resilient and self-sustaining farming systems that harness natural ecological processes, such as nutrient cycling, biological pest control, and ecosystem services, to enhance agricultural productivity while minimizing negative environmental impacts (Altieri et al., 2015).

Adopting agroecological principles in plant breeding and seed production can contribute to the development of crop varieties that are better suited for diverse and sustainable farming systems. By considering the interactions between crops, soil, water, and beneficial organisms, plant breeders can prioritize traits that enhance agroecosystem resilience, resource-use efficiency, and resistance to pests and diseases. This approach fosters the development of crop varieties that can thrive in diverse agroecological contexts, reducing the reliance on synthetic inputs and promoting ecological balance (Khoury et al., 2020).

In conclusion, the challenges of seeking a sustainable future require us to reinvent agricultural systems by mimicking natural systems as much as possible. Plant breeding and seed systems play a crucial role in this transition by developing crop varieties that are resilient, adaptive, and suited to agroecological principles. By embracing agroecology, fostering collaboration, and leveraging digital technologies, we can pave the way for a regenerative and sustainable agriculture that supports food security, biodiversity conservation, and climate resilience. The journey towards mimicking nature's wisdom is an essential path towards a sustainable future for agriculture and the planet as a whole (Lopes, 2021a).

Technology redefining plant breeding and seed systems

The reinvention of plant breeding and seed systems is driven by the recognition that traditional breeding approaches, combined with cutting-edge molecular innovations, are essential for meeting the challenges of the future (Steinwand; Ronald, 2020). While conventional breeding has already made significant contributions to global food production (Duvick, 1996, 1984), the integration of molecular technologies opens up new possibilities for accelerating crop improvement (Van Vu et al., 2022; Kin et al., 2020; Ahmad, 2023; Lopes, 2021a).

Advancements in genotyping assays, sequencing technologies, and bioinformatics have made it more affordable and accessible for breeders to analyze and utilize genetic information. Marker-assisted selection and genomic selection are now powerful tools that enable breeders to make more precise and efficient selections, leading to the development of improved varieties with desired traits. Additionally, the availability of reference pangenomes and the use of high-throughput phenotyping technologies further enhance the breeding process by providing comprehensive genetic and phenotypic information (Hickey et al., 2019; Varshney et al., 2020; Bohra et al., 2020; Steinwand; Ronald, 2020).

Among the recent biotechnological developments, the advent of genome editing technologies, particularly CRISPR/Cas (Strzyz, 2020), has revolutionized the field of plant breeding (Ahmad, 2023). Genome editing offers the ability to precisely modify plant genomes, allowing breeders to create novel alleles or introduce specific genetic variations into elite varieties. This opens up new avenues for developing crops with enhanced traits, such as disease resistance, abiotic stress tolerance, and improved nutritional profiles. Moreover, genome editing enables breeders to explore non-genic variations, including epigenetic and cis regulatory variations, which contribute to the diversity of plant traits and offer new possibilities for crop improvement (Crisp et al., 2022).

The combination of traditional breeding methods with molecular innovations has the potential to drive agricultural diversification, specialization, and value aggregation. Beyond increasing productivity, these advancements can contribute to addressing challenges related to food safety, food quality, and sustainability. For example, the development of crop varieties with enhanced nutritional profiles can help combat malnutrition and improve human health. Similarly, crops with improved disease resistance and stress tolerance can reduce the need for chemical inputs and promote environmentally friendly farming practices (FAO, 2021; Lopes, 2021a; Varshney et al., 2020; Stetkiewicz et al., 2023).

Beyond the wonders of biology and modern biotechnology, the integration of innovations in information technology, communications, remote sensing, advanced instrumentation, automation, and robotics will revolutionize the agricultural landscape (Martha; Lopes, 2023; Yousaf et al., 2023; Prabha; Pathak, 2023). Precision agriculture, enabled by these tools and processes, will become common practice, transforming cultivar development and the configuration of seed industries. With advanced sensors, monitoring of production systems will reach unprecedented levels of precision, allowing for real-time decision-making and optimization. Nanotechnology, operating at the scale of the billionth of a meter, will unlock new possibilities for developing efficient and durable machines, equipment, and products.

Harnessing these advances in agriculture is of strategic importance in addressing the challenges that lie ahead. The world faces the pressing task of feeding a growing population while ensuring diversity, adequate nutrition, and sustainability (TWI2050, 2018; Sachs et al., 2019). To achieve these goals, a wide range of technological advancements is required to preserve and protect natural resources such as soil, water, forests, and biodiversity. Furthermore, increased research is necessary to mitigate the impacts of extreme weather events, adapt to intensifying biotic and abiotic stresses, and address energy insecurity (IPCC, 2019). In this context, plant breeding and seed systems play a crucial role, as they provide the genetic diversity and adaptable varieties necessary for resilient and sustainable agricultural production systems.

However, it is not enough to rely solely on technological advancements. It is equally important to remain informed and responsive to current and emerging trends, as well as the evolving demands and expectations of modern society. Standards associated with the global development agenda, such as the 2030 Agenda and the Sustainable Development Goals (SDGs), emphasize the need for agriculture and related industries to embrace new practices and performance criteria that consider the three dimensions of sustainability: economic, social, and environmental (Rockström et al., 2009; TWI2050, 2018; Sachs et al., 2019; Rockström et al., 2020). By aligning with these goals, plant breeding and seed systems can contribute to the achievement of sustainable development targets, promoting food security, rural livelihoods, and environmental stewardship.

To fully realize the potential of these innovations, it is crucial to ensure that ethical considerations, regulatory frameworks, and transparent communication with consumers and stakeholders guide their deployment. Public-private partnerships, collaboration across disciplines, and investment in research and development are vital for driving the adoption and responsible use of these technologies in plant breeding and seed systems.

In reality, the reinvention of plant breeding and seed systems is essential to address the challenges of the future. By integrating traditional breeding approaches with cutting-edge molecular innovations, harnessing the power of precision agriculture and advanced technologies, and aligning with the principles of sustainability (Martha; Lopes, 2023), these sectors can contribute significantly to global food security, economic prosperity, and environmental sustainability.

As we navigate a rapidly changing world characterized by population growth, climate change, and other global challenges (Khanna, 2016; TWI 2050, 2018), the transformation of plant breeding and seed systems becomes a strategic imperative. Through collaboration, innovation, and a commitment to sustainable development, we can shape a future where agriculture and food production systems are resilient, productive, and in harmony with nature.

The evolving landscape of bioeconomy markets

As we embark on the reinvention of plant breeding and seed systems, it is crucial to recognize that markets and profits continue to play a central role and that the traditional economy will also tend to be reinvented. In the emerging bioeconomy, the traditional notion of markets is undergoing a profound transformation, driven by shifting consumer preferences, evolving regulatory frameworks, and the growing demand for sustainable and ethically produced goods (Bugge; Hansen; Klitkou, 2016; El-Chichakli et al., 2016; USA, 2016; Deng et al., 2022).

Biodiversity and climate change are critical components of the complex equation that has shaped our civilization. With the advent of globalization, trade, and advanced transportation systems, human activities have exerted increasing pressure on the finite resources of our planet (Steffen; Crutzen; Mcneill, 2007; Subramanian, 2019). This heightened human impact, coupled with the effects of climate change and biodiversity loss, poses significant threats to ecosystem resilience, agricultural systems, public health, and global stability (TWI2050, 2018; Sachs et al., 2019).

The urgent need for sustainability has propelled it to the top of society's priority agenda (UNITED NATIONS, 2015). As the world's population continues to grow, along with our consumption capacity, there is a growing realization that our economic model must rely on renewable, recyclable, and biologically based resources (De Boer; Ittersum, 2018; Ghisellini; Cialani; Ulgiati, 2016). This realization forms the foundation for the emerging bioeconomy, which has gained prominence on the global stage (National Bioeconomy Blueprint, 2012; El-Chichakli et al., 2016; Bugg; Hansen; Klitkou, 2016).

In response to these challenges, there is a rising interest in low-carbon, resource-saving technologies that can promote sustainable land use and agricultural production systems (Böhringer et al., 2022; Chen et al., 2018). The future of plant breeding and seed systems must embrace an integrative and systemic perspective, focusing on the nexus of various challenge areas and harnessing genetic variability to drive sustainability in rural areas (Sperling et al., 2020). This calls for greater attention to research in genetic resources and crop breeding, expanding the diversity base and developing improved seeds with new biological functions that can help agriculture meet the demands of a sustainable future.

In the past, markets were primarily driven by the pursuit of economic gains and the maximization of profits. While economic viability remains a fundamental aspect of any business endeavor, the bioeconomy introduces new dimensions to the concept of markets. Consumers are increasingly demanding products that are not only economically competitive but also environmentally friendly, socially responsible, and aligned with their values and aspirations.

This changing landscape presents both challenges and opportunities for plant breeding and seed systems. On the one hand, there is a need to develop and deliver innovative crop varieties that meet the evolving demands of consumers and the bioeconomy. These varieties should possess not only desirable agronomic traits but also characteristics that align with sustainability principles, such as resource efficiency, reduced environmental impact, and resilience to climate change (D´Amato; Korhonen; Toppinen, 2019, D´Amato; Bartkowski; Droste, 2020; D´Amico, 2022).

On the other hand, the emergence of new markets and value chains in the bioeconomy opens up exciting possibilities for plant breeders and seed producers. The demand for bio-based products, such as biofuels, bioplastics, and bio-based chemicals, presents opportunities for the development of specialty crops with unique traits tailored to specific industrial applications. Moreover, the bioeconomy promotes the integration of different sectors, fostering collaboration and innovation across industries, and creating novel market opportunities for plant breeding and seed systems (Karp et al., 2021; Mehta et al., 2021; Patermann; Aguilar, 2021; Stegmann; Londo; Junginger, 2020; Von Braun, 2020).

However, navigating the changing notion of markets in the bioeconomy requires a proactive and forward-thinking approach (Patermann; Aguilar, 2021). Plant breeders and seed producers must invest in understanding consumer preferences, market trends, and regulatory requirements to develop and deliver products that meet the evolving demands of the bioeconomy. This necessitates close collaboration with stakeholders along the value chain, including farmers, processors, retailers, and consumers, to ensure that the developed crop varieties align with market needs and expectations (FAO, 2021; Lopes, 2021a).

Furthermore, ensuring market access and fair remuneration for breeders and producers is essential for the long-term sustainability of the plant breeding and seed systems. Intellectual property rights, fair trade practices, and transparent supply chains are critical components of a functioning and equitable bioeconomy. Adequate protection and recognition of intellectual property rights incentivize investment in research and development, fostering innovation and driving the creation of new crop varieties that meet the demands of the bioeconomy (FAO, 2021; Lopes, 2021a).

As plant breeding and seed systems evolve, it is vital to acknowledge the changing notion of markets in the emerging bioeconomy. While economic viability and profitability remain important considerations, the bioeconomy introduces new dimensions of sustainability, social responsibility, and consumer preferences (D´Amato; Korhonen; Toppinen, 2019, D´Amato; Bartkowski; Droste, 2020; D´Amico, 2022). By mobilizing genetic diversity, embracing low-carbon technologies, and adopting an integrative perspective, these systems can drive the transformation towards a more sustainable and resilient agricultural sector (Lopes, 2021a, b). It is through these efforts that we can build a future where agriculture and the bioeconomy coexist in harmony with nature, ensuring food security, environmental stewardship, and a prosperous society.

PATHWAYS TO REINVENT AND ADVANCE PLANT BREEDING AND SEED SYSTEMS

The agricultural research community faces numerous challenges in ensuring that genetic diversity is available to support global food security and a sustainable future for all. Strengthening crop-breeding capacity, promoting sustainability, effectively linking food, nutrition, and health, and help the world transition to a low-carbon bioeconomy are some of the essential priorities. By fostering collaboration, investing in research and development, and embracing innovation and sustainability, we can build a resilient and sustainable future. Here are some concrete challenges that plant breeding and seed systems will have to face, to assure that genetic diversity plays a pivotal role in providing a secure and nutritious global food supply while minimizing environmental impact and promoting the well-being of present and future generations.

Strengthening crop breeding capacity

In the face of numerous changes and disruptions in various dimensions such as climate change, demography, and technology, strengthening crop breeding capacity becomes paramount (Mba; Guimaraes; Ghosh, 2012). To effectively respond to the challenges ahead and ensure future food and nutritional security, it is crucial to enhance the capacity for developing new, adapted, and productive crop varieties through genetic improvement. This necessitates a focused approach on plant genetics and biotechnology, as well as the implementation of innovative strategies in crop breeding (Voss-Fels; Stahl; Hickey, 2019).

Climate change presents a significant challenge to agricultural systems worldwide, with shifts in temperature, rainfall patterns, and the increased frequency of extreme weather events. Strengthening crop-breeding capacity is essential to develop climate-resilient varieties that can withstand these changing environmental conditions. Plant breeders need to focus on identifying and incorporating traits that confer tolerance to heat, drought, flooding, and other climate-related stresses. This requires an understanding of the underlying genetic mechanisms involved in stress response and the use of advanced technologies such as genomic selection and marker-assisted breeding to expedite the development of improved varieties (Mba; Guimaraes; Ghosh, 2012; Xiong; Reynolds; Xu, 2022; Steinwand; Ronald, 2020; Bohra et al., 2020; Varshney et al., 2020).

Demographic changes also pose challenges to crop breeding capacity. As the global population continues to grow, there is a need to develop crop varieties that can meet the increasing demand for food. Moreover, changing dietary preferences and nutritional requirements call for the development of crops with enhanced nutritional profiles (Calicioglu et al., 2019). Strengthening crop-breeding capacity involves the exploration and utilization of diverse genetic resources to identify and incorporate traits related to improved yield, nutritional value, and other desirable agronomic characteristics. This requires a comprehensive understanding of the interactions between genes and complex traits and the use of cutting-edge techniques such as gene editing to precisely manipulate plant genomes (Bradshaw, 2017; Stetkiewicz et al., 2023; Hickey et al., 2019; Voss-Fels; Stahl; Hickey, 2019; Varshney et al., 2020).

Advancements in technology offer opportunities to enhance crop-breeding capacity. The use of high-throughput phenotyping, remote sensing, and data analytics can accelerate the screening and selection of desirable traits, allowing breeders to efficiently evaluate large populations of plants and identify promising candidates for further breeding efforts (Kim et al., 2016; Marsh et al., 2021; Song et al., 2021). Additionally, the integration of artificial intelligence and machine learning algorithms can help analyze complex datasets and uncover novel genetic associations, facilitating the development of superior crop varieties (Khan et al., 2022; Ersoz; Martin; Stapleton, 2020; Rai, 2022).

To strengthen crop-breeding capacity, investment in infrastructure, research facilities, and human resources is essential. Collaborative networks, both national and international, can promote knowledge-sharing, access to genetic resources, and the exchange of expertise and technologies. Capacity-building initiatives should be implemented to train breeders in the latest techniques and methodologies, ensuring that they are equipped with the necessary skills to navigate the complexities of modern crop breeding. Furthermore, the establishment of robust breeding programs and the availability of funding support are vital for sustained progress in crop improvement (FAO, 2021; Lopes, 2021a).

Prioritize resilience to climate change

Climate change presents formidable challenges to global food security, including extreme weather events, shifting temperature and precipitation patterns, and increased pest and disease pressures (IPCC, 2019, 2021; Ali, 2020; Xiong; Reynolds; Xu, 2022). To address these challenges, plant breeding and seed systems must prioritize resilience to climate change and play a vital role in developing crops that can withstand these impacts and ensure sustainable food production. This involves developing climate-resilient varieties by selecting traits that enable crops to tolerate heat stress, drought, waterlogging, salinity, and other climatic factors (Khan et al., 2022; Rai, 2022; Zhao; Liu; Huang, 2023).

Advanced breeding techniques, such as marker-assisted selection and genomic selection, can accelerate the development of climate-resilient varieties. Additionally, plant breeding can help mitigate the negative impacts of extreme weather events by developing crops with traits like flood tolerance, improved heat stress tolerance, and resistance to wind damage. Adapting crops to changing temperature and precipitation patterns, optimizing flowering time, improving water-use efficiency, and managing pest and disease pressures are other critical aspects (Kissoudis et al., 2016; Marsh et al., 2021; Cvejić et al., 2022; Karthika; Govintharaj, 2022).

In addition to breeding climate-resilient varieties, adopting agroecological practices can enhance the resilience of agricultural systems to climate change. Agroecology emphasizes ecological principles, biodiversity conservation, and the integration of crops with their surrounding ecosystems. By promoting agroecological approaches such as agroforestry, cover cropping, and crop rotation, plant breeding and seed systems can support climate resilience by fostering healthy, diverse agroecosystems that can better adapt to changing conditions (Altieri et al., 2015; Zhu et al., 2019; FAO, 2021).

Farmers' knowledge and experiences are invaluable in developing climate-resilient crop varieties (Ceccarelli; Galie; Grando, 2013). Plant breeding and seed systems should actively engage with farmers, involving them in participatory breeding programs, on-farm trials, and knowledge-sharing platforms. This collaborative approach can help bridge the gap between scientific research and farmers' needs, ensuring that climate-resilient varieties are adapted to local contexts and farming practices. Smallholder farmers, who are often the most vulnerable to climate change impacts, play a critical role in global food production. Plant breeding and seed systems should prioritize the development and dissemination of climate-resilient crop varieties specifically tailored to the needs and conditions of smallholder farmers. This can help enhance their adaptive capacity, food security, and livelihoods in the face of climate change (Almekinders; Elings, 2001; Weltzien; Christinck, 2017; Ceccarelli; Grando, 2022).

In addition, policy and regulatory frameworks play a crucial role in enabling the adoption and dissemination of climate-resilient crop varieties. Governments can support plant breeding and seed systems by implementing policies that incentivize the development and adoption of climate-resilient varieties, provide funding for research and development, streamline regulatory processes for the release of new varieties, and promote sustainable agricultural practices. Additionally, international collaborations and agreements can facilitate the exchange of germplasm and promote cooperation in addressing climate change challenges across borders (Lowaars et al., 2006; Sperling et al., 2020; FAO, 2021).

By prioritizing resilience to climate change in plant breeding and seed systems, we can strengthen the resilience of global food systems and enhance the adaptive capacity of farmers in the face of climate-related challenges. This requires a multi-faceted approach that combines the development of climate-resilient crop varieties, the adoption of agroecological practices, investment in research and development, supportive policy frameworks, robust seed systems, and active engagement with farmers. Together, these efforts contribute to building a more sustainable and resilient agricultural sector capable of ensuring food security in a changing climate.

Promoting sustainable use of water

The sustainable use of water in agriculture is a pressing challenge, especially as irrigated agriculture expands and extreme weather events such as droughts become more frequent due to climate change (Passioura, 2006; Pereira, 2017). To ensure food security and minimize environmental impacts, optimizing water use in agriculture is crucial. Plant breeding and seed systems have a significant role to play in addressing this challenge and promoting the sustainable use of water (Condon et al., 2004).

Investment in research and development is essential to further advance the sustainable use of water in agriculture. Continued exploration of genetic resources, combined with cutting-edge technologies and innovative breeding approaches, can unlock new opportunities to enhance water-use efficiency in crops. Additionally, research efforts should focus on understanding the complex mechanisms underlying drought tolerance and water-use efficiency, enabling breeders to develop more resilient and productive crop varieties.

The sustainable use of water in agriculture is a critical challenge that can be addressed through plant breeding and seed systems. By accessing genetic variability, utilizing biotechnological tools, and embracing precision agriculture, breeders can develop crop varieties that optimize water use, enhance water-use efficiency, and contribute to the sustainable production of food while minimizing environmental impacts. Collaboration, research investment, and knowledge sharing are essential to ensure progress in promoting the sustainable use of water in agriculture (FAO, 2021; Lopes, 2021a).

Promoting more effective protection of agriculture

Ensuring the protection of agriculture from exotic organisms and invasive species is a critical challenge for global food production. As the movement of pests and diseases becomes increasingly facilitated by globalization, trade, and tourism, plant breeding and seed systems have a vital role to play in promoting more effective protection of agricultural systems (Paini et al., 2016).

Through the exploration of genetic diversity, plant breeders can identify natural sources of resistance to pests and diseases. This genetic variability provides the foundation for the development of crop varieties that are inherently more resistant, reducing the reliance on chemical pesticides and promoting sustainable pest management practices. By incorporating resistance traits into commercial cultivars, breeders can help protect agricultural systems from the detrimental impact of pests and diseases (Krut, 2022, Niks et al., 2019).

Furthermore, advancements in biotechnology offer additional opportunities for more effective protection of agriculture. Genetic engineering and gene editing techniques enable precise manipulation of specific genes and traits related to pest and disease resistance. By introducing or enhancing these traits, breeders can develop crop varieties with improved defense mechanisms against pests and diseases, thereby bolstering the overall protection of agricultural systems (Van Vu et al., 2022; Kin et al., 2020; Ahmad, 2023; Lopes, 2021a).

Continuous investment in research and development is crucial to staying ahead of emerging pest and disease threats. By actively monitoring and studying the evolving nature of pests and diseases, breeders can proactively develop crop varieties with improved resistance to emerging threats. This proactive approach allows for a more effective and timely response to new challenges, reducing the potential impact on agricultural production.

Helping link food, nutrition, and health

The linkage between food, nutrition, and health presents both challenges and opportunities for plant breeding and seed systems (FAO, 2019b, 2020). As the importance of disease prevention and well-being grows, there is a need to develop crops with high nutritional and functional density that can promote better health outcomes. Plant breeding plays a vital role in addressing these challenges and seizing the opportunities to improve food, nutrition, and health (Lopes, 2021a).

One of the key challenges is to develop crops with high nutritional value that meet the specific dietary needs of individuals and populations. This includes breeding for enhanced levels of vitamins, minerals, antioxidants, and other bioactive compounds in crops. By selecting and breeding for these traits, plant breeders can contribute to the development of nutrient-dense crops that can help address micronutrient deficiencies and improve overall nutrition (Simon et al., 2011).

Another challenge is to minimize waste and optimize the production of healthy food (Schanes; Dobernig; Gözet, 2018). Plant breeding can play a significant role in developing crops that are not only nutritious but also have minimal waste during processing and consumption. This can include breeding for traits such as reduced post-harvest losses, improved shelf life, and enhanced storage properties, ensuring that more of the harvested crop reaches consumers in a usable and nutritious form.

Demographic changes, such as an aging population, also present opportunities for plant breeding and seed systems. As the dietary needs of individuals change with age, there is a need for crops that cater to these specific requirements. Plant breeders can develop crops with enhanced functional properties, such as increased fiber content, improved digestibility, and reduced allergenicity, to support the nutritional needs of different age groups (Shvachko et al., 2021; Steele et al., 2013).

The use of advanced breeding techniques, such as genomics and molecular breeding, can expedite the development of crops with improved nutritional profiles. These techniques enable breeders to identify and select specific genes and genomic regions associated with desired nutritional traits. By integrating these approaches into breeding programs, plant breeders can accelerate the development of crops that meet the requirements of improved food, nutrition, and health (Van Vu et al., 2022; Kin et al., 2020; Ahmad, 2023; Guo et al., 2021; Roell; Zurbriggen, 2020; Zhu; Gao, 2020).

Collaboration among breeders, nutritionists, food scientists, and health professionals is crucial to effectively link food, nutrition, and health. By working together, these stakeholders can ensure that the crops developed through plant breeding align with the nutritional recommendations and health goals. This collaboration can facilitate the exchange of knowledge, data, and resources, enabling more targeted breeding efforts that result in crops that contribute to improved food, nutrition, and health outcomes.

Contribute to sophisticate post-harvest management

Post-harvest losses and the deterioration of harvested crops pose significant challenges to food security and sustainability (Paraschivu et al., 2022). Plant breeding offers valuable opportunities to address these challenges by developing crops with improved post-harvest characteristics, including extended shelf life, reduced losses, and enhanced food quality and safety.

One of the key areas of focus in improving post-harvest management is extending the shelf life of harvested crops (Mbinda; Mukami, 2022). Breeders can select for traits that contribute to delayed senescence, improved storage tolerance, and reduced susceptibility to spoilage organisms. By identifying and incorporating these traits into crop varieties, breeders can offer farmers and food processors crops that have an extended shelf life, allowing for longer storage and reduced post-harvest losses.

Another aspect to consider is reducing post-harvest losses caused by pests, diseases, and physical damage. Plant breeding can contribute to developing crop varieties with enhanced resistance to pests and diseases, minimizing the need for post-harvest treatments and reducing losses due to infestation or decay. Additionally, breeding for traits such as improved structural integrity and resistance to mechanical damage can help reduce losses caused by handling and transportation (FAO, 2019b).

Promote intelligent and sustainable land use strategies

Land use and land use change pose significant challenges for sustainable agriculture (Mora et al., 2020). Challenges that may become opportunities for plant breeding to contribute to the sustainable intensification of land use, enhancing use and efficiency of areas already allocated to production, thus avoiding further pressure over forested and fragile landscapes (Godfray, 2015; Cordeiro et al., 2015). By addressing these challenges and leveraging available opportunities, breeders can play a crucial role in developing improved crops and seeds that are well suited for sustainable land management practices.

One of the main challenges is the need to recover and utilize degraded and abandoned agricultural land instead of resorting to further deforestation. This requires the development of crops that can thrive in these degraded environments, withstand adverse conditions, and contribute to the restoration of soil fertility and ecosystem functions (Martha, 2021; Vilela; Callegaro; Fernandes, 2019). Plant breeding efforts can focus on identifying and incorporating traits that enhance adaptability, resilience, and productivity in these challenging landscapes.

Integrating production systems, such as crop-livestock and crop-livestock-forest, offers a promising approach for sustainable land use (Cordeiro et al., 2015; Martha; Lopes, 2023). These integrated systems promote efficient resource utilization, reduce greenhouse gas emissions, and enhance biodiversity conservation. Plant breeding can contribute by developing and disseminating crop varieties that are well adapted to these integrated systems, maximizing productivity while minimizing environmental impacts. This includes breeding for traits such as plant structure, nitrogen fixation, disease resistance, and compatibility with diverse cropping systems.

In addition, low-carbon agriculture and resilient farming practices are essential for sustainable land use (Brasil, 2010, 2012). This requires the development of crop varieties that can thrive in low-input systems, with reduced reliance on synthetic fertilizers, pesticides, and irrigation. Plant breeding can contribute by selecting and improving traits related to nutrient use efficiency, water-use efficiency, and tolerance to biotic and abiotic stresses. By developing crops that require fewer inputs and are better adapted to changing climatic conditions, plant breeding can enhance the sustainability and resilience of agricultural systems.

Furthermore, genetic resources and breeding research are crucial for identifying and utilizing the biodiversity present in natural and agricultural ecosystems, including farmers' fields (Ceccarelli; Grando, 2022; Cecarelli et al, 2013). This includes exploring the genetic diversity within and between crop species, as well as wild relatives, to discover valuable traits for sustainable land use. By integrating this genetic diversity into their programs, breeders can develop crop varieties that exhibit improved performance, resilience, and resource-use efficiency in different land use systems.

Collaboration among breeders, agronomists, ecologists, and planners is vital to address the challenges and capitalize on the opportunities presented by land use. By working together, these stakeholders can ensure that plant breeding and seed systems are aligned with sustainable land management goals. This collaboration can facilitate the exchange of knowledge, data, and resources, enabling more informed breeding decisions and the development of improved crop varieties that contribute to sustainable land use practices.

Plant breeding in the era of precision agriculture

Precision agriculture, with its integration of advanced technologies and data-driven decision-making (Bhakta; Phadikar; Majumder, 2019), presents both challenges and opportunities for plant breeding and seed systems. The ability to implement site-specific management practices opens up new avenues for improving agricultural productivity, resource efficiency, and sustainability.

Precision agriculture requires crop varieties with specific traits that align with the needs of site-specific management practices. Breeders need to focus on developing crops that are responsive to precise inputs, such as fertilizers, water, and pest management. This involves identifying and enhancing traits related to nutrient use efficiency, water stress tolerance, disease resistance, and response to environmental cues. By incorporating these traits into improved seeds, breeders can provide farmers with crops that perform optimally in precision agriculture systems (Basu; Parida, 2023; Abichou; Solan; Andrieu, 2019; Adams; Ritchie; Rajan, 2021).

Site-specific management generates vast amounts of data, including crop performance data, environmental conditions, and soil characteristics. This data can be leveraged through genomic selection and marker-assisted breeding to accelerate the breeding process. By identifying genetic markers associated with desired traits, breeders can use these markers as tools for early selection and screening of plants with the desired traits. This enables faster and more precise breeding decisions, leading to the development of improved varieties tailored for precision agriculture (Chen et al., 2019; Qiao et al., 2023).

Precision agriculture heavily relies on sensor technologies to collect data on various environmental parameters, such as soil moisture, nutrient levels, and crop health. Breeders face the challenge of integrating sensor technologies into their programs to collect relevant data for genotype-phenotype associations. This requires collaboration between breeders, agronomists, and data scientists to ensure the collection of accurate and high-quality data that can inform breeding decisions and the development of targeted traits (Qiao et al., 2023; Araus et al., 2022; Dakir; Barramou; Alami, 2022).

High-throughput phenotyping, which involves the rapid and automated measurement of plant traits on a large scale, is a challenge that can be tackled with the help of precision methods and tools. This allows breeders to evaluate a diverse range of germplasm for desired traits under varying environmental conditions. By utilizing advanced phenotyping platforms and imaging technologies, breeders can capture valuable data on traits such as yield potential, stress tolerance, and nutrient use efficiency. This data-driven approach enhances the precision and efficiency of plant breeding, enabling the selection of superior varieties for precision agriculture systems (Bhakta; Phadikar; Majumder, 2019. Qiao et al., 2019; Dakir; Barramou; Alami, 2022).

Precision agriculture allows for field-specific management practices, enabling farmers to tailor their approaches to individual areas within a field. This creates an opportunity for breeders to develop customized varieties that excel in specific microenvironments or management zones (Abichou; Solan; Andrieu, 2019; Basu; Parida, 2023). It is possible to anticipate that in the future breeders will be able to use precision agriculture data and insights to develop region-specific or even field-specific crop varieties that maximize productivity and resource use efficiency. Customized variety development have enormous potential to empower farmers to optimize their production systems, to increase overall profitability and reach sustainable standards.

Collaboration among breeders, agronomists, data scientists, and agricultural technology experts will obviously be necessary in harnessing the full potential of precision agriculture for plant breeding and production system improvement. By working together, these stakeholders can ensure the effective integration of sensor technologies, data management systems, and advanced phenotyping platforms into breeding programs. This collaboration will facilitate the collection, analysis, and interpretation of data, leading to more informed breeding decisions, helping enhance the efficiency, sustainability, and productivity of agricultural systems.

Plant breeding in the transition to a low-carbon bioeconomy

Agriculture will play a crucial role in the transition to a sustainable and low-carbon economy by contributing as a provider of renewable energy and biomass feedstocks (Lopes, 2022; Martha; Lopes, 2023). With the aim of decarbonizing industries that heavily rely on non-renewable fossil sources for energy, chemicals, and materials, agricultural research must focus on developing crop varieties that are specifically optimized for biomass feedstocks and bioenergy production. By harnessing the genetic diversity within crops, researchers can enhance the efficiency and productivity of bioenergy crops, enabling cost-effective strategies for renewable energy production and the development of sustainable alternatives to fossil-based products (Lopes, 2021a, b).

This emphasis on genetic diversity for new uses highlights the importance of plant breeding and seed systems in enabling the bioeconomy to transition away from fossil fuels and towards renewable and sustainable resources (Vangheluwe et al., 2023). By expanding the genetic diversity available in agricultural crops, researchers can unlock the potential for novel traits and characteristics that are essential for meeting the demands of renewable energy production and the sustainable production of bio-based materials (Lopes, 2022).

Incorporating genetic diversity for new uses into plant breeding and seed systems requires a comprehensive understanding of the specific needs and requirements of the bioenergy and biomass industries. This includes identifying and developing crops that have high biomass yields, optimal energy conversion efficiency, and traits that enhance the sustainability and viability of bioenergy production systems. Additionally, it involves exploring innovative biotechnological approaches, such as metabolic engineering and synthetic biology, to enhance the production and quality of bioenergy feedstocks (Woźniak-Gientka; Tyczewska, 2023; Vangheluwe et al., 2023; Wei et al., 2022).

By leveraging genetic diversity and incorporating it into plant breeding and seed systems, agriculture can play a pivotal role in providing sustainable alternatives to fossil-based energy sources and materials (Lopes, 2022). This shift towards renewable resources not only contributes to the decarbonization of industries but also offers opportunities for rural development, job creation, and economic growth in agricultural communities.

Culinary innovation and social-economic opportunities

Another important aspect to consider is the potential for leveraging genetic diversity to meet consumer demand for new flavors, aromas, and unique culinary experiences (Durazzo, 2019). This presents a significant opportunity for social inclusion and wealth generation in rural areas. Consumer preferences and culinary trends are continually evolving, with increasing interest in diverse and exotic flavors, unique ingredients, and traditional cuisines (Topczewska et al., 2022). This demand for novelty and variety opens up avenues for farmers, breeders, and the seed industry to explore and capitalize on the rich genetic diversity of crops and underdeveloped biodiversity sources.

By focusing on genetic resources and crop improvement strategies that emphasize flavor profiles, aromatic characteristics, and culinary attributes, plant breeders can develop new varieties that cater to consumer preferences. This involves identifying and harnessing the genetic diversity present in crop plants to create unique and exciting culinary experiences. Furthermore, promoting local and traditional crops, which possess distinct flavors and cultural significance, can contribute to preserving biodiversity and supporting local economies. By cultivating and commercializing these crops, farmers can tap into niche markets, direct-to-consumer sales, and value-added product development (Lopes, 2017; Lopes, 2023).

The exploration of genetic diversity for new uses not only enhances the culinary experience for consumers but also creates opportunities for income diversification, entrepreneurship, and rural development. By embracing the diverse flavors and culinary potential offered by genetic diversity, agricultural communities can foster social inclusion, preserve cultural heritage, and generate economic prosperity. The utilization of genetic diversity for new flavors, aromas, and unique culinary experiences represents a promising avenue for social and economic development in rural areas. By aligning crop improvement strategies with evolving consumer demands, farmers, breeders, and the seed industry can contribute to social inclusion and wealth generation while preserving biodiversity and cultural heritage.

Support development of new protein sources and innovative plant-based foods

The emergence of plant-based proteins and innovative plant-based food products is revolutionizing the way we think about sustainable and environmentally friendly nutrition (Langyan et al., 2022). As the demand for plant-based proteins continues to grow, plant breeding and seed systems have a vital role to play in meeting these challenges and unlocking the opportunities presented by this shifting food landscape.

Plant breeding and seed systems could focus on genetic improvement to develop crop varieties that are specifically tailored for plant-based protein sources. This involves harnessing the power of genetic diversity to enhance traits such as protein content, nutritional quality, taste, texture, and other characteristics relevant to plant-based protein production (Giacalone; Clausen; Jaeger, 2022). By leveraging the potential of genetic resources, plant breeders can create crop varieties that meet the evolving needs and preferences of consumers, ensuring a sustainable and diverse range of plant-based protein options.

As the demand for plant-based proteins grows, it is crucial to adapt agricultural systems to support their production. Plant breeders need to develop and disseminate crop varieties that can thrive in sustainable farming practices, such as organic farming, regenerative agriculture, and agroforestry. These practices promote biodiversity, minimize chemical inputs, and enhance soil health, thereby supporting the sustainable production of plant-based proteins. By breeding crops specifically suited to these sustainable systems, plant breeders can contribute to the overall resilience and ecological sustainability of agricultural production (Durazzo, 2019; Ceccarelli; Grando, 2022; Weltzien; Christinck, 2017).

Plant breeding and seed systems can also offer a unique opportunity to enhance sustainability and resource efficiency in plant-based protein production. By developing crop varieties that are adapted to local growing conditions, breeders can minimize the need for synthetic fertilizers, pesticides, and excessive water usage. Additionally, by focusing on traits such as nitrogen fixation, efficient nutrient utilization, and drought tolerance, plant breeders can create crops that are more resilient to environmental stressors, reducing the ecological footprint of plant-based protein production (Guo; Lin, 2021; Durazzo, 2019).

The rise of plant-based proteins presents an exciting opportunity to diversify our crop portfolio and expand market opportunities. Plant breeders can explore and utilize the vast genetic diversity available in plant species to develop new crop varieties with desirable traits for plant-based protein production. This includes lesser-known plant species and underutilized crops that have the potential to become valuable sources of plant-based protein. By expanding crop diversity and commercialization, seed systems can contribute to a more resilient and sustainable food system while creating new market opportunities for farmers.

Rescuing and development of neglected and underutilized crops

Conserving and utilizing genetic diversity, including traditional and neglected crops, is of paramount importance for ensuring a resilient and sustainable food production system. Plant breeding have a crucial role to play in enhancing the genetic diversity of crops and improving neglected and underutilized species, contributing to the diversification of food production and enhancing resilience (Hunter et al., 2019).

Traditional and neglected crops possess valuable genetic resources that have often been overlooked in modern agriculture. Many of these have been cultivated for generations by local communities and offer unique traits such as disease resistance, tolerance to harsh environmental conditions, and nutritional richness. However, due to changing dietary patterns, market demands, and the focus on a limited number of major crops, many traditional and neglected species have been marginalized or even abandoned (FAO, 2019a; Padulosi et al., 2021).

Plant breeding can help rescue and improve neglected and underutilized crops by focusing on their genetic potential. By incorporating desirable traits from traditional and neglected crops into breeding programs, breeders can enhance the adaptability, productivity, and nutritional value of these crops. This can lead to the development of new varieties that are better suited to diverse agroecological conditions, have improved pest and disease resistance, and offer nutritional benefits.

Collaboration with local communities, farmers, and indigenous knowledge holders is essential in accessing and utilizing the genetic diversity of traditional and neglected crops. Their valuable knowledge and expertise can provide insights into the cultivation, utilization, and potential uses of these crops, facilitating the identification of desirable traits and the development of improved varieties (Ceccarelli; Grando, 2022; Weltzien; Christinck, 2017).

To support the enhancement of genetic diversity and the rescue of neglected and underutilized crops, investment in research, capacity building, and infrastructure is crucial. Public and private sector collaborations, along with supportive policies, can facilitate the integration of traditional and neglected crops into mainstream agriculture. Funding for research and development programs aimed at improving these crops can help unlock their potential and create market opportunities by addressing challenges related to nutrition, climate change, and agricultural sustainability.

CONCLUSIONS

Rethinking plant breeding and seed production in the era of fast and profound changes is not just a necessity, but also a responsibility. By embracing innovation, leveraging genetic diversity, enhancing post-harvest management, addressing biotic and abiotic stress, and promoting sustainable practices, we can transform our agricultural systems to be more resilient, more responsive to society´s needs and expectations while environmentally friendly. The reinvention of plant breeding and seed systems is a critical step towards achieving a sustainable future where agriculture harmoniously coexists with the natural world and meets the needs of present and future generations.

REFERENCES

ABICHOU, M.; SOLAN, B.; ANDRIEU, B. Architectural response of wheat cultivars to row spacing reveals altered perception of plant density. Frontiers in Plant Science, 10:999, 2019.

ADAMS, C. B.; RITCHIE, G. L.; RAJAN, N. Cotton phenotyping and physiology monitoring with a proximal remote sensing system. Crop Science, 61(2):1317-1327, 2021.

AHMAD, M. Plant breeding advancements with "CRISPR-Cas" genome editing technologies will assist future food security. Frontiers in Plant Science, 14:1133036, 2023.

ALI, Q. et al. Breeding plants for future climates. In: Hasanuzzaman, M. (ed.). Plant Ecophysiology and Adaptation Under Climate Change: Mechanisms and Perspectives I: Springer, p.753-795, 2020.

ALMEKINDERS, C. J. M.; ELINGS, A. Collaboration of farmers and breeders: Participatory crop improvement in perspective. Euphytica, 122:425-438, 2001.

ALTIERI, M. A. et al. Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development, 35(3):869-890, 2015.

ARAUS, J. L. et al. Crop phenotyping in a context of global change: What to measure and how to do it. Journal of Integrative Plant Biology, 64(2):592-618, 2022.

AYOADE, O.; RIVAS, P.; ORDUZ, J. Artificial intelligence computing at the quantum level. Data, 7(3):28, 2022.

BASU, U.; PARIDA, S. K. Restructuring plant types for developing tailor-made crops. Plant Biotechnology Journal, 21(6):1106-1122, 2023.

BHAKTA, I.; PHADIKAR, S.; MAJUMDER, K. State-of-the-art technologies in precision agriculture: A systematic review. Journal of the Science of Food and Agriculture, 99(11):4878-4888, 2019.

BOHRA, A. et al. Genomic interventions for sustainable agriculture. Plant Biotechnology Journal, 18(12):2388-2405, 2020.

BÖHRINGER, C. et al. Potential impacts and challenges of border carbon adjustments. Nature Climate Change, 12:22-29, 2022.

BONGOMIN, O. et al. Exponential disruptive technologies and the required skills of industry 4.0. Journal of Engineering, Article ID 4280156, 2020.

BRADSHAW, J. E. Plant breeding: Past, present and future. Euphytica, 213:60, 2017.

BRASIL. Banco Central do Brasil. Resolução nº 3.896 de 17 de agosto de 2010. Institui, no âmbito do Banco Nacional de Desenvolvimento Econômico e Social (BNDES), o Programa para Redução da Emissão de Gases de Efeito Estufa na Agricultura (Programa ABC). Diário Oficial da União, Brasília, 18 ago. 2010. Available in:<https://www.bcb.gov.br/pre/normativos/busca/downloadNormativo.asp?arquivo=/Lists/Normativos/Attachments/49552/Res_3896_v1_O.pdf>. Access in: September 19, 2023.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura: Plano ABC (Agricultura de Baixa Emissão de Carbono), Brasília: MAPA/ACS, 2012. 173p.

BUGGE, M. M.; HANSEN, T.; KLITKOU, A. What is the bioeconomy? A review of the literature. Sustainability, 8(7):691, 2016.

CALICIOGLU, O. et al. The future challenges of food and agriculture: An integrated analysis of trends and solutions. Sustainability, 11(1):222, 2019.

CARON, P. et al. Food systems for sustainable development: Proposals for a profound four-part transformation. Agronomy for Sustainable Development, 38:41, 2018.

CECCARELLI, S.; GALIE, A.; GRANDO, S. Participatory breeding for climate change-related traits. *In*: KOLE, C. Genomics and breeding for climate: Resilient crops. vol. 1 Concepts and Strategies. Berlin, Heidelberg: Springer Berlin Heidelberg, p. 331-376, 2013.

CECCARELLI, S.; GRANDO, S. Return to agrobiodiversity: Participatory plant breeding. Diversity, 14(2):126, 2022.

CHEN, K. et al. CRISPR/Cas genome editing and precision plant breeding in agriculture. Annual Review of Plant Biology, 70:667-697, 2019.

CHEN, S. et al. Plant diversity enhances productivity and soil carbon storage. Proceedings of the National Academy of Sciences, 115(16):4027-4032, 2018.

CHOI, J.; OH, S.; KIM, J. The useful quantum computing techniques for artificial intelligence engineers. 2020 International Conference on Information Networking (ICOIN), p1-3, 2020.

CONDON, A. G. et al. Breeding for high water-use efficiency. Journal of Experimental Botany, 55(407):2447-2460, 2004.

CORDEIRO, L. et al. Integrated crop-livestock and integrated crop-livestock-forest systems: Strategies for sustainable intensification of soil use. Cadernos de Ciência & Tecnologia, 32:15-53, 2015.

CRISP, P. A. et al. Beyond the gene: epigenetic and cis-regulatory targets offer new breeding potential for the future. Current Opinion in Biotechnology, 73:88-94, 2022.

CVEJIĆ, S. et al. Innovative approaches in the breeding of climate-resilient crops. In: Benkedia, N. (ed.). Climate Change and Agriculture: Perspectives, Sustainability and Resilience Wiley, p.111-156, 2022.

D'AMATO, D.; BARTKOWSKI, B.; DROSTE, N. Reviewing the interface of bioeconomy and ecosystem service research. Ambio, 49(12):1878-1896, 2020.

D'AMICO, G. et al. Smart and sustainable bioeconomy platform: A new approach towards sustainability. Sustainability, 14(1):466, 2022.

DAKIR, A.; BARRAMOU, F.; ALAMI, O. B. Opportunities for artificial intelligence in precision agriculture using satellite remote sensing. In: BARRAMOU, F. et al. Geospatial intelligence. Advances in Science, Technology & Innovation. Springer, Cham, p. 107-117, 2022.

D'AMATO, D.; KORHONEN, J.; TOPPINEN, A. Circular, green, and bio economy: How do companies in land-use intensive sectors align with sustainability concepts? Ecological economics, 158:116-133, 2019.

DE BOER, I. J.; VAN ITTERSUM, M. K. Circularity in agricultural production. Wageningen University & Research. 2018. 74p.

DENG, L. et al. Recent advances in circular bioeconomy based clean technologies for sustainable environment. Journal of Water Process Engineering, 46:102534, 2022.

DURAZZO, A. The close linkage between nutrition and environment through biodiversity and sustainability: Local foods, traditional recipes, and sustainable diets. Sustainability, 11(10):2876, 2019.

DUVICK, D. N. Plant breeding, an evolutionary concept. Crop Science, 36(3):539-548, 1996.

DUVICK, D. N. Progress in conventional plant breeding. In: GUSTAFSON, J. P. Gene manipulation in plant improvement II. 16th Stadler Genetics Symposium Boston, MA: Springer US. p. 17-31, 1984.

EL-CHICHAKLI, B. et al. Five cornerstones of a global bioeconomy. Nature, 535:221-223, 2016.

ERSOZ, E. S.; MARTIN, N. F.; STAPLETON, A. E. On to the next chapter for crop breeding: Convergence with data science. Crop Science, 60(2):639-655, 2020.

FAO; IFAD; UNICEF; WFP; WHO. The state of food security and nutrition in the world 2023: Urbanization, agrifood systems transformation and healthy diets across the rural-urban continuum. Rome, FAO. 2023. Available in: <https://doi.org/10.4060/cc3017en>. Access in: August 3, 2023.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS - FAO. Global conference on green development of seed industries. 2021, Rome: FAO. Available in: <https://www.fao.org/3/cb7275en/cb7275en.pdf>. Access in: August 3, 2023.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS - FAO. The State of the World's biodiversity for food and agriculture. Commission on Genetic Resources for Food and Agriculture Assessments. Rome (FAO). 2019a. 572p.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS - FAO. The state of food and agriculture: Moving forward on food loss and waste reduction. Rome. 2019b. 182p.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS - FAO. Tracking progress on food and agriculture-related SDG indicators 2020. 2020. Rome. Available in: <https://www.fao.org/family-<farming/detail/en/c/1439675/>. Access in: August 3, 2023.

FRANK, S. et al. Reducing greenhouse gas emissions in agriculture without compromising food security? Environmental Research Letters, 12(10):105004, 2017.

GHISELLINI, P.; CIALANI, C.; ULGIATI, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114:11-32, 2016.

GIACALONE, D.; CLAUSEN, M. P.; JAEGER, S. R. Understanding barriers to consumption of plant-based foods and beverages: Insights from sensory and consumer science. Current Opinion in Food Science, 48:100919, 2022.

GODFRAY, H. C. J. The debate over sustainable intensification. Food Security, 7:199-208, 2015.

GUO, T.; LIN, H.-X. Creating future crops: A revolution for sustainable agriculture. Journal of Genetics and Genomics, 48(2):97-101, 2021.

HANNA, N. A role for the state in the digital age. Journal of Innovation and Entrepreneurship, 7:5, 2018.

HARRINGTON, L. Exponential technology. AACN Advanced Critical Care, 29(1):11-14, 2018.

HERRERO, M. et al. Innovation can accelerate the transition towards a sustainable food system. Nature Food, 1:266-272, 2020.

HICKEY, L. T. et al. Breeding crops to feed 10 billion. Nature Biotechnology, 37:744-754, 2019.

HUNTER, D. et al. The potential of neglected and underutilized species for improving diets and nutrition. Planta, 250:709-729, 2019.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC. Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. 2019. Available in: <https://www.ipcc.ch/srccl/download/>. Access in: September 18, 2023.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC. Climate change 2021: The physical science basis. 2021. Available in: <https://reliefweb.int/report/world/climate-change-2021-physical-science-basis?gclid=EAIaIQobChMIl5rs19ilgQMV2eFcCh2ctw25EAAYAyAAEgJGLfD_BwE>. Access in: September 18, 2023.

JARARWEH, Y. et al. Smart and sustainable agriculture: Fundamentals, enabling technologies, and future directions. Computers and Electrical Engineering, 110:108799, 2023.

KARP, S. G. et al. Bioeconomy and biofuels: The case of sugarcane ethanol in Brazil. Biofuels, Bioproducts and Biorefining, 15(3):899-912, 2021.

KARTHIKA, G.; GOVINTHARAJ, P. Breeding climate-resilience crops for future agriculture. In: SHANKER, A. K. et al. Climate change and crop stress. Academic Press, p. 1-32, 2022.

KHAN, M. H. U. et al. Applications of artificial intelligence in climate-resilient smart-crop breeding. International Journal of Molecular Sciences, 23(19):11156, 2022.

KHANNA, P. Connectography: Mapping the future of global civilization. New York: Random House, 1. ed. 2016. 496p.

KHOURY, C. K. et al. Crop wild relatives of the United States require urgent conservation action. Proceedings of the National Academy of Sciences, 117:33351-33357, 2020.

KIM, C. et al. Application of genotyping by sequencing technology to a variety of crop breeding programs. Plant Science, 242:14-22, 2016.

KIM, K. D.; KANG, Y.; KIM, C. Application of genomic big data in plant breeding: Past, present, and future. Plants, 9(11):1454, 2020.

KISSOUDIS, C. et al. Future-proof crops: Challenges and strategies for climate resilience improvement. Current Opinion in Plant Biology, 30:47-56, 2016.

KRUT, M. Innovations on scientific support of plant breeding for resistance against diseases and pests. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (68):197-207, 2022.

LANGLEY, D. J. et al. The internet of everything: Smart things and their impact on business models. Journal of Business Research, 122:853-863, 2021.

LANGYAN, S. et al. Sustaining protein nutrition through plant-based foods. Frontiers in Nutrition, 8: 772573, 2022.

LOPES, M. A. Descarbonização e circularidade: Respostas dos sistemas alimentar e agroindustrial aos objetivos de desenvolvimento sustentável. Brasília, DF: Embrapa Agroenergia. 2022. 82p.

LOPES, M. A. A agricultura mimetizando a natureza. Correio Braziliense. 2021a, Brasília, DF. Available in: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1137770/a-agricultura-mimetizando-a-natureza>Access in: August 2, 2023.

LOPES, M. A. Agronegócio do futuro será regido por métricas socioambientais e governança. Folha de São Paulo, 2021b. Agronegócio sustentável, 10p. Available in: <https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1137996>. Access in: August 2, 2023.

LOPES, M. A. Alimentos e territórios. Revista Globo Rural, edição de março de 2023. Available in: <https://www.embrapa.br/en/busca-de-noticias/-/noticia/79219780/artigo---alimentos-e-territorios?p_auth=vg60uVfG>. Access in: August 2, 2023.

LOPES, M. A. O turismo rural como gerador de renda e riqueza no campo. Jornal Correio Braziliense, Brasília, DF, 8 jan. 2017. Available in: <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1061017/1/Oturismoruralcomogeradorderendaeriquezanocampo.pdf> Access in: August 2, 2023.

MARSH, J. I. et al. Crop breeding for a changing climate: Integrating phenomics and genomics with bioinformatics. Theoretical and Applied Genetics, 134:1677-1690, 2021.

MARTHA, J.; LOPES, M. A. Charting new sustainable agricultural innovation pathways in Brazil. Scientia Agricola, 80:e20230067, 2023.

MAZZUCATO, M. The entrepreneurial state: Debunking the public vs. private myth in risk and innovation. Londres: Anthem Press, 2013. 266p.

MBA, C.; GUIMARAES, E. P.; GHOSH, K. Re-orienting crop improvement for the changing climatic conditions of the 21st century. Agriculture & Food Security, 1:7, 2012.

MBINDA, W.; MUKAMI, A. Breeding for postharvest physiological deterioration in cassava: Problems and strategies. CABI Agriculture and Bioscience, 3:30, 2022.

MEHTA, N. et al. Advances in circular bioeconomy technologies: From agricultural wastewater to value-added resources. Environments, 8(3):20, 2021.

MORA, O. et al. Exploring the future of land use and food security: A new set of global scenarios. PLoS ONE 15(7):e0235597, 2020.

NATIONAL BIOECONOMY BLUEPRINT. Industry reports: National bioeconomy blueprint. Industrial Biotechnology, 8(3):97-102, 2012

NEWMAN, L. et al. Agriculture for the Anthropocene: novel applications of technology and the future of food. Food Security, 15(3):613-627, 2023.

NIKS, R. E. et al. Breeding Crops with resistance to diseases and pests. Wageningen Academic Publishers, Wageningen, The Netherlands. 2019. 204p.

PADULOSI, S. et al. Orphan crops for sustainable food and nutrition security: Promoting neglected and underutilized species. Routledge. 2021. 470p.

PAINI, D. R. et al. Global threat to agriculture from invasive species. Proceedings of the National Academy of Sciences, 113(27):7575-7579, 2016.

PAN, J. Harmonious coexistence between humans and nature must be promoted. In: PAN, J. China's global vision for ecological civilization. Springer. p.57-72, 2021.

PARASCHIVU, M. et al. Are food waste and food loss a real threat for food security. Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development, 22(1):479-484, 2022.

PASSIOURA, J. Increasing crop productivity when water is scarce: From breeding to field management. Agricultural Water Management, 80(1-3):176-196, 2006.

PATERMANN, C.; AGUILAR, A. A bioeconomy for the next decade. EFB Bioeconomy Journal, 1:100005, 2021.

PEREIRA, L. S. Water, agriculture and food: Challenges and issues. Water Resources Management, 31(10):2985-2999, 2017.

PHILIPPI, JR. A.; ANDREOLI, C. V. Sustentabilidade no agronegócio. USP e Universidade Federal do Paraná. Editora Manole. 2021. 832p.

PRABHA, C.; PATHAK, A. Enabling technologies in smart agriculture: A way forward towards future fields. In: 2023 INTERNATIONAL CONFERENCE ON ADVANCEMENT IN COMPUTATION & COMPUTER TECHNOLOGIES -InCACCT, p. 821-826, 2023.

QIAO, Y. et al. AI, sensors and robotics in plant phenotyping and precision agriculture. Frontiers in Plant Science. 13:1064219, 2023.

RAI, K. K. Integrating speed breeding with artificial intelligence for developing climate-smart crops. Molecular Biology Reports, 49(12):11385-11402, 2022.

ROCKSTRÖM, J. et al. A safe operating space for humanity. Nature, 461:472-475, 2009.

ROCKSTRÖM, J. et al. Planet-proofing the global food system. Nature Food, 1:3-5, 2020.

ROELL, M.-S.; ZURBRIGGEN, M. D. The impact of synthetic biology for future agriculture and nutrition. Current Opinion in Biotechnology, 61:102-109, 2020.

SACHS, J. et al. Six transformations to achieve the sustainable development goals. Nature Sustainability, 2:805-814, 2019.

SCHALLER, R. R. Moore's law: Past, present and future. IEEE Spectrum, 34(6):52-59, 1997.

SCHANES, K.; DOBERNIG, K.; GÖZET, B. Food waste matters: A systematic review of household food waste practices and their policy implications. Journal of Cleaner Production, 182:978-991, 2018.

SCHWAB, K. The fourth industrial revolution. Geneva: World Economic Forum. 2016. Available in: <https://www.weforum.org/about/the-fourth-industrial-revolution-by-klaus-schwab>. Access in: August 3, 2023.

SCHWOOB, M. H. et al. Agricultural transformation pathways toward the SDGs. In: SERRAJ, R.; PINGALI, P. (eds). Agriculture and food systems to 2050: Global trends, challenges and opportunities. World Scientific Series in Grand Public Policy Challenges of the 21st Century vol 2. p. 417-438, 2018.

SHVACHKO, N. A. et al. Bioactive components in oat and barley grain as a promising breeding trend for functional food production. Molecules, 26(8):2260, 2021.

SIMON, P. W. et al. Plant breeding for human nutritional quality. Plant Breeding Reviews, 31:325-392, 2011.

SONG, P. et al. High-throughput phenotyping: Breaking through the bottleneck in future crop breeding. The Crop Journal, 9(3):633-645, 2021.

SPERLING, F. et al. Systems-based approaches for development co-operation to meet diverse needs and aspirations in an interdependent world. In: HYNES, W.; LEES, M.; MÜLLER, J. (eds.). Systemic thinking for policymaking: The potential of systems analysis for addressing global policy challenges in the 21st century. OECD Publishing, Paris, p.77-88, 2020.

STATISTA. Empowering people with data. Number of internet and social media users worldwide as of April 2023. 2023. (in billions). Available in: <https://www.statista.com/statistics/617136/digital-population-worldwide/>. Access in: September 18, 2023.

STEELE, K. et al. Breeding low-glycemic index barley for functional food. Field Crops Research, 154:31-39, 2013.

STEFFEN, W.; CRUTZEN, P. J.; MCNEILL, J. R. The Anthropocene: Are humans now overwhelming the great forces of nature? Ambio, 36:614-621, 2007.

STEGMANN, P.; LONDO, M.; JUNGINGER, M. The circular bioeconomy: Its elements and role in European bioeconomy clusters. Resources, Conservation & Recycling: X, 6:100029, 2020.

STEINWAND, M. A.; RONALD, P. C. Crop biotechnology and the future of food. Nature Food, 1(5):273-283, 2020.

STETKIEWICZ, S. et al. Food system actor perspectives on future-proofing European food systems through plant breeding. Scientific Reports, 13:5444, 2023.

STIGLITZ, J.; GREENWOLD, B. Creating a learning society. New York: Columbia University Press. 2014. 680p.

STRZYZ, P. CRISPR-Cas9 wins nobel. Nature Reviews Molecular Cell Biology, 21:714, 2020.

SUBRAMANIAN, M. Humans versus earth. Nature, 572:168-170, 2019.

THE WORLD IN 2050 - TWI2050. Transformations to achieve the sustainable development goals. Report prepared by The World in 2050 initiative. IIASA Report. International Institute for Applied Systems Analysis (IIASA). Laxenburg, Austria. 2018. 157p.

TOPCZEWSKA, J. et al. Culinary trails in popularizing ethnic cuisines. Journal of Ethnic Foods, 9:43, 2022.

UNITED NATIONS. Transforming our world: The 2030 agenda for sustainable development A/RES/70/1. United Nations, 2015. 41p.

VAN VU, T. et al. Genome editing and beyond: What does it mean for the future of plant breeding?. Planta, 255(6):130, 2022.

VANGHELUWE, N. et al. Facilitating research uptake by the seed and plant breeding sector for bioeconomy development in the EU. EFB Bioeconomy Journal, 3:100059, 2023.

VARSHNEY, R. K. et al. 5Gs for crop genetic improvement. Current Opinion in Plant Biology, 56:190-196, 2020.

VILELA, E. F.; CALLEGARO, G. M.; FERNANDES, G. W. Biomas e agricultura: Oportunidades e desafios. Rio de Janeiro: Vertente edições, 2019. 304p.

VON BRAUN, J. Bioeconomy and its set of innovations for sustainability. Industrial Biotechnology, 16(3):142-143, 2020.

VOSS-FELS, K. P.; STAHL, A.; HICKEY, L. T. Q&A: Modern crop breeding for future food security. BMC biology, 17:18, 2019.

WEI, X. et al. From biotechnology to bioeconomy: A review of development dynamics and pathways. Sustainability, 14(16):10413, 2022.

WELTZIEN, E.; CHRISTINCK, A. Participatory breeding: Developing improved and relevant crop varieties with farmers. In: SNAPP, S.; POUND, B. Agricultural systems. Academic Press. p. 259-301, 2017.

WORLD ECOMOMIC FORUM -WEF. The global risks report 2022. 17th Edition. Cologny, Suíça: World Economic Forum. 2022. 177p.

WOŹNIAK-GIENTKA, E.; TYCZEWSKA, A. Genome editing in plants as a key technology in sustainable bioeconomy. EFB Bioeconomy Journal, 3:100057, 2023.

XIONG, W.; REYNOLDS, M.; XU, Y. Climate change challenges plant breeding. Current Opinion in Plant Biology, 70:102308, 2022.

YOUSAF, A. et al. Artificial intelligence-based decision support systems in smart agriculture: Bibliometric analysis for operational insights and future directions. Frontiers in Sustainable Food Systems, 6:1053921, 2023.

ZANI, P. A. What does the scientific community owe future generations of biologists? Biology in the era following centuries-long anthropogenic change. BioScience, 73(5):331-332, 2023.

ZHAO, J.; LIU, D.; HUANG, R. A review of climate-smart agriculture: Recent advancements, challenges, and future directions. Sustainability, 15(4):3404, 2023.

ZHU, H.; LI, C.; GAO, C. Applications of CRISPR: Cas in agriculture and plant biotechnology. Nature Reviews Molecular Cell Biology, 21:661-677, 2020.

ZHU, Y. H. et al. Evolutionary agroecology: Trends in root architecture during wheat breeding. Evolutionary Applications, 12(4):733-743, 2019.